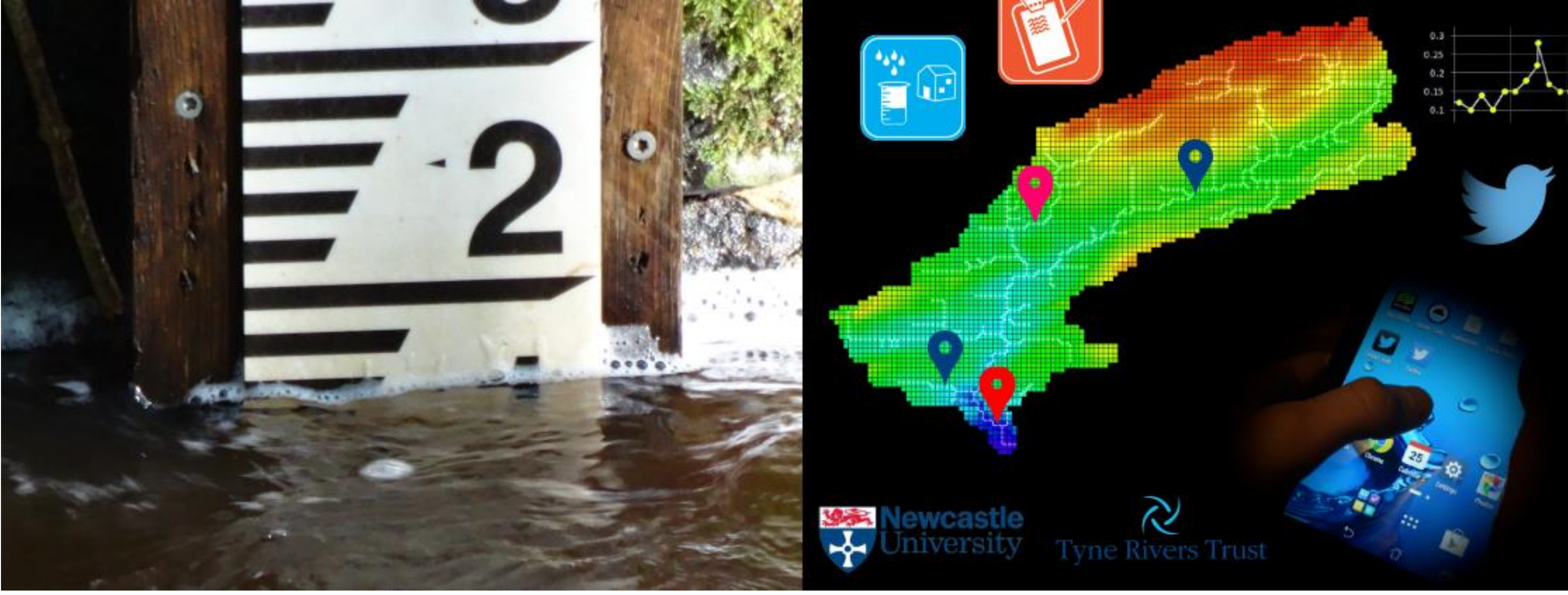

Community-based ('citizen science') monitoring for catchment characterisation, modelling and management

By

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Declaration

I certify that no part of the material offered in this thesis has been previously submitted by me for a degree or other qualification in this or any other university.

Signed:

E. Starkey.

Eleanor R. Starkey

Abstract

Despite there being well-established meteorological and hydrometric monitoring methods, many smaller UK catchments remain ungauged. This leaves characterisation, modelling, forecasting and management activities a challenge when working on a local level. Many 'citizen science' projects are encouraging the public to participate in data collection activities and generate new knowledge across a range of environmental disciplines, but they have not been fully investigated within catchment science.

This project has designed and implemented an innovative community-based monitoring scheme within the 42km^2 Haltwhistle Burn catchment (Northumberland, UK) to explore the feasibility, reliability, value and sustainability of citizen science within the catchment management process. Like many rural UK catchments, the Haltwhistle Burn responds rapidly, experiences flash flooding, and does not benefit from any traditional monitoring networks. Various simple, low-cost and internet-based methods have enabled the public to collect and share rainfall, river level, water quality and flood-related observations successfully over a 29-month period. This generated a patchwork of heterogeneous catchment information.

Although a wide range of people actively participated, 73% of the total number of observations were generated by just four dedicated individuals or households. Despite monitoring efforts being sporadic and unpredictable, rainfall and river level observations were favoured. Participation levels also intensified during high flows or flood events; web-based tools, particularly Twitter, then played an important role in sharing these real-time observations. However, spatial and temporal monitoring efforts are biased towards individual capabilities and interests, and should therefore fill data gaps rather than replace traditional monitoring schemes. Training, ongoing facilitation and feedback help to generate meaningful and good quality data.

A traditional hydrometric monitoring network was installed to aid in assessing the quality and value of community-based observations. Examples presented here verify that citizen science can generate high quality data, provided that robust validation and verification measures are in place. Evidence suggests that participants were conscious of collecting consistent datasets, but this does not guarantee reliable data from every citizen scientist.

The value of community-based observations have been demonstrated by using them to build and run a physically-based, spatially-distributed hydrological model. Results reveal how the local network of community-based observations, when used alongside traditional sources of hydro-information, supports the characterisation of catchment response more accurately than when using traditional observations alone. Community-derived datasets appeared to be most valuable during local flash flood events, particularly towards peak discharge. Such information is often missed or poorly represented by ground-based gauges, or significantly underestimated by rainfall radar, as this study clearly demonstrates.

Community-based observations were also used to tailor the design of a natural flood management (NFM) scheme above the town of Haltwhistle. Post-installation monitoring has revealed that image-based observations collected using simple monitoring methods can provide concerned locals with meaningful and relatable (therefore valuable) information. Such outcomes are important when relieving common barriers affecting the widespread uptake of NFM.

It is acknowledged that the long-term retention of volunteers and the sustainability of citizen science is a challenge. The full monitoring period exposed that participation levels escalated, peaked and then tailed off within Haltwhistle. However, the winter 2015/16 widespread floods reactivated mass data collection. Driven by an existing community-led group, an additional case study site in Northumberland (Acomb) also demonstrates how the public want to monitor, acknowledge the benefits of local datasets, and are capable of initiating and funding their own monitoring scheme. Sustainable (long-term) citizen science therefore requires strong leadership and pertinent (flood risk) motivations. Raising volunteers' awareness on how to maximise the value of their own monitoring efforts will also reduce monitoring fatigue. Furthermore, options have been explored to demonstrate how citizen science can be scaled up to a regional and national level, and be integrated into the existing flood risk and catchment management process.

Although the co-production of environmental knowledge is not a new phenomenon, evolving technology and communications provides a timely and cost-effective solution to mass data collection. Without this data, very little information would be available to characterise catchments and implement localised management measures with confidence. This participatory approach also offers the public an exciting opportunity to share valuable local knowledge, gain ownership, and be actively part of the catchment management process.

Overall, it is concluded that citizen science and the wider community-based monitoring toolkit should now be seen as a fundamental component of any catchment study. The findings and impact generated as a result of this Ph.D. have therefore made a significant contribution to research in this area, and lay the foundations for future community-based projects.

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Contents

Declaration i

Abstract iii

Acknowledgements v

Contents vi

Abbreviations xii

List of Figures xiv

List of Tables xviii

Chapter 1. Introduction 1

1.1. Background – catchments, communities and citizen science 2

1.2. Hypothesis and research questions 6

1.3. Thesis structure 8

Chapter 2. Literature Review 11

2.1. Chapter introduction 12

2.2. Catchments: understanding the water environment 13

2.2.1. Defining the term ‘catchment’ 13

2.2.2. Catchment connectivity: land, water and humans 16

2.2.3. Common catchment issues and climate change 17

2.2.4. Case study (1): the 2007, 2012, 2013-2014 and 2015-2016 UK floods 21

2.2.5. Case study (2): Agricultural intensification and rural runoff in the UK 23

2.3. Managing the water environment: a traditional perspective 24

2.3.1. Roles and responsibilities 24

2.3.2. Overview of legislation, policies and frameworks (UK/EU) 26

2.3.3. Traditional monitoring, data availability and catchment characterisation 28

2.3.4. Disseminating and communicating catchments to the public 31

2.3.5. Case study: Global Thinking, Local Action – The Rivers Trust 34

2.4. A new direction: integrated catchment management 35

2.4.1. Coupled human and natural systems 35

2.4.2. Bottom-up philosophy: the Catchment Based Approach (CaBA) ... 35

2.4.3. Evidence-based catchment management ... 38

2.4.4. Natural Flood Management (NFM) ... 39

2.4.5. Case study (1): Belford Burn NFM scheme, Northumberland ... 42

2.4.6. Case study (2): Taking responsibility on a local level – community flood plans ... 44

2.5. Monitoring by communities: a citizen science approach ... 46

2.5.1. Defining citizen science ... 46

2.5.2. The rise in citizen science for environmental monitoring schemes ... 48

2.5.3. Benefits, challenges and credibility of citizen science ... 50

2.6. Using community-based observations ... 53

2.6.1. Modelling for catchment management ... 53

2.6.2. Visualisation and communication: importance of feedback and presenting catchment information in a meaningful way ... 56

2.7. (Community-based) Participatory Action Research (PAR) ... 59

2.8. Summary (the research gap) ... 60

Chapter 3. Case study sites and focus community ... 61

3.1. Chapter introduction ... 62

3.2. Catchment and community selection ... 62

3.3. Catchment description and pressures ... 65

3.3.1. Overview of the Haltwhistle Burn catchment ... 65

3.3.2. Topography, stream order and sub-catchments ... 66

3.3.3. Geology, soils and land cover ... 67

3.3.4. Climate and climate change ... 69

3.3.5. Flood risk and other catchment issues (knowledge prior to community involvement) .. 71

3.4. Tyne Rivers Trust's CRF project ... 74

3.5. Additional case studies ... 75

3.6. Chapter summary ... 76

Chapter 4. Designing and implementing the community-based (citizen science) monitoring scheme 77

4.1. Chapter introduction 78

4.2. TRT's existing volunteer-based activities 78

4.3. Overarching methodology: the citizen science framework 82

4.3.1. Initial considerations: from a researcher's perspective 82

4.3.2. Initial considerations: from a facilitator's perspective 84

4.3.3. The citizen science framework 85

4.4. Community engagement 88

4.4.1. Ethical assessment 88

4.4.2. Community engagement 89

4.4.3. Initial knowledge exchange 92

4.5. Designing the community-based (citizen science) monitoring scheme 94

4.5.1. Initial considerations 94

4.5.2. Proposed monitoring techniques (methods and tools) 96

4.5.3. Proposed data entry/submission techniques (methods and tools) 103

4.5.4. Encouraging complete, consistent and good quality data collection – examples 107

4.6. Implementing the community-based monitoring (citizen science) scheme 112

4.7. Results: can communities feasibly monitor their local catchment? 117

4.7.1. Who participated? 117

4.7.2. Motivations for participation 120

4.7.3. What have they monitored? Which parameters are favourable? 121

4.7.4. How were observations captured and submitted? 124

4.7.5. Spatial resolution: where did they monitor? 129

4.7.6. Temporal resolution: when did they monitor? 133

4.7.7. Additional findings affecting feasibility 140

4.8. Examples of ongoing feedback 142

4.9. Chapter discussion and summary 145

4.9.1. Discussion – feasibility of citizen science 145

4.9.2. Summary – feasibility of citizen science 148

Chapter 5. Evaluating the quality and reliability of community-based observations....150

5.1. Chapter introduction.... 151

5.2. Overview of the data quality (DQ) literature 152

5.3. Traditional monitoring network....155

5.3.1. Overview of all traditional monitoring sites 155

5.3.2. Environment Agency and Met Office data availability (existing data)....158

5.3.3. Project-specific hydrometric network installed....159

5.3.4. Results: catchment characterisation (with focus on 2014 and winter 2015/2016 floods) 175

5.4. Ensuring reliable community-based observations are available for use 188

5.4.1. Overview - feasibility and availability do not imply reliability....188

5.4.2. Expectations: how do community-based observations differ from traditional data?....188

5.4.3. Next steps: QA and QC framework for community-based observations....190

5.4.4. Initial data screening (QC checks) and acceptance 193

5.4.5. Common issues affecting DQ: what to look out for based on experience....208

5.5. Is community-based data reliable?.... 211

5.5.1. A comparison against traditional datasets 211

5.5.2. Data quality case studies....231

5.5.3. Catchment characterisation using community-based observations 236

5.5.4. Other factors/issues to consider 239

5.6. Chapter discussion and summary....242

5.6.1. Discussion – reliability of citizen science....242

5.6.2. Summary – reliability of citizen science....245

Chapter 6. Demonstrating the value and integration of community-based observations in catchment science 248

6.1. Chapter introduction....249

6.2. Adding value to the catchment modelling process 249

6.3. Integrating community-based monitoring into the catchment management process 252

6.3.1. The importance of integrating citizen science into the catchment management process 252

6.3.2. Overview of the Slaty Sike NFM scheme 254

6.3.3. Local knowledge & community-based observations: identifying the catchment issues 255

6.3.4. Slaty Sike: location and catchment characteristics 257

6.3.5. Design: runoff management plan & land owner consultation 258

6.3.6. Construction 259

6.3.7. Monitoring feature performance (with focus on winter 2015/16 floods) 261

6.3.8. Future and impact of the Slaty Sike NFM scheme 280

6.4. Chapter summary – value and integration of community-based data 282

Chapter 7. Sustainability of community-based monitoring in catchment science 284

7.1. Chapter introduction 285

7.2. Long-term monitoring (Haltwhistle Burn) 286

7.3. Integration on a local level: additional case study from Northumberland 290

7.3.1. Red Burn Catchment, Northumberland 290

7.3.2. A comparison – Haltwhistle and Acomb 294

7.4. Integration on a regional or national level: exploring options 295

7.5. Chapter summary – sustainability of community-based monitoring 299

Chapter 8. Research summary, wider discussion and conclusions 301

8.1. Chapter introduction 301

8.2. Research summary and wider discussion 301

8.2.1. Research summary 301

8.2.2. Key elements involved in setting up a successful, good quality and sustainable community-based monitoring scheme 305

8.2.3. Wider discussion and significance of work 307

8.3. Conclusions 309

8.4. Limitations and recommendations for further work 313

References 316

Appendices 338

Appendix 3A – Location of Environment Agency RRC (Northumberland only) 338

Appendix 3B – TRT'S CRF project briefing 339

Appendix 4A – Project information and participant consent sheets (ethical) 341

Appendix 4B – River Watch Photo Post text (Broomshaw example) 344

Appendix 4C – Training cards (monitoring and data submission techniques) 345

Appendix 4D – Blank 'monitoring preferences and capabilities' questionnaire 349

Appendix 4E – Evidence of community-based training and piloting events 352

Appendix 5A – Gauge summary sheets (NU hydrometric network) 353

Appendix 5B – Modified stage-velocity-area (SVA) rating curve method 361

Appendix 5C – Overview of catchment response (traditional data plots) 367

Appendix 5D – Parameter-specific QC checks applied to the community-based observations 372

Appendix 5E – Extended list of community-based anecdotes collected 374

Appendix 5F – RLGB observations (low flow) obtained using a multi-burst camera setting 378

Appendix 6A – Introducing SHETRAN, the research gaps and the modelling framework implemented 379

Appendix 6B – Calibrating and validating SHETRAN 385

Appendix 6C – SHETRAN Models 1A-1H (Starkey *et al.*, 2017 publication) 393

Appendix 6D – SHETRAN Models 2A-2I and 3A-3H 411

Appendix 6E – Slaty Sike NFM gauge summary sheet & QC checks (traditional) 413

Appendix 6F – Slaty Sike NFM observations (community-based) 415

Appendix 7A – Acomb's flood timeline generated using community-based observations 417

Appendix 7B – Case study used by the Met Office to redevelop WOW 418

Appendix 8A – Evidence of wider benefits as a result of community-based monitoring 419

Abbreviations

A4A, Action4Acomb

AE, Actual evapotranspiration

AFAG, Acomb Flood Action Group

AWS, Automatic weather station

BADC, British Atmospheric Data Centre

BGS, British Geological Survey

CaBA, Catchment Based Approach

CB, Caw Burn

CEH, Centre for Ecology and Hydrology

CRF, Catchment Restoration Funds

Defra, Department for Environment, Food and Rural Affairs

DEM, Digital elevation model

$\overline{\boldsymbol{Difference}}$, Average difference

DO, Dissolved oxygen

DQ, Data quality

DTC, Demonstration Test Catchment

EA, Environment Agency

EEA, European Environment Agency

EPA, Environmental Protection Agency

ESDB, European Soils Database

ET, Evapotranspiration

$\boldsymbol{ETo}$, Reference evapotranspiration

EU, European Union

F/ULO, Farmer / upstream land owner

FAO, Food and Agriculture Organization

FPP, Fixed point photography

FWR, Foundation for Water Research

GUI, Graphical user interface

HB, Haltwhistle Burn

HOST, Hydrology of Soil Types

IC, Initial conditions

IPT, Impress pressure transducer

Ks, Saturated hydraulic conductivity

LB, Left bank

LCM, Land Cover Map

m AOD, Metres above Ordnance Datum

MIDAS, Met Office Integrated Data Archive System

MORECS, Met Office Rainfall and Evaporation Calculation System

NAO, North Atlantic Oscillation

NBS, Nature-based solutions

NCC, Northumberland County Council

NFM, Natural flood management

$\mathbf{NO_2}$, Nitrites

$\mathbf{NO_3}$, Nitrates

NRFA, National River Flow Archive

NSE, Nash-Sutcliffe efficiency

NU (or **NCL**), Newcastle University

O, Other

Obs, Observation

OOE, One-off-event

OS, Ordnance Survey

P, Precipitation

PAR, Participatory action research

PB/WC, Passer-by / wider community

PBIAS, Percentage Bias

PBSD, Physically-based spatially-distributed

PE, Potential evapotranspiration

PGB, Pont Gallon Burn

PO_4, Phosphates

P*r*, Exceedance probability

Q, Discharge

QA, Quality assurance

QC, Quality control

Q*obs*, Observed discharge

Q*peak*, Peak discharge

Q*sim*, Simulated discharge

r, Pearson product-moment correlation coefficient

R^2, Coefficient of determination

RAF, Runoff attenuation feature

RB, Right bank

RGSA, River grid squares accumulation

RLGB, River level gauge board

RMSE, Root Mean Square Error

RP, Return period

RQ, Research question

RR, Rainfall-runoff

RRC, Rapid Response Catchment

RWFG, River Watch & Flood Group

SAC, Special Area of Conservation

SD, Soil depth

SEPA, Scottish Environment Protection Agency

SHETRAN, Système Hydrologique Europeén TRANsport

SOF, Strickler overland flow

SPRHOST, Standard percentage runoff

SSSI, Site of Special Scientific Interest

SVA, Stage-velocity-area

TBR, Tipping bucket rain

TRT, Tyne Rivers Trust

UAV, Unmanned aerial vehicle

VGI, Volunteered geographical information

WFD, Water Framework Directive

WLR, Water level recorder

WMO, World Meteorological Organization

WOW, Weather Observations Website

WQ, Water quality

WwNP, Working with Natural Processes

Y, Water level or depth

ΣQ, Total discharge

Δt, Timestep

• Traditional and community-based

∗ Traditional only

♦ Community-based only

◊ Rejected

List of Figures

Figure 1 (intro). *Land, water and people are connected…* 1

Figure 1.1. December 2015 record-breaking hydro-meteorological observations 2

Figure 1.2. Thesis components 8

Figure 2 (intro). *Review of Current Knowledge (ROCK) booklet* 11

Figure 2.1. Schematic of generic river networks and the catchment landscape 14

Figure 2.2. The river network draining the Eden catchment 15

Figure 2.3. Invasive non-native aquatic species campaign 18

Figure 2.4. Number of people living on the floodplain in England 20

Figure 2.5. Damage and disruption as a result of the summer 2007 floods 21

Figure 2.6. Mean temperature and total rainfall for the UK (Dec-Jan) since 1910 22

Figure 2.7. Organisations and authorities responsible for Flood Risk Management in England 25

Figure 2.8. The main drivers for catchment management 27

Figure 2.9. Map showing the Met Office's network of automatic weather stations 31

Figure 2.10. Examples of public engagement material used by the Environment Agency 33

Figure 2.11. Example of live river levels available online to the public 33

Figure 2.12. TRT's key areas of work, including community engagement 34

Figure 2.13. Humber River Basin split into smaller catchments as part of the CaBA 37

Figure 2.14. Natural flood management features in the Belford Burn catchment 43

Figure 2.15. A poster used by flood wardens to raise wider community awareness in Acomb 45

Figure 2.16. A framework used to define citizen science (by Haklay, 2012) 46

Figure 2.17. What citizen scientists are doing to traditional research projects 52

Figure 2.18. Schematic of catchment modelling and the main steps involved 55

Figure 2.19. TRT's 'RiverSim', an innovative and interactive way of involving communities 56

Figure 2.20. Communicating flood risk to the Exeter community using 3D visualisation 58

Figure 3 (intro). *The Haltwhistle Burn catchment – a typical upland headwater catchment* 61

Figure 3.1. Location of the Haltwhistle Burn catchment on a national, regional and local level 64

Figure 3.2. Topography, Strahler stream order and sub-catchment configuration (Haltwhistle Burn catchment) 66

Figure 3.3. Bedrock, surface geology, soil parent material, soil textures and land cover (Haltwhistle Burn catchment) 68

Figure 3.4. Average annual rainfall totals across the UK (A). Monthly and annual rainfall totals and temperature at Spadeadam (B-C) 70

Figure 3.5. Environment Agency flood risk maps and historical flood extents in and around the Haltwhistle Burn catchment 73

Figure 3.6. Location map of the Red Burn catchment in Acomb, Northumberland 76

Figure 4 (*intro*). *The growth in inexpensive and more readily available technology has allowed a community-based monitoring scheme to be implemented* 77

Figure 4.1. TRT's current/past monitoring and engagement activities 80

Figure 4.2. The overarching citizen science framework implemented during this project 87

Figure 4.3. Cumulative Twitter 'impressions' for the @HaltwhistleBurn account between Nov-2013 and Feb-2016 91

Figure 4.4. Catchment issues map embedded on the project website. Data gathered during a participatory mapping exercise with the community 93

Figure 4.5. Steps taken to develop the proposed citizen science monitoring techniques 96

Figure 4.6. Community-based data entry and submission techniques proposed 103

Figure 4.7A. Illustrations and descriptions of the web-based data entry and submission tools (A) 105

Figure 4.7B. Illustrations and descriptions of the web-based data entry and submission tools (B) 106

Figure 4.8. Example training card (rainfall) 108

Figure 4.9. RLGB FPP line-of-sight determined by the position of the River Watch Photo Posts 109

Figure 4.10. Star-based system used to rate the quality of community-based observations 110

Figure 4.11. Examples where quantitative/semi-quantitative data are extracted from simple citizen science techniques 110

Figure 4.12. Web form used to encourage consistent data collection/entry 111

Figure 4.13. Steps taken during the implementation phase of the citizen science programme 112

Figure 4.14. Questionnaire results used to determine initial monitoring preferences 113

Figure 4.15. Example leaflet used to recruit members of the wider community 116

Figure 4.16. Number of individuals who were engaged, and those who then monitored at least once within the 29-month period 117

Figure 4.17. Pyramid illustrating how engagement and monitoring levels flourished 118

Figure 4.18. Total number of observations per individual/household/group involved 119

Figure 4.19. Total number of observations per category of people within the community 119

Figure 4.20. Total number of individuals/households/groups who monitored each type of parameter at least once, and total number of individual observations collected. 124

Figure 4.21. Community-based data entry and submission techniques used by the public (1) 127

Figure 4.22. Community-based data entry and submission techniques used by the public (2) 128

Figure 4.23. How Twitter has provoked wider monitoring benefits 129

Figure 4.24. Spatial coverage of community-based observations 130

Figure 4.25. Frequency of community-based observations made over time 134

Figure 4.26. Total number of observations collected over time: grouped by parameter type (what) and volunteer (who) category 135

Figure 4.27. Examples - participants monitored in the dark or whilst dog walking 140

Figure 4.28. Examples - participants made additional observations during high flow and highlighted equipment maintenance issues 142

Figure 4.29. A community-based monitoring matrix (summary of findings) 146

Figure 5 (intro). *Traditional and community-based monitoring methods* 150

Figure 5.1. Schematics to illustrate random and systematic error and accuracy, precision and bias, on fieldwork measurements 153

Figure 5.2. A time series containing artificial errors to illustrate common problems 153

Figure 5.3. Location of all traditional ground-based monitoring gauges used or discussed 156

Figure 5.4. Traditional monitoring process and DQ framework adopted 160

Figure 5.5. Double-mass plots of daily rainfall totals used to validate NU rain gauges 161

Figure 5.6. Schematic of a typical 'IPT' and 'Diver' gauging station installed 163

Figure 5.7. Example of QC check involving IPT (Y) and manual (Ym) river level observations 165

Figure 5.8. Final diver calibration equations, results and associated errors 168

Figure 5.9. Final IPT and Diver QC checks: double-mass curves for all gauge combinations 169

Figure 5.10. Temporal availability of river level data, with key events of interest highlighted 170
Figure 5.11. Key steps implemented to derive discharge (Q) from water level measurements 170
Figure 5.12. The modified SVA method adopted to produce six rating curves 172
Figure 5.13. Schematic of the telemetry system installed at Broomshaw 174
Figure 5.14. Catchment's response over the full monitoring period (CB at Gibbs Hill) 176
Figure 5.15. Temporal variability: Areal monthly and seasonal rainfall totals 178
Figure 5.16. Areal frequency plots characterising the Haltwhistle Burn's precipitation regime 179
Figure 5.17. Extreme rainfall durations: maximums for each duration specified 180
Figure 5.18. Spatial variability: cumulative rainfall totals over time and events of interest 181
Figure 5.19. Temporal variability: monthly river levels and Q 182
Figure 5.20. Temporal extremes: peak water levels for the CB at Cawfields (top 30) 183
Figure 5.21. Spatial contribution of discharge at a sub-catchment level 183
Figure 5.22. Relationship between catchment area and mean/maximum observed Q 185
Figure 5.23. Spatial and temporal: flow duration curves for each gauging station 185
Figure 5.24. Summary of the Haltwhistle Burn's characteristics and hydrological controls 187
Figure 5.25. Community-based DQ framework adopted to demonstrate reliability 191
Figure 5.26. Initial data screening and generic community-based QC checks applied 194
Figure 5.27. Precision checks: comparing community-based rain gauges against each other 197
Figure 5.28. QC checks used to reject gauge 6 (Cawburn) 199
Figure 5.29. Precision checks: comparing RLGB data against each other 201
Figure 5.30. Monthly maximum, average and minimum RLGB observations 202
Figure 5.31(A-C) Multi-triangulation QC approach: includes all community-based data 205
Figure 5.32. Spatial combination of traditional and community-based gauges analysed 212
Figure 5.33. Double-mass and regression plots for each rain gauge combination 213
Figure 5.34. Double-mass, regression & cumulative plots: Townfoot gauge 216
Figure 5.35. Double-mass, regression & cumulative plots: PGB Headwaters 216
Figure 5.36. Spatial extremes: totals observed by all traditional and community-based gauges 217
Figure 5.37. Extreme rainfall totals: wettest 30 days ranked and plotted 219
Figure 5.38. Timing of the top 30 wettest days observed: Townfoot, Blenkinsopp Hall & Areal 220
Figure 5.39. Paired traditional & community-based (RLGB) river level observations at Broomshaw 222
Figure 5.40. Error plot involving each pair of traditional and community-based river level observations, and 5th December 2015 RLGB example 223
Figure 5.41. Histograms of all individual river level observations collected at Broomshaw 224
Figure 5.42. Time-series of all individual river level observations collected at Broomshaw 224
Figure 5.43. 'River level' duration curves for traditional and community-based data 227
Figure 5.44. Monthly maximum, average and minimum river level observations captured by the Broomshaw traditional sensor, and the three community-based RLGB sites 228
Figure 5.45. Seasonal maximum, average and minimum river level observations captured by the Broomshaw traditional sensor and the three community-based RLGB sites 229
Figure 5.46 Monthly and seasonal regression plots summarising the relationship between traditional and community-based river level data (Broomshaw) 229
Figure 5.47. Examples when the community captured the 'wave effect' 231
Figure 5.48. Observing water level during turbulent flow conditions using traditional sensors 232
Figure 5.49. RLGB observations using the camera's multi-bust mode during turbulent flows 233

Figure 5.50. A comparison between one RLGB observation and its traditional equivalent ... 234
Figure 5.51. Community-based water quality monitoring locations and results (18/10/2014) ... 235
Figure 6 (intro). *Demonstrating how citizen science can bring an important tool to the catchment management process* ... 248
Figure 6.1. All NSE results ranked to highlight model performance ... 251
Figure 6.2. Schematic summarising the potential value of community-based observation in the catchment modelling and characterisation process ... 252
Figure 6.3. Summary and timeline of the Slaty Sike NFM process ... 255
Figure 6.4. Sharing the runoff management plan with relevant stakeholders ... 259
Figure 6.5. Map locating all of the Slaty Sike NFM demonstration features, and photographs ... 261
Figure 6.6. Schematic of the Slaty Sike NFM monitoring scheme ... 262
Figure 6.7. WLR data retrieved from Slaty Sike Divers 1 (upstream) and 2 (downstream of ponds) ... 263
Figure 6.8. Event-based WLR data retrieved from Slaty Sike Divers 1 and 2 ... 264
Figure 6.9. WLR data retrieved from Slaty Sike Diver 3 (upstream of the leaky dam) ... 265
Figure 6.10. Photographs taken by the community – Slaty Sike overland flow ... 267
Figure 6.11. A timeline illustrating when the community monitored the NFM scheme ... 267
Figure 6.12. Community-based NFM observations: Batch 1 ... 269
Figure 6.13. Community-based NFM observations: Batch 2-3 ... 270
Figure 6.14. Community-based NFM observations: Batch 4 ... 271
Figure 6.15. A summary of NFM performance based on the time-lapse videos ... 276
Figure 6.16. Piloting the 'kite-cam' for post-construction NFM monitoring: Slaty Sike ponds ... 279
Figure 6.17. Project stakeholders, including the public, playing the game 'Kerplunk' ... 281
Figure 7 (intro). *Citizen science has been implemented within the Haltwhistle Burn catchment but has raised questions regarding long-term monitoring capabilities* ... 284
Figure 7.1. Challenges to consider following the Haltwhistle Burn citizen science pilot project ... 285
Figure 7.2. Total number of individual RLGB observations collected over the 29-month monitoring period to demonstrate long-term monitoring efforts ... 287
Figure 7.3. Evidence of community-based monitoring continuing into 2017 ... 289
Figure 7.4. Timeline of events as a result of A4A and AFAG implementing their own citizen science monitoring scheme ... 292
Figure 7.5. Monitoring equipment to be purchased through TRT's 'Adopt a Stream' initiative ... 298
Figure 8.1. An example of a media headline as a result of this project (Henderson, 2017) ... 305
Figure 8.2. Key elements involved in setting up and running a successful community-based monitoring scheme ... 306
Figure 8.3. Modern day catchment management stakeholders and the movement of knowledge ... 309

List of Tables

Table 1.1. A summary of the thesis structure ... 9
Table 2.1. Negative impacts caused by modern day farming practices ... 24
Table 2.2. Examples of traditional monitoring equipment used to characterise the water environment ... 30
Table 2.3. Examples of NFM/WwNP features ... 41
Table 2.4. Examples of citizen science projects in the weather and water environment ... 49
Table 2.5. Challenges associated with citizen science and environmental monitoring schemes ... 53
Table 3.1. Chronology of relevant meteorological & flood-related events (Haltwhistle area) ... 72
Table 4.1. Engagement methods adopted across the Haltwhistle Burn community ... 90
Table 4.2. Initial considerations during the citizen science monitoring toolkit design phase ... 95
Table 4.3. Community-based monitoring activities described for rainfall totals ... 98
Table 4.4. Community-based monitoring activities described for river levels ... 99
Table 4.5. Community-based monitoring activities described for extreme weather/flood observations and impacts ... 100
Table 4.6. Community-based monitoring activities described for water quality ... 101
Table 4.7. Community-based monitoring activities described for weather diaries ... 102
Table 4.8. Examples of heterogenic community-based observations collected and submitted ... 122
Table 4.9. Community-based data captured for each parameter and associated information ... 126
Table 4.10. The intersection and proximity of community-based observations with geographical features 131
Table 4.11A. Temporal coverage of community-based observations collected (A) ... 137
Table 4.11B. Temporal coverage of community-based observations collected (B) ... 138
Table 4.12. Examples of instant and periodic feedback mechanisms adopted ... 144
Table 5.1. Traditional monitoring sites (and metadata) used or discussed ... 157
Table 5.2. Number of Y-Q points obtained for each monitored site & error analysis for each rating curve .. 173
Table 5.3 Examples of high and low flow conditions within the Haltwhistle Burn ... 177
Table 5.4. Comparison between winter 2015/16 extreme rainfall totals (traditional and published) ... 181
Table 5.5. Rainfall runoff (RR) coefficients for the CB at Cleughfoot ... 187
Table 5.6. Factors affecting DQ: comparison between community-based and traditional ... 189
Table 5.7. Summary of the DQ controls put in place during and after monitoring activities ... 192
Table 5.8. Examples of data DQ issues encountered during the community-based scheme ... 210
Table 5.9. Correlation and summary statistics for each gauge combination: daily rainfall ... 214
Table 5.10. Correlation and summary statistics for each gauge combination: monthly rainfall ... 214
Table 5.11. Correlation and summary statistics for each gauge combination: seasonal rainfall ... 214
Table 5.12. Winter 2015/16 extreme rainfall totals (community-based, traditional & published) ... 219
Table 5.13. Extracts of data to illustrate typical RLGB scenarios at Broomshaw ... 226
Table 5.14. Top 30 daily river level maxima: traditional Broomshaw gauge and three RLGBs ... 230
Table 5.15. Characterising the Haltwhistle Burn catchment using community-based data ... 237
Table 6.1. Community-based observations which highlight the catchment's sediment issues ... 256
Table 6.2. The Slaty Sike NFM demonstration site ... 257
Table 6.3. Time-lapse camera specifications and settings used to monitor NFM performance ... 273
Table 6.4. Selection of time-lapse images which convey pond and leaky dam performance ... 277
Table 7.1. Evidence that citizen science is now integrated within the Acomb community ... 293

Chapter 1. Introduction

Figure 1 (intro). *Land, water and people – catchments are connected systems exposed to multiple pressures. However, people (i.e. the public) are slowly becoming more informed and involved in the flood risk and catchment management process. Image source:* (top) West County Rivers Trust – http://wrt.org.uk/ (bottom) Environment Agency https://twitter.com/EnvAgencyYNE.

1.1. Background – catchments, communities and citizen science

While rivers and their surrounding catchments are subject to multiple pressures, and people are becoming increasingly aware and concerned about the natural environment, flooding is arguably the most persistent environmental hazard to local communities within the UK (Thorne, 2014). Low pressure systems passing in from the south-west, accompanied by localised and heavy convective storms, generally dominate the severe and wet weather events experienced. Over the past decade, most regions in the UK have experienced some form of widespread flooding, with a number of record-breaking rainfall totals and river levels being witnessed (even since this Ph.D. project began in October 2013). This includes the winter 2015/2016 floods when a remarkable number of storms and resulting impacts were experienced (Burt and Kendon, 2016; Marsh *et al.*, 2016). During this period, many places in northern England, Scotland and Wales witnessed rainfall totals which were greater than 250% of the 1971-2000 average, and mean river flows were categorised as 'exceptionally high' (Figure 1.1). The Environment Agency (2016) confirmed that 6300 properties were flooded in Cumbria alone. Similar scenarios are also being experienced across Europe annually, with billions of euros being allocated towards flood damage.

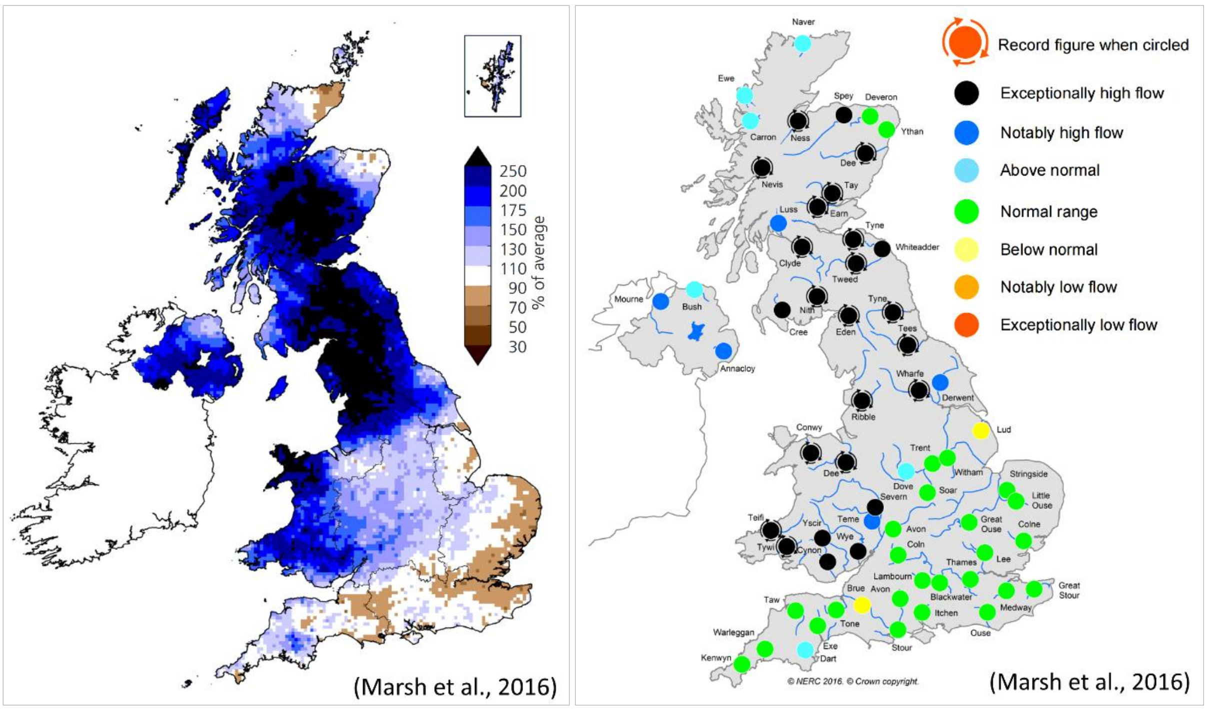


Figure 1.1. December 2015 record-breaking hydro-meteorological observations: Rainfall maps as a percentage (%) of the 1971-2000 average (left) and monthly mean river flow trends (right).

Despite the UK having some of the world's most reliable (high quality) and dense hydrometric and meteorological monitoring networks, data remains scarce for many small and rural catchments (Faulkner *et al.*, 2012; Illingworth *et al.*, 2014; Buytaert *et al.*, 2016). To put this into context, the

UK's National River Flow Archive (NRFA) contains approximately 1500 formal river flow gauging stations, and while the number of monitoring stations have risen considerably since the 1960s (CEH, 2017), providing a total of over 59,000 years' worth of daily flow data combined, a network of this size equates to one flow gauging station per ~200km stretch of UK river network (CEH, 2016). Faulkner *et al.* (2012) state that over 90% of small catchments (<25km^2) are consequently ungauged, despite being important hydrological contributors. This does not provide adequate information to the one in six properties that are at risk from flooding (Environment Agency, 2009a). Formal monitoring sites are generally positioned on larger main rivers and clustered around towns and cities, away from upstream tributaries.

Catchments are inevitably spatially and temporally complex though; empirical datasets are required for scientists to characterise whole-catchment behaviour over time, model floods, improve forecasts and subsequently enhance community resilience as part of the wider catchment management process. Catchment modelling activities are particularly susceptible to uncertainty if they do not benefit from good quality, high resolution and ground-based datasets (Beven, 2009). Attention has also turned to flash floods in recent years because they are still poorly understood. These hydrologically important events, which have abrupt onsets, are harder to capture and characterise given that they are rarer, spatially localised and short lived (Archer and Fowler, 2015; Archer *et al.*, 2016; Perks *et al.*, 2016). There are many hydrological episodes which are poorly forecast, and go unreported and unmonitored because they are simply too localised, despite frequent media reports of 'widespread' flooding on a national scale. Nevertheless, 'local level' issues are those which ultimately cause the impact, upheaval and misery to people on the ground. Without some form of knowledge, the foundations for catchment research and management are poor, leaving communities at risk, rather than resilient.

Of course flooding is not the only pressure; restoration activities relating to water quality, morphology, habitats and biodiversity are high priorities for the rapidly emerging River Trusts. Furthermore, climate change scenarios comprising wetter winters and more intense summer storms are expected to exacerbate already complex catchment management issues throughout the UK and western Europe (Chan *et al.*, 2015; Forzieri *et al.*, 2016; Kendon *et al.*, 2014). The importance of data is further emphasised when considering the performance of new catchment management features, such as 'natural flood management' (SEPA, 2015), which lack before, during and after intervention monitoring, and are poorly represented by models. Knowledge increases confidence levels which in turn fuels investment and wider uptake.

Nevertheless, the 2007+ floods catalysed substantial change in the way in which stakeholders carry out catchment management activities. Governmental policies, frameworks and flood reviews (e.g. Pitt, 2008) have started to recognise the potential benefits of engaging, collaborating and actively involving local communities within affected catchments, and this is rapidly being recognised as a vital component of an integrated catchment management toolkit (Bracken *et al.*, 2014; Large *et al.*, 2017). A 'community-led' or 'bottom-up' approach is starting to bridge the gap between different stakeholders and their priorities. Local communities are being encouraged to take ownership of their local water environment at a catchment scale, rather than just their back yard (CaBA, 2016; Defra, 2013). As a result, there has been substantial growth in the number of volunteers working alongside catchment stakeholders in recent years, including flood wardens and those supporting restoration work. Since establishment in 1996, Eden Rivers Trust for example has worked with over 55 schools, engaged with over 10,000 people, and now rely on a team of more than 200 volunteers (Eden Rivers Trust, 2017). Traditionally, engineers and catchment scientists worked in isolation, providing little communication to the public and no involvement whatsoever.

In addition (yet still largely detached) to community involvement in UK catchment management, the number of volunteers (non-experts) collecting and sharing information about the natural environment has advanced enormously worldwide. This 'citizen science' approach has allowed the general public to work alongside scientists and researchers to co-produce new knowledge across a range of environmental disciplines, especially wildlife, biodiversity and conservation (Bonney and Dickinson, 2012; Tweddle *et al.*, 2012; Pocock *et al.*, 2014a; Cooper, 2016). Although the public's level of involvement varies (thus terminology used to describe it, such as crowd-sourcing or volunteered geographical information), it is allowing mass spatial and temporal data collection, which scientists could not attain alone. The growth in more readily available and low-cost technologies, such as smartphones, social media and the internet itself, is allowing citizen science initiatives to grow energetically today. Besides new data, the wider values behind this participatory approach include the various social benefits that it has to offer communities, including engagement, participation, education and empowerment (Hacker, 2013).

It is only recently that this low-cost solution to data collection has started to flourish in hydrology and water resource management (Buytaert *et al.* 2014; 2016). However, involving communities in the data collection phase is still poorly organised and its potential has not been fully understood or even recognised, therefore it is significantly underused within the UK. A recent survey carried out by Blaney *et al.* (2016) highlighted how governmental bodies in the UK (including the Environment Agency, Met Office and Defra) are starting to engage with volunteers, but citizen science for river and flood monitoring is currently one of the least adopted across the environmental spectrum. Citizen science is underused because there are a number of challenges to overcome, preventing catchment scientists from integrating it into practice on a formal basis (Blaney *et al.*, 2016). Data quality and reliability concerns have created barriers, and studies have yet to demonstrate the value of this new type of data, or how it can be integrated into existing practices (e.g. flood modelling and catchment characterisation). It is also common for volunteers to lose interest over time, meaning that some 'professionals' are sceptical of fully relying on the public to support their work. Scientists are also often unfamiliar with the engagement, facilitation, training and dissemination activities, which are all prerequisites of a successful citizen science monitoring scheme (Barthel *et al.*, 2016). Nonetheless, there are considerable opportunities yet to explore, including utilisation of observations, rather than just collection and mapping.

This thesis presents a catchment study which has actively merged the practice of community-based (citizen science) monitoring together with the current integrated and community-led catchment management process. It has investigated the aforementioned gaps and concerns, and has addressed many of the barriers which are currently restricting the wider uptake of citizen science within the field of catchment science. Results are focussed around demonstrating the feasibility, reliability (quality), value (integration) and sustainability of community-based observations when characterising, modelling and managing catchments. To achieve this, work has primarily been carried out in the Haltwhistle Burn catchment, a tributary of the River Tyne in north east England, and the resident community there. It also draws upon examples where the project has already had significant impact in the real world, locally and nationally, which has proved to be a significant benefit of engaging with, and involving, the public in scientific research. This project has also relied upon a wide range of monitoring, modelling, GIS and catchment management techniques, which 'traditional' or professional catchment scientists use, and are regarded as reliable and well-established methods in the literature (Shaw *et al.*, 2011). Findings will be of interest to catchment managers, hydrologists, as well as community and environmental groups who have a common interest in holistic catchment management and who wish to expand their management toolkits.

Although a citizen science monitoring scheme has been implemented, for the purpose of this thesis, a 'community-based' approach is referred to throughout because the level of community involvement (experienced here, and intended in practice) extends far beyond just data collection.

The term 'community' also refers to a group of people who have a common interest (Durham University, 2012; Hacker, 2013), which, in the context of this study, relates to the public who have an interest and/or have had some form of involvement with the local weather and water environment in and around a catchment boundary.

1.2. Hypothesis and research questions

Through findings from existing community-based projects in other environmental disciplines (e.g. Roy *et al.*, 2012) and the current position of the UK's catchment management process, it is hypothesised that:

Community-based ('citizen science') monitoring activities can support the catchment characterisation, modelling and management process because they provide valuable spatial and temporal knowledge about the behaviour and state of individual rural catchments on a local level. The active involvement of the public subsequently triggers various social benefits which are crucial for generating more resilient communities and thus meeting policy targets today.

This is being demonstrated through the following set of research questions (and subsequent objectives for each):

1. Can communities **feasibly** monitor their local catchment using a simple and low-cost citizen science approach?
    a) Engage with a relevant focus community in a catchment which suffers from multiple pressures, including flooding, sediment and water quality issues;
    b) Develop and design a simple and low-cost citizen science monitoring scheme with supporting training, data collection and data submission tools;
    c) Implement, facilitate and review the feasibility of the new citizen science monitoring scheme, and conclude whether it is possible to collect data in this way;
2. Are community-based data **reliable** and meaningful to catchment stakeholders, including the 'professionals'?
    a) Design, install, maintain, process and analyse results from a 'traditional' monitoring network within the same rural catchment;

b) Collate, process and analyse data collected by the community in order to characterise catchment response spatially and temporally, with focus on significant flood events of interest;

c) Compare community-based observations with each other, and with nearby traditional datasets to evaluate the quality, and determine how reliable and meaningful this new source of data is to catchment stakeholders.

3. Can community-based data be used to model, characterise catchment response and be **integrated** into the management process as a new and **valuable** source of catchment information?

a) Set up and run an appropriate hydrological catchment model using traditional data sources;

b) Use data collected by the community to add spatial and temporal detail to the model and determine whether it adds value (and if possible, where) to the modelling process;

c) Use community-based monitoring to support a real catchment management application.

4. Is a community-based monitoring approach **sustainable**?

a) Summarise participation levels and monitoring efforts over time within the main focus community;

b) Determine whether additional communities can implement their own citizen science scheme (based on good practice already gained);

c) Investigate options for regional and national uptake.

In turn, the above objectives will provide valuable data to all catchment stakeholders which is required to make evidence-based decisions with confidence. It is also assumed that a knowledgeable, well-informed and involved community creates a more resilient community.

This research has been part funded by one of Defra's Catchment Restoration Fund (CRF) projects led by Tyne Rivers Trust (TRT). Deliverables and research findings have subsequently contributed to the overall CRF project outcomes as evidence-based knowledge and community involvement were essential for project completion. The community in and around the Haltwhistle Burn catchment in Northumberland has acted as the main 'focus community' for this Ph.D. project. As with any participatory research project, public involvement and subsequent outcomes can often be unpredictable (Hacker, 2013). However, this has been perceived as a benefit here as it has generated new research opportunities and shaped more realistic outcomes. The aforementioned objectives provided an opportunity to demonstrate the feasibility of community-based monitoring for catchment science, therefore results are location- and community-specific. Nevertheless, results presented within this thesis provide a set of useful 'indications' relevant to other UK catchments and communities suffering from similar pressures and data scarcity issues.

1.3. Thesis structure

Figure 1.2 illustrates the backbone of this thesis which relates the hypothesis to the research questions and objectives.

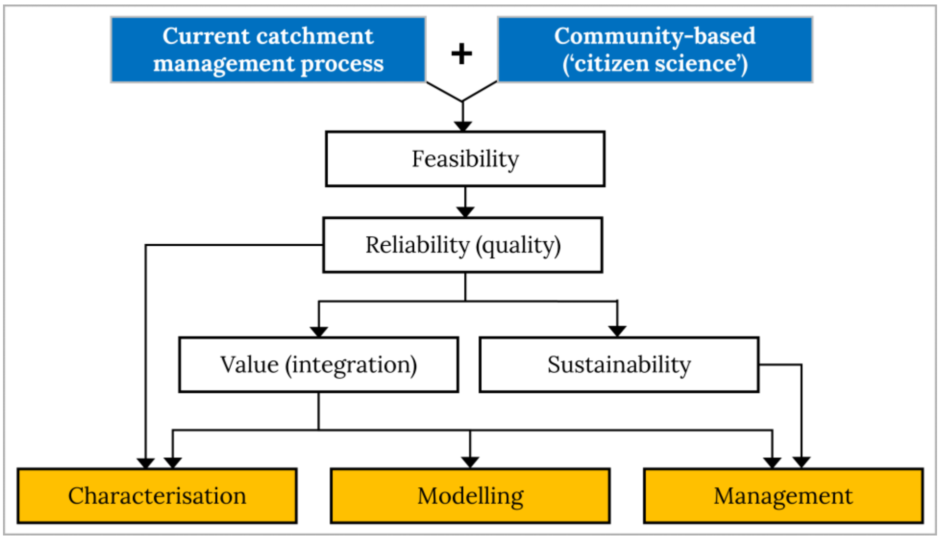


Figure 1.2. Thesis components: relating the hypothesis to the research questions and objectives.

Table 1.1 outlines the thesis structure required to answer the research questions, including an overview of each chapter's content. Working with communities through a 'participatory action research' approach (Hacker, 2013; Bryman, 2016) has meant that the nature of this Ph.D. has started to drift away from a traditional project in catchment science and engineering. The structure and format of this thesis therefore reflects the nature the work carried out. In many places qualitative information is presented to strengthen arguments being made, including accounts witnessed out in the field, along with direct quotes extracted from individuals involved (quotes are included in this document as primary findings and are formatted in *"blue italics"*). Each new chapter also starts with an 'intro' figure to set the scene. And finally, due to the substantial amount of community-based monitoring tools used and observations received from the public, links to online material are provided where necessary as everything could not be included in this document (e.g. photo albums and the project website).

Chapter	Research Q.	Content overview
2. Literature review	All.	Provides a broader overview of catchment science, community-based activities and the benefits and challenges of citizen science. Participatory Action Research is also introduced for the first time. This chapter highlights the research gaps in more detail.
3. Case study sites and focus community	1A.	The main case study site (Haltwhistle Burn catchment) is located and described, with focus on physical properties affecting hydrological response. Key catchment pressures are highlighted and a detailed account of TRT's CRF project is then presented. An additional focus community (Acomb in Northumberland) is also introduced.
4. Designing and implementing the community-based (citizen science) monitoring scheme	1A- 1C.	Chapter 4 provides an overview of existing community-based activities within the Haltwhistle Burn and wider Tyne Catchment. It then presents the engagement process actively applied within the Haltwhistle Burn catchment as a real case study. Methods and results relating to the design, implementation, facilitation and data collection phase of the citizen science monitoring programme are presented. This has allowed the scheme's feasibility to be assessed, and hence answer 'can communities monitor their local catchment?' Monitoring preferences and use of different data submission tools are also discussed, along with ethics. It is argued that feasibility does not imply reliability, and hence Chapters 5-6 investigate the reliability and value of citizen science separately.
5. Evaluating the quality and reliability of community-based observations	2A- 2C.	Chapter 5 relates to the reliability (data quality) aspect of the community-based monitoring scheme. A new traditional hydrometric monitoring network was installed to capture catchment response (rainfall and river level) using robust and automatic monitoring equipment, and co-locate (where possible) the community-based observations. The two monitoring schemes are described along with any quality assurance and control measures adopted. Statistical and graphical methods are used to demonstrate the quality of the community-based observations, present relevant case studies, and extract meaningful hydrological information.
6. Demonstrating the value and integration of community-based observations in catchment science	3A-3C.	Chapter 6 provides a brief summary of the modelling work carried out to demonstrate the value of community-based observations and ability to integrate them into the modelling process. A hydrological catchment model ('SHETRAN') has been set-up for use within the Haltwhistle Burn catchment.

Chapter	Research Q.	Content overview
		Key findings fundamental to catchment science are presented, alongside references to published outputs. To further demonstrate the value, this chapter presents a case study from the Haltwhistle Burn catchment to show how participants have directly influenced and monitored a real (long-term) catchment management application. This case study relates to a new natural flood management scheme that was constructed within the Slaty Sike sub-catchment in 2015. Additional monitoring tools (time-lapse and 'kite-cam') are also presented as potential and unique citizen science monitoring methods.
7. Sustainability of community-based monitoring in catchment science	4A-4C.	Chapter 7 investigates the sustainability of community-based monitoring. This has been achieved by exploring participation levels within the Haltwhistle Burn catchment over the full duration of the project. An additional community-based monitoring scheme (Red Burn catchment in Acomb, Northumberland) is presented qualitatively and analysed based on observational work. The Acomb community implemented their own monitoring scheme following Haltwhistle's footsteps. National options are also explored.
8. Overall discussion and conclusions.	All.	Chapter 8 summarises the overall research project and discussion, bringing together findings from all four research questions. This includes a list of the key elements involved in setting up a successful, good quality and sustainable community-based monitoring scheme. Conclusions, limitations and recommendations for further work are then presented.

Table 1.1. A summary of the thesis structure and how each chapter relates back to the original research questions and objectives.

Chapter 2. Literature Review

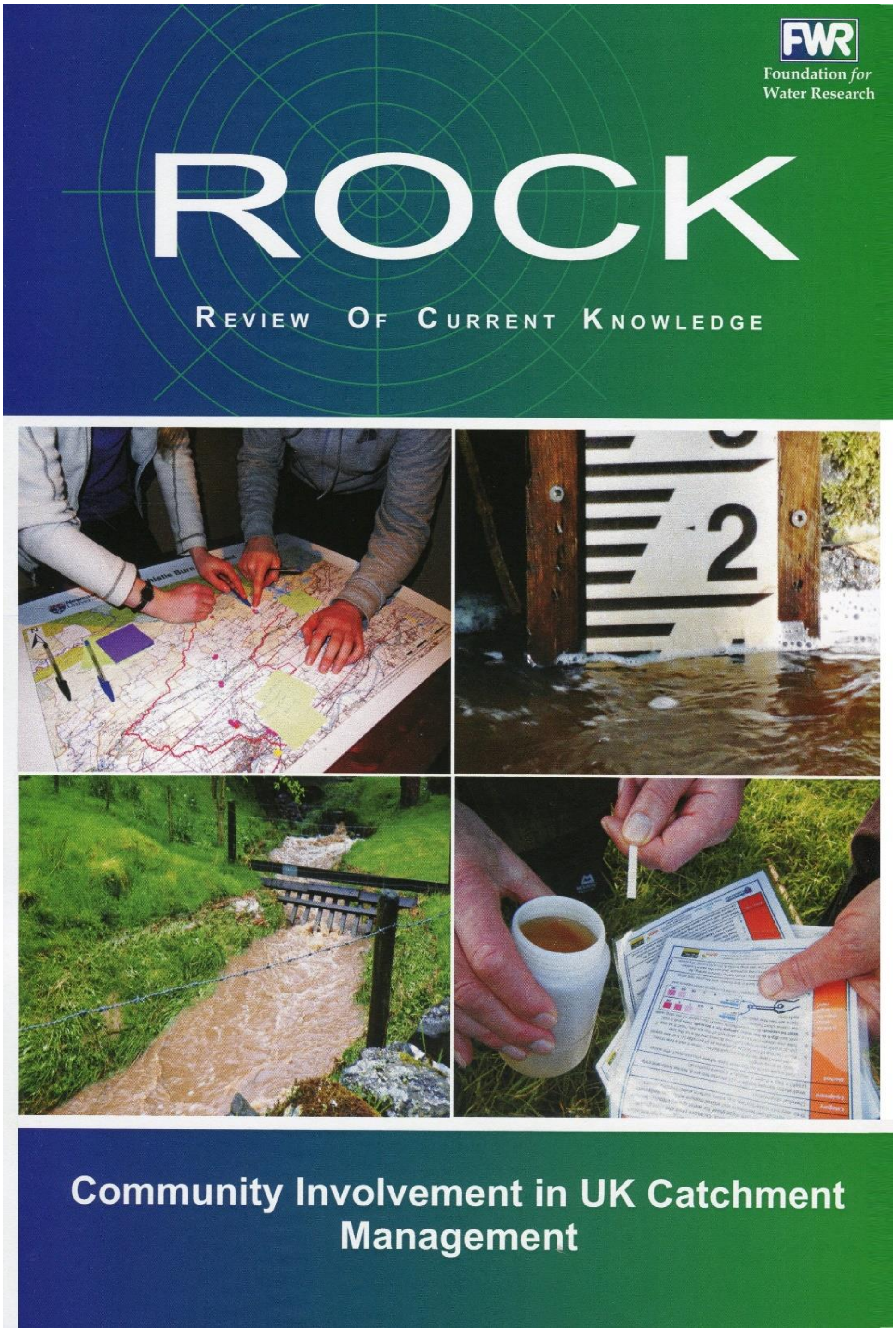


Figure 2 (intro). *Review of Current Knowledge (ROCK) booklet written by Starkey and Parkin (2015) for the Foundation for Water Research (FWR). Open access copies can be downloaded directly from the FWR website:* http://www.fwr.org/Catchment/frr0021.pdf.

2.1. Chapter introduction

This chapter presents a literature review which focuses on the growth in community involvement in catchment management. The review highlights issues related to monitoring, modelling and understanding the complexity of river catchments which are subject to multiple pressures. It details how countries, such as the UK, are now regularly managing catchments on a local level with the involvement of local people. Citizen science has been explored, underlining that this form of monitoring is still underestimated, underused and poorly organised within catchment science. Case studies are presented to emphasise how we are now within '*exciting*' times due to the rapid growth in technology and communication tools, which can, and should, be employed in innovative and integrated ways to support catchment management activities. This chapter then concludes by summarising the key research gaps found within the literature (and in practice) relevant to community involvement and citizen science activities which have motivated this research project.

The majority of this literature review was appraised and then published by the FWR, providing a contemporary addition to the 'Review of Current Knowledge' (ROCK) publication library. These FWR booklets (Figure 2 *intro*) are designed to educate the public on water and wider environmental issues, and support a well informed and knowledgeable society. Despite content being primarily written for the FWR, it also provided a useful 'go to' reference document for the communities and catchment stakeholders with whom this project have worked or engaged with since October 2013. The booklet was also shared and used by various catchment stakeholders and organisations nationally, such as The Rivers Trust, who embedded it with the 'Citizen Science and Volunteer Monitoring and Resources' toolbox[1]. Since published by the FWR in 2015, around 10,000 copies have been bought and downloaded, providing a useful indication of its popularity, therefore impact. Content has since been updated for inclusion in this chapter to reflect more recent developments in this field.

This literature review provides a broad overview to community-based catchment science. Where necessary, more specific reviews are presented in later sections, particularly where methodologies are being sought. It should be noted that this chapter reflects the nature of this project as it contains a review of academic literature, alongside relevant policies and (sometimes unpublished) projects currently being carried out on the ground. This type of review was necessary as community-based or citizen science projects were only just starting to flourish in

[1] http://www.catchmentbasedapproach.org/resources/volunteer-monitoring

academia when the project commenced. A review of the wider literature and websites was also essential because this is how scientists typically communicate and work with the public. A review of catchment issues, traditional monitoring and modelling methods, catchment stakeholder roles and responsibilities, policies and management frameworks also assisted with putting the embarked work into practice and dictated which parameters the community should monitor.

2.2. Catchments: understanding the water environment

2.2.1. Defining the term 'catchment'

Water and its surrounding environment is a fundamental resource to humans, plants and wildlife. On land, this commonly includes ditches, streams, rivers, lakes and water which is stored or travels underground through soils and rocks (groundwater). Despite global variations in terminology, 'catchment' is a term widely used in the UK today by professionals to describe 'the land area which collects all surface runoff flowing in a network of channels to exit at a particular point on the river' under the influence of gravity (Downs and Gregory, 2004; Bren, 2015). This means that catchment boundaries, thus size and shape, are governed by the surrounding topography. Catchments can therefore vary significantly in scale (size), from thousands of kilometres squared, to less than one kilometre squared. Smaller catchments are often referred to as 'sub-catchments', and several of these are typically nested within a larger catchment. This concept can be illustrated by the Thames catchment which covers an area of over 12,000km^2 and has 18 major sub-catchments flowing into the River Thames itself (Thames Rivers Trust, 2014). Variations in catchment scale causes uncertainty across all aspects of hydrology, and controls research being carried out today (e.g. Serinaldi and Kilsby, 2016).

Catchments naturally comprise several components, such as the river and stream network itself, valley sides, floodplains, confluences, sediment, habitats and wildlife. However, most modern day catchments are extensively modified by humans and have experienced urbanisation and/or rural activities. Simple schematics of river catchment networks and a river catchment landscape can be found in Figure 2.1. In reality, river networks are far more complex that those shown in Figure 2.1. A useful example is the Eden catchment (north west England) which covers an area of 2300km^2. The River Eden itself is only 130km long, yet all 98 water bodies in this catchment have a combined length of more than 2490km (Eden Rivers Trust, 2013), as Figure 2.2 illustrates.

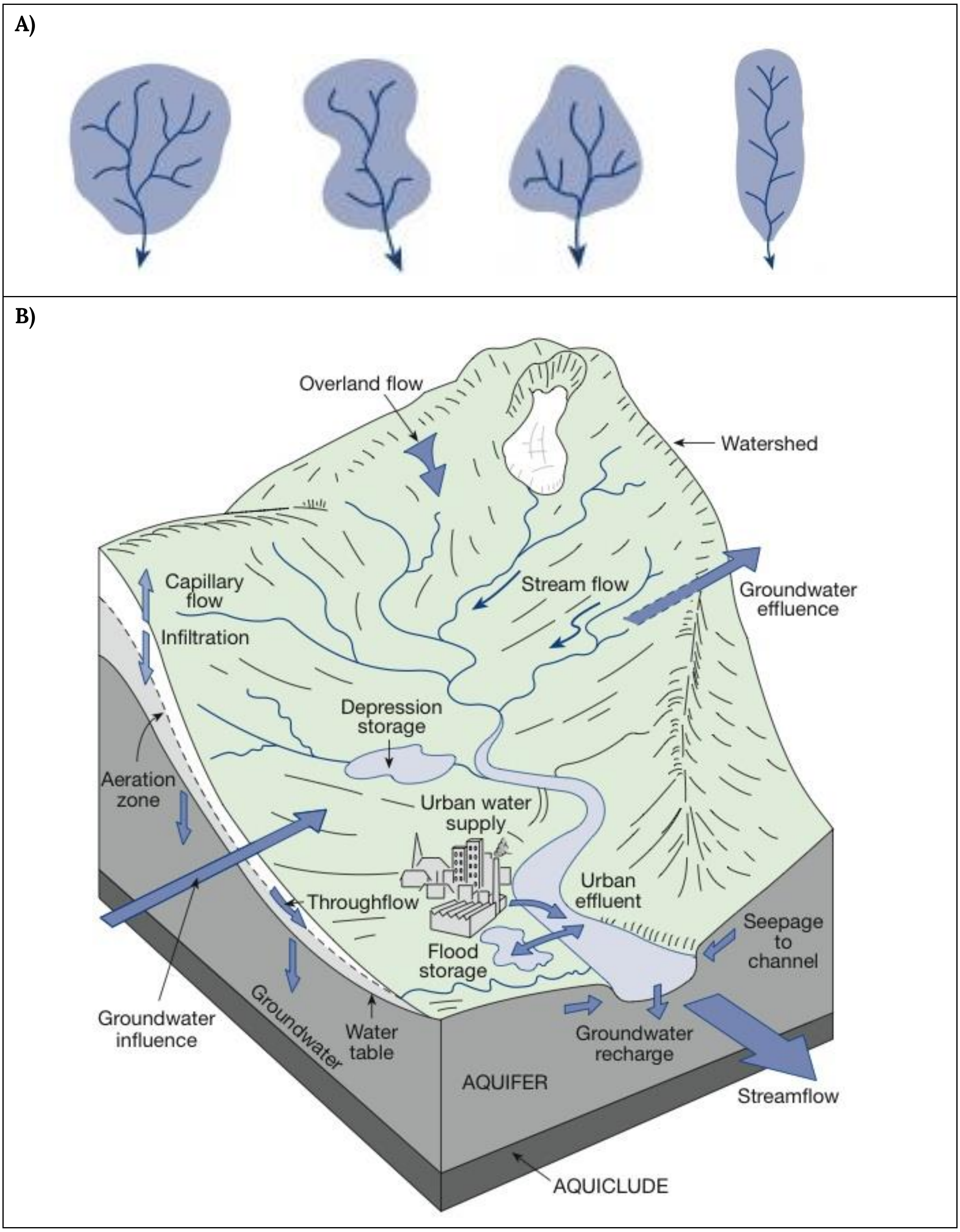


Figure 2.1. Schematic of (A) generic river catchment networks and (B) a typical river catchment landscape (Source: Smithson *et al.*, 2008).

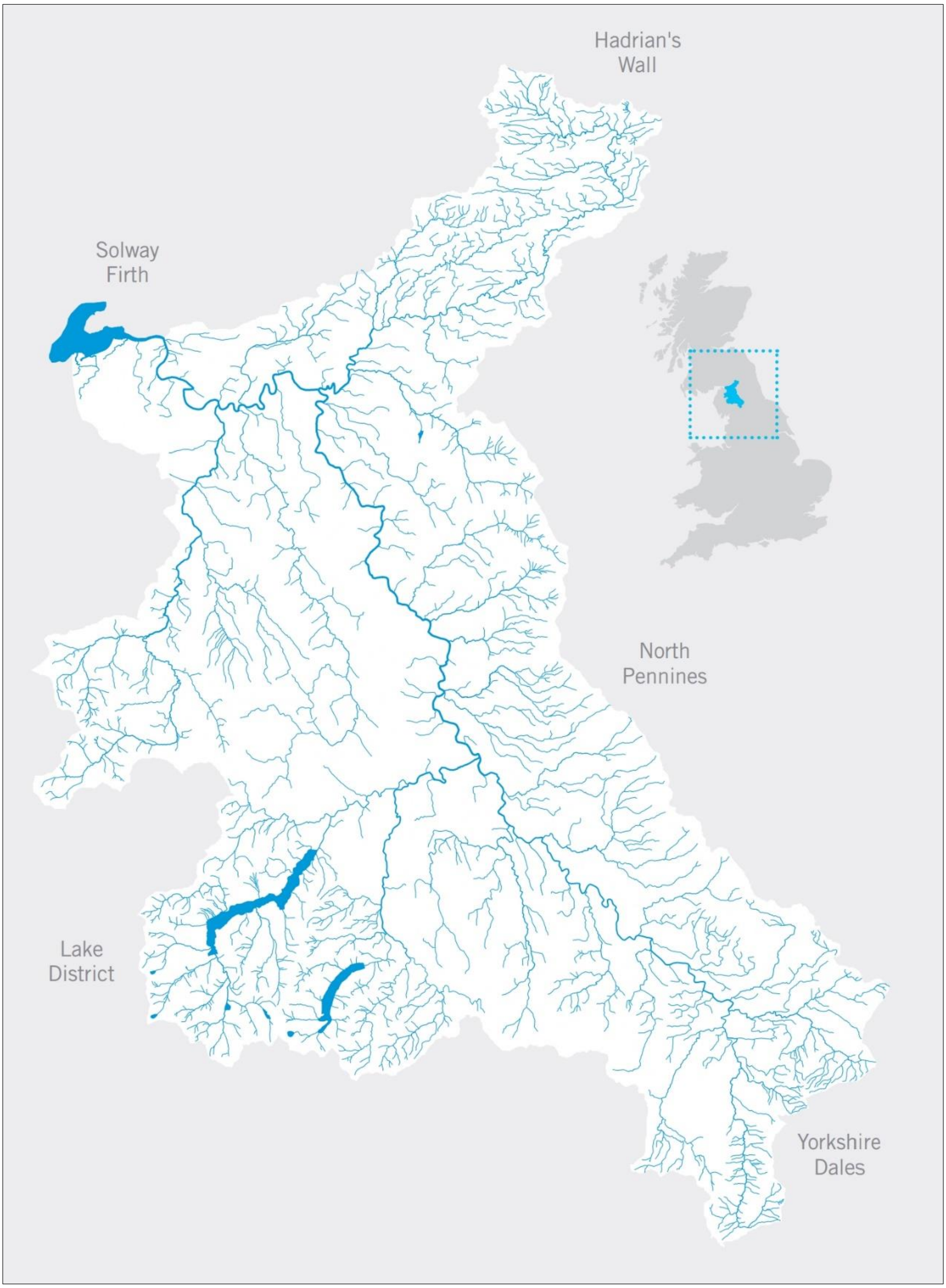


Figure 2.2. The river network draining the Eden catchment in north west England (Source: Eden Rivers Trust, 2013).

2.2.2. Catchment connectivity: land, water and humans

As the term 'network' suggests, streams and rivers are linked from source to outlet, and because they pass over and drain an entire catchment area, there are various land and water interactions occurring. Newson (1997) describes a catchment as an 'interconnected transport system' which transfers both water and sediment downstream. The quantity and quality of the water, and the diversity of aquatic species at the catchment outlet are therefore a signature of an integrated response to everything occurring upstream of that point (Bren, 2015). This is why 'catchment connectivity' is used in catchment science (e.g. Downs and Gregory, 2004; Barron *et al.*, 2009; Newson, 2010; Bracken *et al.*, 2013; Hrachowitz *et al.*, 2013). The behaviour of an individual catchment therefore varies significantly both spatially (across the catchment area) and temporally (Serinaldi and Kilsby, 2016). Spatial scales range from the full catchment or sub-catchment scale, right through to individual reaches, plots or points of interest (Hrachowitz *et al.*, 2013). Behavioural timescales can vary from millions of years (geological processes) down to annual, monthly, weekly, daily, hourly and sub-hourly, with sub-hourly to annual timescales being of most interest to catchment scientists.

Often without fully realising and appreciating it, humans also live and work within catchment systems. This means that human activities influence the characteristics and behaviour of catchments. Human activities are often seen as having a negative impact on catchment response, for example, land cover or land use change, channel modification, water abstraction and waste release. A significant amount of research has shown that modern land use changes have considerable impacts on the quantity, quality and morphology of the river environment (O'Connell *et al.*, 2007; Ewen *et al.*, 2010; Norton *et al.*, 2012; McIntyre *et al.*, 2013). Although rivers have been of high importance since agricultural communities began, and modification of catchment landscapes is long established, Downs and Gregory (2004) emphasise that since the 1960s it has been more widely appreciated that direct changes to the river system can have a profound effect downstream. Most modern-day catchments are affected by a combination of natural processes and human activities. It is therefore fair to say that no two catchments or sub-catchments are alike because their behaviours are shaped and controlled by a number of factors, including topography, weather/climate, soils, geology, land cover, vegetation cover and human activities (Newson, 1997; Ward and Robinson, 2000; Downs & Gregory, 2004; Boon, 2012; Holden, 2012; Bracken *et al.*, 2013; McIntyre *et al.*, 2013). This makes it difficult for scientists and engineers to make sense of the complexity of catchments and the signatures that they create, even at a local level.

Despite this sub-chapter containing quite obvious background information, it is easy for catchment stakeholders and researchers to forget these fundamental principles. It is important to remember that, although there are various ways in which land and human activities can affect the water environment, the river system also plays a significant role in shaping the surrounding landscape and human activities, hence the phrase 'Rivers of the Anthropocene' (Large *et al.*, 2017). River networks are by no means a closed system, and a multi-disciplinary approach is required when managing them.

2.2.3. Common catchment issues and climate change

Owing to the large number of factors affecting the quantity, quality and morphology of a catchment and its river network, catchment stakeholders are inevitably faced with a number of catchment issues. Common UK catchment issues (also applicable to most catchments worldwide (Bren, 2015)) include:

Flooding: There are various sources of flooding including river, surface water, groundwater, tidal, coastal, sewer and reservoir flooding (Environment Agency, 2009a). River and surface water flooding are most common on land and are associated with periods of heavy or prolonged rainfall, often causing 'flash floods'. The European Commission (2014a) highlighted that Europe experienced over 213 major flood events between 1998 and 2009. The UK is typically prone to convective summer flash floods (Archer and Fowler, 2015; Archer *et al.*, 2016; Perks *et al.*, 2016) as well as pro-longed and saturated winter events (Kendon and McCarthy, 2015; Marsh *et al.*, 2016; Thompson *et al.*, 2017). UK-based examples are provided in Section 2.2.4.

Drought: Prolonged periods where precipitation is absent can leave catchments parched, causing river and groundwater levels to drop significantly. River networks can even dry up completely. This affects water supplies and aquatic species, particularly fish. The UK's vulnerability has been highlighted following events such as the spring 1995 to summer 1997 drought (Marsh *et al.*, 2007).

Poor water quality: High levels of pollution can cause the physical and chemical properties of the water environment to change and reach levels which are unusual or unnatural to the water body of interest. Although pollution incidents can be triggered naturally, it is known to be exacerbated by human activities, including agricultural intensification (Withers *et al.*, 2014).

Morphologically active rivers: Rapid rates of erosion and transportation of material, usually sediment or soil during storm events, can knock river systems out of equilibrium, alter channel geometry, and leave them in an unstable state (Newson, 1997; Downs and Gregory, 2004). This provides downstream sediment sources, and can (for example) damage man-made structures, block up culverts and increase flood risk (TRT, 2015).

Degradation of habitats and species: The UK's river corridors contain a diverse range of aquatic habitats and species. Many of these are sensitive and require optimum conditions in order to survive, grow and reproduce. Dramatic changes to the quantity, quality and morphology of a river network or reach will affect population rates. White-clawed crayfish, freshwater pearl mussels and salmon are examples of sensitive aquatic species indigenous to the UK. Capable of living for over 100 years, freshwater pearl mussels for instance were abundant across Scotland during the 19th Century. They are now extinct or diminishing rapidly in two-thirds of the original locations found (Cosgrove *et al.*, 2012).

Invasion of non-native species: Various invasive non-native plant and animal species have been introduced into UK waters and are damaging the environment, causing a threat to native species, and are creating significant economic impacts (The Rivers Trust, 2014a). Rivers Trusts representing catchments across England and Wales have been campaigning to stop the spread of invasive non-native aquatic species, for instance the killer shrimp, American mink, signal crayfish, giant hogweed, Himalayan balsam and Japanese knotweed (Figure 2.3).

Figure 2.3. Invasive non-native aquatic species campaign promoted by The Rivers Trusts (2014a).

Climate change: The UK is expected to experience an intensification of precipitation extremes, including heavier summer downpours and wetter winters (Pitt, 2008; IPCC, 2014; Kendon *et al.*, 2014). This will affect catchment response, including an increased frequency of flood events. Boon (2012) stressed that 'the influence of climate change on rivers will undoubtedly be near the top of the list of threats over the next few years'. Thompson *et al.* (2017) have analysed recent winter storms and suggest that 'unprecedented UK rainfall' is already occurring in our climate system, and hence direct and recent observations are essential.

Due to potential loss of life, damage to properties, businesses and infrastructure, as well as the number of recent events experienced, flooding is the pervasive environmental concern to the UK and much of Europe (Norbury *et al.*, 2015; McEwen *et al.*, 2016). Local communities also experience direct impacts from flooding, meaning that they are much more aware of this type of catchment issue. According to the Environment Agency's National Assessment of Flood Risk (2009a), around 5.2 million (one in six) properties are at risk of flooding in England alone (Figure 2.4). The Scottish Environment Protection Agency (SEPA, 2011) has confirmed that around 125,000 properties are at risk from flooding in Scotland and estimate the average annual cost of flood damage to be as much as £850 million. Despite the importance of flood knowledge, these hydrological events are still poorly monitored, modelled and understood by professionals, particularly flash floods, which require detailed information in order to characterise them and understand the impacts caused (Archer and Fowler, 2015; Perks *et al.*, 2016; Sene, 2016).

Each of the catchment issues listed above are often linked to, and exacerbated, during a flood event. This is primarily because flood waters exert such power, causing sediment and pollution entrainment upstream, and sudden changes and destruction downstream. The connectivity of a catchment is also at its maximum during the peak of a flood event, so the lower catchment system is heavily affected by headwater sub-catchments.

There are a number of UK and European policies, frameworks and plans in place, as well as responsible and regulating bodies to ensure catchment issues are managed sustainably (see Section 2.3.1). Monitoring (Section 2.3.3) and modelling (Section 2.6.1) of catchment-related parameters and processes assist with understanding catchment behaviour, providing evidence to confidently manage the catchment issues previously described. Although many human activities cause negative impacts on the natural environment, catchments and their ecosystems also provide vital resources to humans. They provide 'ecosystem services' or 'natural capital', which encompass the multiple benefits provided by ecosystems that contribute to human life, such as food and water (Everard, 2012). Different stakeholders therefore have different perspectives and vested interests, which can be a challenge to manage sustainably (Taylor *et al.*, 2014; Withers *et al.*, 2014).

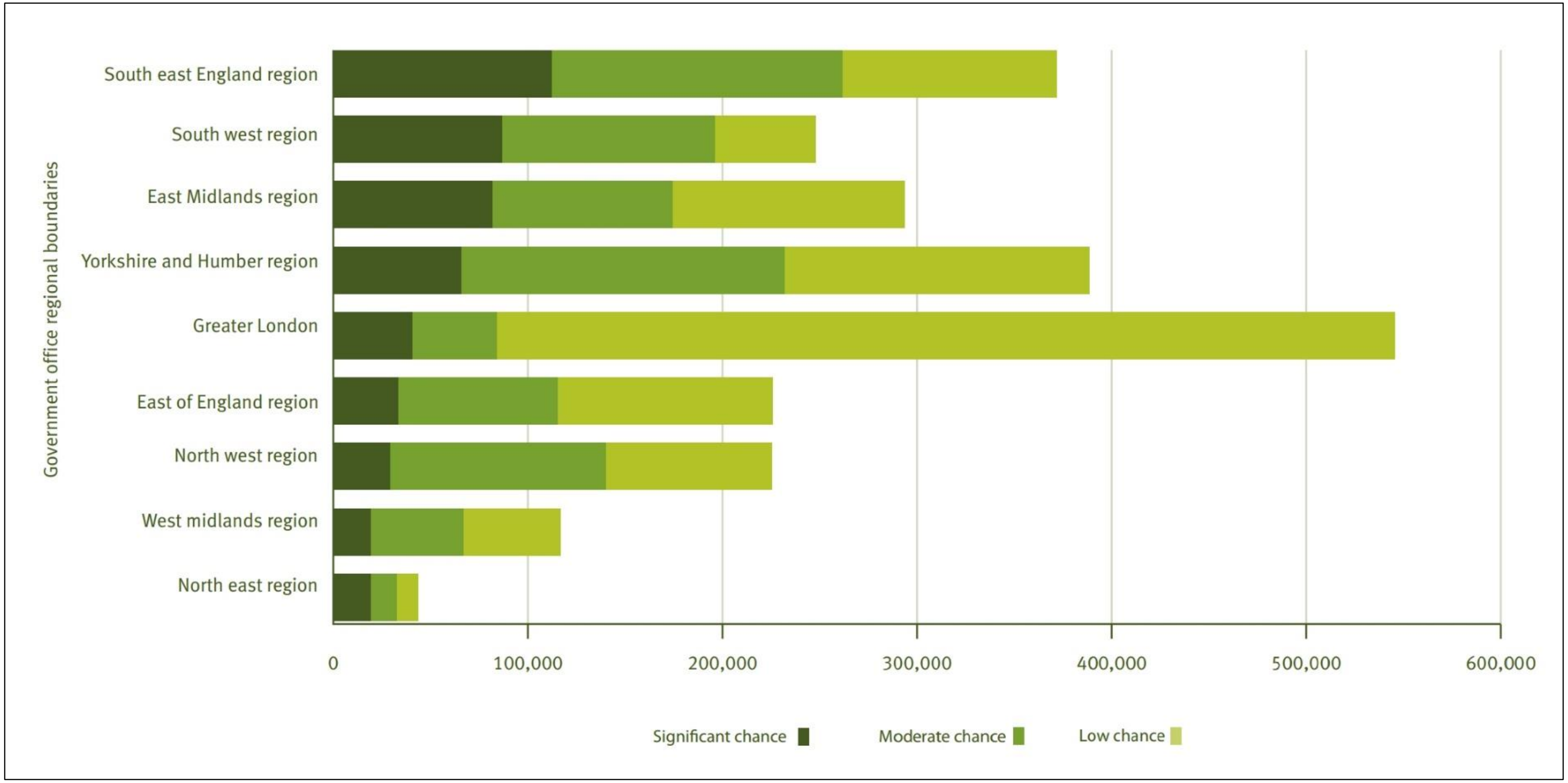


Figure 2.4. Number of people living on the floodplain in England (ranked by Government office regional boundaries) who have a low, moderate or significant chance of flooding (Source: Environment Agency, 2009a).

2.2.4. Case study (1): the 2007, 2012, 2013-2014 and 2015-2016 UK floods

The UK has experienced a number of flood events in recent years, including summer 2007, summer 2012, winter 2013/2014 and the record breaking winter 2015/2016 floods. Although these are well-known events, many smaller and localised flood events occur more frequently and often without warning.

In 2007 the UK experienced the wettest summer on record, with heavy rainfall falling in an exceptionally short period of time (Pitt, 2008; Shaw *et al.*, 2011; McEwen *et al.*, 2016). A flood review was undertaken by Sir Michael Pitt who confirmed that emergency services rescued approximately 7000 people, 13 people died and a total of 55,000 properties were flooded (Pitt, 2008). There was also mass disruption to transport networks, critical infrastructure and some communities were completely isolated and surrounded by flood water (Figure 2.5). The Pitt Review made several recommendations, primarily to ensure the UK is better-prepared for floods in the future, which governmental organisations have acted on since being announced.

Figure 2.5. Widespread damage and disruption as a result of the summer 2007 floods (Pitt, 2008).

There were also multiple flood events in the UK throughout 2012. For example, on the 6-7th July Devon, Dorset and Somerset experienced persistent and heavy rain, leading to a number of 'Severe Flood Warnings' being issued by the Environment Agency. Headlines such as 'Floods as torrential rain hits UK' (BBC, 2012) were common to the public at the time. 28th June 2012 saw unusually warm and humid air move northwards across the UK. This resulted in intense heavy thunder storms, causing widespread river and surface water flooding across North East England, including the famous 'Toon Monsoon' in Newcastle upon Tyne (Northumberland County Council, 2013; Kutija *et al.*, 2014). At the time, the Met Office confirmed that 2012 was the second wettest year since records began, with the total UK 2012 rainfall being over 1330mm (Met Office, 2013a).

Extreme flooding occurred in the south east and south west of England over the prolonged period of December 2013 to February 2014 (Kendon and McCarthy, 2015; Thompson *et al.*, 2017). This event generated huge debates between local residents and land owners with the Environment Agency and other relevant governmental bodies. People were left flooded for months, including during the 2013 Christmas period, with dredging, austerity, the 'Somerset Levels' and upland catchment management all being at the forefront of the discussions (e.g. Hope, 2014).

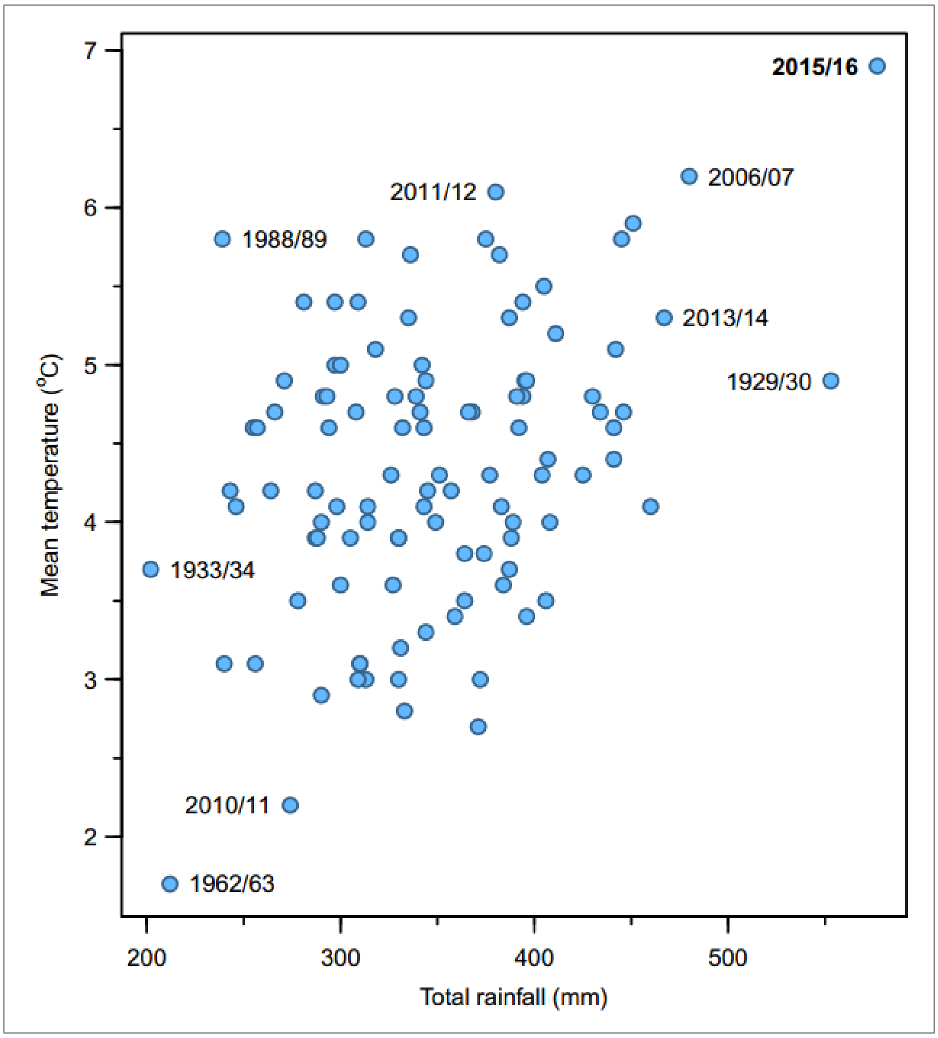


Figure 2.6. Mean temperature and total rainfall for the UK over the three-month winter period of December to January, since 1910 (Source: Marsh *et al.*, 2016).

More recently, widespread flooding occurred between November 2015 and January 2016 across northern England, southern Scotland and Wales. As Parry *et al.* (2016) describe, a series of extreme weather events generated saturated grounds, leading to record breaking rainfall totals and river levels being observed at a number of locations, including Corbridge in Northumberland, and Honister Pass in Cumbria (341.4mm of rain fell in 24-hours). A review by Marsh *et al.* (2016)

confirmed that this was the UK's wettest three month period since 1910, with December 2015 being the warmest and wettest on record (Figure 2.6).

These flood events highlight the importance of hydro-information for catchment management further. The aforementioned flood events have significantly refreshed memories and increased flood risk awareness in recent years, many of which have left communities emotionally traumatised (Wentworth, 2014b; Norbury *et al.*, 2015; McEwen *et al.*, 2016).

2.2.5. *Case study (2): Agricultural intensification and rural runoff in the UK*

Agricultural activities have changed considerably in the UK (and Europe) since the 1940s and have, in general, intensified to meet the demands of a rising global population, and in line with technology. Withers *et al.* (2014) have reviewed key agricultural milestones which have had an impact on the way farmers have used catchments, including the Common Agricultural Policy introduced across the European Union (EU) to support productivity and subsidise farmers.

Agricultural practices had become so successful that by the 1980s and 1990s, there were food surpluses and the impact on the environment was starting to show (Withers *et al.*, 2014). Farming practices have become more efficient through the use of machinery and fertiliser which has negatively affected the land-water interface in multiple ways (Table 2.1). Referring back the Eden catchment in north west England, out of a total area of 2300km^2, 97% of the catchment is used for agricultural activities, equating to more than 2000 individual farms (Eden Rivers Trust, 2013). A large amount of research has been undertaken within the Eden to better understand the relationships between different farming practices, downstream impacts from rural runoff, and how this changes through utilisation of rural land management techniques (e.g. Owen *et al.*, 2012; Terry *et al*, 2014). It does however remain a challenge when fully appreciating how catchment response is changing locally, especially when data scarcity and modelling issues persist.

Farmers are both land owners and users of catchments, they live and work in and around the river environment, and are also a rich and valuable source of local knowledge (Oliver *et al.*, 2012). Farmers are therefore key stakeholders in the catchment management process.

Cause	Impact
Use of fertilisers and pesticides	Fertilisers and pesticides encourage crop growth but can also diffuse into the river network, especially during winter months or following heavy rain. This can increase phosphate and nitrate levels in watercourses, enriching the water body with nutrients and encouraging algae to grow. If algae flourishes, it can clog up the river system, lower light and oxygen levels, and suffocate aquatic species (eutrophication). Some species are sensitive to high levels of pollutants themselves.
Increased stocking density, overgrazing and in-stream cattle activity	Increasing the number of cattle may 'overgraze' the land. This can damage the soil structure and reduce vegetation cover, which in turn reduces infiltration rates and encourages soil, sediment and pollution particles to wash away. Water also reaches the network much faster than in a natural case. Overgrazing can also lead to river bank collapse ('poaching'), alter the river morphology, damage habitats, and cause in-channel disturbances.
Use of machinery and cultivated soils	Heavy farm machinery compact the land, altering the underlying soil structure. In particular, this reduces pore space and the soil's capacity to retain water. Plough lines and tyre tracks can connect fields with watercourses.
Diffusion of animal manure	Whether it leaks from a designated manure heap or whilst cattle are grazing in close proximity to a stream or river, animal waste (ammonia) is toxic to fish and invertebrates.
Field drainage	Farmers have drained fields through dykes, ditches and pipes to maximise agricultural outputs. This has further connected the land with water, which encourages rapid runoff.

Table 2.1. Negative impacts caused by modern day farming practices on the land-water interface (sourced from O'Connell *et al*, 2007; Terry *et al.*, 2014; Withers *et al.*, 2014).

2.3. Managing the water environment: a traditional perspective

2.3.1. Roles and responsibilities

The roles and responsibilities associated with managing the water environment across the UK have changed dramatically over the years, and are expected to change again once Britain leaves the EU. Professionals now recognise that a multidisciplinary approach is required. The European Environment Agency (EEA) is a part of the EU which works closely with the national environment agencies from cooperating countries. The Department for Environment, Food and Rural Affairs (Defra) is a division in the UK Government responsible for the protection of the natural environment and sustainable development. In England, Defra has appointed the Environment Agency to lead on regulating rivers, contaminated land, water quality and the conservation of fish and ecology. SEPA, Natural Resources Wales and the Northern Ireland Environment Agency are the equivalent for the rest of the UK. Despite being the overarching statutory bodies, they all still work in close collaboration with other relevant authorities and organisations on a local level.

On a catchment scale, roles and responsibilities depend on whether flood risk or wider catchment issues are of interest. Due to past events and potential impacts on people, property and infrastructure, flood risk management is a key concern for the UK Government and is why there are a number of authorities and organisations collectively responsible (Figure 2.7 - again exemplified for England, but the same structure applies to rest of the UK). The Environment Agency and Natural England are also primarily responsible for managing the wider environment, including water quality monitoring and management, with support from other organisations.

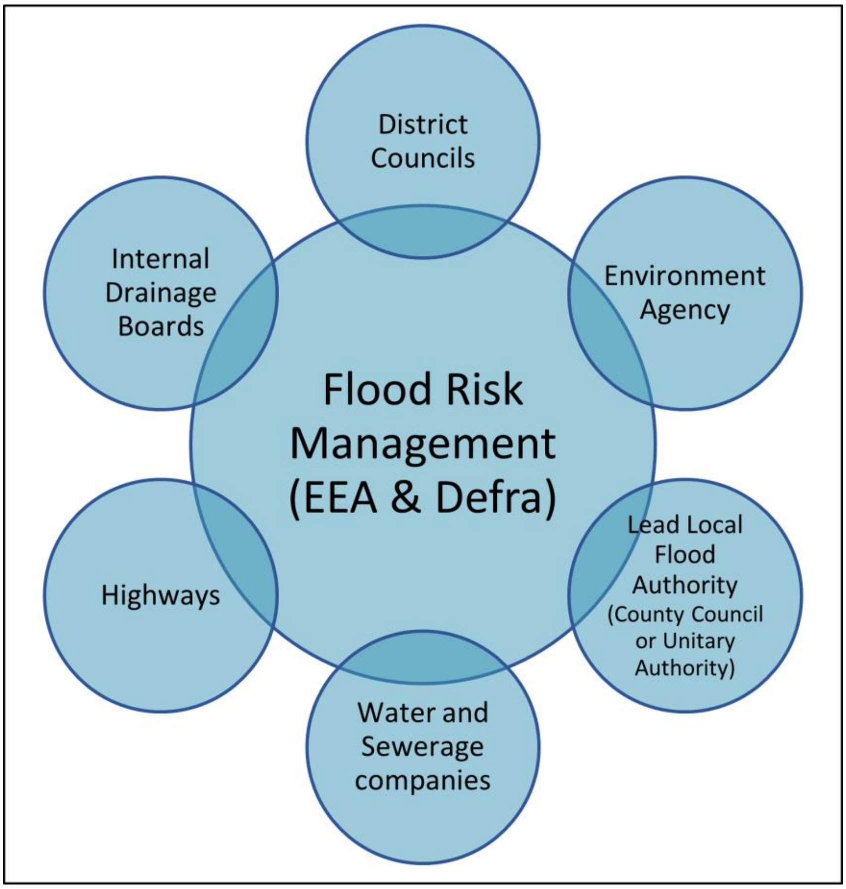


Figure 2.7. Organisations and authorities traditionally responsible for Flood Risk Management in England (Defra, 2014). Note that stakeholder arrangement will change once Britain leaves the EU.

Although they are not statutorily responsible, a wide range of local groups and organisations are now becoming increasingly involved in the flood risk and catchment management process, forming flood and catchment partnerships. For example, Rivers Trusts (case study in Section 2.3.5), National Parks, Wildlife Trusts and local community groups are now all key stakeholders, thus Figure 2.7 could potentially be extended. The involvement of local people or groups opens up a whole new array of opportunities.

2.3.2. Overview of legislation, policies and frameworks (UK/EU)

The EU and UK Government often shape policies around environmental disasters which have been experienced, thus management efforts are often reactive, particularly following widespread flood events. A well-known example is the Pitt (2008) review which consulted with relevant stakeholders to review experiences and the lessons to be learned from the UK 2007 summer floods. The report highlighted how the UK should increase the public's awareness of, and resilience to, flooding and be better prepared for future events, for example (Pitt, 2008):

"*The review calls for urgent and fundamental changes in the way the country is adapting to the likelihood of more frequent and intense periods of heavy rainfall*" (Foreword).

"*The Government should give priority to both adaptation and mitigation in its programmes to help society cope with climate change*" (Recommendation 1).

"*The Environment Agency and the Met Office should work together, through a joint centre, to improve their technical capability to forecast, model and warn against all sources of flooding*" (Recommendation 6).

"*The Government should establish a programme to support and encourage individuals and communities to be better prepared and more self-reliant during emergencies*" (Recommendation 70).

Making Space for Water (Defra, 2005) carried out an earlier review which concluded that the Government should develop a more comprehensive, holistic and integrated approach to flood risk management. Although they are not legislative, both reports have profoundly driven, shaped and reinforced how catchments have been managed over the past 10-15 years, and still underpin choices made today. Many more extreme weather events have also occurred since they were published, and have thus reinforced these recommendations.

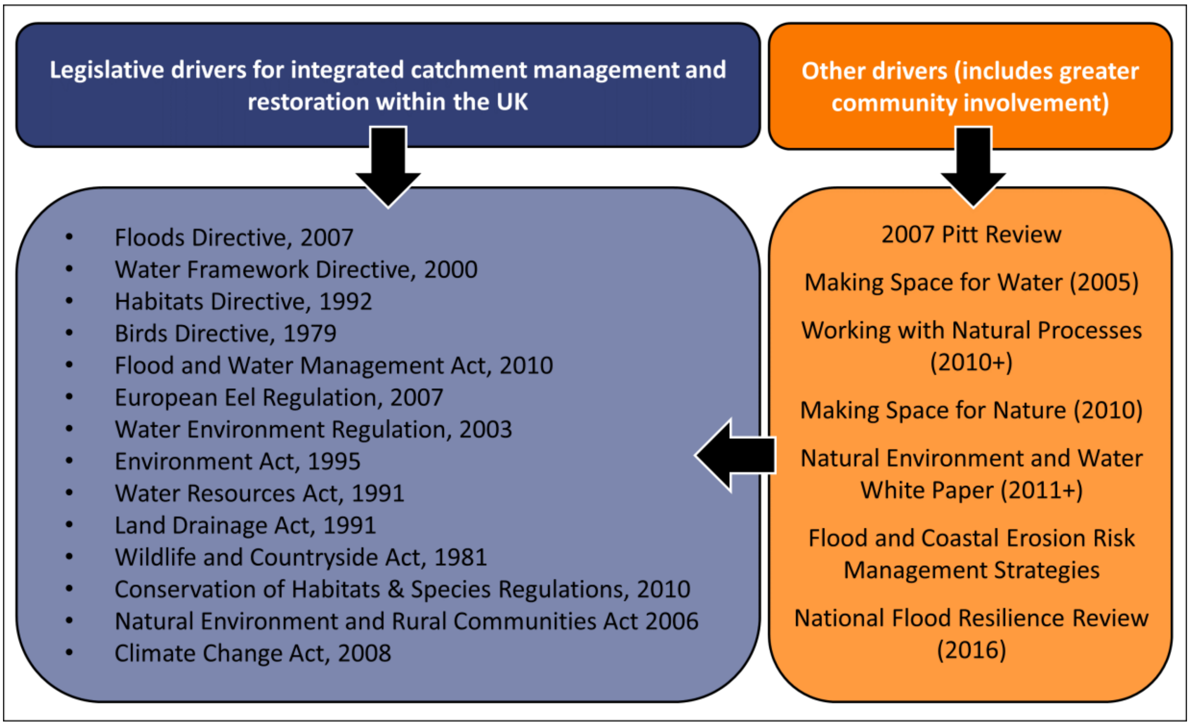


Figure 2.8. The main drivers for catchment management (adapted from Barlow *et al.*, 2014). Directives apply on an EU level and the remaining drivers/acts apply to England and Wales. Scotland and Northern Ireland have similar drivers in place.

Several catchment-related legislative policies and frameworks are in place today across the UK which principally drive catchment management activities and set plausible targets. They span across the whole catchment management spectrum, supporting the management and conservation of floods, water quality, habitats, species and water as a resource (dominant drivers are listed in Figure 2.8). The EU Floods Directive and Water Framework Directive (WFD) drive most of the monitoring and catchment management activities, and are also closely linked to more specific legislations, including the Nitrates Directive (1991), Groundwater Directive (2007) and The Bathing Water Directive (2006). The majority of the catchment issues detailed within Section 2.2.3 only hinder reaching targets set out by each of these laws. The two key Directives are described detail below:

EU Floods Directive (2007/60/EC): First published in 2007, this Directive requires members to assess all watercourses and coastlines, identify and map all areas at risk of flooding, and quantify the risks to people and property. The development of flood risk management plans have been requested for each river basin, and focus on flood prevention, preparation and preparedness (European Commission, 2014a). UK specific Acts reinforce this piece of legislation, particularly the Flood and Water Management Act 2009 in England and Wales, the Flood Risk Management (Scotland) Act 2009, and the Water Environment Regulation (Northern Ireland) 2009. Flood-related legislation now emphasises the need to communicate flood risk with the public and ensure they also have access to flood risk information. Flood risk management plans have been created for individual river basins across the UK, setting out how flood risk will be managed.

EU Water Framework Directive (2000/60/EC): This Directive came into force in 2000, as it was increasingly recognised that Europe's waters are under pressure from human activities and climate change. The WFD aims to prevent deterioration and ensure all European waters are at least in 'good condition', a classification which takes chemical, ecological and hydromorphological considerations into account. Similarly to the Floods Directive, the WFD aims to acquire public support and involvement, and recognises that watercourses flow between different political boundaries (European Commission, 2014b). River Basin Management Plans have been created for individual basins across the UK which document their current status and set targets to improve water quality.

It is clear that there have been, and still are, many different policies and frameworks in place which leave the catchment management process fragmented. Nevertheless, to some extent this has been recognised, and organisations are creating multi-partnership projects in order to tackle multiple issues and provide interventions and mitigation options which offer multiple benefits.

2.3.3. Traditional monitoring, data availability and catchment characterisation

In order to characterise river networks and corridors, identify sources and pathways, detect changes and relationships, achieve the aforementioned legislative targets, and provide catchment managers with confidence when trying to implement mitigation measures, various monitoring techniques can be performed. Traditionally, monitoring is carried out by professionals who are trained to install and maintain instruments, download, process and analyse the data, as well use it for specific applications. This provides information on the quantity and the quality of the water environment (Bren, 2015) and even if the parameters are being measured indirectly, it still provides catchment managers with an indication of the behaviour and health of the water environment. However, as Herschy (2009) points out, good practice in catchment management is dependent on reliable and good quality data collected out in the field.

As expected, catchment monitoring has improved in line with technology, allowing spatial and temporal datasets to be created for any measurable hydrological parameter. Historically, monitoring equipment could only be observed and recorded manually. Today instruments are capable of logging and storing data within the device itself, and if monitoring budgets allow, real-time data can be obtained remotely by means of a 'telemetry system' (Shaw *et al.*, 2011; Younos and Heyer, 2015; Sene, 2016). Telemetry systems transfer and receive data wirelessly and have radically improved the Met Office and the Environment Agency's ability to forecast extreme weather and floods, providing emergency responders and the public with 'heads up' information. It has also improved the UK's spatial coverage of monitoring equipment as devices can now be left to work in remote and inaccessible locations. Automated monitoring equipment has the added benefit of being able to take a measurement as often as the user specifies, including temporal resolutions finer than one-minute. Table 2.2 provides a few examples of equipment commonly used to monitor catchments. Furthermore, remotely sensed data from radar and satellite observations are now possible, providing a better appreciation of spatial variability across catchments (Bren, 2015; Younos and Heyer, 2015).

There are records to suggest that rain gauges were first used in Korea in the 1400s AD (Shaw *et al.*, 2011). While many professionals and amateurs will have made their own observations over time, Bayliss and Reed (2001) and Kjeldsen *et al.* (2014) comment that generally systematic hydrological measurements and subsequent time series data is only available from around the 1850s in the UK, with the average record length being only 20-40 years. Water quality, morphology and habitat related monitoring networks are less established. There are national rainfall, weather and river level monitoring stations installed across the UK today, which are owned and operated by the Met Office, Environment Agency, SEPA, Natural Resources Wales and the Northern Ireland Environment Agency (Shaw *et al.*, 2011). For instance, the Met Office (2016a) now has over 200 automatic weather stations across the UK and are estimated to be approximately 40km apart (see map in Figure 2.9). The National River Flow Archive (NRFA - http://www.ceh.ac.uk/data/nrfa/) also holds data obtained from more than 1500 UK hydrometric gauging stations. However, looking at the density of the national monitoring networks, they still fail to characterise individual catchments on a local level (Faulkner *et al.*, 2012). There are some denser, nested and multi-scale hydrometric monitoring networks installed, but are generally associated with research projects, such as Defra's 'Demonstration Test Catchments' (DTC's) (Owen *et al.*, 2012) and are likely to close when the project (funding) terminates. As a result, small catchments usually remain ungauged (Hrachowitz *et al.*, 2013).

Despite the advantages of modern fieldwork techniques, equipment is expensive to buy and maintain, and monitoring stations only represent a single point on the Earth's surface, rather than spatial variability. Users must be trained and have relevant computer skills and software to operate them. Monitoring equipment is also subject to vandalism and theft, particularly if solar panels are on display. Given that individual catchments are extremely variable, monitoring is also required on a local level if evidence is expected to inform management decisions. A cost-benefit analysis is often used to determine whether it is necessary to install and run a monitoring site (Herschy, 2009; Shaw *et al.*, 2011), therefore small rural catchments often fall short.

Traditional monitoring equipment	
 **Rain gauge:** rain gauge being programmed to measure rainfall at regular intervals.	 **Water level recorder:** measures temperature and pressure which converts into water level.
 **Logger box:** telemetry system uses a SIM card to transmit and receive data via the internet.	 **Solar panel:** often used to power hydrometric networks, in this example a water level recorder.
 **Water quality monitoring hut:** built to house automatic water quality monitoring kit on site.	 **Weather station:** an automatic weather station monitoring many parameters e.g. wind speed.

Table 2.2. Examples of traditional monitoring equipment used to characterise and quantify the water environment, for instance by Owen *et al.* (2012). Photographs by E.Starkey.

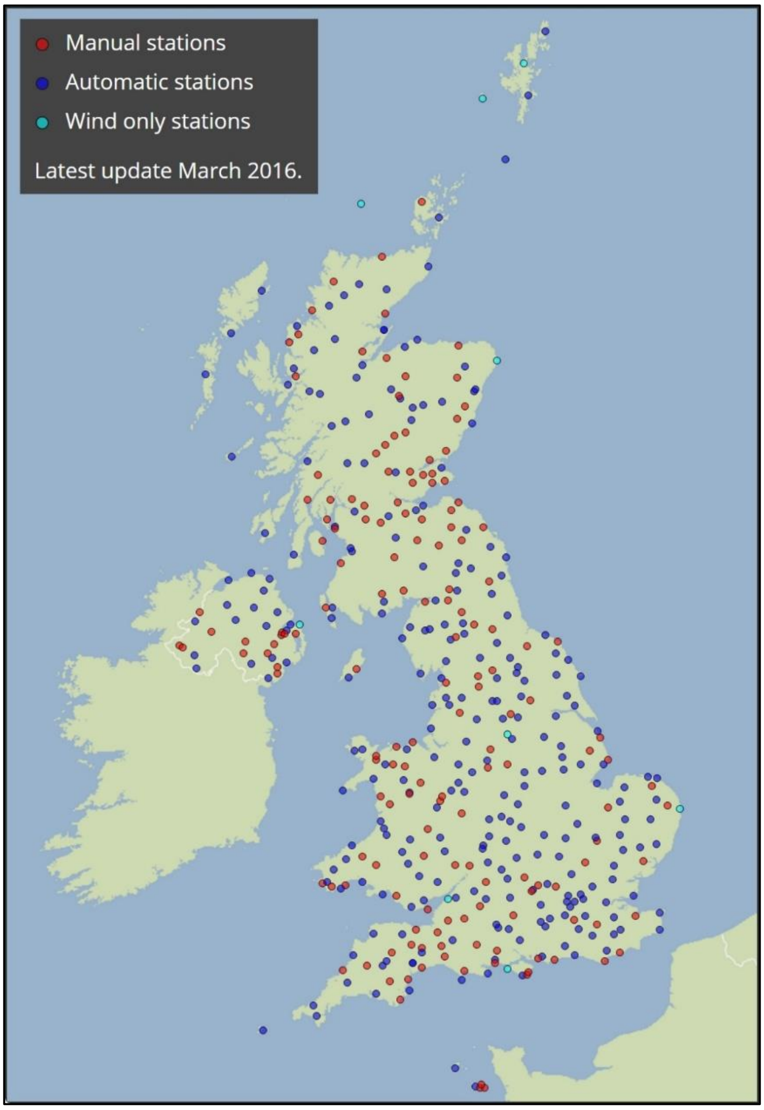


Figure 2.9. Map showing the Met Office's network of automatic weather stations (blue dots). Red dots represent manual stations which are operated by volunteers (Source: Met Office, 2016a).

Although legislative frameworks now request that the communities should be better-informed about catchment related issues, and open Government data licences have been introduced, hydrometric datasets are still not readily available to the public or for commercial purposes. This also applies to researchers to some extent as it can be a lengthy process to find out what data is available, obtain copies, and comply with copyright procedures. Professionals are monitoring and using the data in isolation; many communities are simply unaware that there may be a hydrometric monitoring network in close proximity to their homes.

2.3.4. Disseminating and communicating catchments to the public

Following Pitt's (2008) recommendation that the public should be made more aware of flooding and also self-reliant during an event, significant efforts have been made to ensure a number of information sharing tools and services are now available. Pertinent examples include:

"*Know your flood risk*" campaign[2]**:** The Environment Agency are regularly raising awareness and encouraging the public to find out whether they live or work within a flood risk area (see examples in Figure 2.10).

What's in your back yard[3]**:** An Environment Agency mapping portal which allows the public to search for environmental information in their own area. For example, river and sea levels are graphed online in real-time, and are also linked to social media (Figure 2.11). Equivalent organisations have similar facilities available in Scotland, Wales and Northern Ireland.

Flood forecasting and warning[4]**:** The Environment Agency, SEPA, Natural Resources Wales and Environment Agency (Northern Ireland) now push flood warnings out to the public once river levels reach a certain trigger level, or when there is a significant risk to life. These services are often limited to the major watercourses where telemetered equipment exists.

Met Office National Severe Weather Warning Service[5]**:** Warnings and alerts are issued to the public when severe or hazardous wind, rain, snow, fog or ice conditions are expected.

Flood alleviation schemes[6]**:** Public drop-in sessions are organised to share plans with local communities. This gives the public a chance to understand flood risk within their local area and how it will be mitigated.

Communities are certainly playing a much greater role in the flood risk management process today, even if it is just engaging and learning about flooding through social media. However, being led by statutory organisations themselves, the approaches listed within this section still entail a 'top-down' approach. Despite the importance of catchment connectivity, local communities are still not encouraged to consider wider catchment issues and solutions beyond their back yard. Rivers Trusts on the other hand are encouraging and enabling the public to explore their local water environment for the first time, as Section 2.3.5 details.

[2] https://floodsdestroy.campaign.gov.uk/ (Environment Agency)
[3] http://apps.environment-agency.gov.uk/wiyby/default.aspx (Environment Agency)
[4] For example, http://floodline.sepa.org.uk/floodupdates/ (SEPA)
[5] http://www.metoffice.gov.uk/public/weather/warnings/ (Met Office)
[6] For example, https://twitter.com/EnvAgencyYNE/status/797372159500894208 (Environment Agency)

Figure 2.10. Examples of public engagement material used by the Environment Agency to raise flood risk awareness (EnvAgency, 2014).

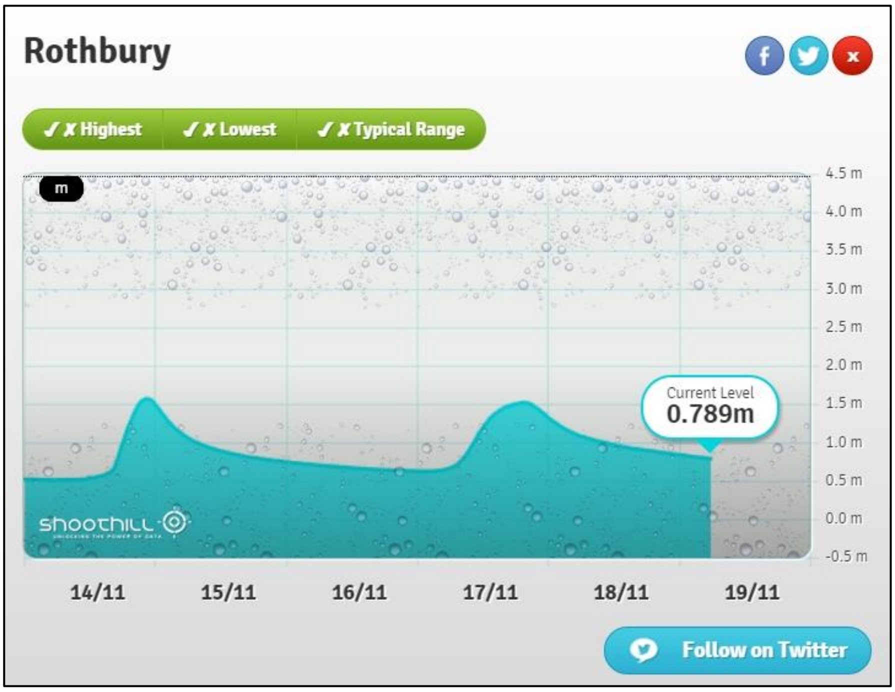


Figure 2.11. Example of live river levels available online to the public (Source: Shoothill, 2014).

2.3.5. Case study: Global Thinking, Local Action – The Rivers Trust

Established in 2001 and renamed in 2011, The Rivers Trust is a registered environmental charity representing a network of Rivers Trusts that work on a local level within individual catchments. They promote sustainable and holistic approaches to catchment management, with great emphasis on engaging, educating and actively working with members of the public and supporting community-based restoration projects (The Rivers Trust, 2014b).

There are catchment-based Rivers Trusts across England and Wales, River and Fisheries Trusts of Scotland, and the Ballinderry River Enhancement Association in Northern Ireland. Tyne Rivers Trust (TRT) for instance is based in North East England. With projects focussed around habitat, wildlife and water quality improvement works from source to outlet within the Tyne Catchment (Figure 2.12), TRT is dedicated to involve local communities every step of the way. Input from local land owners, farmers and other interested individuals, in the form of local knowledge, is extremely valuable. Involvement also increases their own environmental knowledge at a catchment scale.

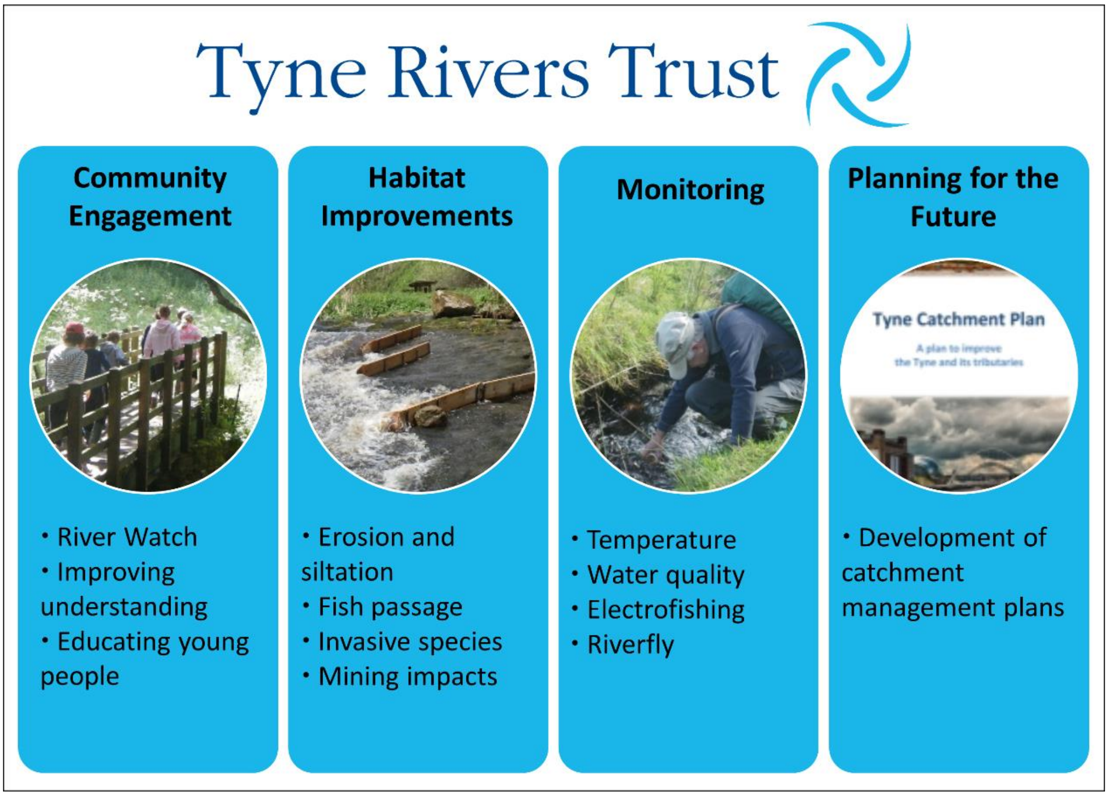


Figure 2.12. TRT's key areas of work, including community engagement (TRT, 2016) which are common across all local Rivers Trusts.

2.4. A new direction: integrated catchment management

2.4.1. Coupled human and natural systems

It is well established that there are multiple and complex catchment issues, that land and water are connected, and that catchments are influenced by both human activities and natural processes. Together with debates following recent flood events, the EU and UK catchment-based policies are encouraging stakeholder participation, including the general public. By considering all of these drivers, catchment management is becoming progressively integrated. Today catchment management, particularly flood risk, is therefore becoming more 'people-centred' and social scientists are starting to work in collaboration with catchment scientists and engineers (Montanari *et al.*, 2013; Bracken *et al.*, 2014; O'Connell and O'Donnell, 2014; Bracken *et al.*, 2016). This holistic approach allows the catchment management process to span across the social, economic and environmental aspects of sustainability. O'Connell and O'Donnell (2014) point out that public/stakeholder involvement is required because they live within, and are affect by, catchment issues, and discuss the concept of 'coupled human and natural systems'. To further refine this concept, Sivapalan *et al.* (2012), Di Baldassarre *et al.* (2012) and Montanari *et al.* (2013) present the term 'socio-hydrology' in the context of floods, stating that almost one billion people live on floodplains and so humans and nature have notably co-evolved over time. They conclude that humans are now part of the water cycle and should not be isolated from the management process. Similar to Large *et al.* (2017) whom explore catchment-based challenges within the Anthropocene era, McMillan *et al.* (2016) advocates that humans and catchments have been interacting for thousands of years, and points out that no wonder the term 'socio-hydrology' has emerged. However, the recent and increased use of this term highlights how catchment management is currently evolving.

2.4.2. Bottom-up philosophy: the Catchment Based Approach (CaBA)

Although the EU WFD was launched back in 2000, the first cycle of River Basin Management Plans produced in the UK were deemed inadequate. It was concluded that there were limited efforts to include all relevant stakeholders, there was limited flexibility on a local level, and that catchment management was too broad scale. Funded by Defra and the Environment Agency, the 'Catchment Based Approach' (CaBA) was subsequently launched in 2011, a new approach which fundamentally (Defra, 2013):

- Recognises the need for an integrated approach to catchment management and for multiple benefits to be achieved (rather than just targeting water quality);

- Encourages people to think locally, yet catchment wide in order to meet the requirements of national and international standards;
- Identifies what really matters on a local level;
- Promotes the development of innovative and holistic catchment management measures and the sharing of best practice;
- Calls for greater partnership and stakeholder engagement – an integration of people who have a shared interest in the water environment;
- Ensures communities are more informed about their local water environment, are engaged to preserve and improve the status of their catchment, take ownership of the issues around them (sense of empowerment), and support the delivery of local measures.

The latter point is a particularly important aspect of CaBA which Defra (2013) hopes will support transparent and shared decision making, as well as achieve multiple benefits in order to improve the quality of the water environment. Public participation also supports the delivery of the many drivers listed in Figure 2.8.

Twenty-five CaBA pilot projects were launched on the ground in May 2011 which were then evaluated in early 2013. So much interest was shown by organisations wanting to host these pilots that Defra awarded funding to a further 41 smaller pilot catchments to kick-start the catchment-based approach. Pilot catchments were set up to test the viability of CaBA whilst developing best practice (Defra, 2013). Cascade Consulting evaluated the pilot phase on behalf of Defra which established that there are no blueprints for the CaBA process; each catchment has its own set of circumstances and priorities which local stakeholders need to identify (Cascade Consulting, 2013; Corbelli, 2013). The evaluation confirmed that it was widely agreed CaBA pilot projects were successful and worthwhile, presenting a strong case for wider adoption. It has highlighted a number of useful methodologies and tools which can assist stakeholders to, for example, identify what is important within a catchment, and what type of catchment data is required. Some pilots also emphasised how important it is to identify existing groups of people in a catchment in order to stimulate effective collaboration (Cascade Consulting, 2013).

CaBA was fully rolled out in June 2013. Being a 'catchment-based' approach, this meant that England's 10 river basins suddenly became approximately 80 individual hydrological catchments where the CaBA would be applied. For instance, the Humber River Basin was divided into 15 catchments (Figure 2.13) which would drastically support a commitment to localism.

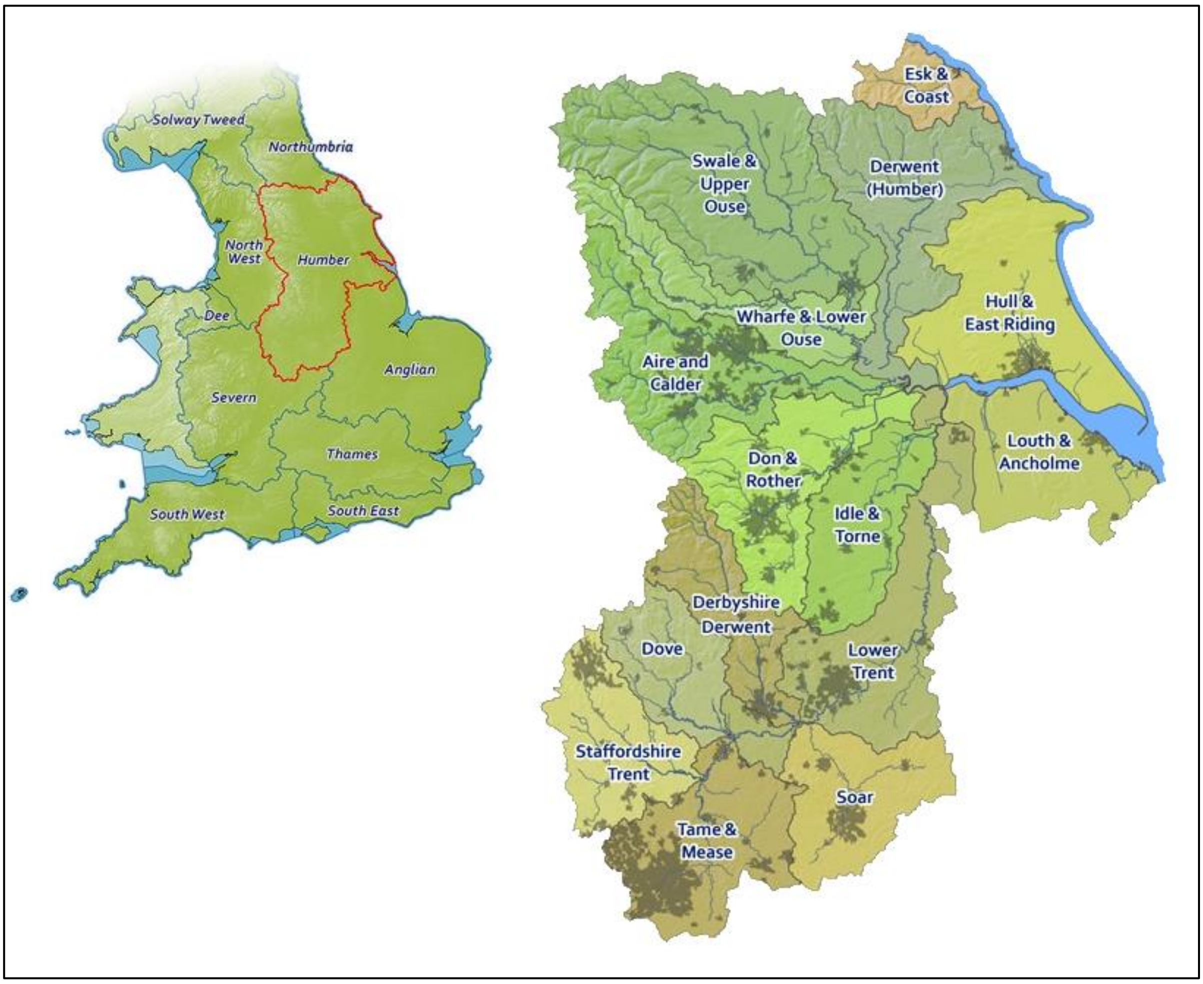


Figure 2.13. Humber River Basin (left map) which has been split into 15 catchments as part of CaBA (right map) (Source: CaBA, 2014).

An online CaBA forum (http://catchmentbasedapproach.net/) and Catchment Change Management Hub [(http://ccmhub.net](http://ccmhub.net)) were developed and launched to provide catchment stakeholders and members of the public with a central place to find, share and comment on catchment information. They have been carefully designed (taking stakeholder feedback into consideration) in order to cater for different and wider audiences.

As stakeholder collaboration grows and members of the public become increasingly involved in the catchment management sector, the co-production and collective use of tools and material will be essential, as will the involvement of social scientists. Despite increased requirements for public participation, it can be a challenge to engage with local communities successfully and sustainably. It is imperative that involvement is open to anyone across the community, that their time and efforts are valued, and that they too benefit from the participatory process, rather than being exploited or becoming fatigued. Engagement, training, tools, creativity and continuous feedback are required to ensure the public do not become disinterested over time. Varying (and sometimes contrasting) levels of understanding, expectations, attitudes and perspectives of the public within each catchment must also be managed carefully. Public engagement and participation therefore opens up a new set of skills which catchment scientists and engineers increasingly require to support the delivery of CaBA and other catchment-based drivers.

2.4.3. Evidence-based catchment management

Catchment management activities must be underpinned by robust and reliable evidence-based science (Wentworth, 2014b). This will provide catchment managers and relevant stakeholders with confidence that they are implementing cost-effect measures, and are prioritising those returning multiple benefits. The need for quantitative evidence stems from evidence-based policies and frameworks such as CaBA and the WFD. The Chartered Institution of Water and Environmental Management held a conference at the University of London in September 2014[7], with focus on 'evidence requirements' in the field of Natural Flood Management (NFM – see Section 2.4.4 for further details). It was noticeable that there are a number of catchment restoration projects being carried out across the UK, but in order to implement new and innovative approaches, and subsequently share best practice, rigorous evidence is required to determine how effective they are. Most conference speakers concluded that measurable evidence is exceptionally valuable, that long term datasets are required at a catchment scale, and that monitoring must continue into the future. The Environment Agency also launched a 'Research and Development Framework' (Barlow *et al.*, 2014) which again heavily leaned towards ensuring evidence-based science is available to support the decision-making process. To add to this, reliable evidence is also necessary to provide local residents and land owners with confidence that catchment management techniques proposed are viable and worthwhile.

Although there are national (formal) networks monitoring the water environment and a number of short-term networks installed for detailed research purposes, such as in the DTCs (Owen *et al.*, 2012), many of the smaller and more rural catchments have few historic and contemporary datasets available. This is problematic if evidence is required to support modelling and management measures on a local level. This is when engagement with local communities and the transfer of lay and local knowledge could become hydrologically valuable (McEwen *et al.*, 2016),

[7] Chartered Institution of Water and Environmental Management (CIWEM) - 'Natural Flood Management: The Evidence Requirements for Wider Delivery' 10th September 2014 at SOAS, University of London.

providing 'evidence' in new formats which scientists are less familiar with, as opposed to traditional quantitative information.

2.4.4. Natural Flood Management (NFM)

River, coastal and tidal flooding (and erosion) has traditionally been managed and the risks reduced through the use of 'hard' engineering techniques. This has involved building man-made structures which are designed to separate and retain flood water from properties and infrastructure. Techniques include building barriers, dams, walls and revetments, and in many populated areas, bank straightening and stabilisation. This has led to various large-scale engineering projects; for instance the Thames Barrier is one of the largest moving flood barriers in the world, which has significantly reduced the likelihood of tidal flooding to Central London. Spanning 520 meters across the River Thames, the barrier cost £500 million to build, consists of 10 heavy steel gates (Environment Agency, 2012a) and requires extensive amounts of ongoing monitoring, testing and repair work to prevent failure in the future.

Although hard engineering solutions typically offer high standards of protection, it is being increasingly acknowledged (Wentworth, 2011; Barlow *et al.*, 2014) that, when used isolation, they:

- Offer very little or no benefits to other environmental Directives, Acts and Frameworks, thus they do not usually provide multiple benefits or integrated solutions to the wider river corridor;
- Are expensive to build, maintain, monitor and repair, as risks associated with failure always remain;
- Are known to 'pass on' the problem downstream or downdrift, interfere with natural processes, and negatively impact biodiversity;
- Are not regarded as cost-effective solutions for areas with a low number of properties at risk of flooding (villages and small towns);
- Provide very few opportunities for stakeholders, especially the public, to become involved in the management process as efforts and confidence are focussed on the engineers.

Natural Flood Management (NFM) has emerged over recent years as an innovative way of managing multiple catchment issues. There are various definitions used to describe NFM, with SEPA defining it as:

"*A suite of measures used to manage flood risk which includes a range of techniques that aim to work with natural hydrological and morphological processes to manage the sources and pathways of floodwaters.*" (SEPA, 2012; 2015).

NFM alters, enhances, restores and/or uses the landscape features (Wentworth, 2011; SEPA, 2015; Cook *et al*., 2016; Lavers and Charlesworth, 2017; Defra, 2018) by emulating and working with natural processes (rather than against), generating a 'soft' or 'green' engineering approach to flood risk management. The main philosophy of NFM is to hold back (attenuate) and store flood water until the peak of the event has subsided, reducing the river network's velocity, which in turn decreases its erosive power and ability to transport debris (Norbury *et al.*, 2015). Reviews, Directives, Acts and Frameworks (Figure 2.8) have all contributed to the development and use of NFM because they all commonly request i) greater working with natural processes, ii) adoption of innovative solutions on a catchment and local scale, and iii) management of future flood risk, including climate change.

Flood risk is not necessarily the overarching issue at every site. As the Environment Agency rightly points out (Barlow *et al*., 2014; Lavers and Charlesworth, 2017), 'working with natural processes' (WwNP) can entail management methods which secure and improve biodiversity, water quality and sediment systems too, as well as flood risk reduction. Both NFM and WwNP are therefore closely aligned with the CaBA, which targets water quality (but also offers multiple benefits). However, NFM, WwNP and CaBA are still separate and integration issues have not been fully resolved.

Table 2.3 provides some examples of innovative NFM (and wider WwNP) features which have been implemented within the UK, many of which entail using ponds, dams, logs ('debris') and trees. It is also important to note that techniques and names of features often vary between catchment; site-specific interventions are tailored to the combination of properties, processes and activities present at the location of interest. The Belford Burn NFM pilot in Northumberland is also described in Section 2.4.5, providing an excellent example of how soft engineering can provide multiple benefits in a smaller and more rural catchment, whilst reducing flood risk.

NFM or WwNP scheme & description	Example of feature/scheme
'Slowing the flow' – Pickering, North Yorkshire (Forestry Commission, 2014) The town of Pickering is vulnerable to flash flood events. 'Soft' techniques have been introduced to assist with storing and slowing the flow higher up in the catchment. Techniques include woody debris, flood storage bunds and creation of floodplain woodlands. Community involvement has been the key to the project's success.	
Bowmont Catchment - Scottish Borders (Wilkinson *et al.*, 2014a). NFM measures have been installed in the Bowmont catchment to capture sediment, protect the riverbank from erosion and store water on the floodplains during high flows. An example includes 'log jams' which work with natural processes to trap sediment, reduce erosion and improve habitats. Local land owners were key stakeholders.	
Littlehaven Beach – South Tyneside (South Tyneside Council, 2014). To protect against coastal erosion and flooding, South Tyneside Council encouraged a 'managed retreat' approach along the South Shields coastline. An attractive promenade was built for locals and tourists, whilst the beach was widened by 50m. Previous coastal defences were deteriorating so locals welcomed the works.	

Table 2.3. Examples of NFM/WwNP features which are now regarded as innovative and holistic catchment management measures. Many features incorporate 'woody' or 'green' designs.

Although NFM and wider WwNP techniques have been adopted across the UK to date, there are still big challenges associated with implementing this approach more widely and sustainably (SEPA, 2012; Lavers and Charlesworth, 2017; Defra, 2018). This is primarily because of:

- The absence of reliable and meaningful data (observed evidence and reliable modelling) which can be used to quantify and predict how effective these approaches are at a catchment scale;

- Getting land owners and other stakeholders on board and to appreciate the benefits of NFM;
- Who should make space for, pay and maintain features in the future.

Nevertheless, NFM is becoming increasingly recognised (e.g. by the UK Government) as a more sustainable land management approach which should complement traditional flood defences, offer multiple benefits to the wider landscape, and be integrated into catchment-wide management plans (Wentworth, 2011; Norbury *et al.*, 2015; SEPA, 2015).

2.4.5. Case study (1): Belford Burn NFM scheme, Northumberland

The Belford Burn catchment in Northumberland is a small ($5.7km^2$) and predominantly rural catchment which has historically and recently been flooded (Wilkinson *et al.*, 2010). Due to the low number of properties officially at risk, it was not cost-effective to implement traditional (hard) flood defences such as flood walls, and the village did not qualify for a national Environment Agency flood defence scheme.

As part of a research pilot study led by Newcastle University and the Environment Agency, the Belford Burn catchment became one of the first UK NFM demonstration sites, with a whole suite of low-cost features tested (Norbury *et al.*, 2015). Described as runoff attenuation features (RAFs), a number of strategically placed soft engineered features were constructed within the landscape to intercept, store, slow down and filter flood water at source to reduce flood peaks, and improve water quality (Wilkinson *et al.*, 2008; Wilkinson *et al.*, 2010; Barber and Quinn, 2012). RAFs included bunds, drain barriers, runoff storage features (ponds), woody debris dams, buffer strip management, planting vegetation and willow barriers (Figure 2.14). NFM features have been designed to release flood water slowly, and are therefore temporarily activated following heavy rainfall.

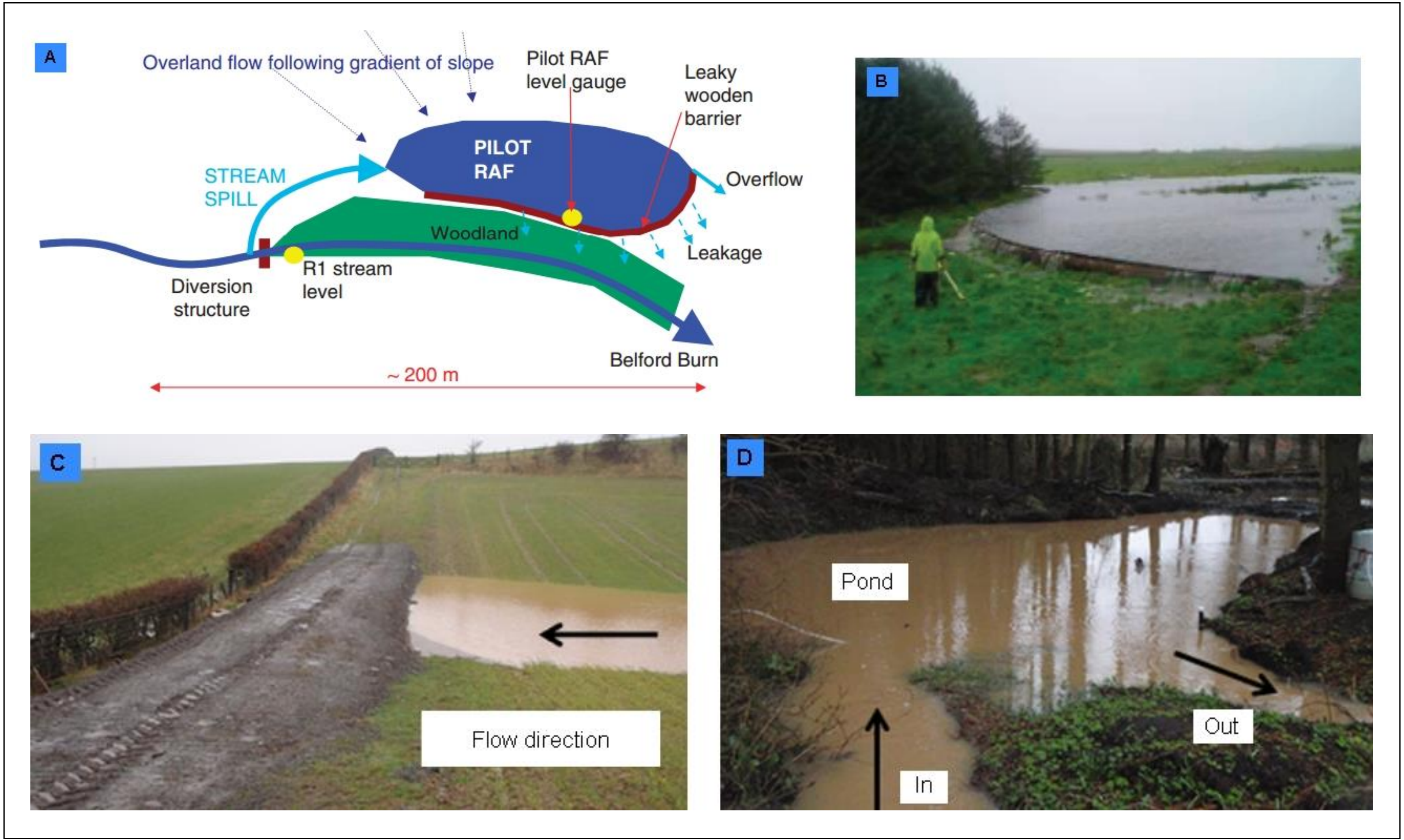


Figure 2.14. Natural flood management features in the Belford Burn catchment: (a) general RAF schematic, (b) example of a RAF, (c) example of a field bund, (d) example of a storage pond (Source: Wilkinson *et al.*, 2008; Wilkinson *et al.*, 2010; Barber and Quinn, 2012). Project website: https://research.ncl.ac.uk/proactive/belford/.

Prior to the pilot project, there were no traditional monitoring equipment in the catchment, therefore a network of instruments were placed upstream, within, and downstream of RAF features to try quantify performance. Data was also required to characterise the local hydrology and locate problematic sub-catchments. Residents and local land owners also viewed evidence during workshops to see how their local water environment was responding to the features installed, with Wilkinson *et al.* (2008) emphasising the importance of stakeholder involvement and feedback. Evidence suggests that the RAFs have been effective at storing and slowing the flow, significantly reducing the travel time of the flood peak, supporting biodiversity, and improving water quality. Similarly to the Belford Burn, NFM research projects generally lack pre- and post-intervention monitoring (Wentworth, 2014b), hence long-term datasets.

2.4.6. Case study (2): Taking responsibility on a local level – community flood plans

In an attempt to increase flood risk awareness and ensure people are better prepared and self-sufficient during a flood event (as recommended by Pitt, 2008), many communities now have community flood plans in place. These plans have been created in different ways, some of which have been produced entirely by the community themselves, while others have welcomed support from the Environment Agency, SEPA, flood forums or flood partnerships. As the name suggests, flood plans aim to assist communities with planning for potential flood events, but more specifically, they ensure that communities (Environment Agency, 2012b):

- Understand different sources of flooding, the national flood warning systems, and which organisations respond during an event;
- Know which areas are at risk within their community;
- Have planned, and are equipped for, a flood event;
- Are able to respond effectively to minimise impacts;
- Have designated flood wardens (volunteers) in place who can be contacted during a flood to assist others;
- Have a list of useful contact numbers containing members of the community and emergency responders;
- Consider practicing for a flood event.

The village of Acomb (Northumberland) provides an excellent case study where the local community has recently implemented a flood plan. The village has been affected by river and surface water flooding over recent years, including during summer 2012. Driven by an already established community group, 'Action4Acomb', this small community now has a flood plan coordinator, a lead flood warden, and at least 12 flood wardens in place. These volunteers are responsible for designated areas of the village, monitoring weather and flood forecasts, communicating flood risk to the wider community (see poster in Figure 2.15), reporting flooding to relevant organisations, checking for blockages, and making flood-related observations. Through questionnaires, Action4Acomb have also liaised closely with the wider community to receive feedback on their flood plan and encourage locals to understand flood risk on a personal/property level.

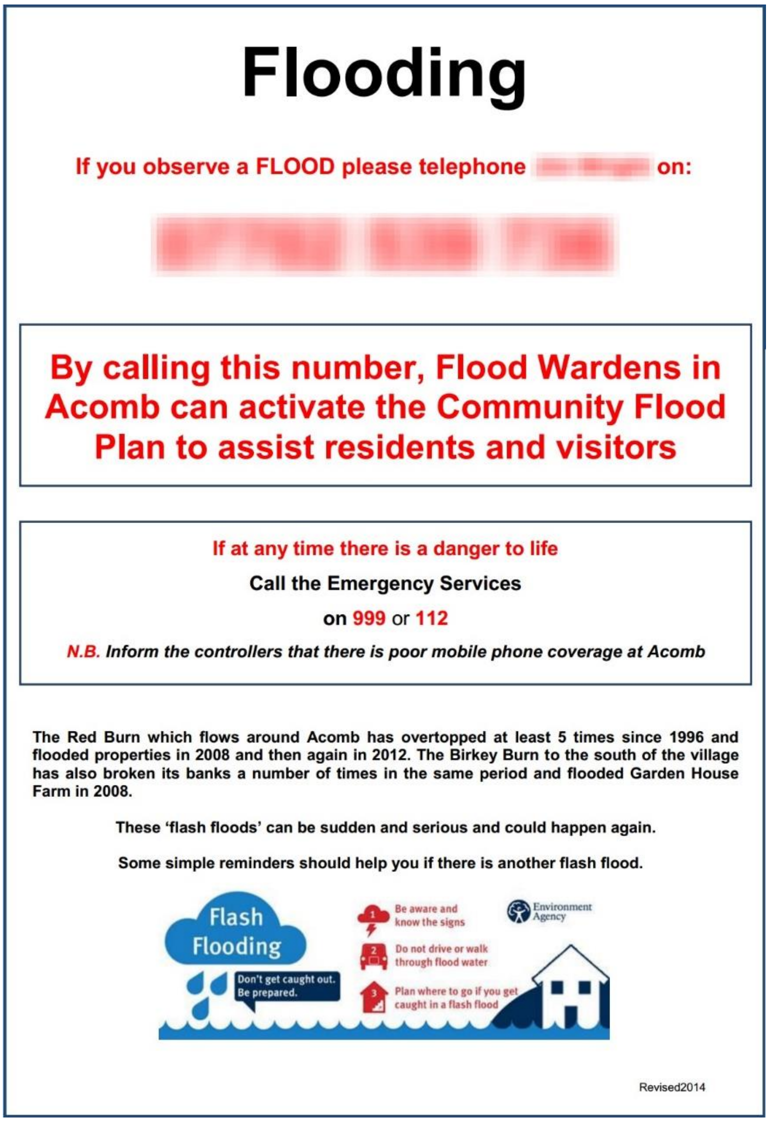


Figure 2.15. A poster used by flood wardens in Acomb (Northumberland) to raise wider community awareness (Source: courtesy of Action4Acomb).

Community flood plans are another example of how local communities are becoming more involved in the flood risk and catchment management process. This shift also encourages communities to build relationships and communicate with different stakeholders.

2.5. Monitoring by communities: a citizen science approach

2.5.1. Defining citizen science

Citizen science is the modern day term used to describe the process when members of the public perform research design, data collection, sharing of knowledge and/or analysis activities alongside professional scientists (Goodchild, 2007; Buytaert *et al.*, 2014; 2016; Bonney *et al.* 2016; Cooper, 2016). Wentworth (2014a) states that citizen scientists support trained scientists to answer real-world environmental issues because scientists can never do this alone due to the sheer scales and complexities involved. This co-production of knowledge is currently opening up new and innovative opportunities for scientific research projects, and is extremely relevant across most environmental disciplines (Socientize Consortium, 2013; Cooper, 2016).

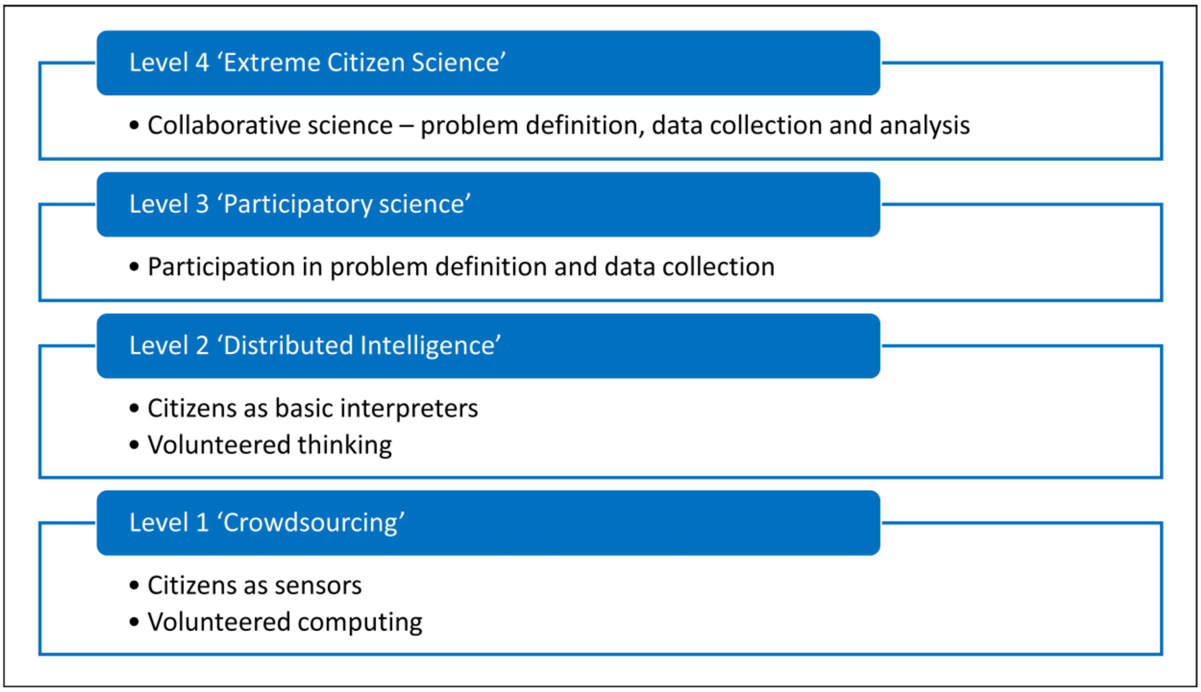


Figure 2.16. A framework which Haklay (2012) uses to define citizen science based on engagement and involvement levels.

The process of recruiting and encouraging volunteers to support environmental monitoring schemes is not a new phenomenon. For instance, Charles Darwin was not trained as a scientist himself, and he also relied on data collected by volunteers to emerge his theory of evolution by natural selection in the 19th Century (Science Communication Unit, 2013). A social scientist, Alan Irwin, introduced the term citizen science in 1995 (Irwin, 1995), yet was only added to the Oxford

English Dictionary in 2014. Some projects do not necessarily categorise themselves as 'citizen science', instead terms such as 'community-based', 'participatory', 'volunteered geographical information' (VGI) or 'crowd-sourced' are often used (Goodchild, 2007; Buytaert *et al.*, 2014). Various definitions have emerged simply because there are different types of citizen science projects active, and with varying levels of involvement. Haklay (2012) has produced a generic framework which categorises citizen science based on engagement and involvement levels (Figure 2.16). However, this framework fails to include ownership, empowerment and change within Level 4. Citizen science projects can also occur on a range of scales, from individual or local efforts, through to national and even global scales (Socientize Consortium, 2013). Furthermore, activities may be designed and driven by different groups of people and occur for varying lengths of time (Socientize Consortium, 2014).

Although public involvement and the co-production of environmental knowledge is not a new occurrence, evolving technologies, tools and communication facilities have meant that it has grown massively over the last few years. Goodchild (2007) describes this growth as an 'explosion' which is creating a global database of geo-information. Smartphones, social media, apps, crowd-sourcing and wireless data connections allow citizen scientists (through mass participation) to submit data anywhere, at any time, and about any topic. Many of these observations can also be geo-located, providing locational information with a reasonable level of accuracy (Goodchild, 2007; Hardy, 2013; Fohringer *et al.*, 2015).

To date, modern citizen science has largely supported natural science disciplines due to the importance of the environment to people, because people are interested in conserving their environment more than ever before, and because it drives change on a local level (Winfield, 2014). Citizen science has also been used for more high profile applications, for example, an article written by Stout (2014) compliments citizen scientist efforts after being used to track a missing Malaysian aircraft in 2014.

Despite its growing popularity, citizen science has also raised a number of challenges and barriers, particularly relating to the scientific value of information obtained by citizen scientists and how far it can really support traditional scientists to solve real-world applications (Goodchild, 2007). It also means that physical (environmental) scientists need to start thinking in an interdisciplinary way and should collaborate with, for example, social scientists and develop new scientific cultures.

2.5.2. The rise in citizen science for environmental monitoring schemes

Volunteers have assisted bird watching and other wildlife monitoring programmes since the 1900s. For example, the Christmas Bird Count is one of the longest running surveys which attracts thousands of volunteers each year in North America (Science Communication Unit, 2013). Following a digital revolution, citizen science has spread across various environmental disciplines, particularly those which need patterns, species and change detecting, both spatially and temporally. Citizen scientists can use the internet and smartphones to submit observations almost immediately. Real-time observations sourced from citizen scientists have therefore already supported environmental hazards and disasters, for instance:

- Aulov and Halem (2012) describe how humans were used to provide real-time data during the 2010 Deep Water Horizon oil spill disaster within the Gulf of Mexico. Images were posted by members of the public on Flickr, an online image and video sharing site, and used to determine the extent of the oil spill and forecast movement. Humans were essentially acting as a data collection 'sensor';
- Stone *et al.* (2014) evaluated the success of a community-based monitoring scheme involving local citizens who collected scientific data around a volcano in Ecuador. This network of volunteers, and their observations, significantly reduce the risks associated with local volcanic eruptions, acts as a communication channel, enhances preparedness prior to an eruption, and thus provides their own early warning system;
- The US Geological Survey has developed a Twitter Earthquake Detection ('TED') system which gathers real-time tweets (containing specific words and locational information) from members of the public to improve earthquake response (Aulov and Halem, 2012).

The public are becoming increasingly involved in monitoring the weather and water environment (see local, national and international case studies in Table 2.4). Despite these illustrations and its potential (Buytaert *et al.*, 2014; 2016), there is little evidence to suggest that citizen science is being routinely integrated into the UK or European flood risk and catchment management process, and communities are not proactively collecting data (Blaney *et al.*, 2016). However, citizen science has been shown to have potential in developing countries, where data are scarce and formal monitoring systems are relatively poor, as Walker *et al.* (2016) recognised in Ethiopia. In Tanzania, Gomani *et al.* (2010) detail how a low-cost approach provided local people with a sense of ownership within their catchment. Participatory methods are known to provide distinct benefits to the public; they help to identify local problems and develop management scenarios relevant to community concerns (Ridder and Pahl-Wostl, 2005; Bracken *et al.*, 2014). These benefits are important because uninformed communities can result in inefficient resource utilisation (Tambudzai *et al.*, 2013; Watanabe *et al.*, 2014).

Environmental citizen science project	Description
OPAL surveys 	The Open Air Laboratories network encourages UK citizen scientists to take part in ongoing tree, bug, climate, biodiversity, water, air and soil surveys. Project outcomes are predominantly focused around the educational values of participation. (www.opalexplorenature.org/surveys)
Fluker Post Project 	This simple citizen science scheme in Australia encourages members of the public to take and submit photographs from a fixed point (at a 'Fluker Post'), when passing, to assist land managers with on-going environmental issues, and detect changes over time. (www.flukerpost.com/)
Met Office WOW 	Supported by the UK's Department for Education, the Met Office launched a 'Weather Observation Website' (WOW) in 2011 which encourages ordinary people to submit weather measurements, descriptions and photographs to a shared website. The facility is now used worldwide, with more than 38 million observations being submitted within the first year (http://wow.metoffice.gov.uk/).
Creek Watch 	Creek Watch is a crowd-sourcing project in California which allows members of the public to submit simple data about their local watercourses using an iPhone app to tackle pollution issues. Data collected is fairly basic, but it provides professionals with an indication of the water's health. (http://creekwatch.researchlabs.ibm.com/)

Environmental citizen science project	Description
CoCoRaHS	The 'Community Collaborative Rain, Hail and Snow' network encourages volunteers to make precipitation observations in their back garden or local area using low cost measuring equipment across the US. The data is mapped online and is used for many applications and by various audiences, including schools, individuals and the National Weather Service (www.cocorahs.org; Cooper, 2016).
MorpethFlood and ToonFlood 	Newcastle University applied a one-off crowd-sourcing approach to gather information from local residents in North East England following two severe flash flood events (Morpeth and Newcastle in 2008 and 2012). Data was then used to reconstruct how the floods occurred, which later supported a flood defence scheme (http://ceg-morpethflood.ncl.ac.uk/).
BBC Weather Watchers 	The BBC launched an online crowd-sourcing club in November 2015, known as 'Weather Watchers', to encourage the public to share local weather observations. Each submission contains location, date and time information, along with a photograph and weather icon. A selection of submissions are used to inform viewers during weather forecasts about earlier weather conditions experience (https://www.bbc.co.uk/weatherwatchers/).

Table 2.4. Examples of citizen science projects where information has/is being collected by the public about the weather and water environment.

2.5.3. *Benefits, challenges and credibility of citizen science*

When considering citizen science across wider environmental disciplines, it is known to offer a comprehensive range of benefits to scientists, research projects and communities themselves. The Socientize Consortium (2014) released a White Paper on Citizen Science for Europe, highlighting the general benefits (Figure 2.17). A number of authors have recently reviewed environmental citizen science and it is apparent that the benefits are becoming more widely recognised. Key benefits and capabilities associated with environmental monitoring by citizen scientists are detailed below:

Mass data collection: although particpation levels may vary between individuals, together citizen scientists have the potential to collect mass data over a wide area, and in a cost-effective manner

(Science Communication Unit, 2013; Pocock *et al.*, 2014a). Local knowledge is also extremely valuable for aquiring historical contexts and rare events;

Good quality and real-time data: in some cases it has been found that volunteers collect datasets that are of a similar or higher standard to those collected by professional scientists (e.g. Danielsen *et al.*, 2013; Holt *et al.*, 2013). Volunteers have a wealth of valuable local knowledge and they are often cautious of 'skewing' scientific data. If required, there are tools available to provide instantaneous observations and check data automatically. However, limited studies have specifically focussed on the quality of community-based hydro-meteorological observations. Walker *et al.* (2016) is one of very few that have (in the context of groundwater supplies in Ethiopia), and concluded that good quality observations can be collected by the public, but the authors stress the importance of robust data quality checks.

Tools already exist: the general public already have access to the internet, smartphones, social media, apps and other relevant communication, sensor and data submission tools. There are also a number of open source and open access tools, software and maps available for use (Tweddle *et al.*, 2012; Wentworth, 2014a);

Environmental education: monitoring activities are known to raise awareness and understanding of environmental issues. Volunteers also gain new skills themselves whilst participating (Science Communication Unit, 2013);

Collaboration with scientists: Volunteers have the opportunity to work with scientists and feel part of the team (Tweddle *et al.*, 2012). Citizen science can also fall into the category of 'Participatory Action Research', a research method frequently used by social scientists (see Section 2.7);

Wider community involvement: monitoring activities open up new opportunities to the wider community and any age group, building a network of people who share the same goals;

Community ownership and empowerment: Hacker (2013), Burgos *et al.* (2013), Winfield (2014) and McEwen *et al.* (2016) suggest that getting communities involved in participatory and active research builds relationships, breaks down barriers, encourages data-driven decisions and communities begin to take ownership of issues around them. In turn this can catalyse change on the ground at a local level and translate research into practice. Large *et al.* (2017) advocates that this benefit is particularly important in catchment science when trying to implement NFM.

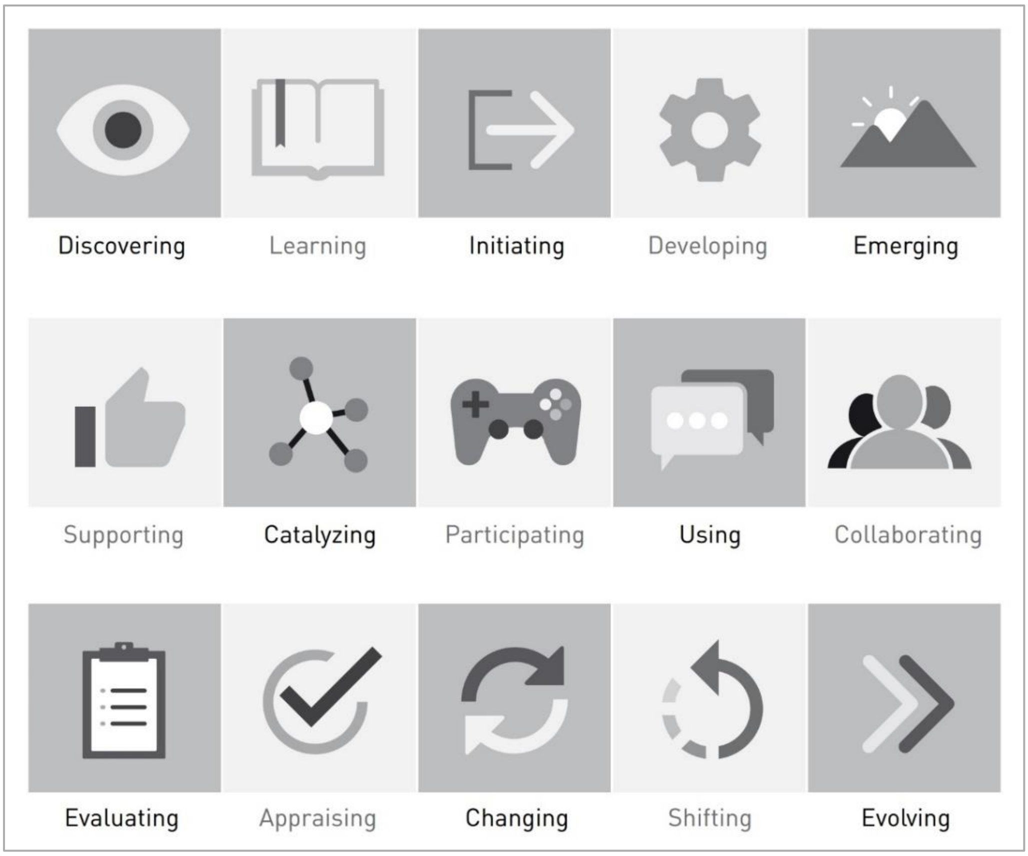


Figure 2.17. What citizen scientists are doing to traditional research projects (Source: Socientize Consortium, 2014).

Although citizen science monitoring offers a range opportunities to support scientists, it also brings a number of challenges and barriers, as Table 2.5 summarises. Credibility currently acts as the main barrier to the real-world and routine use of citizen science data, although it does depend on its end use. Further research is required before citizen science observations can be fully accepted and used by professional scientists. Nevertheless, some scientists are starting to appreciate that monitoring carried by communities can only add to, and support, traditional techniques by providing additional resources and new types of data (Winfield, 2014). The importance and value of citizen science is also starting to become recognised, as the following quotes demonstrate:

"*Data collected by volunteers already plays a critical role in environmental monitoring. With appropriate quality assurance measures, citizen science can generate high quality environmental data*" Parliamentary Office of Science and Technology (Wentworth, 2014a).

"*In the debate that is ongoing all across Europe, the bottom-line question is: Do we want to improve Europe or give it up? My answer is clear: let's engage!*" President of the European Commission (Socientize Consortium, 2013).

"Enable communities affected by flooding to themselves engage in exploring flood risks by making rainfall and flow gauge data publically available at an appropriate level of granularity. Facilitate their becoming 'citizen scientists' and collecting data helpful to future flood risk estimation and planning, including both scientific data and experiential information." Defra (2016) National Flood Resilience Review, September 2016.

Despite the challenges listed in Table 2.5, there are still calls for greater community involvement, the generation of new data, and the integration of local knowledge into science, policy and practice (Buytaert *et al.*, 2014; 2016; McEwen *et al.*, 2016).

Challenge	Description
Funding	Despite being 'low cost', there are expenses associated with developing new tools, training material, websites etc. Specialists may be required to keep tools up-to-date.
Engagement	It can be challenge to engage with a wide audience and keep volunteers interested over time. Citizen science may be seen as a chore to some if it is repetitive.
Evolving tools and technology	Many people can be unfamiliar with specific or new technology, especially if it evolves rapidly. Volunteers may find it difficult to adapt.
Data quality and reliability	Citizen scientists are amateurs, collecting data using simple and low-cost techniques. Accuracy and reliability of observations are generally perceived as being low compared with that collected by trained scientists, and is often in qualitative or descriptive formats. Some organisations may also become overwhelmed by data.
Facilitation	Monitoring programmes will require a professional or community-based leader (and time) to design and drive the project. It is also essential that monitoring efforts are appreciated by providing regular feedback to communities involved.
Ethics	Data protection acts must be considered carefully when storing, sharing and using data from multiple sources. This includes anonymising monitoring locations if the project involves individual properties.

Table 2.5. Key challenges associated with citizen science and environmental monitoring schemes (Source: Tweddle *et al.*, 2012; Burgos *et al.*, 2013; Socientize Consortium, 2013; 2014; Buytaert *et al.*, 2014; 2016; Wentworth, 2014a; Large *et al.*, 2017).

2.6. Using community-based observations

2.6.1. Modelling for catchment management

It is not possible to monitor every parameter and process at fine spatial and temporal resolutions when trying to understand the behaviour and response of individual catchments, particularly in smaller sub-catchments. To add to this, extreme weather events are often short lived and rare, particularly flash flood events, so there is little time to gather evidence (Archer and Fowler, 2015). Catchment issues like climate change are also related to future scenarios which cannot be monitored. Professional scientists and engineers therefore readily represent catchment boundaries, processes and behaviour through time and space using mathematical equations and algorithms (Shaw *et al.*, 2011). A computer can use these equations embedded within modelling software to simulate or predict catchment behaviour including river levels, water quality parameters, flood extents, and morphological and ecological activity (Beven, 2012; Bren, 2016). Catchment models are used to simulate past, present and future scenarios (Novak *et al.*, 2010), including the prediction of impacts associated with catchment management measures. Catchment modelling is however a challenging activity and is inherently subject to uncertainty given that the models require real, high quality, reliable and lengthy datasets in order to emulate reality (McIntyre *et al.*, 2005; Beven, 2007; 2012; Vidon, 2015).

It is important to remember that computer models are a simplification of the real world which are heavily dependent on the quality of the data used to build the model, and any assumptions which have been made (Vidon, 2015). Some catchment models represent highly simplified basins where information is 'lumped' together, whereas others are 'spatially distributed' providing more detailed information across the catchment (McIntyre *et al.*, 2005). Bathurst *et al.* (2017) accentuates the importance of spatial rainfall data in headwater catchments when modelling flood peak discharge. McIntyre *et al.* (2005) and Serinaldi and Kilsby (2016) argue that ungauged catchments can be modelled in other ways (e.g. using ensembles), but this leads to considerable uncertainty around peak flows. It is unlikely that these alternative techniques model at scales meaningful to local flood risk management. Furthermore, Hrachowitz *et al.* (2013) advocate how modellers have tried to develop universal models for global use, but in reality, specialised and detailed models are better for representing local catchment signatures. Spatial modelling has been achievable in recent years as the modelling process has significantly improved in line with computational power. 1D (dimensional), 2D and now 3D models are used to solve catchment issues.

The simple schematic in Figure 2.18 illustrates the concept of modelling and the generic stages involved. Although catchment models seek to overcome the limitations of being unable to monitor everything and everywhere, they still require real data as input data (boundary conditions), but also to calibrate and validate models. This is where citizen scientists could potentially support the modelling process (Buytaert *et al.*, 2014; Mazzoleni *et al.*, 2015) because they provide real information collected out on the ground on a local level. There are concerns over the varying quality and formats of data which is why citizen science data are not yet routinely used to support the catchment modelling process. Once citizen science observations are pooled together, they are often regarded as being sporadic in nature as oppose to those collected by more traditional and automated methods. Buytaert *et al.* (2014; 2016) have carried out an extensive review of citizen science in the context of hydrology and has suggested that interpolation and merging of datasets (with other citizen science and/or traditional datasets) is one solution. Spatially distributed catchment models are also required in order to make use of the abundance of different monitoring sites, thus have the potential to identify spatial patterns across a catchment (Bren, 2015). However, use of photographs and videos (which are most commonly collected by citizen scientists) could be challenging as catchment models generally require standardised and specific data formats and resolutions.

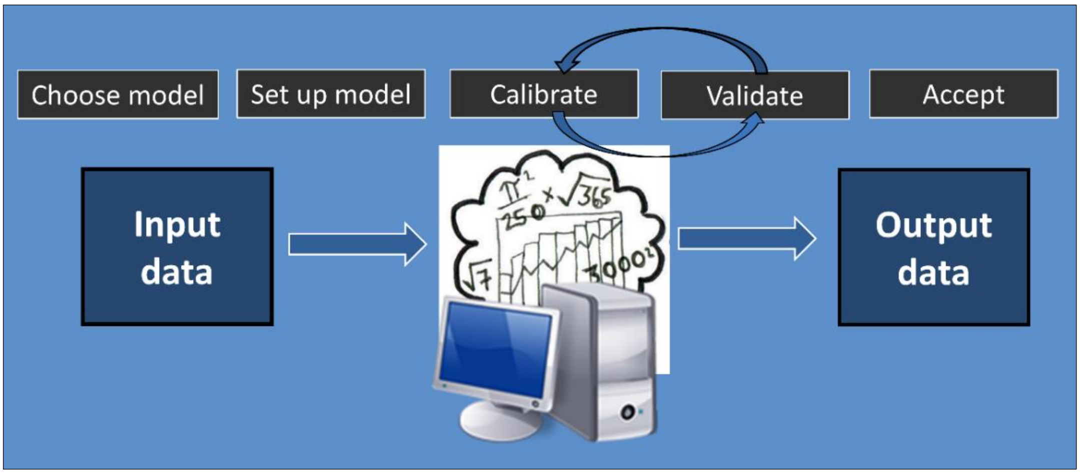


Figure 2.18. Schematic of catchment modelling and the main steps involved (after Beven, 2012).

Kutija *et al.* (2014) used data collected by the Newcastle upon Tyne community following the 28th June 2012 'ToonFlood' event to improve the performance of their model. Observations including time, location, a description of the flood impacts and photographs were crowd-sourced from the public and used to validate and calibrate a hydrodynamic flood model, 'CityCAT'. Kutija *et al.* (2014) concluded that this type of citizen science data has proven to be extremely useful, increasing their confidence in CityCAT's ability to model complex flows during urban flash floods.

Citizen scientists can also support the modelling process in other ways. For example, Climate*prediction*.net (2016) is the world's largest climate modelling experiment which makes use of volunteers' computing power. The project team run climate models on volunteers' personal computers to reduce computation demands, and increase the amount of data processed. Results are sent back to the project team where they then contribute to the wider climate change picture. There are also many examples of 'participatory modelling' activities in the literature where catchment management stakeholders, including locals, work with professional modellers to take part in the different modelling stages (e.g. Garrod *et al.*, 2013). TRT (2015; 2016) use their 'RiverSim' with local community groups, a river simulator containing sand which behaves in a similar way to river beds, banks and floodplains (Figure 2.19). Participants can physically carve into the river by hand, thus can model different management scenarios. Despite variations in citizen science based modelling techniques, all activities provide volunteers with increased awareness and understanding of catchments and the management process.

Figure 2.19. TRT's 'RiverSim', an innovative and interactive way of involving communities in the modelling process (photographs by TRT, 2015).

2.6.2. Visualisation and communication: importance of feedback and presenting catchment information in a meaningful way

To date, the communication of catchment information has generally focussed on raising the publics' awareness of both flood risk and climate change to evoke societal change and resilience (e.g. Evans *et al.*, 2014; van der Linden *et al.*, 2014). The use of communication technologies has played an important role in allowing material to reach a wider audience and connect communities on a global scale (McEwen *et al.*, 2016). Use of ambassadors and documentary films (e.g. Leonardo DiCaprio in 'Before the Flood'[8]) and the rise in Science, Technology, Engineering and Mathematics (STEM) outreach activities (Cox and Depoe, 2015) are valuable examples. However, many researchers accentuate there are still clear knowledge misalignments between scientists and the public (van der Linden *et al.*, 2014; Bliuc *et al.*, 2015; van der Linden *et al.*, 2015). For instance, Bliuc *et al.* (2015) states that less than half the US population believe in human-induced climate change, despite 97% of climate change research papers agreeing and presenting clear facts about this issue. Bliuc *et al.* also suggest that political and socio-economic factors influence the publics' decisions on this matter, and because climate change is perceived by the public as being an impersonal issue, there is still a scientific communication failure. Furthermore, despite flood risk being a dominant catchment issue on a personal and community-based level, effective and regular communication techniques are still required (Evans *et al.*, 2014). Many believe that it is a language barrier (especially when trying to communicate uncertainty), and that short and simple messages provide effective ways to deliver scientific messages to the public (Faulkner *et al.*, 2007; van der Linden *et al.*, 2014).

If local communities are to become i) more involved in the catchment management process and ii) act as citizen scientists and observe the water environment (or any scientific monitoring programme), it is important that the feedback loop is complete and they benefit from new knowledge that is being generated about their local water environment (Fohringer *et al.*, 2015; Le Coz *et al.*, 2016). Roy *et al.* (2012) carried out an extensive review on 35 well-known environmental citizen science projects. A large number of these projects confirmed that, through hands-on experience, constant communication and effective feedback to volunteers is vital in order to retain motivation and participation. This approach ensures that the public's contribution is acknowledged.

All catchment information shared with the public should be presented in meaningful and effective ways. This applies to data collected by citizen scientists, but it also stands when professionals are trying to disseminate and communicate information to the public, especially flood risk (as detailed in Section 2.3.4). Information needs to be understood by all stakeholders, including a lay person who has little or no experience of engaging with traditional sources of scientific data, or terminology. It is common for catchment modellers to work in isolation and to (for example) present flood maps which are poorly understood by the public. In the context of flood risk management, a resident of Morpeth in Northumberland remarked *"how can we the*

[8] 'Before the Flood' (2016) available (open access) on YouTube - https://youtu.be/d1tznG1r_TM

residents come to the table with coherent arguments when we are pitted against the new god of mathematical modelling?" (Wright, 2013). Haklay (2008) also commented on how maps often separate rather than include people in understanding their environment, including the Environment Agency's flood risk maps.

Evans *et al.* (2014) successfully communicated flood risk through three-dimensional (3D) visualisations to raise awareness on a local level (Figure 2.20). They stress how difficult it is to communicate flood risk to communities effectively. 3D visualisations of the River Exe in Exeter were therefore created, and involved displaying places of interest (buildings and infrastructure), the river overtopping muddy water, the spread and inundation of a flood, aerial imagery, a fly through over the whole city, and extracts from different time stamps during the flood to enhance the flood story. The visualisations were shown to the community during workshops and were regarded as being an effective and realistic engagement tool. Holmes *et al.* (2016) also used 'digital storytelling' techniques as a way of communicating flood information to the River Severn communities. This knowledge exchange method was appraised by the stakeholders involved. Illingworth (2016) has taken science communication a step further and translated scientific messages into poetry. However, the three examples presented have only involved a one-way information sharing process, and have not involved citizen scientists.

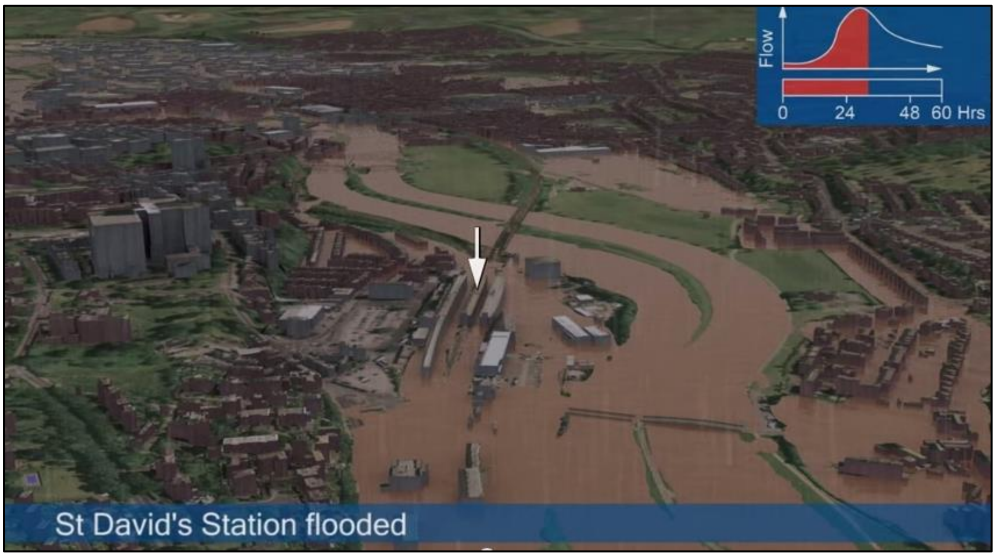


Figure 2.20. Communicating flood risk effectively to the Exeter community using 3D visualisation tools (Evans *et al.*, 2014). See YouTube animation: https://www.youtube.com/watch?v=0QL0hYIURyk

An additional consideration is how catchment information will be disseminated back to the community. Websites, news channels, social media and face-to-face workshops (Roy *et al.*, 2012; Le Coz *et al.*, 2016) are likely to reach a wider public audience and be much more effective than academic papers. By closing the feedback loop in this way, it allows the public to understand the meaning behind their data, and it illustrates that they are contributing new knowledge.

2.7. (Community-based) Participatory Action Research (PAR)

So far, this chapter has largely discussed community engagement and involvement regarding science in practice and in policy (i.e. catchment stakeholders on the ground). However, it is important to consider this theme from a researcher's perspective. Working with local communities to achieve scientific research goals is not a new approach, particularly for social scientists who frequently collect a combination of qualitative and quantitative observations (Bryman, 2016). 'Participatory Action Research' (PAR) collaborates with communities to co-produce knowledge in order to find solutions to problems which have a relevance to everyone involved, especially local people (Durham University, 2012; Hacker, 2013; Bracken *et al.*, 2014). McIntyre (2008) and Hacker (2013) describes PAR as 'researching with them, rather than upon them', and typically aims to influence change on social and environmental issues (Kindon *et al.*, 2007). This type of research therefore branches away from traditional techniques and philosophies, allowing communities to be actively involved, and participate in any stage of the research process (Durham University, 2012). Kindon *et al.* (2007), Hacker (2013) and Bryman (2016) stress that this approach helps to break down the barriers between researchers and communities, incorporates local experiences (thus voices the community), and promotes a shift (share) in power.

Depending on the specific research techniques adopted, the terminology used to describe PAR can vary, for instance action research (Bryman, 2016) or community-based participatory research (Hacker, 2013). While some researchers, such as Cooper *et al.* (2007), argue that PAR is separate to the citizen science model, they both share the same grounded principles and broader goals, notably community empowerment and local action (as described in Section 2.5.3). Durham University (2012) believe PAR also involves the data collection phase, and Bonney *et al.* (2016) challenge the generic definitions of citizen science, emphasising that activities often involve much more than data collection anyway. Consequently, some citizen science or community-based monitoring projects should be placed under the umbrella of PAR as a more specific research method. PAR has been readily used by researchers to solve health, medicine and education related issues (McIntyre, 2008; Hacker, 2013; Bryman, 2016) because they involve the study of people, rather than the physical environment. As a researcher implementing a PAR project, a number of issues, such as ethics, time scales and data ownership need to be addressed (Hacker, 2013).

2.8. Summary (the research gap)

A citizen science approach is starting to provide professional scientists with an effective, inexpensive and timely solution which is required to meet the pressures and demands for evidence-based environmental decision making on a local level. Despite flourishing in many other environmental disciplines, it is clear that it is not yet well organised or regularly relied upon within the catchment management process (or even just flood management). Many benefits associated with citizen science have the potential to slot comfortably within the existing catchment-related policy Directives, Acts, Frameworks, organisations and wider drivers previously detailed within this chapter. More specifically, involving the public through citizen science or a community-based approach has the potential to encourage catchment-wide observations to be made, encourage residents and land owners to appreciate catchment connectivity, support local decisions, raise awareness of issues, strengthen work carried out by governmental organisations and Rivers Trusts, and generally welcome the public to be part of the catchment management process.

It is clear that hydrologists have developed and refined standard monitoring and modelling methodologies and technologies over decades which automatically raises concerns over the quality, thus scientific credibility, of citizen science data in this sector (Buytaert *et al.*, 2014). Next steps involve testing citizen science monitoring techniques alongside more traditional methods to understand the capabilities and value (use) of citizen science, particularly in the characterisation, modelling and management process. Rainfall, river levels, flood events, water quality, sediment, habitat and biodiversity related community-based monitoring schemes, whether they are existing schemes or new, all have the potential to support catchment management and restoration activities. However, going against reliable and traditional methods is a daunting step to take. Clearer guidance and templates are therefore required to fully understand the process of involving the public in water and weather monitoring activities. Key concerns relating to the feasibility, reliability, value and sustainability of community-based observations should therefore be addressed.

Chapter 3. Case study sites and focus community

Figure 3 (intro). *The predominantly rural Haltwhistle Burn catchment (a tributary of the Tyne in northern England), exhibits characteristics and issues typical of an upland headwater catchment.*

3.1. Chapter introduction

In order to demonstrate the feasibility, reliability, value and sustainability of community-based monitoring schemes within catchment science, a real catchment and focus community was required to act as a pilot site. Given the limited availability of UK-based citizen science projects for hydrology and water resource management in 2013-2014 (when this project commenced), it was not possible to extract existing citizen science observations for use as a secondary source of information. It was also important to implement a new community-based scheme and work directly with the public as the designing, training, facilitation and feedback phases are fundamentally important to citizen science (Tweddle *et al.*, 2012; Burgos *et al.*, 2013; Socientize Consortium, 2013; 2014; Pocock *et al.*, 2014a), thus were expected to yield important research findings here. As Hacker (2013) points out, the direct involvement of researchers in participatory studies can also influence the public's participation levels. After an initial desktop study and discussions with local catchment partners, it was apparent that River and Wildlife Trusts across the UK already hold some datasets collected by volunteers, but these generally favour ecological and habitat surveys, rather than hydrometric or meteorological monitoring networks. A co-location study using traditional and community-based monitoring equipment was required here.

Chapter 3 justifies the catchment and community selection process used to determine where the majority of the research questions (1-3) were carried out. It then provides locational information and describes the catchment and community of interest, with focus on physical properties affecting hydrological response. Catchment pressures are introduced (although Chapter 4 describes these in more detail), along with Tyne Rivers Trust's (TRT's) wider catchment management project, which this Ph.D. project has contributed towards. Monitoring strategies are described in Chapters 4 and 5.

3.2. Catchment and community selection

The catchment selection process involved a number of considerations, particularly those affecting the feasibility of engaging with an appropriate community. It was necessary for the desired catchment to be subject to multiple pressures, have flooded in recent years, and hence hold a set of attributes common to many unmonitored rural headwater catchments in the UK. It was also assumed that choice of region or river basin district would not significantly disturb the project outcomes because they all contain communities and catchments which require monitoring, modelling and management. As a result, selection was confined to the Tyne catchment in north east England (it was closer in proximity), which is overseen and managed by

TRT. The Haltwhistle Burn catchment was subsequently selected for use as the primary case study site (see Figure 3.1 for catchment location and features/places of interest). However, an additional community positioned within the Tyne catchment has contributed to the project's outcomes at times, particularly when investigating the sustainability aspect (see Section 3.5).

Known for being located in the 'Centre of Britain', the Haltwhistle Burn catchment in Northumberland was chosen to demonstrate a community-based monitoring approach because:

- It is rural and unmonitored – no traditional or official monitoring networks exist within the catchment boundary, therefore long-term datasets are completely absent;
- Although limited traditional evidence exists, the catchment (therefore town located close to its outlet) suffers from a suite of pressures, including flooding, pollution and morphological activity (sediment issues);
- The town has strong community foundations; various environmental groups already exist and members of the community are already engaged, including the River Watch and Flood Action Group;
- Through the existing Flood Action Group, members of the Haltwhistle Burn community have an interest in flooding, while some have been directly affected by flooding;
- Only a small number of properties are classified as being at risk from fluvial flooding (Environment Agency, 2009b), thus the Haltwhistle Burn is unlikely to be monitored or qualify for any Environment Agency flood defence schemes in the near future;
- The catchment is classified by the Environment Agency as being a 'rapid response catchment' (RRC)[9];
- It has good accessibility (e.g. footpath network) to encourage catchment-wide activities;
- The catchment is a tourist hotspot, providing passers-by an opportunity to participate;
- Catchment management and restoration works were planned for the Haltwhistle Burn catchment, along with community engagement, through TRT's CRF project, offering further research prospects and community 'gatekeepers'.

[9] According to the Environment Agency's 2013/14 RRC register.

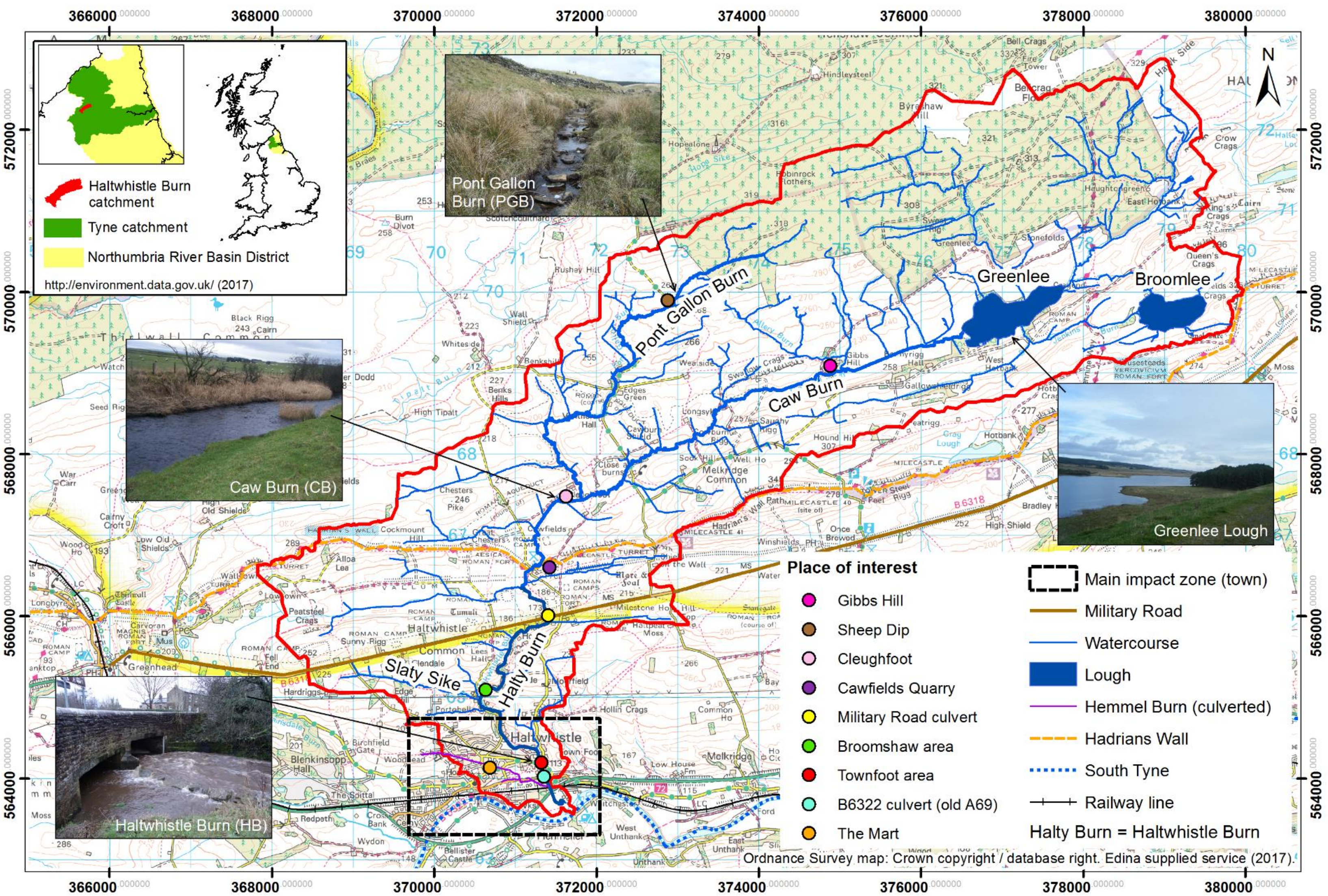


Figure 3.1. Location of the Haltwhistle Burn catchment on a national, regional and local level. Watercourses and places/features of interest are highlighted. Note that the Hemmel Burn's source falls just outside the catchment boundary as the majority of this watercourse is culverted beneath the town.

3.3. Catchment description and pressures

3.3.1. Overview of the Haltwhistle Burn catchment

Located within the County of Northumberland, the Haltwhistle Burn is one of the River South Tyne's major tributaries. The South Tyne is characterised by waterlogged soils, steep valley sides and a flashy sub-catchment response. The South Tyne catchment is nested within the wider 2300km^2 Tyne basin, which is generally eastward-draining over rural landscapes, towards the urban and industrial areas of Hexham, Prudhoe, Gateshead and Newcastle, before discharging into the North Sea (Environment Agency, 2009b; Ellwood, 2015). Aside from these busy urban areas, the Tyne contains many smaller and close-knit communities, including Haltwhistle, Acomb, Wark and Ovingham.

As Figure 3.1 illustrates, the 42km^2 Haltwhistle Burn catchment drains east to west across farmland, heaths and bedrock by a complex stream network, before heading south towards the town of Haltwhistle, the main impact zone and community of interest. Comprised of mostly unnamed streams and ditches, the drainage network is heavily constrained and elongated by the Great Whin Sill outcrop, which intrudes across the region's landscape. With parts of the catchment designated as a Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC – Greenlee and Broomlee Lough), the presence of the Greenlee Lough National Nature Reserve, and also Hadrian's Wall (World Heritage Site), it is both a scenic and historically valuable location to both locals and tourists. Haltwhistle is also a gateway to the Northumberland National Park, and the geographic centre of Britain.

Pont Gallon Burn (PGB), Caw Burn (CB) and Haltwhistle Burn (HB) form the catchment's backbone, which together travel over a distance of approximately 19km. Since the town of Haltwhistle (population of just under 5000 – Office for Nation Statistics, 2011 census) is located close to the catchment outlet, where the land becomes steep and narrow as a result of an incised gorge, flood risk is exacerbated. This hydrological 'pinch-point' has experienced a number of flood events in recent years, which in turn has triggered water quality issues and morphological instability. The Haltwhistle Burn catchment does not contain any national hydrometric monitoring networks, therefore the community does not benefit from an official flood warning system. The nearest NRFA stations are located on the South Tyne at Featherstone and Haydon Bridge (5-10km away), and neither can be used to reflect the Haltwhistle Burn's response. Prior to this project, characterisation, modelling and management work were difficult to achieve.

There is little evidence to suggest that the Haltwhistle Burn has been a focal point for academic research in previous years, with flood studies, such as Archer *et al.* (2007), being carried out at much broader scales. However, the evolving catchment management process has permitted a number of partnership projects to commence in recent years, including the Haltwhistle flood investigation study by Northumberland County Council[10] and TRT's CRF project (see Section 3.4). These two studies have been running in parallel to this Ph.D. project.

3.3.2. Topography, stream order and sub-catchments

The digital elevation model (DEM) presented within Figure 3.2 illustrates the catchment's topography, along with stream order and sub-catchment boundaries.

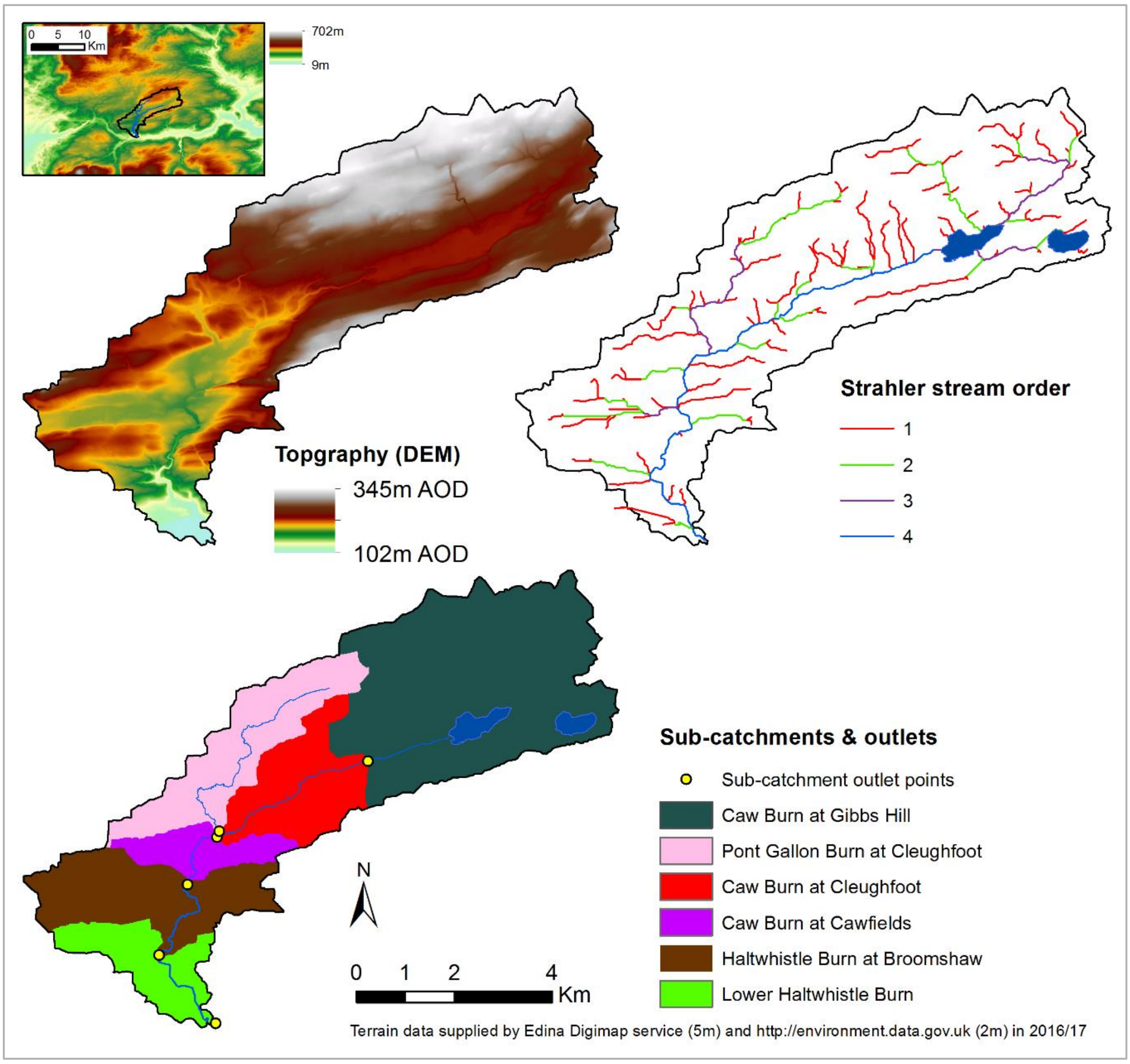


Figure 3.2. DEM illustrating the topography of the Haltwhistle Burn catchment (top left), Strahler stream order (top right) and sub-catchment configuration (bottom).

[10] NCC's flood investigation and feasibility study – to identify possible actions to reduce flood risk around the town of Haltwhistle (with focus on the Hemmel Burn and drainage infrastructure http://bit.ly/2jwiQyc).

Elevation ranges from 345 metres above Ordnance Datum (m AOD) in the north east of the catchment, to 102m AOD by the outlet. In the upper catchment, the land falls on either side towards Greenlee Lough (shallow lake at 223m AOD), forming a subdued valley. The topography remains fairly flat for a few kilometres west, before descending towards the south west. Once below the B6318 Military Road in the lower part of the catchment, it becomes steep and narrow within the gorge section, before reaching Haltwhistle and the South Tyne confluence.

Stream order is used to define stream size in a drainage basin based on the hierarchy of tributaries (Bren, 2015). The stream network map in Figure 3.2 (created using ArcGIS spatial analyst tools) confirms that the majority of watercourses feeding into the Haltwhistle Burn (which enters the impact zone downstream) are 1st and 2nd order streams. Sub-catchment areas also reveal where and how different parcels of land contribute to the river regime in the upper, middle and lower reaches across the catchment. The Caw Burn and Pont Gallon Burn dominate the upper catchment, and due to a vast quantity of 1st and 2nd order streams feeding directly into the Haltwhistle Burn close to the outlet (therefore town), they will react quickly to local and intense rainfall events (Bren, 2015).

3.3.3. Geology, soils and land cover

Figure 3.3 illustrates the spatial variations in bedrock, superficial geology, soils and land cover across the Haltwhistle Burn catchment.

The catchment's geology is fairly simple and characteristic of the region, comprising of softer sedimentary rocks and contrasting volcanic outcrops. Alternating bands of limestone, sandstone and mudstone dominate the catchment following their formation during the Carboniferous period approximately 300 million years ago (Clarke, 2007; Land Use Consultants, 2010). Shortly after, volcanic intrusions formed The Great Whin Sill (impermeable dolerite), which significantly controls the catchment's rural drainage regime today. Glacial activity also carved into the landscape between the hard and soft deposits, leaving a set of escarpments (north-south facing) and open valley floors (Clarke, 2007). The sandstone gorge section in the lower catchment also confines the Haltwhistle Burn (Beckensall, 2013).

According to British Geological Survey (BGS) data in Figure 3.3, the catchment is described as having a reasonably high permeability potential due the underlying geology. However, soils are generally waterlogged throughout the year owing to high annual rainfall totals and peat bogs in the upper catchment. Impeded loamy-clayey soils persist in the lower catchment.

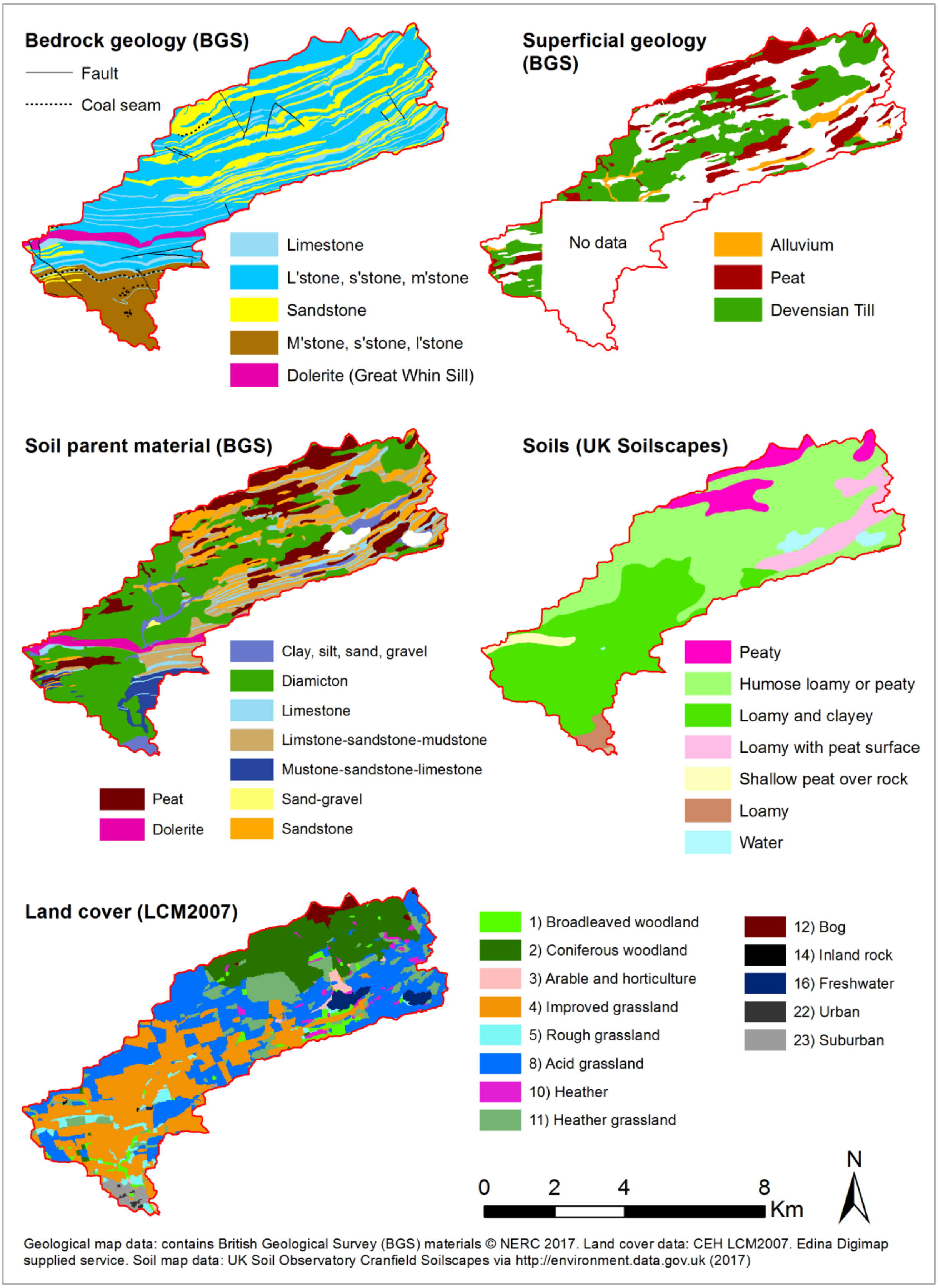


Figure 3.3. Bedrock and surface geology, soil parent material, soil textures and land cover across the Haltwhistle Burn catchment (L'stone, Limestone; S'stone, Sandstone; M'stone; Mudstone).

Although wildlife and recreational resources prevail today, historically, the Haltwhistle Burn catchment was a busy location for Roman and Industrial activities. Roman walls, forts and aqueducts have featured in the landscape over time and the power of the Burn has driven machinery (Land Cover Consultants, 2010; Beckensall, 2013). The geology and hydrology significantly dictated industrial activity from the 1800s, with lime kilns, woollen mills, coal pits, sandstone brickworks and limestone quarrying heavily interacting with the Haltwhistle Burn (Haltwhistle Partnership, 2017). TRT (2015) studied historical Ordnance Survey (OS) maps and found that, whilst industrial and mining activities have declined, impermeable surfaces (roads and the town), commercial forestry and improved pastures have spread in the last 150 years.

Alongside rural tourism, arable and pastoral farming activities in the upper and middle regions of the catchment dictate land use today. The land cover map in Figure 3.3 illustrates how the catchment is principally covered by improved, rough and acid grasslands in the middle and lower areas (62%). The coniferous woodland area in the north (18%) forms the southern limit of Wark Forest (Kielder Forest Park) which is managed by the Forestry Commission and commercial loggers. Other than a few scattered farms buildings and isolated dwellings in the Broomshaw, Cawburn, Cleughfoot and Gibbs Hill areas, Haltwhistle is the only settlement which intersects the catchment boundary. Urban and sub-urban only accounts for 1.9% of the total catchment area.

3.3.4. Climate and climate change

The UK's climate is driven by the south-westerly winds which pull in moisture from the Atlantic Ocean, hence it is affected by fluctuations in the large-scale North Atlantic Oscillation (NAO) (Fowler and Kilsby, 2002; Macklin and Rumsby, 2007; Jenkins *et al.*, 2009). Alongside altitude, the frequency and magnitude of the NAO strongly dictates temperature, wind and precipitation variability experienced (Fowler and Kilsby, 2002). However, other weather systems can prevail at times, including short-lived convective fronts with spatial patterns which do not necessarily correlate with relief (Kelway, 1977). While day-to-day variations occur, western and central parts of northern England are generally wetter and cooler on average than other parts of the country (Collinge and Jamieson, 1968; Met Office 2017).

Although officially located within north east England, the Haltwhistle Burn catchment is positioned within the Tyne Gap, a physical divide between the east and west, as well the north Pennine and south Cheviot flanks (Collinge and Jamieson, 1968). Given the strong orographic influence of the Pennine Hills in northern England, Haltwhistle's climatic patterns are also dictated by this natural phenomenon. The Haltwhistle Burn catchment is one of the wettest areas in the Tyne Catchment and Northumberland due to the surrounding topographic barrier, although long-term rainfall totals are comparatively lower than other Pennine regions due to the lower Tyne Gap altitudes (Met Office, 2017).

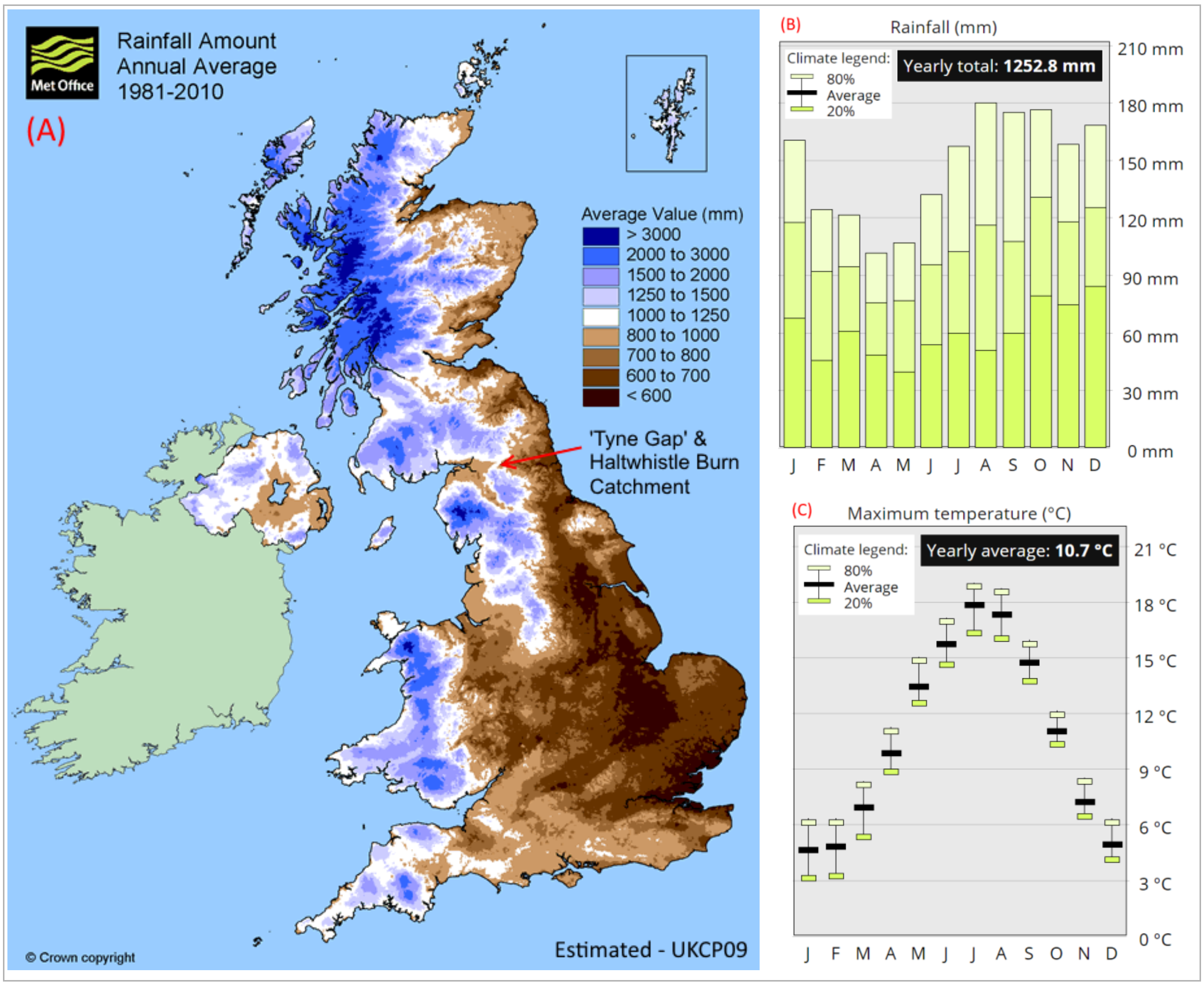


Figure 3.4. (A) Average annual rainfall totals across the UK, (B) monthly and annual rainfall totals at Spadeadam and (C) monthly and annual maximum temperature at Spadeadam. All statistics relate to the 1981-2010 climate period. Note that Spadeadam is located further north (elevation 285m AOD), thus provides an indication for the Haltwhistle Burn (Source: Met Office, 2017).

There are no official Met Office climate stations located within the periphery of the Haltwhistle Burn catchment. The nearest station providing observed climatic trends is Spadeadam (10km north-west of the catchment). Annual climate statistics are presented in Figure 3.4, with UKCP09 average annual rainfall totals (1981-2010) being estimated as 800-1250mm (TRT, 2015) and 983mm (FEH 2013[11]) for the Haltwhistle Burn catchment. Potential and actual evaporation rates (1961-1990) are estimated as 470-530mm per year (Kay *et al.*, 2013), and the Pennine Hills provide shelter from frequent snow events.

[11] Figure extracted from Centre for Ecology and Hydrology's (CEH's) FEH web service https://fehweb.ceh.ac.uk/ in April 2017.

Climate change projections indicate that the UK is expected to experience wetter winters, warmer summers and more extreme weather events (IPCC, 2014; ASC, 2016). Flood risk, drought, changes to water temperatures, and pressures on natural ecosystems are therefore some of the UK's key climate change concerns. In particular, a warmer atmosphere is capable of holding extra moisture, which will exacerbate extreme rainfall events and hydrological activity (Kendon *et al.*, 2014; ASC, 2016). The Environment Agency (2009b) has highlighted climate change (increased rainfall intensities) as being the most likely scenario for increased flood risk within the Tyne catchment, with peak flows expected to increase by 20%. These concerns emphasise the need for increased monitoring and knowledge generation.

3.3.5. Flood risk and other catchment issues (knowledge prior to community involvement)

The Haltwhistle Burn catchment holds an active flood history, with records dating back to at least 1892 (Table 3.1), affecting the town and upstream dwellings in, for example, 2007, 2012 and again more recently (which were captured by the community - see Chapter 4). Only a small number of properties are at risk from fluvial flooding from the Haltwhistle Burn though as the catchment's outlet is positioned over the Townfoot area. The Hemmel Burn's limited culvert capacity and pluvial flooding pose further flood risks to the town itself, inside and outside the catchment boundary, which NCC's flood study investigated.

Relevant Environment Agency flood maps can be found within Figure 3.5. The Environment Agency has historical flood extents recorded in the vicinity of the South Tyne only. Like many rural settlements in west Tynedale, the A69 transport corridor and connecting B-roads have confined the Haltwhistle Burn under bridges and culverts, which block and restrict watercourse capacity during high flow, as Figure 3.5 demonstrates. Nevertheless, the community have stressed that these flood maps lack local detail and have a greater relevance to properties on the South Tyne floodplain.

Aside the Environment Agency records, the number of historical floods documented and the availability of relevant and useable information within the catchment is still scarce, with the majority of evidence relating to the wider Tyne or Northumberland region. For instance, Kelway (1977) details how a rare and unusually severe convective storm hit north east England in August 1975, producing significant flood levels. Table 3.1 presents a chronology of flood-related events sourced from newspapers and the media which have specifically referenced Haltwhistle (therefore the list is not exhaustive). Although the chronology indicates that extreme events have historically occurred, particularly in the 1920s and in the months of June and September, there is limited quantitative or even qualitative evidence to describe them.

Year / Date	Description (relevant to Haltwhistle)	Source
2nd September 1892	Haltwhistle experienced 'heaviest rainfall for some time'. Roads and houses flooded.	Duncan Local Records.
14th June 1900	A storm described as 'the most severe in the district for many years'. Flooding in Haltwhistle unclear.	Carlisle Patriot (June 1900).
11th/12th June 1912	Rain and hail experienced for 1-2 hours. Streets, houses and shops flooded, Westgate to Main Street impassable.	Newcastle Chronicle (June 1912).
20th September 1926	Heatwave created a thunderstorm, experienced in Haltwhistle	Hexham Courant (September 1926).
21st September 1927	South Tyne overflowed near Haltwhistle.	Newcastle Chronicle (September 1927).
11th November 1929	Thunderstorms in the Tyne catchment led to Haltwhistle's 'greatest flood in 50 years'.	Haltwhistle Echo (November 1929).
November 1967	Flooding caused Townfoot Farm to experience 5ft of water. Bridge over the Burn not high enough.	Haltwhistle Echo (November 1967).
June/July 2007	Flooding occurred in Haltwhistle. "Elderly people had to be evacuated after their homes flooded during heavy rainfall at The Mart". "Fire engines were called to pump water away at 6 different locations in Haltwhistle".	Hexham Courant (June 2007).
28th June 2012	North-east England experienced flash flooding during the 5pm rush hour. Affected Haltwhistle, with extensive flooding in Townfoot and The Mart.	ITV Tyne Tees (28th June 2012).

Table 3.1. A chronology of relevant meteorological and flood-related events which occurred prior to this study. Data was largely extracted from a wider database compiled by Archer *et al.* (2016) which has since been disseminated online: http://ceg-fepsys.ncl.ac.uk/outputs/ (2018).

Due to a combination of risk factors (e.g. steep topography) and the resulting vulnerability, Haltwhistle is one of Northumberland's eleven communities listed on the Environment Agency's RRC register (see map in Appendix 3A). Haltwhistle has been categorised as 'high risk' as the catchment has the potential to respond rapidly to rainfall, initiating dangerous velocities and flash flooding. By nature, these events are harder to observe, let alone forecast. The community-based monitoring approach has therefore been used to explore flash floods.

The Haltwhistle Burn also suffers from other catchment pressures, including agricultural diffuse pollution, high rates of sediment erosion and transportation, and it is currently failing to reach the WFD's 'good ecological status' target (TRT, 2015). These are discussed in Section 3.4 and 4.

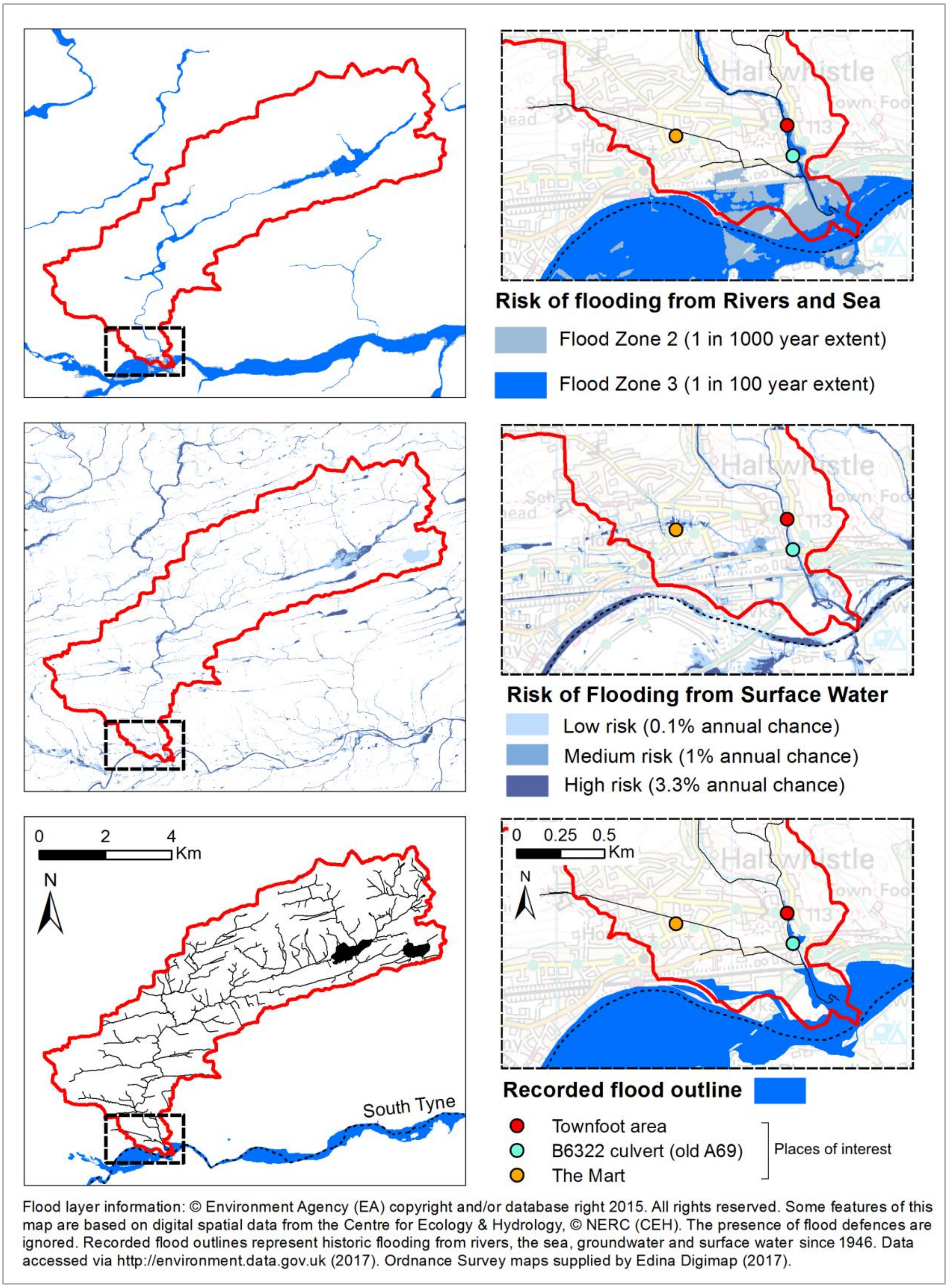


Figure 3.5. Official Environment Agency fluvial and pluvial (surface water) flood risk maps, as well as recorded historical flood extents in and around the Haltwhistle Burn catchment.

3.4. Tyne Rivers Trust's CRF project

As Section 2.3.5 previously highlighted, the role of Rivers Trusts in catchment management is rapidly expanding, particularly with aspects relating to habitat, wildlife and water quality improvements. Such organisations are also increasingly engaging with local communities and schools as a way of educating and including the public in CaBA orientated projects. Funded by Defra (Environment Agency), TRT led a multi-partnership[12] Catchment Restoration Funds (CRF) project within the Haltwhistle Burn catchment from 2012 to September 2015. Although the CRF project was officially targeting a 'poor' WFD (therefore failing) status due to pressures on fish populations, a 'total catchment approach' was proposed to manage and restore the health of the Haltwhistle Burn. This involved appreciating that the Burn suffers from multiple pressures and, together with the concept of catchment connectivity, a holistic catchment-scale approach was adopted. The CRF project briefing note can be found in Appendix 3B.

Whilst not a 'flood project', TRT acknowledged that by controlling runoff during high flows, many smaller issues around the catchment could be addressed, including siltation, invasive species, diffuse and point-source rural pollution, erosion, flooding and fish passage. The following activities were subsequently promoted over three years, many of which were addressed through use of green-engineering techniques or NFM (TRT, 2015):

- Alleviating Greenlee Lough's poor water quality;
- Controlling livestock diffuse pollution;
- Woodland habitat management;
- Fish easement work;
- Urban runoff management;
- Sedimentation in the lower catchment;
- Increased levels of community engagement, flood risk awareness and flood resilience.

It is the final item on the list that created a plausible connection to the Ph.D. aim and objectives. TRT became the 'gatekeeper' into the community, whom had already linked with various community-led groups, including the local flood group, Haltwhistle Burn River Watch group

[12] Official CRF project partners included TRT, Haltwhistle Town Council, Northumberland National Park, NCC, Forestry Commission, Environment Agency, Newcastle University and Hadrian's Wall Heritage Ltd. Other stakeholders have also contributed.

(which TRT initially activated), local National Trust volunteers, Haltwhistle Walking Group, Haltwhistle Young Farmers, and the South Tyne Wildlife group. These groups consist of members of the public who have an interest in promoting the health of the Haltwhistle Burn. Many of these volunteers actively contributed to the CRF deliverables across the catchment, including fish pass, leaky dam and brash bundle construction. These community-based environmental groups operating in and around the Haltwhistle Burn catchment have therefore provided a 'focus community' for this project, as well as passers-by who have sporadically interacted with the catchment.

Being part-funded by TRT's CRF project provided an opportunity to link catchment science, notably hydro-meteorological monitoring, to the CRF's end management and restoration goals. Community-based monitoring provided before, during and after intervention data, which TRT could not attain alone. As this thesis highlights throughout, the community-based monitoring approach has significantly contributed to the CRF project deliverables, its legacy, as well as the England River Prize application, which subsequently won the 'multi-partnership' category in 2014 (TRT, 2015)[13].

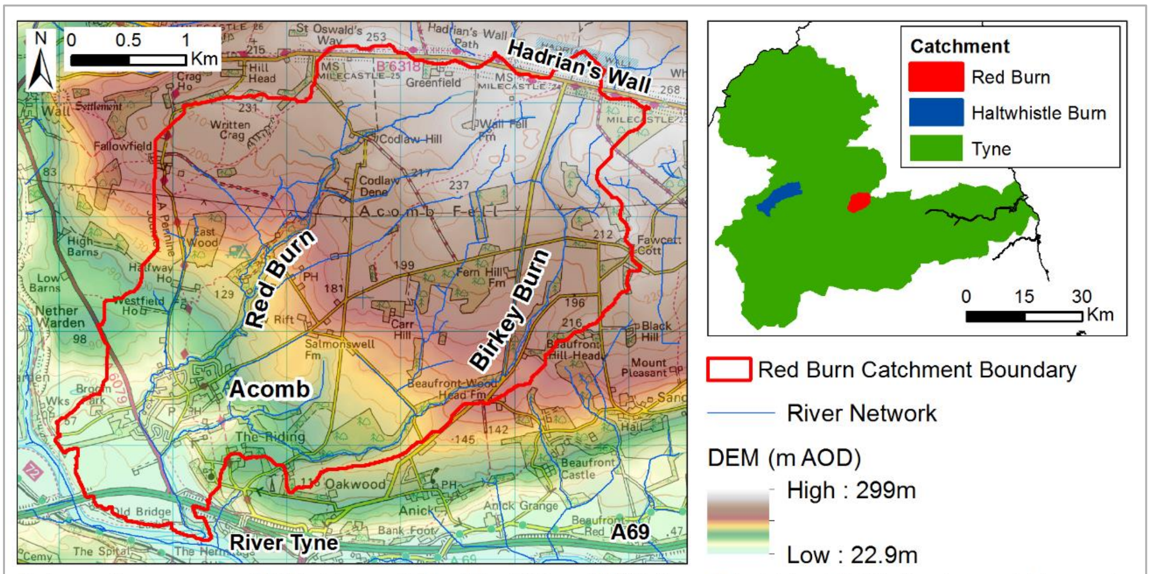
3.5. Additional case studies

In order to demonstrate the sustainability of a community-based monitoring approach (Objective 4B), additional case studies have been explored and are reported at times alongside the Haltwhistle Burn catchment (particularly Chapter 7).

Unlike traditional research methods where the researcher is the sole decision maker, 'opportunistic' case studies arise when members of the public influence the research approach, primarily by requesting to be a research collaborator or participant. This approach strengthens the 'participatory' aspect of community-based research as the project outcomes are co-produced. In many cases, this type of research is unforeseen and arises part-way through community-based fieldwork, thus is common to social research projects (Bryman, 2008). Other communities may also become involved unintentionally. There are many risks associated with incorporating opportunistic sites, including changes to project timescales and the loss of research control (Kindon *et al.*, 2007; Durham University, 2012; Hacker, 2013). However, there are mutual benefits to both the researcher and the community group involved, allowing research findings to be assessed in more practical and natural settings (Hacker, 2013).

[13] http://www.therrc.co.uk/england-river-prize-2014

The 14km^2 Red Burn catchment in Northumberland (a tributary of the Tyne, approximately 22km east of Haltwhistle) has provided the dominant opportunistic case study site. The village of Acomb is susceptible to flash flooding (see RRC map in Appendix 3A), yet the Red Burn and Birkey Burn are unmonitored. The community group, locally known as 'Action4comb' (A4A), expressed their concerns about the lack of local information and subsequently became engaged with the project part-way through the fieldwork phase. A4A have set up their own monitoring scheme, which has been observed here for research purposes. The location of the Red Burn catchment is presented within Figure 3.6. Additional case studies or examples (following enquiries) are also discussed within this thesis where appropriate.



Ordnance Survey maps and DEM data supplied by Edina Digimap (2016). Some data obtained via http://environment.data.gov.uk

Figure 3.6. Location map of the Red Burn catchment in Acomb, Northumberland.

3.6. Chapter summary

This chapter has introduced the main case study site and focus community required to meet the overall aim and objectives. It has emphasised that the Haltwhistle Burn catchment in Northumberland presented numerous opportunities when piloting a community-based monitoring approach, and TRT's CRF project also offered a real (and live) catchment management project on the ground. Despite parts of the town being located outside the catchment boundary, this study has focussed on the Haltwhistle Burn catchment itself, rather than the Hemmel Burn. It has also incorporated engagement and enquiries from other communities (notably Acomb in Northumberland) where necessary, particularly when discussing the sustainability aspect. Ethical assessments were required before any public engagement and monitoring activities commenced, as Chapter 4 describes.

Chapter 4. Designing and implementing the community-based (citizen science) monitoring scheme

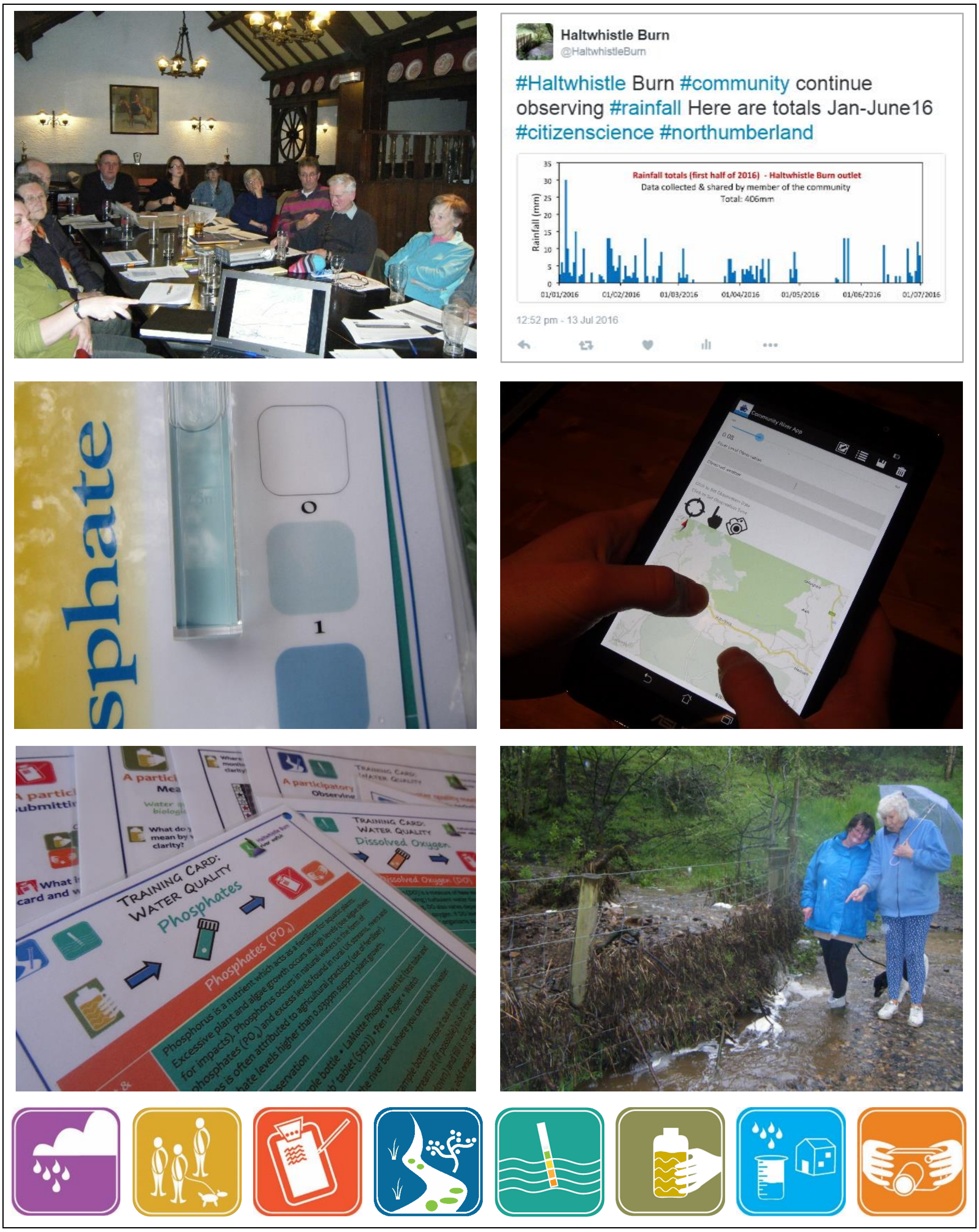


Figure 4 (intro). *The growth in inexpensive and more readily available technology has allowed a community-based monitoring scheme to be implemented within the Haltwhistle Burn catchment. Engagement, facilitation, training and feedback activities have been crucial elements of the project.*

4.1. Chapter introduction

Chapter 2 introduced the concepts of citizen science and emphasised how the involvement of ordinary people in scientific data collection and research is growing substantially today. It also accentuated that, although lay participants co-produce knowledge in their own free time, and hence are classed as unpaid volunteers, citizen science is not free, nor does it just involve a 'data collection' phase. Unless crowd-sourcing is employed (by simply extracting existing observations from the web), the professional scientist or researcher involved must engage with the public, design a monitoring scheme, train participants and provide regular feedback. This means that trained scientists are also acting as facilitators.

This chapter presents the community-based monitoring scheme that was implemented to address **Research Question 1**; can communities feasibly monitor their local catchment using a simple and low-cost citizen science approach? In doing so, it also presents the methods and results relating to **Objectives 1A-1C**. The overarching citizen science methodology adopted is detailed, alongside all the necessary facilitation activities applied. A range of quantitative and qualitative results are presented based on the experiences gained within the Haltwhistle Burn catchment and community, including photographic evidence and observational findings. Together, these results underline the feasibility of citizen science for catchment science, and have been used to conclude whether it is possible to collect data in this way.

4.2. TRT's existing volunteer-based activities

Given that community engagement and involvement is one of TRT's principle goals, prior to this project the organisation had already encouraged a range of volunteer-based activities within the Haltwhistle Burn catchment, and across the wider Tyne. Community participation was also at the heart of the CRF project, deliverables and legacies of which could not have been achieved without such sheer levels of involvement. As a result, it was important to take TRT's existing volunteer-based activities into account here prior to any engagement activities being implemented, so that the citizen science monitoring scheme could be designed to complement existing activities, rather than repeat them. This sub-section provides an account of TRT's main areas of volunteer-based work, which have been composed from experience and knowledge gained directly from TRT as a CRF project partner, and also from some of their relevant management plans and website material.

According to TRT (2017a), their community-based work falls under three categories; raising awareness, river watch and education of young people. Whilst awareness raising and educational events have been successful since the Trust's establishment in 2004, TRT began setting up 'River Watch' groups across the Tyne catchment from 2007 (Figure 4.1). Officially co-ordinated by TRT, these local community groups take part in a range of activities during their spare time, including chemical and biological monitoring, and river restoration work. Although TRT have approached local communities, established these groups and trained them, it was intended that volunteers would adopt the CaBA principles by taking ownership of their local river system. This includes the Haltwhistle Burn River Watch group which closely aligns with the local Flood Action Group.

As Figure 4.1 illustrates, TRT conventionally focus their monitoring efforts on temperature, water quality, electrofishing and riverfly surveys. This combination of chemical and biological monitoring methods dominate as they are required to inform statutory response. It is clear that TRT have carried out monitoring activities across the Tyne catchment, with some water quality sampling within the Haltwhistle Burn catchment. However, these monitoring methods tend to provide seasonal or annual spot samples, rather than continuous, daily or even weekly observations. They are also largely categorised as 'surveys' rather than making use of in-situ instrumentation. Some of these monitoring sites are project-specific, meaning that they are no longer actively monitored. Nevertheless, TRT's established River Watch groups have the opportunity to participate during these fieldwork days under the supervision of trained experts.

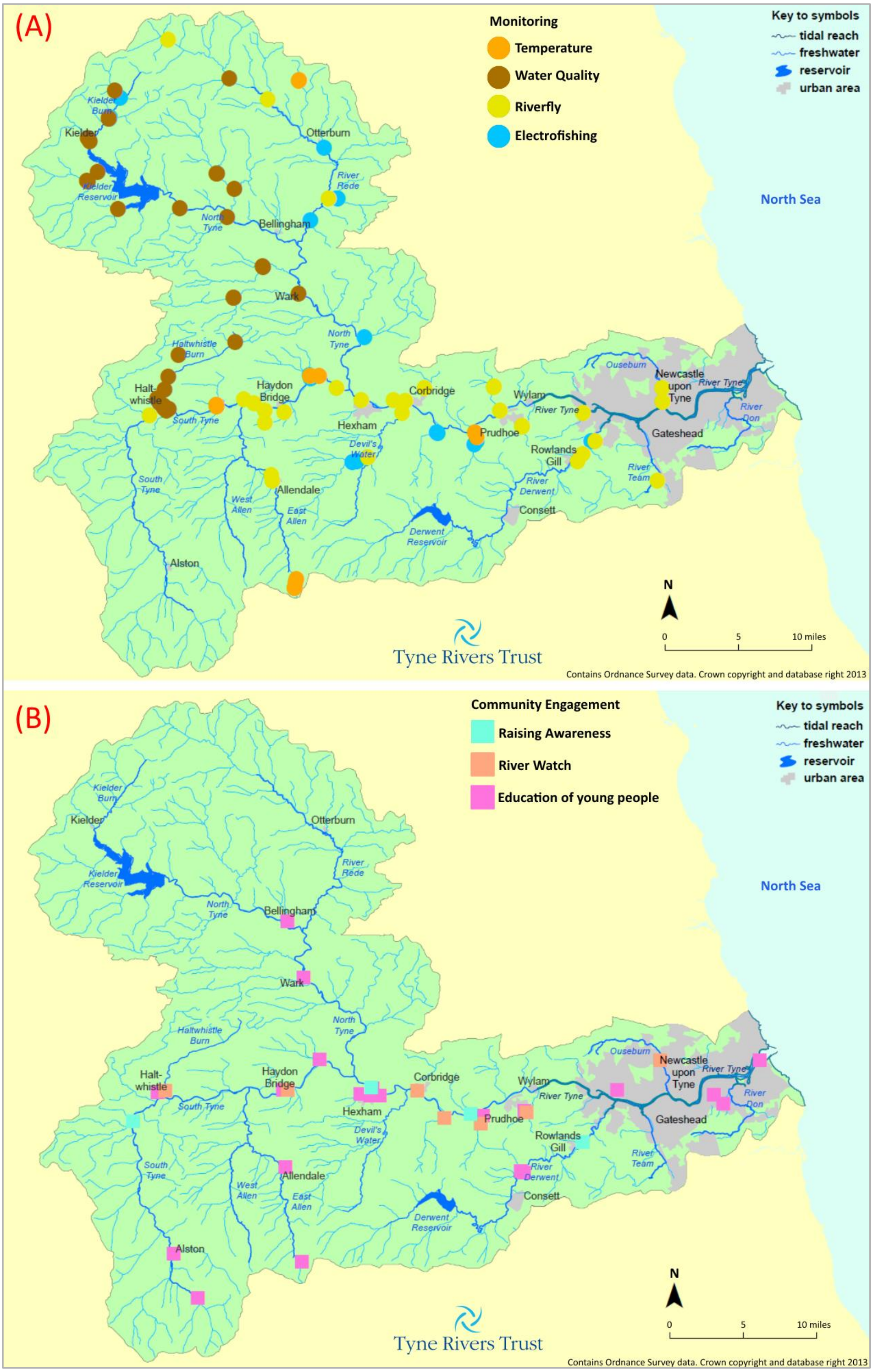


Figure 4.1. (A) TRT's current and past chemical and biological monitoring and (B) Community engagement sites across the Tyne catchment prior to Summer 2013 (map source: TRT, 2017a).

Since mapping key monitoring locations (Figure 4.1) and publishing the Tyne Catchment Plan (TRT, 2012), TRT have led many other volunteer-based initiatives. Those carried out in and around the Haltwhistle Burn catchment include the following physical activities (many of which have supported the CRF project (TRT, 2015)):

- Fish easement work – installing fish passes within the Burn;
- Litter picking – along the riverside footpaths;
- River habitat surveys – walkovers and geomorphological mapping along small stretches of the river;
- Willow management, tree planting and bank protection work;
- 'River Days' with the local schools – inside and outside classrooms;
- 'Give it a go' days with the wider public;
- Monitoring and management of non-native species, including Himalayan 'Balsam Bashing';
- Mapping and monitoring white-clawed crayfish and the invasive signal crayfish;
- Installation of 'leaky dams' and other natural runoff and green-engineering features;
- Coffee mornings (to help raise funds) and River Watch meetings.

Many volunteers involved in the aforementioned activities bring their own skills, tools and experience along which significantly reduces contractor costs. Unlike relevant Environment Agency teams, who engage with the public rather than readily involving them (Blaney *et al.*, 2016), TRT's array of volunteer-based activities are comparable to most river and wildlife trusts across the UK. Although TRT and their nation-wide counterparts are starting to encourage 'River Watch' activities and have organised numerous engagement and educational activities to accompany these initiatives, volunteers generally require TRT's assistance to organise and support these 'river days', and it is clear that they are usually water quality, habitat and biodiversity related. Numerous surveys and physical restoration activities have taken place to date, but there is limited emphasis on collecting quantitative and transferable catchment information, especially during and immediately after flood events.

It is realistic for TRT and other Rivers Trusts to focus on volunteer-based events and data collection activities which support their own mission statements and the statutory frameworks that they are working towards (notably the WFD). However, greater appreciation of catchment connectivity when monitoring is required by linking hydrology, meteorology and flood induced runoff to aspects that they already focus upon. This includes parameters which characterise water quantity as they are closely aligned with water quality and hydromorphology, and thus the overall integrity of a catchment system (Bracken and Croke, 2007; US EPA, 2015a). Monitoring and increased knowledge of hydrology and meteorology will allow catchment stakeholders to consider the physical drivers of catchment response prior to modelling, management and restoration work. Organisations such as TRT have charitable aims and cannot rely on expensive monitoring methods; additional support from volunteers is essential. Existing River Watch and Flood Groups have the capacity and skills to implement a citizen science approach and support various projects and associated goals detailed within the wider Tyne Catchment Plan (TRT, 2012), including target C23 (River Watch), C45 (monitoring), P27 (capturing local knowledge) and P57 (public/community recording of river issues).

4.3. Overarching methodology: the citizen science framework

A community-based (citizen science) monitoring approach has been implemented within the Haltwhistle Burn catchment to assess the feasibly of relying on local people to collect relevant catchment observations by themselves using simple and inexpensive methodologies. These observations provided the necessary primary catchment data required for later research activities. An overarching citizen science framework was therefore created and implemented whilst appreciating the following:

- Generic citizen science frameworks already available (published guidance documents);
- Stakeholders involved – researchers, facilitators and citizen scientists;
- The specific discipline of interest (catchment science and management);
- The specific catchment and community of interest (i.e. the Haltwhistle Burn).

4.3.1. Initial considerations: from a researcher's perspective

During the project proposal stage it was apparent that working with communities in a real case study site would map a different research process compared with others across the physical sciences and engineering disciplines. This meant that the research design, implementation, data collection and analysis methods drifted away from the 'traditional' formats. They have been open to exploration and co-production, and take into account the wider theories behind community-based participatory action research (PAR) previously outlined in Chapter 2 (Kindon *et al.*, 2007).

Whilst this project has strong physical foundations and has been motivated by well-established theories in catchment science, there have been some overlaps with the social sciences at times. This was inevitable given that a real community and real participants were involved, and that the feasibility of the monitoring scheme was heavily dependent on those who participated, why they participated, how they participated, what their preferences were, alongside the actual catchment-specific observations that they managed to collect. A significant amount of interaction with participants was therefore mandatory in order to demonstrate the feasibility of citizen science. It also meant that I was immersed within the community as a researcher and a facilitator for some time, observing how the monitoring approach evolved. This approach is known as ethnography or participant observation, a qualitative research method that allows the researcher to carry out observational work and extract, for instance, quotes, descriptions and photographs to support their findings (Bhattacherjee, 2012; Bryman, 2016). Direct involvement has therefore been essential in order to appreciate this level of detail.

From a researcher's perspective, it was important to ensure that the citizen science scheme was designed and implemented so that a selection of catchment parameters were monitored, and a variety of low-cost data collection and submission tools were trialled. A series of quantitative and qualitative data collection methods were therefore adopted in order to demonstrate the feasibility of citizen science for catchment science, including:

- Initial 'monitoring preferences' questionnaire – to understand what participants prefer to monitor and why;
- Observational work (descriptions, accounts, quotes and photographic evidence) – to reflect on the benefits, drawbacks, feedback and progress of participants over time, as well as the wider benefits of public participation in catchment science. Face-to-face encounters, emails and social media have been used to interact with the public in an informal manner to achieve this;
- Statistics summarising data collection, submission and feedback tools (e.g. engagement levels achieved on social media and the project website) – to demonstrate success rates;

- The actual citizen science observations themselves – used as indicators to understand which parameters participants can monitor, when and how.

A mixed methods approach was used to provide stronger research outcomes. It is often argued that quantitative and qualitative research methods are intrinsically linked, and while qualitative research outputs have been criticised for being subjective and 'messy' (Bhattacherjee, 2012), they have provided valuable evidence directly from the community here and attributed meaning to the citizen science process. Bryman (2016) argues that a qualitative approach allows words and thoughts to be extracted, bringing the researcher closer to the project in a natural setting. Field notes and logs were used to document observations over time in an open setting.

When considering sample sizes, the Haltwhistle Burn catchment was chosen as the main case study site and thus the community dictated how many participants were actually involved. The participants were categorised as the 'focus community'; some participants came and went over the duration of the project, but the presence of the 'community group' remained (although some volunteers did take part and submit observations over the full project period). Chapter 7 contains outputs from Acomb in Northumberland, a second (spontaneous) focus community used to explore the sustainability of citizen science.

Unlike carefully designed and controlled field and laboratory work, there are risks associated with a participatory project. Besides ethical dilemmas (discussed in Section 4.4) and time pressures, the main risk entailed a situation where nobody from the community participated and no citizen science observations were collected (which was not the case here anyway). This would however be a finding in itself and hence did not affect the implementation phase. As is revealed on a number of occasions within this thesis, the community did however present various research opportunities and results along the way, hence they have contributed to the participatory approach adopted. These contributions have allowed monitoring activities to be described as 'community-based', rather than just citizen science.

4.3.2. Initial considerations: from a facilitator's perspective

Whether for research or for practice, a facilitator is required to ensure that the citizen scientists taking part in data collection activities are guided through the full monitoring process (Tweddle *et al.*, 2012). However, prior to this the facilitator must decide whether citizen science is a suitable data collection method, and if it is, they should realistically assess their available resources. Pocock *et al.* (2014b) lists the following set of initial considerations, which have been expanded to make them relevant to catchment science here:

- Clarity of your aim and objectives – lack of data, characterising catchment behaviour or just encouraging public participation?
- Importance of engagement – to encourage and sustain project participation during the lifetime of the project and beyond;
- Resources available – e.g. data collection and submission tools, access to websites and social media;
- Scale of sampling – at a local or catchment scale?
- Complexity of the monitoring protocols – manual methods, automatic methods, or both?
- Motivations for participation – e.g. are the public directly affected by flooding?

Pocock *et al.* (2014a; 2014b) claim that clear aims/objectives, high levels of engagement, larger sampling scales, simple monitoring methods and good reasons for public participation are desirable for successful citizen science schemes. However, this is dictated by available funds and resources, thus may not be possible. In a research context, these factors will affect the feasibility of community-based monitoring and can therefore be explored. Based on a generic decision framework developed by Pocock *et al.* (2014a), citizen science for catchment science is 'very worth considering' because there is scope to collect spatial and temporal observations, assuming volunteer recruitment and retention is successful.

4.3.3. The citizen science framework

Given that citizen science has grown rapidly in recent years and the term itself is fairly broad, there are limited formal frameworks to follow when implementing a scheme within the community. Those that exist are predominately aimed at monitoring schemes being applied in practice, rather than in research (e.g. Roy *et al*, 2012; Tweddle *et al.*, 2012; Pocock *et al.*, 2014a). However Bonney *et al.* (2009), Shirk *et al.* (2012) and Science Communication Unit (2013) claim that frameworks in research and practice are alike, and although project aims and outcomes may differ, the citizen science process can satisfy them together. Some argue that these frameworks are too broad, and that it is not possible to create a standardised version for environmental science (Science Communication Unit, 2013). All sources mentioned here were therefore used to collectively produce a project-specific framework for use within this catchment science study (Figure 4.2).

The ‘overarching’ framework (Figure 4.2) is principally relevant to this chapter and 7 as they rely on, and relate to, the actual collection of primary data by the public and the feasibility of doing this. Although Chapters 5-7 are associated with using these catchment observations (i.e. for data quality, modelling and management applications), where necessary, participant observations, quotes and photographs have been used to support them. The framework was initially applied to the Haltwhistle Burn catchment in October 2013 which officially continued until February 2016 (29 months) for research purposes, although community-based monitoring continued beyond this period.

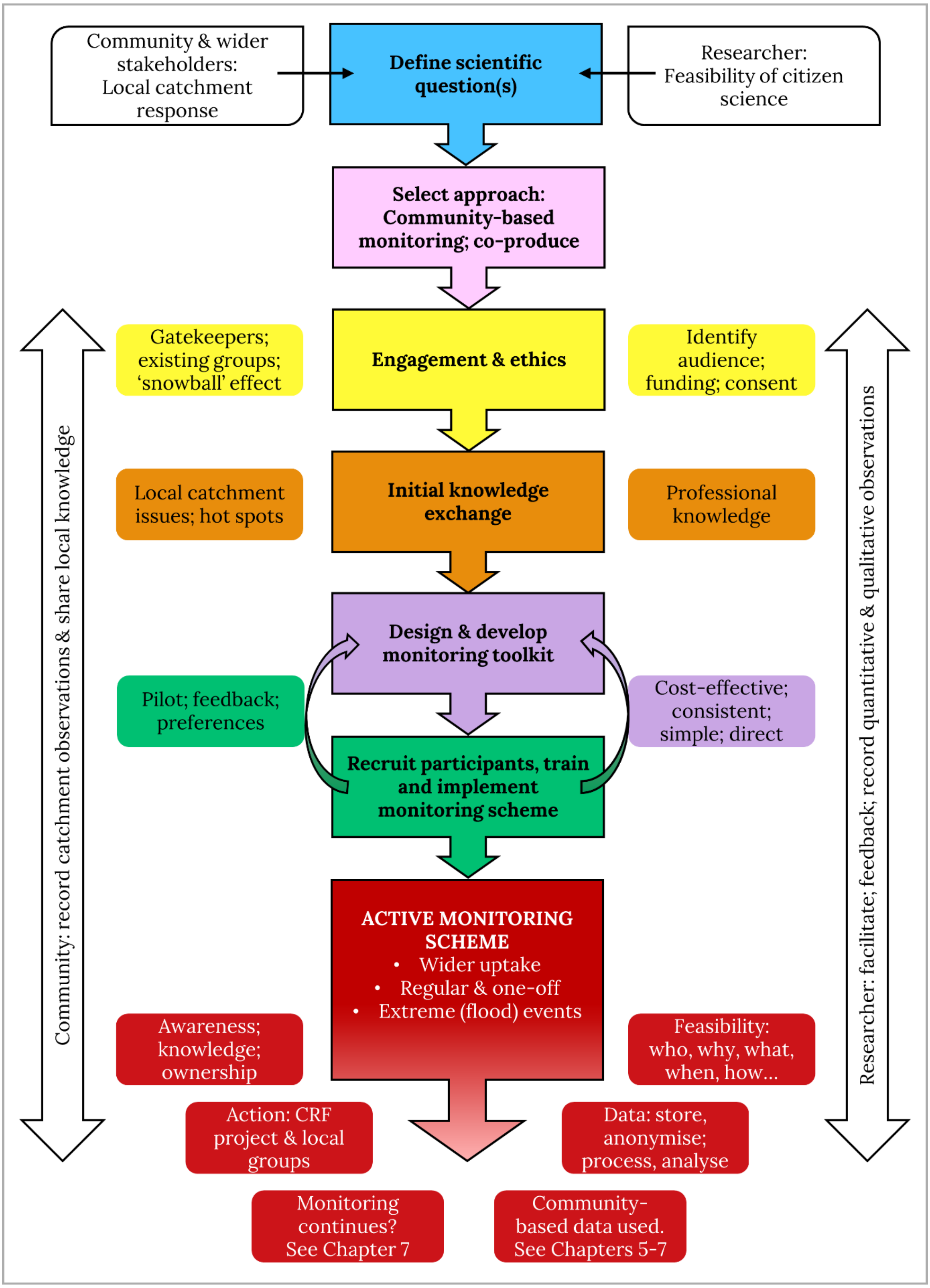


Figure 4.2. The overarching citizen science framework used to implement a community-based monitoring approach.

4.4. Community engagement

4.4.1. Ethical assessment

According to Bhattacherjee (2012) and Bryman (2016), four ethical principles apply when working with the public:

1. Participation is voluntary and harmless: participants can withdraw at any time;
2. Confidentiality: well-being and interests must be respected by controlling and anonymising data;
3. Transparency: disclose any project information so that participants are aware of its purpose, methods and possible uses;
4. Accurate analysis and reporting: once data is anonymised, draw truthful conclusions.

These principals can be obeyed by carrying out an ethical assessment prior to public involvement (Kindon *et al*, 2007; Durham University, 2012). In the context of this catchment study, members of the public principally collected and shared information about the natural environment rather than about themselves. Nevertheless, the citizen scientists provided catchment observations with accompanying date, time and locational information. The focus group had also been observed over time, quotes and photographs had been captured and contact details were stored, all of which included sensitive information. As a result, the following steps were put into place:

- Regular participants were provided with project information sheets which they signed to provide informed consent;
- Written (paper-based or web-based) or verbal consent was obtained from all participants, except social media users (this data is already within the public domain);
- A ‘sign-in’ sheet was used during face-to-face meetings and permission asked to take photographs;
- Restricted access to files (project members only);
- Anonymised observer names and generalised geographical monitoring locations (if home address).

Appendix 4A contains examples of information and consent sheets used.

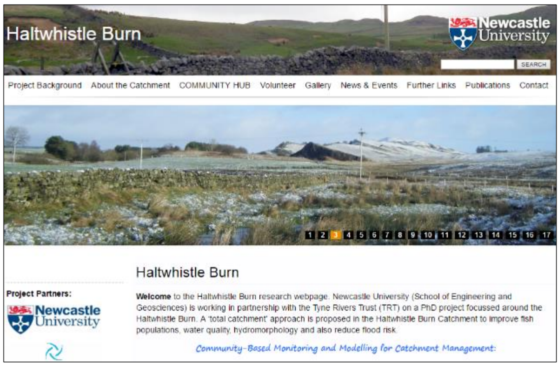
4.4.2. Community engagement

Engagement activities are widely recognised as being a critical component of the citizen science and community-based monitoring process (Science Communication Unit, 2013; Socientize Consortium, 2013; 2014). There is a strong consensus that true public participation projects should engage with the full spectrum of society and that methods should be appropriate as they affect overall participation levels (Science Communication Unit, 2013; Garrod *et al.*, 2013). Early engagement allows the public's experiences, concerns and knowledge to be incorporated into the design process (Socientize Consortium, 2014). Whilst there has been a significant rise in website and social media usage, the engagement plan depends on the anticipated scale of the monitoring programme and resource availability (Roy *et al.*, 2012). For instance, national or international projects usually rely on well-designed websites to engage with the public as they cannot meet everyone face-to-face. Le Coz *et al.* (2016) also concluded that their local engagement activities led to a greater appreciation of flooding. Long-term engagement remains a challenge for any project.

Given the local scale and nature of the community-based monitoring approach proposed, TRT became the initial 'gatekeeper' for the Haltwhistle Burn community by providing a direct link to the already established local River Watch and Flood Groups. These groups were initially approached by hosting an evening workshop within an informal setting that they were familiar with (local social club) during the first week of the project (October 2013). 20 people attended, many of whom were still emotionally affected by the 2012 and 2013 flood events. The proposed community-based monitoring project was outlined during this event, giving the public an opportunity to share and discuss their local catchment knowledge (outcomes are presented in Section 4.4.3).

Through a range of traditional and technology-based engagement techniques, interaction with the wider community then transpired, many methods of which continued throughout the duration of the project. Table 4.1 lists the engagement methods adopted during the project. A variety of techniques were necessary to promote wider engagement and ensure that indirect methods, such as the project website, still linked the public to the research. It also meant that demographics and access to the internet were accounted for.

<table>
<tr><th colspan="2">Engagement methods</th></tr>
<tr>
<td>Face-to-face meetings/workshops (informal River Watch, Flood Group & wildlife meetings)

</td>
<td>Project website (http://research.ncl.ac.uk/haltwhistleburn/)

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<tr>
<td>Leaflets

</td>
<td>Social media (Twitter via @HaltwhistleBurn & 'Haltwhistle Burn' Flickr accounts)

</td>
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<tr>
<td>Local school (via TRT's 'River Day')
</td>
<td>Local community events & businesses e.g. Haltwhistle Walking Festival 2014 & 2015.

</td>
</tr>
<tr>
<td>Signage along the Haltwhistle Burn footpath
</td>
<td>Local newspaper (Hexham Courant 23/05/14)

</td>
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</table>

Table 4.1. Engagement methods adopted across the Haltwhistle Burn community.

Twitter was particularly useful for engaging with wider audiences. The @HaltwhistleBurn account was used to share short messages ('tweets' of 140 characters or less), images and videos, which accumulated over 150,000 'impressions' between November 2013 and February 2016 (Figure 4.3). Impressions are described as the total number of users who saw the tweets on Twitter. The project website homepage was also visited over 4000 times during the same period.

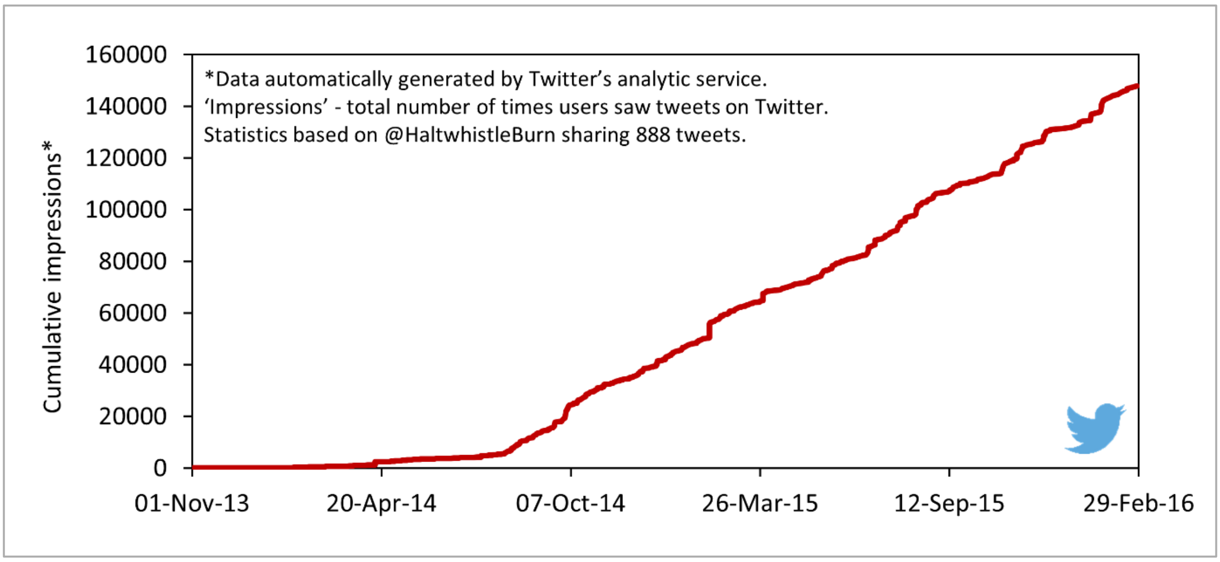


Figure 4.3. Cumulative Twitter 'impressions' for the @HaltwhistleBurn account between November 2013 and February 2016.

Other engagement methods included having discussions with land owners, dog walkers and passers-by whilst out in the catchment, using the River Watch and Flood Group emailing lists, and linking with the local school (via TRT's 'River Day'). Initial engagement efforts then created a 'snowball' effect, whereby members of the community became additional gatekeepers themselves by actively raising project awareness across the Haltwhistle Burn catchment. For instance, one Twitter contact actively publicised project information on Facebook using their own account. Others distributed leaflets, put them in shop windows and left them in Haltwhistle's library. As material became available, publications and media experiences were later used to engage with the public, as well as provide a sense of achievement to those already involved.

The engagement experience has highlighted the following points:

- TRT's role as a gatekeeper was crucial – staff provided direct links into the community;
- People within the community become additional gatekeepers and knowledge exchangers;
- River watch logos (Chapter 4 *intro*), attractive fonts, photographs, videos, handouts, visual props and lay language all supported successful engagement activities;

- The importance of engaging with the wider community to avoid prioritisation and negativity between different groups of people, and include all opinions equally;
- Face-to-face contact was important for people who do not use the internet;
- The existing River Watch and Flood Groups were supportive of being involved in a community-based monitoring programme, with flooding being a key motivator;

Long-term engagement overlaps the recruitment and feedback process. Sections 4.6 and 4.8 provide more details on these two aspects.

4.4.3. Initial knowledge exchange

The October 2013 Haltwhistle Burn inception workshop provided the community with an opportunity to share their local knowledge and raise any catchment-related issues during a participatory mapping exercise. This group-based qualitative method (Chambers, 2006; Forrester et al., 2015; Bracken *et al.*, 2016) involved attendees assembling around four enlarged (A1-sized) and laminated maps of the Haltwhistle Burn catchment with pens and sticky-notes. These maps, containing the catchment's boundary and river network, were used to pinpoint any known historical catchment issues. Some members of the community also enriched these maps by bringing photographic evidence of past flood events along. Before the meeting, the River Watch and Flood Groups were asked to share any catchment information using an online file sharing system[14], which nobody used (tools and technology are discussed later in this chapter). Participatory mapping was therefore regarded as an appropriate method which also shaped discussions between different people across the catchment (Figure 4.4). It was the first time most people had seen the full catchment area: *"I've not seen a map of the full catchment area before. I didn't realise so much land drained towards Haltwhistle"* (workshop participant).

After the meeting, all knowledge generated during the mapping exercise was added to the existing historical catchment issues database (Table 3.1), categorised into themes, hosted on the project website as an interactive map[15] (Figure 4.4), and used to inform the monitoring 'design' phase in Section 4.5. Flash flooding and rapid sediment deposition in and around the town typically dominated discussions, although farmers shared some upper catchment information.

[14] https://dropoff.ncl.ac.uk/
[15] http://research.ncl.ac.uk/haltwhistleburn/communityhub/evidenceofcatchmentissues/

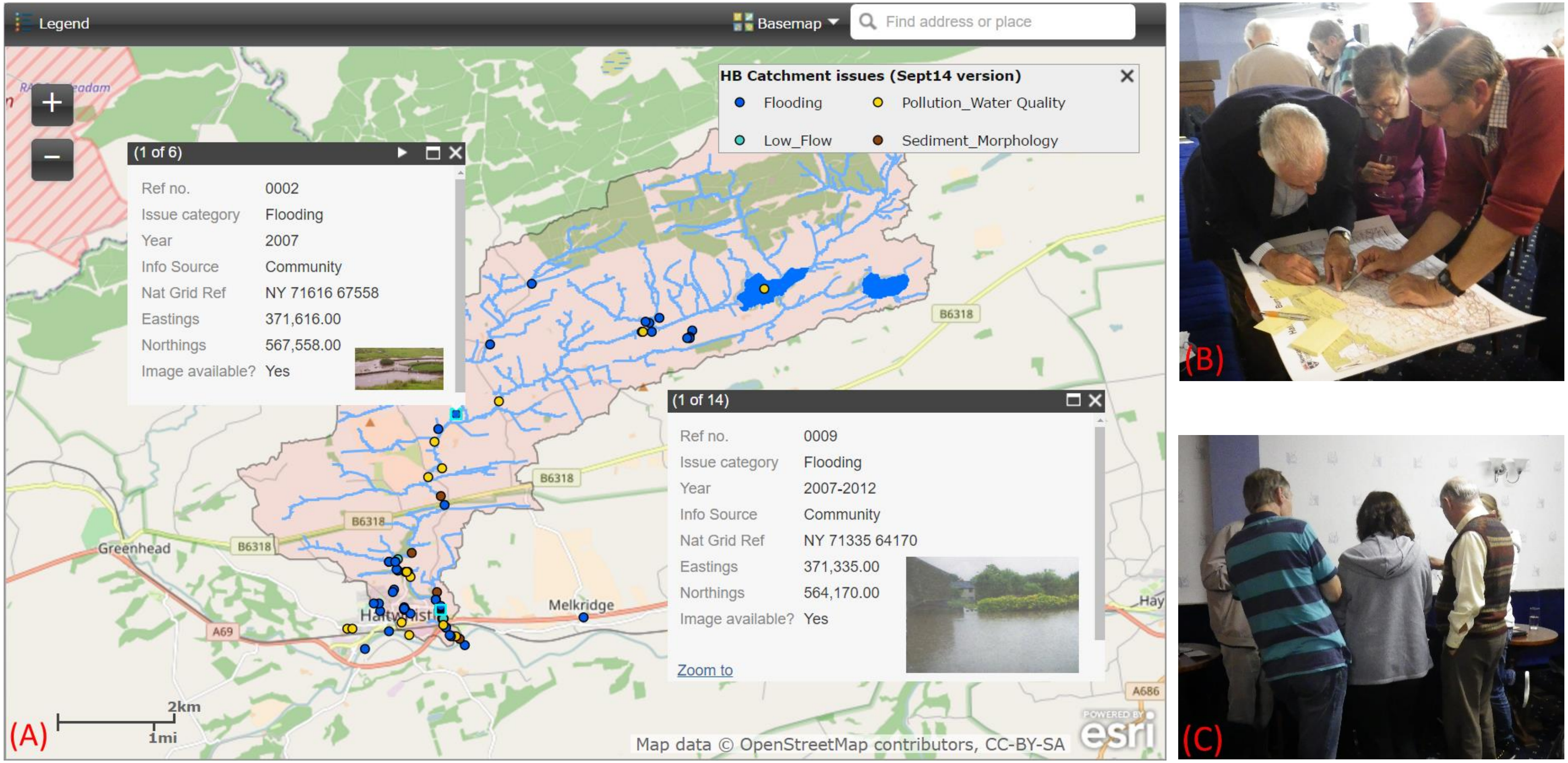


Figure 4.4. Catchment issues which have been digitised, hosted and embedded as an interactive web map on the project website **(A)**. The majority of data points were shared during the participatory mapping exercise **(B-C)** prior to any citizen science monitoring activities.

4.5. Designing the community-based (citizen science) monitoring scheme

4.5.1. Initial considerations

As with traditional hydrometric monitoring networks, the design of a citizen science monitoring scheme can significantly affect the availability and usability of the observations collected (Shirk *et al.*, 2012; Pocock *et al.*, 2014a). The spatial and temporal coverage of data governs the environmental patterns observed and the resulting conclusions articulated. When relying on the public, the nature of the scheme is further dictated by the degree of participation, and consequently the number of observations collected. Given that scientists are relying on unpaid volunteers, participation levels may be sporadic, unpredictable or short-term, which is problematic if their datasets are to be relied upon for scientific applications over time. Data quality issues, mixed data formats and non-quantitative observations are also some of the key reasons why citizen science has not been readily integrated into the water resources sector (Buytaert *et al.*, 2014; 2016). Various aspects of a citizen science monitoring scheme can therefore be deliberately designed and developed so that these challenges (as summarised within Table 4.2) are considered, and where possible overcome, at an early stage (Tweddle *et al.*, 2012).

Although citizen science is not a new phenomenon, it has evolved in recent years as a result of the digital revolution (Wiggins *et al.*, 2011). Citizen science schemes should therefore exploit readily available technology in order to attract a wider audience, standardise monitoring methods and meet data requirements. However, Tweddle *et al.* (2012) argue that simple monitoring protocols are essential for increasing and retaining participation levels. As a result, a compromise may be required between the complexity and value of the observations collected, and the scale of people and subsequent observations acquired (Bonney *et al.*, 2009). Specific case study and community requirements must be considered to motivate participants and make the scheme worthwhile to them. From a facilitator or researchers perspective, the citizen science scheme should also be suitably designed so that it appreciates the equivalent (yet costly) traditional monitoring methods, alongside data resolutions, formats, retrieval, archiving and processing protocols (Bonney *et al.* 2009; Tweddle *et al.*, 2012; Blaney *et al.*, 2016).

Table 4.2 summarises a set of initial monitoring considerations which this project took into account when designing the Haltwhistle Burn citizen science monitoring toolkit. These considerations ranged from common suggestions and examples detailed within the literature, through to local catchment- and community-specific requirements (obtained during initial engagement activities), so that the schemes design aligned with the intended outcomes.

Common citizen science issues & challenges • Amateurs are untrained to monitor complex parameters; • Heterogeneous, qualitative and sometimes 'messy' data is generated; • Varied or unknown data quality; • Retaining participation levels for long-term data collection and repeat/regular visits at pre-determined monitoring sites is difficult; • Data is biased towards urban areas; • Technology can evolve too quickly; • Data storage, processing and analysing tasks take time but are necessary; • Participants need rapid and effective feedback (visualisation); • Projects may fail to deliver, despite investment.	**'Good' practice from the literature** • Develop monitoring protocols to provide structure and standardise methods; • Be flexible, offer multiple choices; • Simple, quick and user friendly monitoring protocols increase participation levels; • Direct and hands-on increases awareness; • Involve the whole community; • Pilot methods with volunteers, adjust according to feedback; • Training and coordinating volunteers increases data reliability and consistency, therefore value; • Cannot please everyone – compromise between the community and scientists; • Design to complement traditional schemes; • Make use of existing tools and materials.
Citizen science approach - examples Monitoring methods: • Manual and physical (hands-on) or automated and indirect; • Affordable and novel technology e.g. low-cost sensors, smartphone apps; • Quantitative and qualitative data. Training: • Instruction and identification sheets, workshops, FAQs, website material. Data submission: • Paper-based, spreadsheets, social media or web-based forms; • Data forms containing desired fields; • Individually and instantaneous (real-time) or aggregated and submitted in batches.	**Traditional monitoring and management** • Legislation – Floods Directive and WFD • CaBA – encourage education, direct involvement and ownership; • Common parameters - meteorological, hydrometric (water quantity), water quality, sediment/morphological; • Quantitatively characterise and detect trends using well-established methods; • Data scarcity – desirable to improve spatial and temporal coverage; • Limited evidence exists for flash floods on a local level; • Need cost-effective monitoring methods; • Repeat surveys and date, time and locational information required.
Catchment-specific considerations • Multiple catchment issues and hotspots – flooding, low flows, pollution, sediment; • Limited internet/phone signal within the catchment; • Urban area is close to the catchment outlet; • Large parcels of privately owned land; • Well used footpaths exist along the main Burn which locals and tourists use.	**Target audience / Haltwhistle Burn River Watch & Flood Group requirements** • Need to expand on TRT's existing engagement and involvement activities; • Demographics – existing groups generally the retired population; • *"We want to know what do to with our observations"*; • *"Need a consistent monitoring approach"*.

Table 4.2. Initial considerations (generic and specific) appreciated during the Haltwhistle Burn citizen science monitoring toolkit design phase (relevant sources: Bonney *et al.*, 2009; Dickinson *et al.*, 2010; Shirk *et al.*, 2012; Tweddle *et al.*, 2012; Buytaert *et al.*, 2014; Pocock *et al.*, 2014a).

In summary, flexible, innovative and simple monitoring schemes are reported as being more successful and sustainable than those involving complex protocols. A range of monitoring methods and tools should be presented to the public given that their skills and preferences vary significantly. Quotes from the Haltwhistle Burn River Watch and Flood Groups, including:

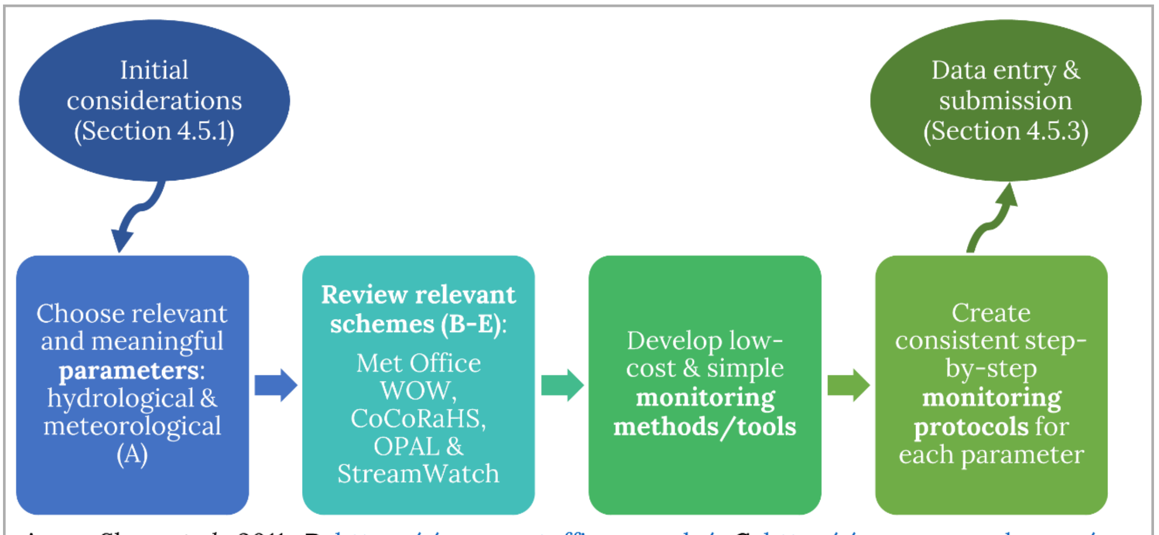
"I have sticky notes [containing observations] pinned up on our notice board in the kitchen"

"We need to reach the wider community. We want more people engaged and actively involved"

suggested that the community group needed an attractive and consistent monitoring approach that would enable them to collect, store and share meaningful data about their local water environment.

4.5.2. Proposed monitoring techniques (methods and tools)

Table 4.2 was used to inform the proposed monitoring techniques specifically designed and piloted within the Haltwhistle Burn catchment. A range of simple and inexpensive techniques have been trialled to determine how participants and specific monitoring methods and tools perform within the context of catchment science. This sub-chapter describes all of the parameters that were initially proposed and presented to the community during the implementation phase (Section 4.6), including any necessary equipment, standardised protocols involved, desired spatial and temporal monitoring scales, attributes expected to be recorded, and other relevant details describing the monitoring approach. Figure 4.5 summarises the main steps taken to develop the proposed monitoring methods.



A: e.g. Shaw *et al.*, 2011 **B**: https://wow.metoffice.gov.uk/ **C**: http://www.cocorahs.org/
D: https://www.opalexplorenature.org **E**: https://australianmuseum.net.au/streamwatch

Figure 4.5. Steps taken to develop the proposed citizen science monitoring techniques. Existing water monitoring schemes (despite being large scale projects) provided initial inspiration.

The following list of catchment 'parameters' were proposed for citizen science monitoring:

- Rainfall totals;
- River levels;
- Extreme weather/flood observations and impacts;
- Water quality indicators;
- Weather diaries.

Although not an exhaustive list, these parameters are regularly and traditionally observed for catchment characterisation and management purposes (Herschy, 2009; Shaw *et al.*, 2011; Bren, 2015; Younos and Heyer, 2015; Sene, 2016), therefore offered a useful comparison between water quantity and water quality during later feasibility and data quality assessments. Tables 4.3-4.7 describe each monitoring technique in detail, including equipment and training required, desired (yet realistic) spatial and temporal resolutions, costs and other relevant logistical information. All equipment described are readily available for ordinary consumers to buy, including the simple chemical tests (phosphates, nitrate/nitrites and dissolved oxygen) which were purchased from a water monitoring specialist (LaMotte Europe) and are approved by the US Environmental Protection Agency (EPA). All activities proposed were regarded as 'volunteer friendly', yet encouraged representative sampling (e.g. World Meteorological Organization, 2008).

The following circumstances also affected the feasibility of the citizen science scheme:

- Volunteers were not paid or offered any rewards for participating;
- Monitoring equipment was funded by the researcher and TRT (i.e. not the community);
- Volunteers were relied upon for data collection and submission, leaving the researcher responsible for data storage, processing, analysis and feedback;
- The Haltwhistle Burn project website was used to communicate project information which was/is hosted by Newcastle University;
- Timescales and project budget constrained which parameters and tools could be tested. However, those chosen focused upon aspects which were perceived as being important in other rural UK catchments when embarking on citizen science for the first time.

Many of these aspects listed were expected to affect the feasibility and longer-term sustainability of citizen science schemes. However, Chapter 7 demonstrates how the Acomb community in Northumberland were able to overcome these constraints and implement their own monitoring programme.

<table>
<tr><td colspan="3">Parameter 1: Rainfall totals</td><td rowspan="6"></td></tr>
<tr><td colspan="3">Description: Plastic rain gauge (graduated measuring cylinder) used to manually observe rainfall totals. Rain (precipitation) is stored in the gauge over a known period of time.</td></tr>
<tr><td colspan="3">Target audience: ‘Regular’ and committed volunteers.</td></tr>
<tr><td colspan="3">Equipment/supplies required: Plastic manual rain gauge and stake/fastening.</td></tr>
<tr><td rowspan="7">Desirable, but not guaranteed (controlled by volunteer)</td><td colspan="2">Temporal coverage: Repeat daily, preferably at 9am.</td></tr>
<tr><td colspan="2">Spatial coverage: Multiple gauges required to pick up sub-catchment variation and at different altitudes.</td></tr>
<tr><td colspan="3">Monitoring protocol: (1) Place rain gauge in garden or field away from shelter. Use stake to secure to the ground and keep upright. (2) Leave gauge for 24-hours. (3) Determine how much rain has fallen by manually observing level against the gauge scale. (4) Empty gauge, clean and put back.</td></tr>
<tr><td colspan="3">Estimated time required to complete task: Very quick, 1-2 minutes to observe.</td></tr>
<tr><td colspan="3">Level of training required: Low/medium, important that the gauge is sited and maintained correctly, consistency, snow/ice, must log even if 0mm.</td></tr>
<tr><td colspan="3">Attributes/metadata to be logged: quantitative rainfall total, date and time of each observation, gauge station name/location, weather description.</td></tr>
<tr><td colspan="3">Data submission interval: Realistically at the end of every month. Useful to share extreme totals with community on the day of occurrence.</td></tr>
<tr><td colspan="4">Costs/maintenance involved: One-off cost for gauge (£5.50), head clearance to be maintained, vegetation cut back and debris cleared out of inlet.</td></tr>
<tr><td colspan="2">Travelling involved: None. Likely to be located at home.</td><td colspan="2">Health & safety: Low risk.</td></tr>
<tr><td colspan="4">Specific traditional monitoring considerations: Difficulty observing short-duration and intense rainfall, wind-induced undercatch, evaporation loss. Must be sited correctly, level and in the same place over time.</td></tr>
<tr><td colspan="4">Reasons for inclusion: Rainfall/precipitation observations are fundamental to catchment hydrology. They quantify inputs to the catchment system.</td></tr>
</table>

Table 4.3. Community-based monitoring activities described for rainfall totals.

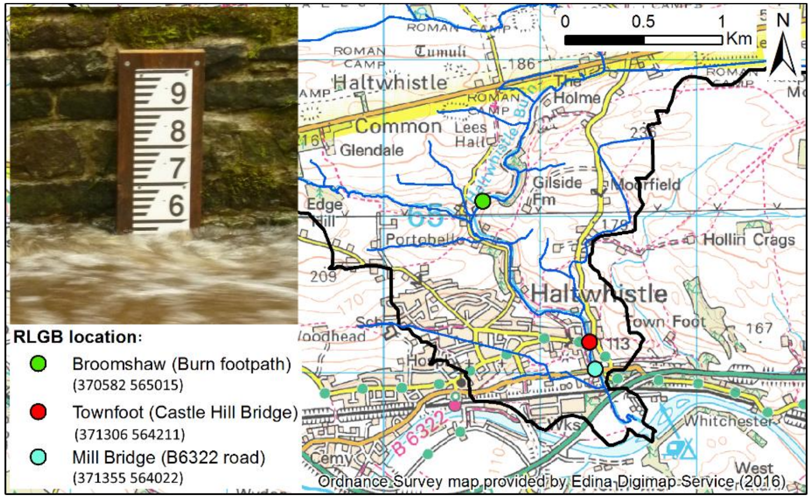
<table>
<tr><td colspan="2">Parameter 2: River levels (stage)</td><td rowspan="5">
</td></tr>
<tr><td colspan="2">Description: River level gauge board (RLGB) (graduated vertical staffs - ‘giant rulers’) secured to the river bank, used to obtain river level manually over time at the same position.</td></tr>
<tr><td colspan="2">Target audience: Anybody passing, one-off or regular observers.</td></tr>
<tr><td colspan="2">Equipment/supplies required: None. Visually observe or use own camera/smartphone.</td></tr>
<tr><td rowspan="8">Desirable, but not guaranteed (controlled by volunteer)</td><td>Temporal coverage: As many as possible (low, normal and high flows).</td></tr>
<tr><td colspan="2">Spatial coverage: TRT already installed three RLGB as part of CRF project at Broomshaw, Townfoot and Mill Bridge (within and close to the impact zone - see map). Safe footpath access was important.</td></tr>
<tr><td colspan="2">Monitoring protocol: (1) Stand on the footpath opposite the RLGB. (2) Visually observe water level using RLGB ruler. (3) If possible take photograph. (4) Make a note of date, time and RLGB location.</td></tr>
<tr><td colspan="2">Estimated time required to complete task: Very quick, 30 seconds to observe. Integrate into existing tasks e.g. dog walking.</td></tr>
<tr><td colspan="2">Level of training required: Low, need to know where the RLGBs are located, observation consistency and scale used.</td></tr>
<tr><td colspan="2">Attributes/metadata to be logged: quantitative river level observation (and/or photograph), date, time and RLGB name.</td></tr>
<tr><td colspan="2">Data submission interval: desirable to have as often as possible, especially during hydrological events.</td></tr>
<tr><td colspan="3">Costs/maintenance involved: One-off cost £30+ per RLGB, no cost to the observer if they use their own cameras etc. RLGB cleaning may be required over time.</td></tr>
<tr><td colspan="2">Travelling involved: Must walk/travel to pre-determined RLGB monitoring sites.</td><td>Health & safety: Must stay on designated footpaths, away from river.</td></tr>
<tr><td colspan="3">Specific traditional monitoring considerations: River/water levels are highly variable and difficult to monitor over time, hence automatic sensors often record every 5, 10 or 15 minutes. Datum affected by erosion and deposition over time. Usually locate sensors on main tributaries and upstream of urban areas.</td></tr>
<tr><td colspan="3">Reasons for inclusion: Opportunity to involve the wider community and test low-cost monitoring tools, including fixed-point photo posts (photographs which validate visual observations) and provide flood-related (depth) information. These RLGB are the same specification as those used e.g. Environment Agency.</td></tr>
</table>

Table 4.4. Community-based monitoring activities described for river levels.

<table>
<tr><td colspan="2">Parameter 3: Extreme weather/flood observations & impacts</td><td rowspan="6"></td></tr>
<tr><td colspan="2">Description: Capture evidence during and immediately after extreme weather (flood) events, including photographs, videos, anecdotes and extra river levels (parameter 2).</td></tr>
<tr><td colspan="2">Target audience: Anybody passing, one-off or regular observers.</td></tr>
<tr><td colspan="2">Equipment/supplies required: None. Visually observe or use own camera/smartphone.</td></tr>
<tr><td rowspan="7">Desirable, but not guaranteed (controlled by volunteer)</td><td>Temporal coverage: Depends on frequency of occurrence.</td></tr>
<tr><td>Spatial coverage: Catchment-wide, stick to footpaths and roads.</td></tr>
<tr><td colspan="2">Monitoring protocol: (1) Visually observe extreme weather or flood event. (2) Take photographs or videos to capture any information describing the event or impacts caused including flood extents, river levels, flow (velocity – video), floating debris, damage, disruption, ecological/habitat destruction, water clarity/colour, river bank change and performance of TRT's catchment management features.</td></tr>
<tr><td colspan="2">Estimated time required to complete task: Could be quick (1-2 minutes) unless travel is required.</td></tr>
<tr><td colspan="2">Level of training required: Very low, mainly relating to health and safety. Also ensure meaningful and usable information is captured.</td></tr>
<tr><td colspan="2">Attributes/metadata to be logged: Anecdotes, photographs and/or videos, date, time and location.</td></tr>
<tr><td colspan="2">Data submission interval: During and immediately after a weather event is desirable to encourage wider engagement, participation and management.</td></tr>
<tr><td colspan="3">Costs/maintenance involved: No cost to the observer if they use their own cameras/smartphones etc.</td></tr>
<tr><td colspan="2">Travelling involved: Regular volunteers may need to walk/travel to known hot-spot areas. Other observations likely to arise from unplanned experiences.</td><td>Health & safety: Observers should never walk or drive through floodwaters. Avoid slippery or unstable river banks and wear warm waterproof clothing.</td></tr>
<tr><td colspan="3">Specific traditional monitoring considerations: Extreme weather events are rarer in nature and difficult to plan fieldwork in advance.</td></tr>
<tr><td colspan="3">Reasons for inclusion: Communities (especially in and around the Haltwhistle Burn catchment) are affected by flooding. Limited evidence exists, particularly during flash floods in rural catchments. Citizen scientists can provide rapid data collection. Includes photographs and videos which they are familiar with generating.</td></tr>
</table>

Table 4.5. Community-based monitoring activities described for extreme weather/flood observations and impacts.

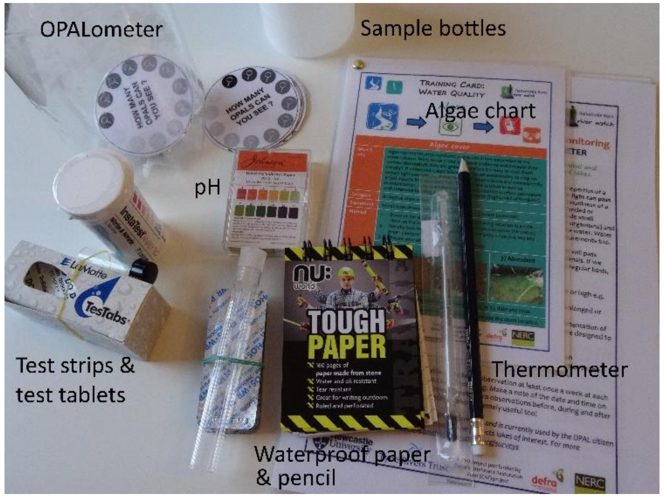
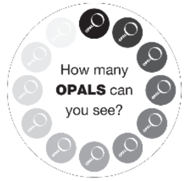
Parameter 4: Water quality indicators		  
Description: Very simple test kit comprising of seven individual observations (physical, chemical and biological), which provide an indication of water quality.		
Target audience: 'Regular' and committed volunteers, one-off session feasible though.		
Equipment/supplies required: Sample bottles, test strips, test tablets (reagents), thermometer, OPALometer, timer, colour charts, instruction cards, pencil and paper.		
Desirable, but not guaranteed (controlled by volunteer)	**Temporal coverage:** Flexible but repeat visits necessary (weekly or monthly).	
	Spatial coverage: Flexible but hot-spot/existing monitoring sites suggested.	
	Monitoring protocol*: (1) Rinse and fill sample bottles with river water. (2) Hold thermometer in sample to determine *temperature*. (3) Test *dissolved oxygen* and *phosphates* using test tablets, wait for water to change colour, compare against graded colour chart. (4) Test *nitrates*/*nitrites* and *pH* using test strips, wait for test strips to change colour, compare against graded colour chart. (5) Visually assess for *algae* in the river, compare against category chart provided. (6) Use OPALometer to visually observe *water clarity (turbidity)* and count how many 'OPAL logos' are visible at the bottom of the bottle. (7) Record all observations.	
	Estimated time required to complete task: Lengthy, at least 30-minutes to carry out all tests.	
	Level of training required: High, many protocols to follow and equipment required for each test. Consistency and safety is important.	
	Attributes/metadata to be logged: Quantitative/semi-quantitative observations for each test. Date, time, location and antecedent weather description.	
	Data submission interval: Realistically at the end of every month. Useful to share unusual finings with community on the day of occurrence.	
Costs/maintenance involved: A full water quality starter kit costs approximately £73. Test strips and test tablets can only be used once, supplies need replacing over time (£67/50 tests). Water clarity tests make use of OPAL's existing resources available to download for free (https://www.opalexplorenature.org/watersurvey; Rose *et al.*, 2016)		
Travelling involved: Must walk/travel to the same monitoring site each time.	**Health & safety:** Avoid completing task during dangerous/high flows. Potential contact with unclean or contaminated water. Carry out tests from river bank.	
Specific traditional monitoring considerations: Water quality is difficult and expensive to monitor, often only provides a snapshot in time, analysis in laboratories.		
Reasons for inclusion: Although 'simple' compared with traditional methods, it tests volunteers' ability to observe a number of parameters which are not flood-related.		

Table 4.6. Community-based monitoring activities described for the water quality indicators. *See Appendix 4C for specific protocols for each parameter.

<table>
<tr><td colspan="2">Parameter 5: Weather diaries</td><td rowspan="4">
</td></tr>
<tr><td colspan="2">Description: Blank weather diaries to be filled in by tourists during their stay within the catchment.</td></tr>
<tr><td colspan="2">Target audience: Tourists/visitors.</td></tr>
<tr><td colspan="2">Equipment/supplies required: None. Visually observe.</td></tr>
<tr><td rowspan="7">Desirable, but not guaranteed (controlled by volunteer)</td><td colspan="2">Temporal coverage: As often as possible, with focus on extreme and unusual events.</td></tr>
<tr><td colspan="2">Spatial coverage: Blank diaries were placed at two pre-defined locations within the catchment: (1) Gibbs Hill and (2) Once Brewed where tourists regularly book to stay.</td></tr>
<tr><td colspan="2">Monitoring protocol: (1) Visually observe weather experienced within the catchment. (2) Write anecdotal evidence within weather diary.</td></tr>
<tr><td colspan="2">Estimated time required to complete task: Very quick, 30 seconds to observe.</td></tr>
<tr><td colspan="2">Level of training required: Very low, diary cover explains protocol.</td></tr>
<tr><td colspan="2">Attributes/metadata to be logged: Weather anecdote, date, time, location.</td></tr>
<tr><td colspan="2">Data submission interval: When experienced/during residential stay.</td></tr>
<tr><td colspan="3">Costs/maintenance involved: Replace if full.</td></tr>
<tr><td colspan="3">Reasons for inclusion: To try capture new sources of meteorological information, capture data in the rural upper catchment and target a different audience.</td></tr>
</table>

Table 4.7. Community-based monitoring activities described for the weather diaries.

Although a range of monitoring considerations were taken into account, it was acknowledged that the proposed monitoring parameters and methods described here were desirable from a catchment science and researcher perspective. As with any citizen science project, initial monitoring methods can evolve, improve or even be completely eliminated from the scheme over time to suit the community of interest. As examples highlight within Section 4.6 and 4.7, the community played a significant role in shaping the design of the citizen science toolkit, and hence created a community-based approach. The design phase therefore contrasts the logistics of a traditional monitoring scheme, which is usually predetermined, formal and streamlined. However, this informal and experimental approach may improve over time once the citizen science design process is better understood, new tools/technologies are available in the future, and citizen science itself has matured.

4.5.3. Proposed data entry/submission techniques (methods and tools)

It can be straightforward for a member of the public to capture an observation by, for example, taking a photograph of a river in flood, and some members of the public already do this regardless of whether or not it is for science. However, there is often a barrier when it comes to physically entering and submitting data to a central system; the observer is not necessarily regarded as a citizen scientist until they share their data with others. It is difficult for community groups to comprehend what to do with their observations once they have them, especially if they do not have the correct skills or infrastructure in place. Furthermore, many hazard modelling and management projects have used crowd-sourced observations but they find that, out of the observations that they have managed to source, essential metadata such as date, time and location are missing (Kutija *et al.*, 2014; Smith *et al.*, 2015). Data entry and submission methods were therefore used here to maximise the availability of observations, and encourage regular volunteers and passers-by to share relevant, consistent and electronic catchment information. Sharing data in this way increases the chances of other participants, the wider community and scientists to benefit from this co-produced knowledge.

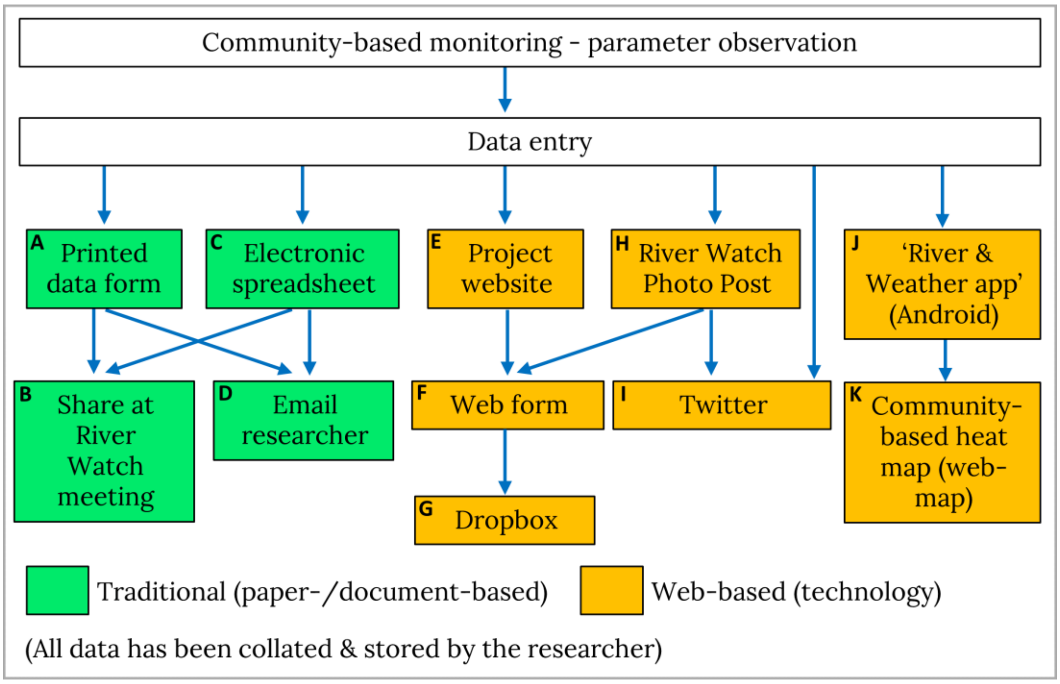


Figure 4.6. Community-based data entry and submission techniques initially proposed. A-D represent 'traditional' techniques, while E-K are 'web-based tools' (see Figure 4.7 for illustrations)

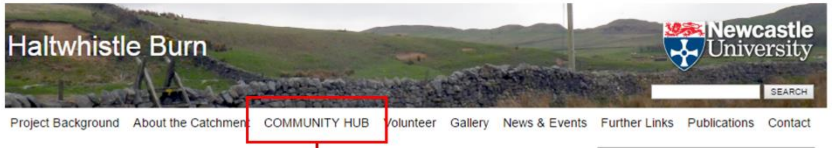
A range of data entry and submission techniques have been designed and tested within the Haltwhistle Burn catchment, providing an opportunity to test the feasibility of traditional and technology-based infrastructure. Figure 4.6 introduces the main data entry and submission tools proposed, and the possible submission routes that participants could take (as some overlap). Although observation type, format and submission frequency dominated which method(s) were appropriate, the flow chart illustrates how participants were left to use method(s) which they preferred. Some methods, such as the web form and Twitter, were also appropriate data entry and submission tools for multiple catchment parameters, and some required additional supporting infrastructure. Techniques proposed have been categorised as either traditional (A-D: paper- or document-based) or web-based (E-K: low-cost or free, therefore open access or open source technology). Web-based methods have been explored because internet access and social media usage has grown significantly in recent years. For instance, in 2016, 8 out of 10 UK adults used the internet daily (or almost daily), smartphones were the most favourable device to do this, and 70% of adults accessed the internet 'on the go'[16].

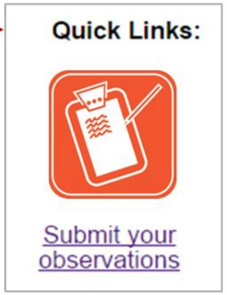
Figure 4.7 illustrates and describes the web-based data entry and submission tools (E-K) in detail. There are various benefits and drawbacks for each method, but Pocock *et al.* (2014a) and Tweddle *et al.* (2012) stress the importance of catering for a wide audience and their varied skills and interests. It is also highly endorsed to make use of existing open access or open source tools because the concept of entering, storing and submitting data is similar across all environmental disciplines (Bonney *et al.*, 2009; Bonney and Dickinson, 2012; Roy *et al.*, 2012). For instance, Twitter is a freely available and widely used tool, and although it is categorised as 'social media', its concept is based around communication and information sharing. Recording observations online (web forms, apps and Twitter) whilst out in the catchment also offers real-time submission and sharing facilities, which was regarded as being essential here, especially in the event of a flash flood. This did however assume that participants would be willing to use their own smartphones. Given the target audience and limited mobile phone (internet) coverage within the catchment, it was also assumed that some participants would prefer to submit their observations using traditional spreadsheets or even paper-based or face-to-face techniques. The latter also offered an alternative in case any technology failed. Additional risks associated with using web-based tools include rapidly evolving technology (can the public adapt quickly enough and will updates be compatible?) and the overreliance on third party tools (restrictions and sudden tool termination).

[16] Office for National Statistics 2016 (https://www.ons.gov.uk/peoplepopulationandcommunity/householdcharacteristics/homeinternetandsocialmediausage).

E) Project website ('Community-hub')

http://research.ncl.ac.uk/haltwhistleburn/

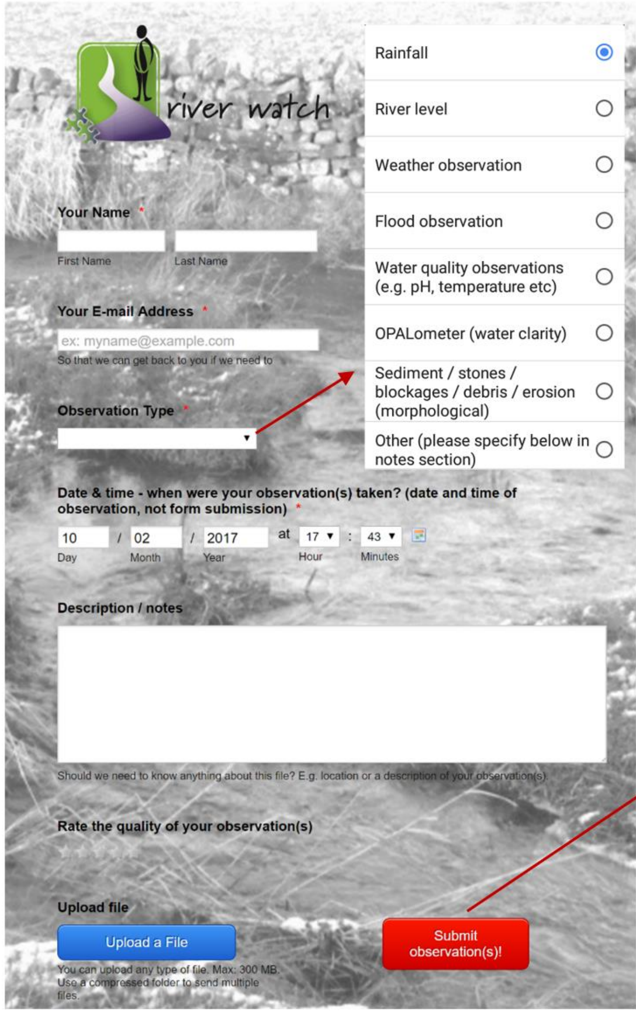




- 'Community-hub' on project website used to submit data;
- 'Quick link' on homepage side banner;
- Takes user to webform (see F);
- Encourages community to view other information whilst on the website.

F & G) Web form (http://bit.do/sendmydata)

- Web form embedded within website (desktop & mobile friendly);



- Fields populated by user, includes date, time & observation type;
- Files or zipped folders can be uploaded with submission;
- Once submitted, data is sent to 'Dropbox' automatically (a free online file storage & sharing tool);

Dropbox

- A 'thank you' page is shown after clicking submit, with links to project data.

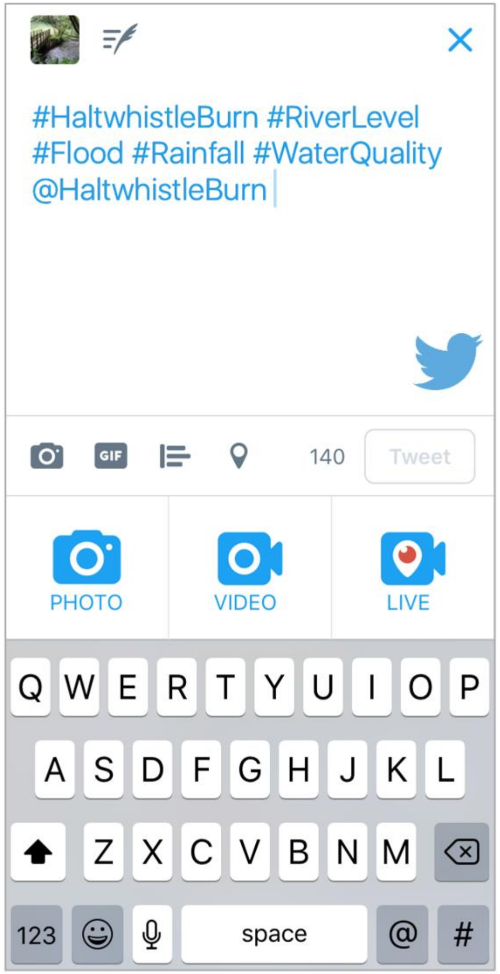
H) River Watch Photo Post

- A5 sized signage erected, adjacent to the three river level gauge boards (RLGB) along the Haltwhistle Burn;
- Encourages regular & one-off river level observations to be made;
- Signage provides instructions on how to submit RLGB data – includes web form (see F) and Twitter (see I) options;
- Allows passers-by to take part in the data collection phase.

Figure 4.7A. Illustrations and descriptions of the web-based data entry and submission tools (E-H). See Appendix 4B for River Watch Photo Post text.

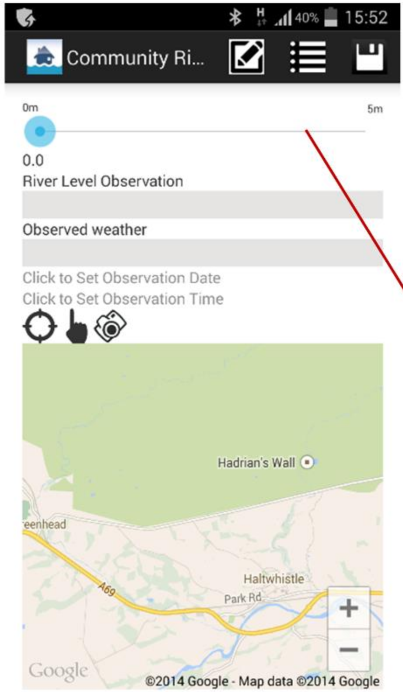
I) Twitter

- Free tool available to use on desktop computers, smartphones and tablets;
- Easy to download from app stores and update over time;
- User can post a short message online ('tweets' are 140 characters or less);
- Message can be accompanied by photographs, hyperlinks, locational information (geo-referenced) and tag other users to alert them;
- Video and live streams now possible;
- Hashtags (see # examples) allow key words or phrases to be identified easily;
- Free data storage and hosting;

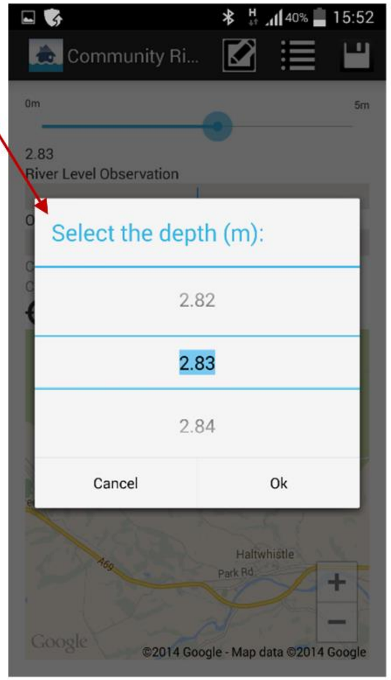


- Wider community engagement anticipated;
- Time stamp is automatic.

J & K) Community 'River and Weather app' (Android)



- Existing app (developed and hosted by Newcastle University) easily adapted to include parameters of interest;



- Once installed on a tablet or smartphone, users input date, time, location, river level depth, weather description and/or flood photograph;
- Can use app offline, save observations and submit later
- Automatic or manual location. Used to create a web-map of all observations submitted.

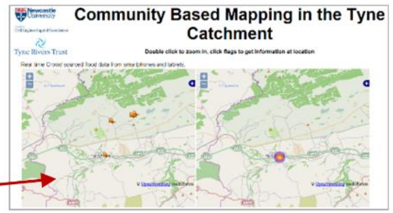


Figure 4.7B. Illustrations and descriptions of the web-based data entry and submission tools (I-K).

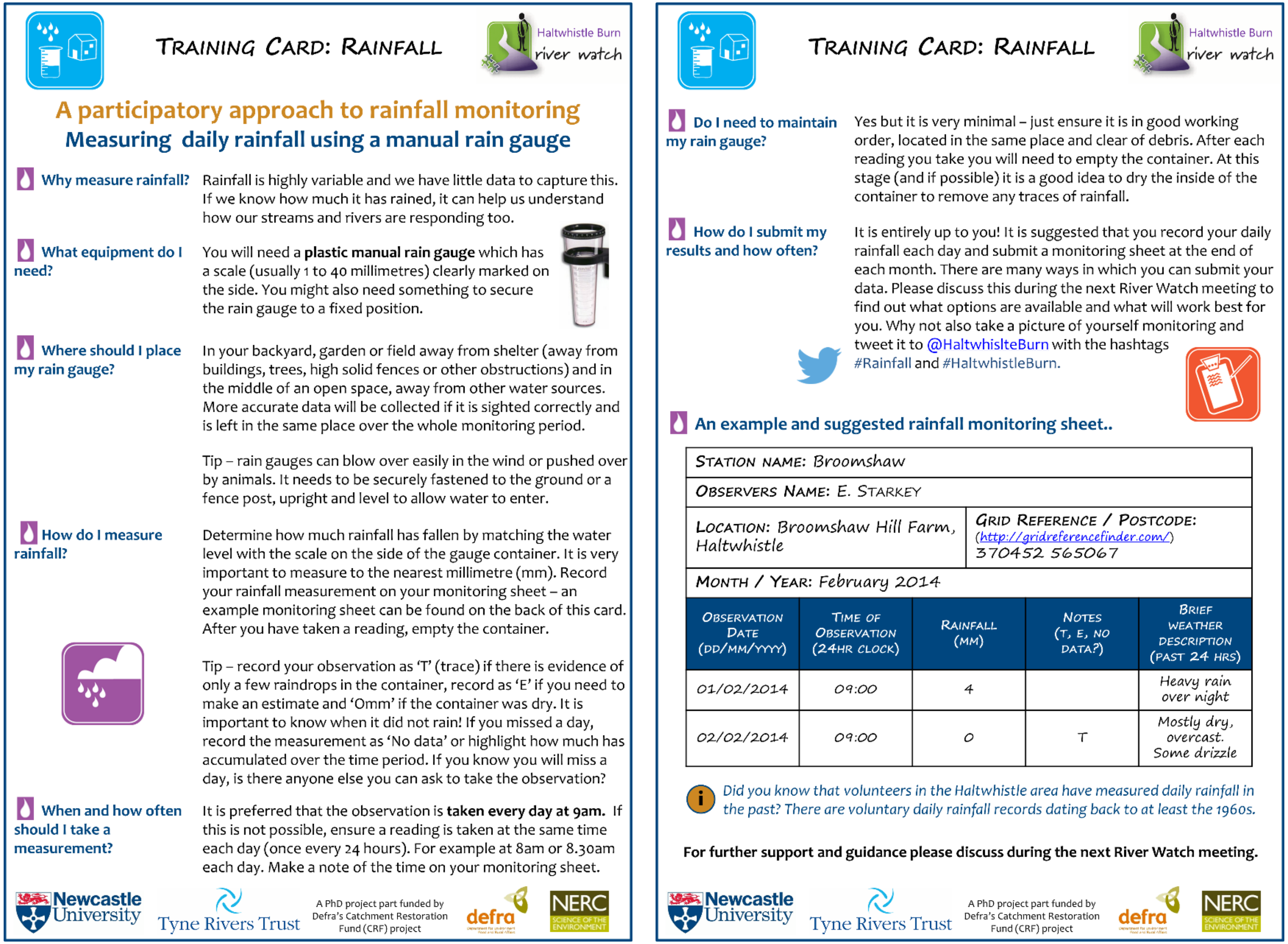
4.5.4. Encouraging complete, consistent and good quality data collection – examples

The proposed monitoring techniques and data entry and submission tools have been designed with consistency, standardisation and data quality in mind. This is particularly important when a variety of people (knowledge, skills and motivations), simple monitoring methods and data formats are involved (Bonney *et al.*, 2009; Tweddle *et al.*, 2012; Roy *et al.*, 2012). Weigelhofer and Pölz (2016) describe volunteer involvement in the data collection process as being 'chaotic', leaving data quality to be one of the greatest challenges during the design phase. Many studies have found that incomplete datasets, subjectivity and observer bias can create data quality issues (Tweddle *et al.*, 2012; Weigelhofer and Pölz, 2016). Bonney *et al.* (2009) claim that carefully designed data forms, clear data collection protocols and participant support are the three most important design aspects that can improve data quality. Appropriate mechanisms are required to promote validation and verification activities. Large projects led by OPAL and the Cornell Lab of Ornithology have incorporated a range of educational material into their schemes to maximise the number of useful observations collected by the public, including posters, FAQs, instruction booklets, CDs, quizzes, multimedia presentations, web pages and identification guides (Bonney *et al.*, 2009; Dickinson *et al.*, 2010; 2016; Rose *et al.*, 2016).

The following set of bullet points describe examples where the design process was specifically targeted to encourage complete, consistent and good quality data collection within the Haltwhistle Burn catchment (i.e. quality assurance methods). Many of these strategies significantly contrast traditional monitoring methods in hydrology and catchment science.

- **Training cards, workshops and face-to-face meetings**

Detailed information sheets known as 'training cards' were produced for every proposed monitoring method and data entry and submission technique (as previously introduced in Section 4.5.2-4.5.3). The primary purpose of the training cards was to provide step-by-step instructions detailing every protocol involved. These cards informed participants what to monitor, why, how and where, along with additional educational facts, examples of data collected, suggested data submission techniques, and links to further information (such as social media and the project website). The training cards were specifically designed and written for a lay audience to encourage longer-term engagement and participation. Protocols detailed within each training card were closely aligned with traditional monitoring procedures (such as those detailed by Shaw *et al.*, 2011; Bren, 2015; Younos and Heyer, 2015) to further increase the validity of community-based observations.



TRAINING CARD: RAINFALL

Haltwhistle Burn river watch

A participatory approach to rainfall monitoring

Measuring daily rainfall using a manual rain gauge

Why measure rainfall? Rainfall is highly variable and we have little data to capture this. If we know how much it has rained, it can help us understand how our streams and rivers are responding too.

What equipment do I need? You will need a **plastic manual rain gauge** which has a scale (usually 1 to 40 millimetres) clearly marked on the side. You might also need something to secure the rain gauge to a fixed position.

Where should I place my rain gauge? In your backyard, garden or field away from shelter (away from buildings, trees, high solid fences or other obstructions) and in the middle of an open space, away from other water sources. More accurate data will be collected if it is sighted correctly and is left in the same place over the whole monitoring period.

Tip – rain gauges can blow over easily in the wind or pushed over by animals. It needs to be securely fastened to the ground or a fence post, upright and level to allow water to enter.

How do I measure rainfall? Determine how much rainfall has fallen by matching the water level with the scale on the side of the gauge container. It is very important to measure to the nearest millimetre (mm). Record your rainfall measurement on your monitoring sheet – an example monitoring sheet can be found on the back of this card. After you have taken a reading, empty the container.

Tip – record your observation as 'T' (trace) if there is evidence of only a few raindrops in the container, record as 'E' if you need to make an estimate and '0mm' if the container was dry. It is important to know when it did not rain! If you missed a day, record the measurement as 'No data' or highlight how much has accumulated over the time period. If you know you will miss a day, is there anyone else you can ask to take the observation?

When and how often should I take a measurement? It is preferred that the observation is **taken every day at 9am.** If this is not possible, ensure a reading is taken at the same time each day (once every 24 hours). For example at 8am or 8.30am each day. Make a note of the time on your monitoring sheet.

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TRAINING CARD: RAINFALL

Haltwhistle Burn river watch

Do I need to maintain my rain gauge? Yes but it is very minimal – just ensure it is in good working order, located in the same place and clear of debris. After each reading you take you will need to empty the container. At this stage (and if possible) it is a good idea to dry the inside of the container to remove any traces of rainfall.

How do I submit my results and how often? It is entirely up to you! It is suggested that you record your daily rainfall each day and submit a monitoring sheet at the end of each month. There are many ways in which you can submit your data. Please discuss this during the next River Watch meeting to find out what options are available and what will work best for you. Why not also take a picture of yourself monitoring and tweet it to @HaltwhisteBurn with the hashtags #Rainfall and #HaltwhistleBurn.

An example and suggested rainfall monitoring sheet..

STATION NAME: Broomshaw

OBSERVERS NAME: E. STARKEY

LOCATION: Broomshaw Hill Farm, Haltwhistle

GRID REFERENCE / POSTCODE: (http://gridreferencefinder.com/) 370452 565067

MONTH / YEAR: February 2014

OBSERVATION DATE (DD/MM/YYYY)	TIME OF OBSERVATION (24HR CLOCK)	RAINFALL (MM)	NOTES (T, E, NO DATA?)	BRIEF WEATHER DESCRIPTION (PAST 24 HRS)
01/02/2014	09:00	4		Heavy rain over night
02/02/2014	09:00	0	T	Mostly dry, overcast. Some drizzle

Did you know that volunteers in the Haltwhistle area have measured daily rainfall in the past? There are voluntary daily rainfall records dating back to at least the 1960s.

For further support and guidance please discuss during the next River Watch meeting.

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Figure 4.8. Example training card (in this case rainfall) developed to increase the consistency and quality of community-based monitoring.

Figure 4.8 presents the 'rainfall' training card developed to illustrate the prevalent layout adopted and the type of content included (see Appendix 4C for others, including 'health and safety' card which was essential for all regular participants). Participants were encouraged to secure their gauge to a fixed position over time, install away from deliberate shelter, record to the nearest millimetre using the scale provided, maintain and clean the gauge on a regular basis, and were informed about the importance of recording date, time, no rain ('0mm') and missing data ('No Data'). All training cards were distributed to the community during River Watch meetings (printed and laminated) or hosted electronically online within the project website's community-hub[17]. However, as Bonney *et al.* (2009) point out, volunteers are still being relied upon to study and follow the training material correctly, or to get in touch to ask further questions.

To cater for a varied audience, River Watch meetings were also turned into training workshops, where equipment was demonstrated and participants asked questions.

- **Fixed point photography (FPP)**

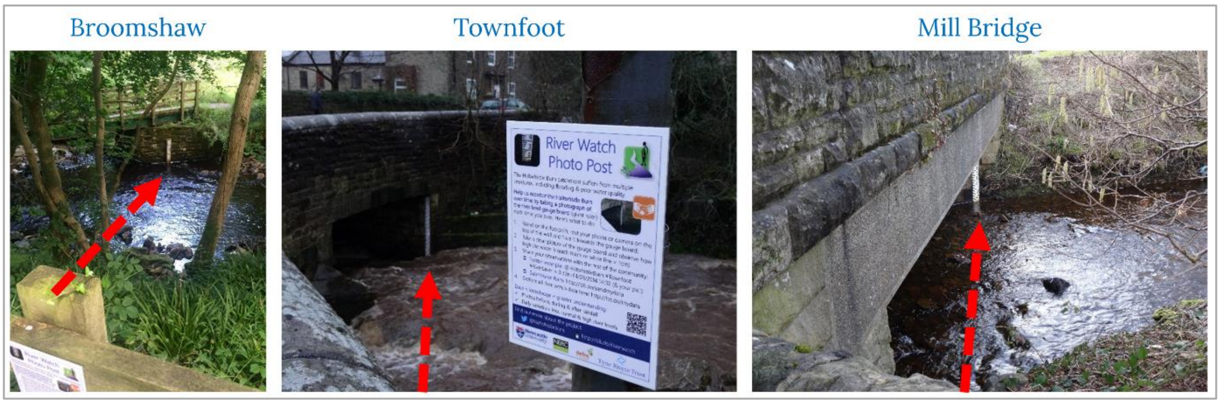


Figure 4.9. RLGB FPP line-of-sight determined by the position of the River Watch Photo Posts.

Previously described River Watch Photo Posts (Figure 4.7A and Appendix 4B) were designed and installed for two fundamental reasons (besides increasing engagement, participation and safety):

- To encourage multiple/different observers to stand in the same place (thus spatial relationship) to view the RLGB over time (Figure 4.9). The signpost provided a reference point to encourage long-term datasets to be generated at the same three locations along the Haltwhistle Burn, similar to a continuous traditional monitoring

[17] http://research.ncl.ac.uk/haltwhistleburn/communityhub/communitytrainingresources/

approach. Given that observers act as 'sensors' in community-based monitoring, this approach aimed to reduce the risk of parallax (systematic instrumental) error;

- To encourage observers to take a photograph to accompany and verify their quantitative river level observation. Instructions encouraged participants to place their camera on top of the signage post and face the lens towards the RLGB.

- **Rate the quality of observations**

A star-based approach was adopted to allow volunteers to rate the quality of their observations when submitting data using the web form (Figure 4.10). Rating allowed the public to highlight the perceived quality of their observations, with five stars being high quality, and one star being low. Although subjective, this star approach was intended to raise participants' awareness of data quality and detect any erroneous errors or outliers during this initial screening stage. A similar quality control process is used by the Met Office WOW system (Tweddle *et al.*, 2012).

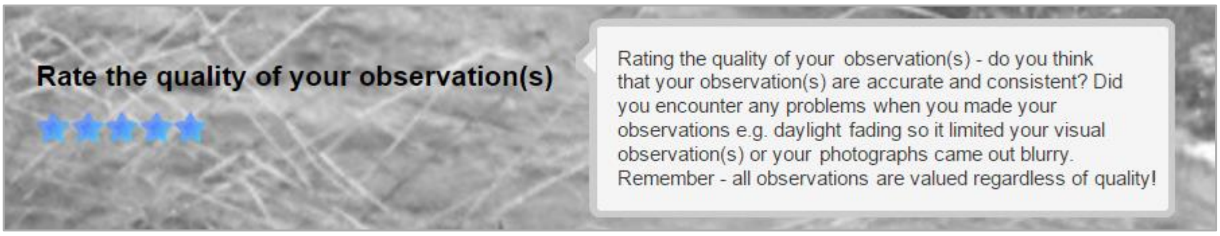


Figure 4.10. Star-based system which encouraged users to rate the quality of their observations.

- **Where possible, quantitative and semi-quantitative data collected**

Although qualitative information (e.g. anecdotes) were encouraged to be shared as an alternative source of information, efforts have been made to ensure all chief parameters of interest were observed quantitatively. For instance, all seven water quality tests either categorised or quantified the parameters of interest. Manufacturers have calibrated colour charts associated with each test strip and test tablet against measured quantities (i.e. colorimetry - see Figure 4.11).

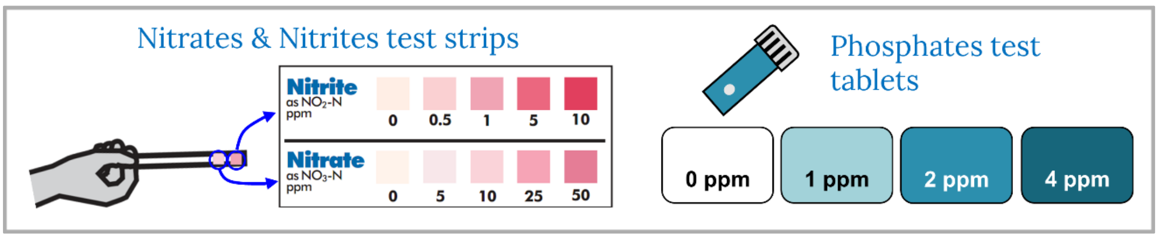


Figure 4.11. Examples where quantitative/semi-quantitative data are extracted from simple citizen science monitoring kits.

- **Blank/example data forms (paper-based and electronic)**

Blank paper-based and electronic data forms (containing examples) were made available to participants, primarily to make it easier and quicker for them to record their observations. These forms also educated users on how to log their observations, increased the likelihood of the scientifically orientated metadata being submitted, and subsequently increased the consistency between different observers. Furthermore, the mandatory option within the web form was particularly useful as users could not click 'submit' until all essential fields were populated. Examples of mandatory fields include date, time and observation type, which were further controlled using drop down menus (Figure 4.12). Philippoff and Baumgartner (2016) found that 'sloppiness' and missing data were the two most prevalent error types in their ecological citizen science experiment, emphasising the importance of neat and complete data collection.

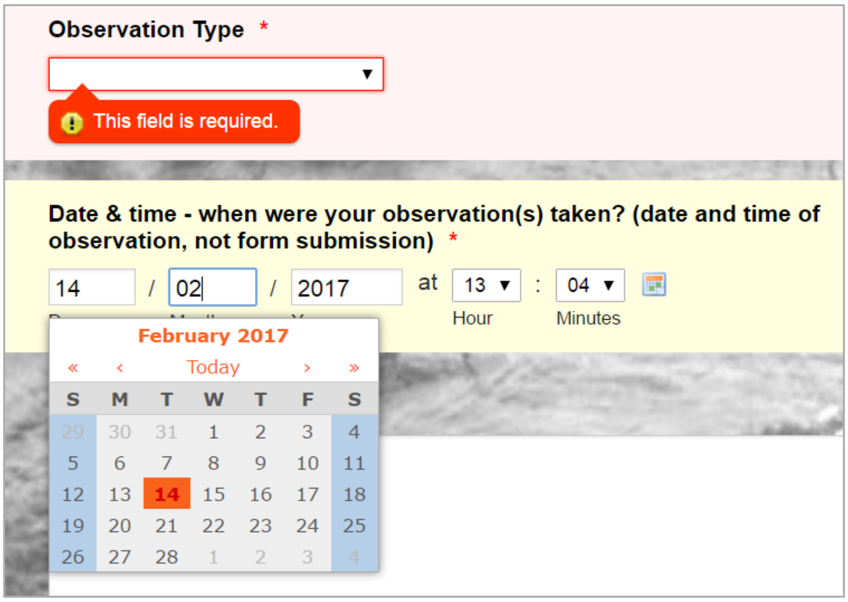


Figure 4.12. Example where the web form was used to encourage consistent data collection/entry and avoid missing data.

- **Uniform monitoring equipment**

In most cases, equipment such as the RLGB, water quality test kits and rain gauges were provided directly to the Haltwhistle Burn community. This meant that multiple observers used the same type of equipment, therefore uniform specifications were used. However, due to the nature of citizen science, it was important to source and make use of any relevant observations made by the public and hence it was not always possible to remove this type of instrumental error.

4.6. Implementing the community-based monitoring (citizen science) scheme

Once the citizen science toolkit had been designed and developed, it was then ready to be implemented within the Haltwhistle Burn catchment and focus community. Figure 4.13 summarises the process followed in order to attain an operational monitoring scheme.

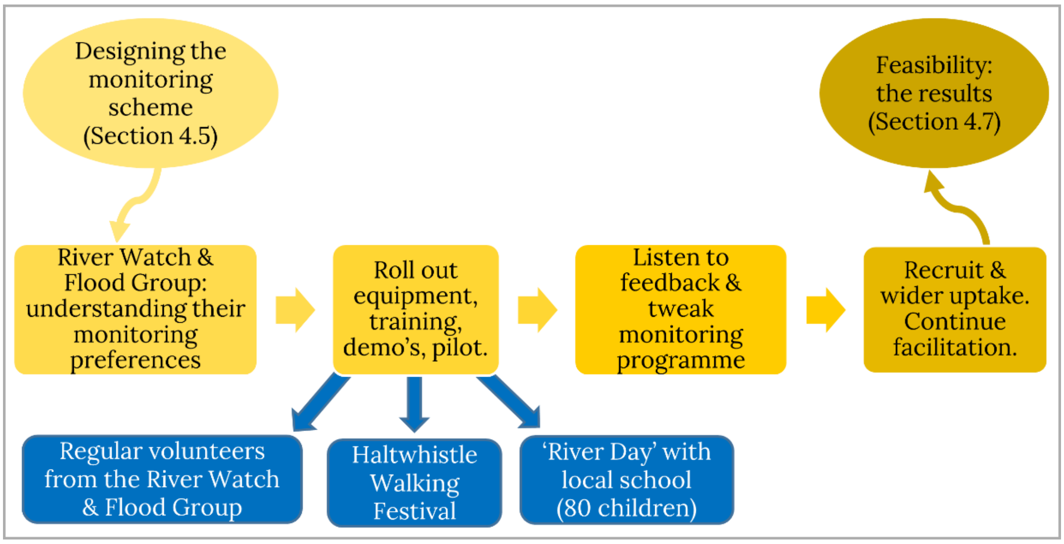


Figure 4.13. Steps taken during the implementation phase of the citizen science programme.

The next milestone River Watch and Flood Group meeting was scheduled in February 2014 which involved understanding individual monitoring preferences and capabilities by distributing a short and self-administered questionnaire. The questionnaire (blank template in Appendix 4D) focussed on understanding what the potential volunteers would like to monitor, where (spatial), how often (temporal), and how they would prefer to submit data. They were also asked to identify their motivations for participation, although results for this question forms part of Section 4.7. Questions were tailored around local catchment knowledge previously highlighted by the group during the engagement process. The majority of questions were structured (tick box answers) as monitoring preferences were controlled by the scheme's preliminary design. The questionnaire was also shared across the River Watch Group emailing list.

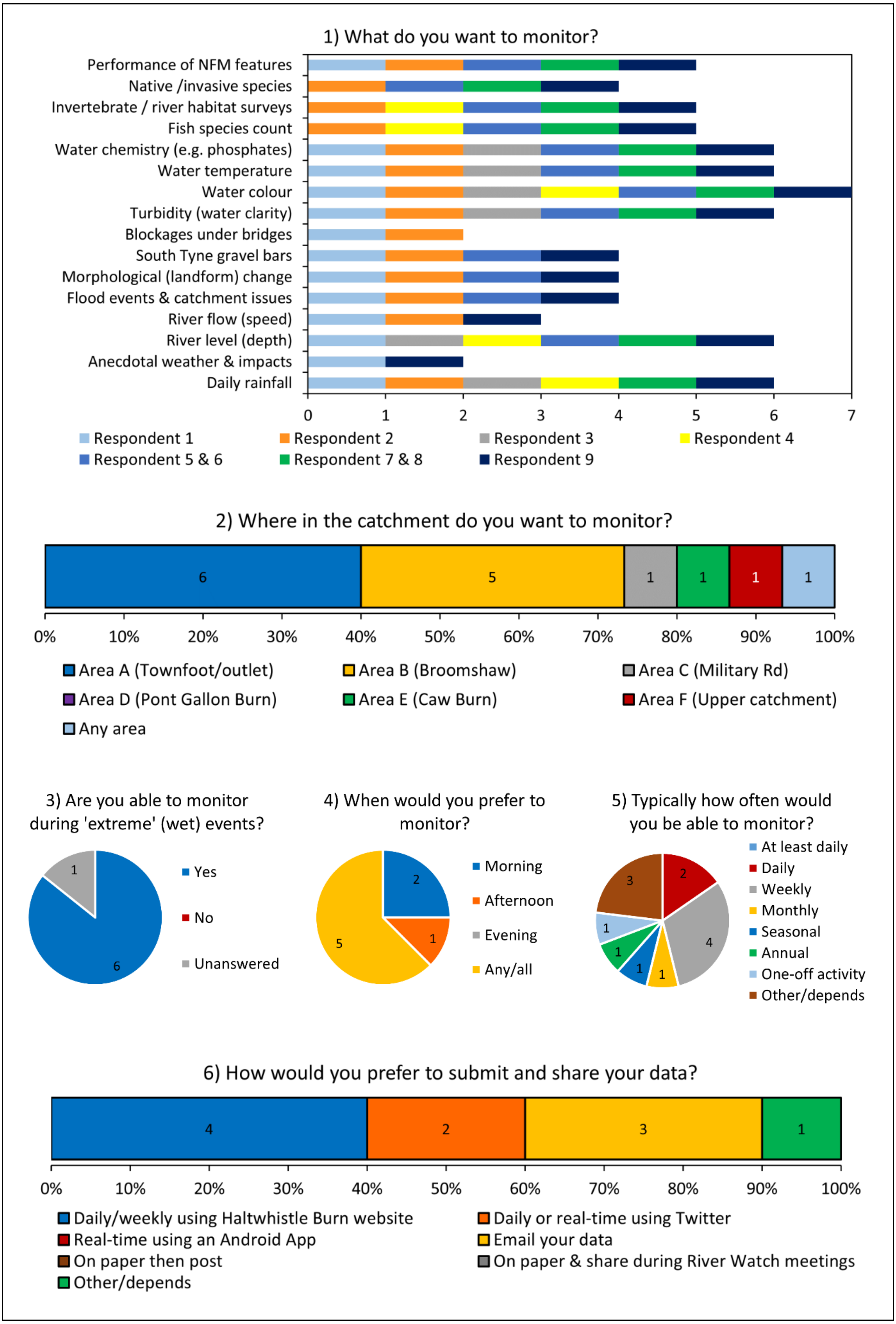


Figure 4.14. Relevant questionnaire results used to determine initial monitoring preferences and capabilities. Note that some respondents selected more than one option for each question.

A total of seven questionnaires (relating to nine respondents) were initially received, results of which can be found within Figure 4.14. These findings provided initial indications that:

- The public want to take part in a community-based monitoring programme;
- Individually, respondents would like to monitor a range of different catchment parameters and issues, notably those related to water quality, alongside rainfall and river levels. There are a few dominant River Watch members who are keen to volunteer and monitor anything;
- Although some volunteers may be able to travel higher up into the catchment, the majority of respondents said they were only prepared to monitor south of the Military Road (i.e. in the Broomshaw and Townfoot areas which are closer to the town);
- Extreme (wet) weather events were not expected to cause a monitoring barrier;
- The temporal resolution of data would depend on the specific task involved, but daily and weekly seemed feasible;
- It would be possible for morning, afternoon and evening observations to be made;
- Most respondents were initially prepared to submit their observations using the project website (web form), send by email and/or via Twitter. Three of the nine respondents said that they would like to try the river and weather app, but they did not own an Android device.

The above findings delivered a positive start, and although only nine respondents officially completed and returned a questionnaire, many other people were still interested in being part of the monitoring project. Based on experience with the Haltwhistle Burn River Watch and Flood Group, it was a challenge to make people read and fill out forms; many preferred to informally discuss options rather than officially commit on paper. Results were also biased towards the nature of the River Watch Group's goals (health of the Haltwhistle Burn, not just flooding) but they still provide an indication of initial preferences from this particular community. Findings were then used to recruit participants, purchase and distribute equipment, and officially launch monitoring activities.

The training material described in Section 4.5 were distributed to participants and hosted online. Face-to-face demonstrations were carried out during River Watch workshops. Following individual requests, guidance was also provided to two participants at their homes (assistance to get the Android app working and specific guidance on how to monitor the Burn from their garden), and another whilst out in the catchment (during water quality monitoring). All of these training sessions offered participants a chance to ask questions and improve their monitoring abilities. Initial participants were then able to pilot monitoring methods and report any problems, preferences or opinions back to the researcher. Equipment was further trialled during the:

- River Day (a TRT initiative) involving 80 school children aged 10-11 whom tested using the rain gauge, RLGB, water quality test kit, and the Android app;
- Seven mile 'citizen science' speciality walk scheduled as part of the Haltwhistle Walking Festival. This allowed nine participants to test the water quality test kit around the Greenlee Lough inlets and outlet.

Examples of evidence relating to the aforementioned training and piloting activities can be found within Appendix 4E. Lessons learned following initial community-based engagement, training and piloting activities included the following:

- Some members of the public were already monitoring rainfall and river levels with their own equipment and wanted to add them to the scheme;
- Monitoring methods and associated protocols seemed to work well during the walking festival and River Day with the school. A range of positive comments were received from participants, such as *"Quite a compact [water quality] little kit isn't it? "Very interesting stuff!"* It did however highlight concerns over the availability of phone and internet signal within the catchment, and that care must be taken when printing water quality colour charts (poor printouts affect the visual colour scales);
- Training cards and workshops helped to clarify monitoring protocols, especially for those who were monitoring prior to February 2014. After a few trials and reassurance, volunteers appeared to get into a routine with relevant monitoring protocols: *"I seem to be getting into the swing of things with Twitter… I can tweet the pic straight from my phone".* The training cards were updated in places according to feedback to ensure clarity;
- There appeared to be a barrier to using the Android app and some volunteers were reluctant to get their smartphones out to take photographs during wet weather. As a result, two waterproof cameras (Fujifilm Finepix XP70) and two small Android tablets (ASUS Memo Pad 7) were distributed to regular and interested volunteers:

"If it [the app] was all set up and ready to go we would be happy to use it"

"I think a camera would be more helpful, robust and weather proof for me"

The cameras were also set up to automatically stamp date and time into each photograph.

- Privacy issues when using Twitter as a data sharing tool were raised by one citizen scientist;
- One regular volunteer highlighted that they didn't know where to stand when observing the RLGBs. They also realised that this affected the accuracy of their observations and subsequently triggered the installation of the River Watch Photo Posts (Figure 4.9).

Overall, it was apparent that most of the feedback was related to personal preferences, specific questions and new suggestions (e.g. alternative monitoring locations to suit their own interests), rather than there being major issues with the proposed citizen science toolkit. Incorporating such requests adds to the complexity of the scheme, meaning that researchers and scientists must be flexible when working with the public. Nevertheless, incorporating feedback here has helped to shape a relevant and co-produced monitoring scheme.

Following the pilot phase, community-based monitoring activities continued and datasets began to develop. The engagement techniques (previously described in Table 4.1) were used to encourage wider involvement across the Haltwhistle Burn community (see also Figure 4.15). The River Watch group and current volunteers also proactively assisted with the recruitment process.

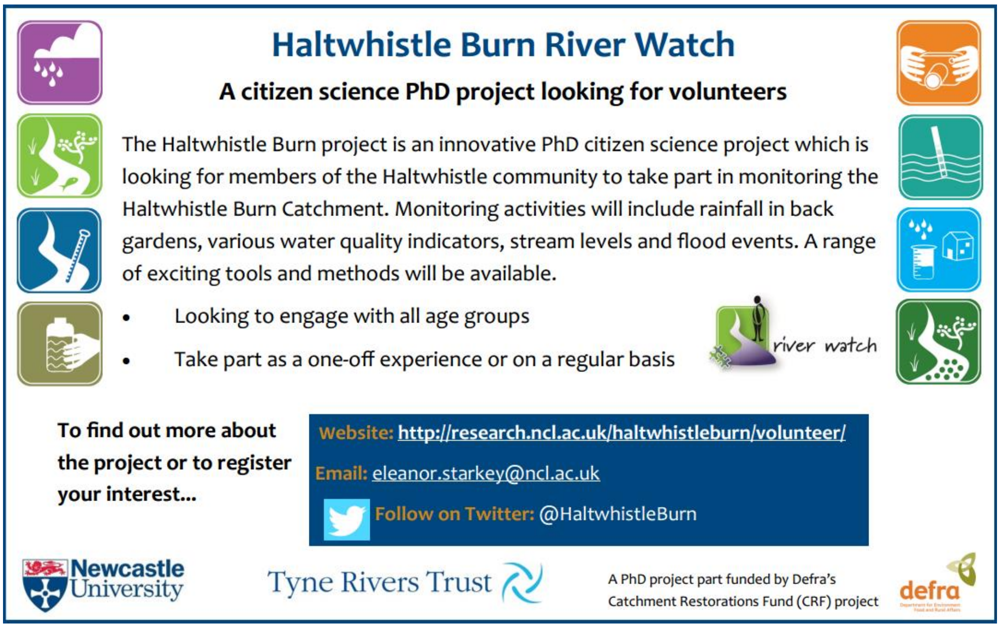


Figure 4.15. Example leaflet used to recruit members of the wider community. Active citizen scientists also distributed them e.g. *"I put one in the bookshop window and handed a few out"*.

4.7. Results: can communities feasibly monitor their local catchment?

After implementing the citizen science framework (flow chart in Figure 4.2) within the Haltwhistle Burn catchment and focus community, an active monitoring scheme continued to grow, evolve and generate relative observations for catchment science. The number and nature of observations submitted and shared by the community have been used as a proxy to represent feasibility, and subsequently determine whether communities can feasibly monitor their local catchment (**Research Question 1, Objective 1C**). Who participated, motivations, parameters monitored, spatial and temporal trends, and how observations were collected and submitted, have all been used to evaluate whether it is possible. Community-based observations which were collected between October 2013 and February 2016 (29 months) have been focused upon.

4.7.1. Who participated?

Figure 4.16 highlights how many individuals were directly 'engaged' with the citizen science monitoring activities, and those who then went on to submit at least one catchment observation ('engaged + monitored'). Involved individuals have been categorised into relevant groups to emphasise their role or position within the Haltwhistle Burn community, including the River Watch and Flood Group, farmers, passers-by, upstream land owners and the wider community.

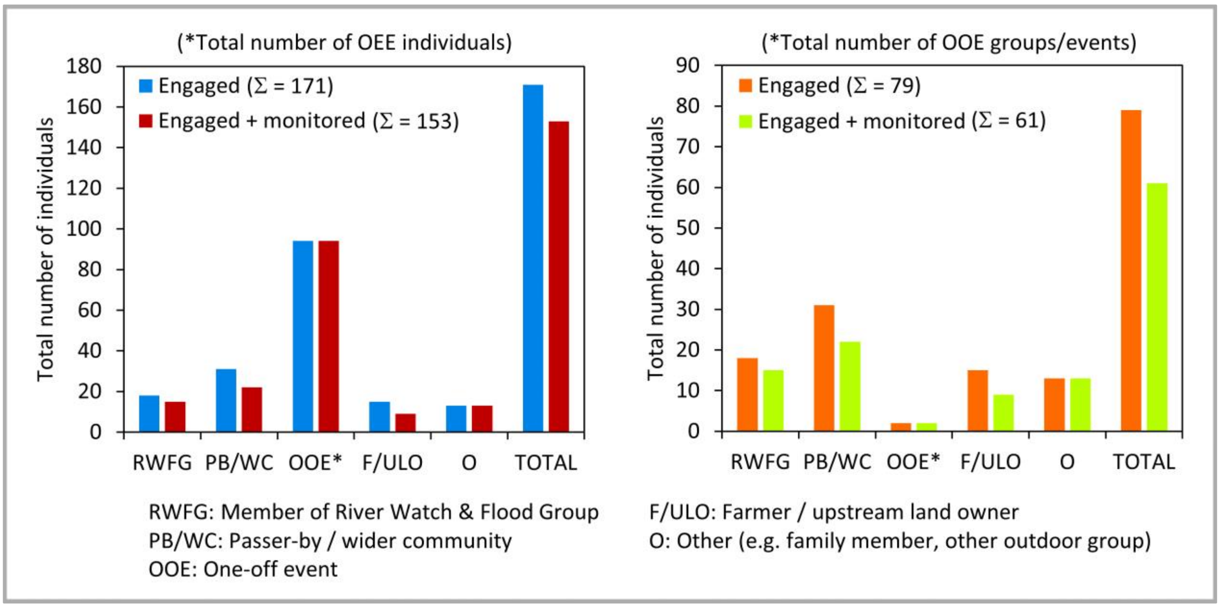


Figure 4.16. Total number of individuals who were engaged with monitoring activities, and those who then monitored at least once within the 29-month period. Individuals have been categorised depending on their position or role within the community. Left: all individuals involved. Right: all individuals involved, with OOE individuals represented by total number of events (i.e. 2).

Over a period of 29 months, a total of 171 people were approach and directly briefed about the community-based monitoring scheme (note that this does not include ‘general’ project engagement through social media, the website and newspaper article). Out of those engaged, 153 people went on to physically monitor one or more catchment parameter (success rate of 89.5%). This meant that once engaged, most people went on to participate. However, given that only 153 participants in total submitted observation(s) over a 29-month period (which is quite low given the size and population of Haltwhistle), the scheme essentially relied upon a small number of people within the community to monitor the Haltwhistle Burn catchment.

Despite low involvement levels, the monitoring scheme did comprise a wide range of groups, from the relevant River Watch and Flood Group, through to passers-by, and upstream farmers and land owners. One-off events (in this case, the ‘River Day’ with the local school and the Walking Festival) proved to be a very quick and effective way of engaging with mass participants in one go, including younger citizen scientists. This latter approach is useful when engagement levels are more important than gathering long-term datasets. For instance, 55% of the total number of engaged participants originated from organised one-off events. Although direct evidence relating to demographic involvement is absent, working closely with the community over time revealed that it is generally the retired population or those who walk the Burn regularly (particularly dog walkers) that provided the majority of catchment observations collected.

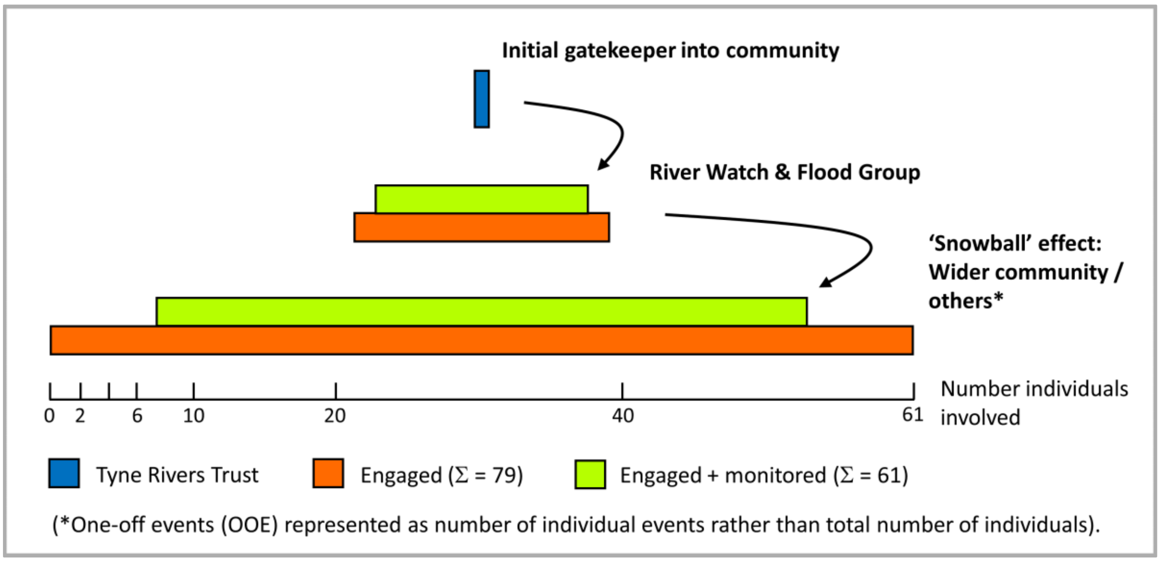


Figure 4.17. Pyramid illustrates how engagement and monitoring levels flourished (‘snowball’ effect) after using an initial gatekeeper and targeting existing river/flood groups.

Figure 4.17 emphasises how TRT initially provided the direct (therefore quick) link into the community. From here, members of the River Watch and Flood Group (RWFG) generated further connections into the wider community, triggering opportunities which significantly increased the number of people involved in the monitoring scheme. Once monitoring, the group also attracted family members and neighbours (O). This often created a 'monitoring household' or 'monitoring group' as they shared monitoring duties with each other, rather than generating separate datasets (forthcoming evaluations therefore represent these groups as one participant).

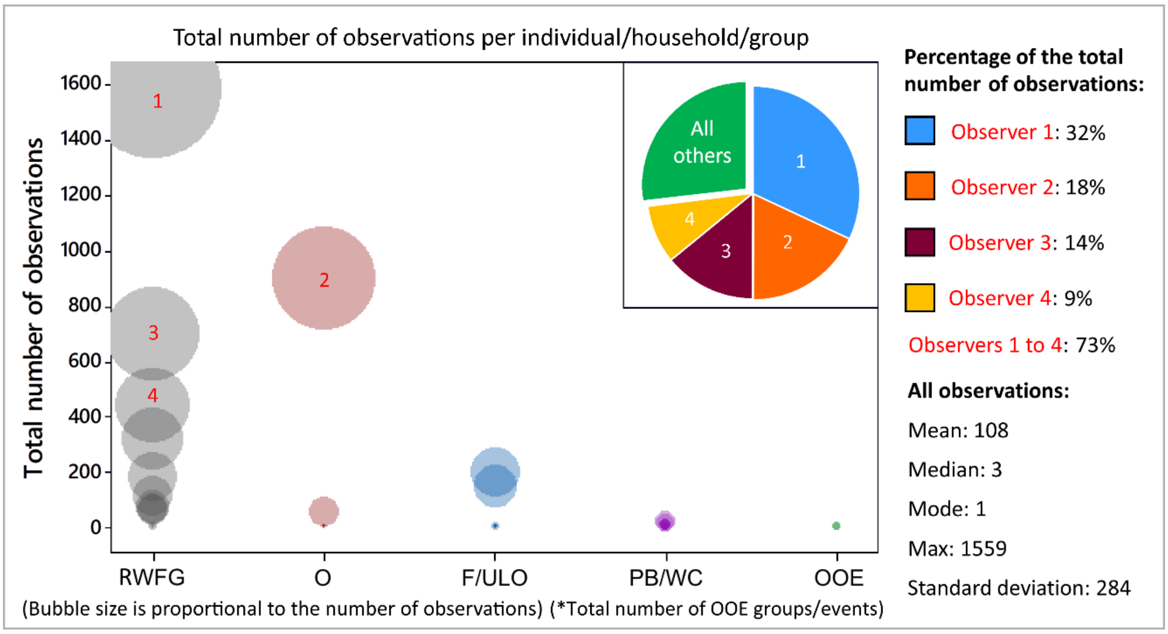


Figure 4.18. Total number of observations per individual/household/group involved (see Figure 4.16 for abbreviations). The top four observers have been highlighted.

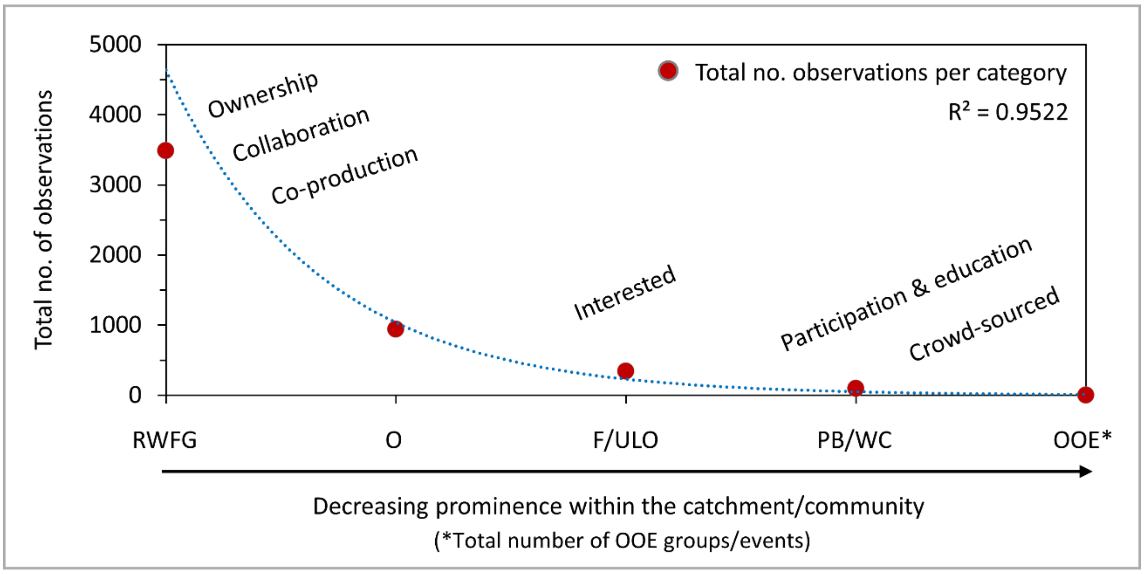


Figure 4.19. Total number of observations per category of people within the community (see Figure 4.16 for abbreviations). An exponential line has been fitted to the ranked dataset.

Over the 29-month period, a total of 4877 individual observations were collected and submitted. Despite there being different categories of people within the community involved, the total number of observations collected was not equally distributed[18]. For instance, the most common number of observations collected was just one (i.e. a one-off monitoring experience), whilst the maximum individual contribution was 1559. Figures 4.18 and 4.19 highlight how the majority of the citizen science observations originated from the RWFG (71%) and Others (O) category (e.g. family member, neighbour etc. at 19%). Figure 4.18 also highlights how almost three quarters (73%) of the observations were collected by just four dedicated individuals (or households) alone. When ranked and fitted with a trend line, it is clear that the total quantity of observations collected increases 'exponentially' (R^2 of 0.95) for citizen scientists who have a greater prominence within the community. Passers-by and one-off events were initially interested and contributed, but were not committed long-term. In two separate cases it was found that monitoring had occurred prior to the citizen scientist programme. It was also established that upstream farmers were interested but they did not have the time to monitor (*"Farmers are too busy to mess about monitoring"*). Availability was a significant monitoring restriction, particularly for those who worked full-time (*"If I had the time I would spend forever messing about monitoring")*, hence the enthusiasm was there for many regardless of participation levels.

4.7.2. Motivations for participation

Given that the citizen scientists were unpaid and monitoring activities were optional, all partakers gave up their own time, thus were motivated for different reasons. Motivations have been difficult to capture given that people have joined and left the project over time, particularly passers-by. As a result, emerging themes have been extracted from participation forms, questionnaires (Appendix 4A and 4D), conversations with participants, and also during observational work (e.g. during meetings). Motivations are summarised as follows:

- General interest and curiosity;
- They have been previously flooded or live beside the river (*"I am keen to learn about the lag time". "[We had] water lapping at our doorstep*);
- *"Love the Haltwhistle Burn"* and interested in helping to preserve and improve it (including habitats and biodiversity);
- Educational benefits and enthusiasm to try a range of monitoring activities;

[18] Total observations refers to all individual submissions or spatio-temporal observations made, except water quality (one observation per set of tests) and flood photographs (one observation per set of photographs submitted if multiple exist for the same location or event of interest).

- Regularly walk along the Haltwhistle Burn (including dog walkers);
- They are part of the RWFG, therefore felt that they had a duty to participate (community spirit);
- Weather/meteorological enthusiasts (*"the weather fascinates me"*);
- It complemented their own profession or qualifications, for instance *"I was a geography teacher so I am a bit of a weather enthusiast"*;
- They were monitoring already and wanted to learn how to *"monitor and record our observations properly"*, and prove that rainfall is extremely variable across the catchment.

There was a surprisingly large number of people with an interest in meteorology, and despite flooding issues in and around the Haltwhistle Burn catchment, some volunteers confirmed that they enjoyed the *"interesting events"* (i.e. the rarer flood events). It is also possible that members of the community may have participated to support the research project itself. Furthermore, it is likely that passers-by contributed out of curiosity when passing the RLGBs.

4.7.3. What have they monitored? Which parameters are favourable?

Over the 29-month period, a wide range of observations and formats were successfully collected and submitted by the Haltwhistle Burn community. Observations received have been assessed here to quantify which parameters were monitored, how many times, and therefore which were most prevalent within the community. It was found that, other than the weather diaries, the Haltwhistle Burn community monitored all parameters proposed, including:

- Rainfall – quantitative totals accompanied by anecdotal weather descriptions;
- River levels – photographs, videos and/or direct quantitative observations;
- Evidence during floods or extreme events (includes low flow, snow and weather-related impacts) – photographs, videos, anecdotal descriptions and extra qualitative river levels;
- Water quality (WQ, all seven tests) - quantitative and semi-quantitative observations in line with the training cards provided;
- Performance of nature flood management features (NFM) – photographs and anecdotes.

Apart from one rain gauge, all monitoring equipment distributed was used to generate data.

Floods/extremes/impacts

Just a bit soggy on @HaltwhistleBurn today - this at 2.55pm #flood

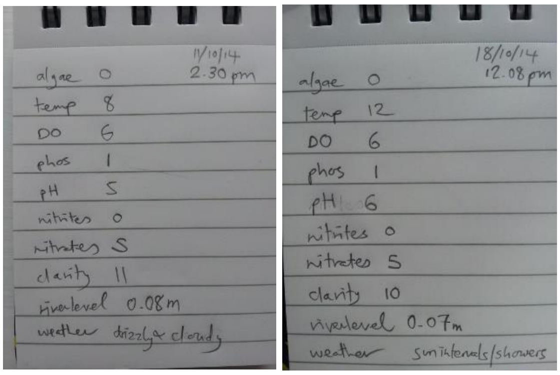
River levels (RLGB)

Rainfall

Location:	[redacted]				
Month/Year:	Jan-15				
Obs Date	Day	Time Obs	Rainfall (mm)	Notes (T,E No Data?)	Brief Weather Description (Past 24 hours)
01/01/2015	Thur	9am	4		Wet Miserable day
02/01/2015	Fri	9am	24		Horrid day, rained continually
03/01/2015	Sat	9am	10		Wet Miserable day quite chilly
04/01/2015	Sun	9am	0		Dry but cold day
05/01/2015	Mon	9am	0	T	Damp, windy and cold
06/01/2015	Tues	9am	0		Dry but cold day and Windy
07/01/2015	Wed	9am	2		Wet, windy and cold
08/01/2015	Thur	9am	20		Very Wet and Windy
09/01/2015	Fri	9am	4		Wet, windy and cold
10/01/2015	Sat	9am	10		Wet, windy and cold
11/01/2015	Sun	9am	11		Wet, windy and cold

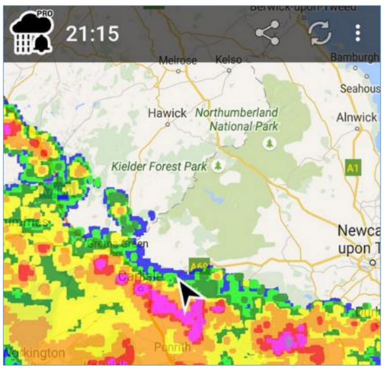
When were your observation(s) taken?	04/12/2015 9 am 55mm
Description / Notes	Storm Desmond. The first time my rain gauge in the garden has reached this high!

Water quality (WQ)



Early warnings via Twitter

Here comes the rain again. Heads up #Carlisle @HaltwhistleBurn



Some heavy rain nearby. #Haltwhistle looks to be getting a hammering. Just a few spits here #brampton @HaltwhistleBurn .

Very intense rainfall 45mm pr/hr. #Brampton #Cumbria. @HaltwhistleBurn it's on its way to you

Other weather parameters (example: a land owner's weather station that already existed prior to the monitoring scheme).

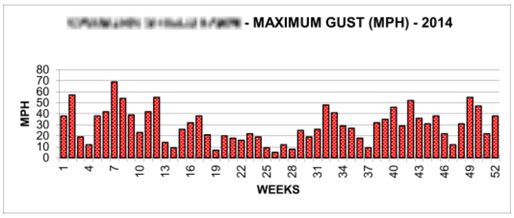


Table 4.8. Examples of heterogeneous community-based observations collected and submitted.

As Figure 4.20(A) exemplifies, flooding and extreme events were the most attractive parameters to monitor (71% of participants). This was followed by river levels at the RLGBs (56% of participants). However, only seven citizen scientists in total monitored rainfall, an activity which required specific equipment and regular commitment. The monitoring scheme was also shaped by the community themselves as they added some of their own monitoring activities to the citizen science toolkit. For instance, those who used social media (Twitter) were able to communicate real-time weather-related information to others directly from the ground (e.g. rainfall radar animations and descriptions - see example in Table 4.8). These 'early warnings' were described by the community as 'heads-up' and encouraged partakers to be prepared. An upstream land owner also possessed their own weather station, which contributed temperature and wind data ('Other weather' category). Despite initial monitoring preferences (Section 4.6), 1.8 catchment parameters were monitored on average by each individual/household/group involved over the 29-month period. Most citizen scientists only monitored one or two parameters, with four being the maximum capacity within this particular community. In many cases, the same participant observed floods and river levels (two parameters) at the same time.

Figure 4.20(B) presents the results relating to the total number of individual observations collected (and per category of participants). Despite floods and extreme weather events being monitored at least once by most people, river levels generated the greatest number of individual observations (2488 which equates to 51% of the total collected), closely followed by rainfall (2034, equating to 42%). This is because regular volunteers (notably the RWFG) were committed to, and understood the importance of, generating spreadsheets of data over time. It was also noticeable that flood-related observations and early warnings on Twitter were often associated with one-off passers-by. NFM features were the least observed because they were installed part-way through the monitoring scheme (refer to Chapter 6 for more information). Some water quality observations were generated but were almost certainly restricted by the lengthy of protocols involved and the specific test kits required (*"the equipment is easy to use but there's quite a lot to do!"* Member of RWFG).

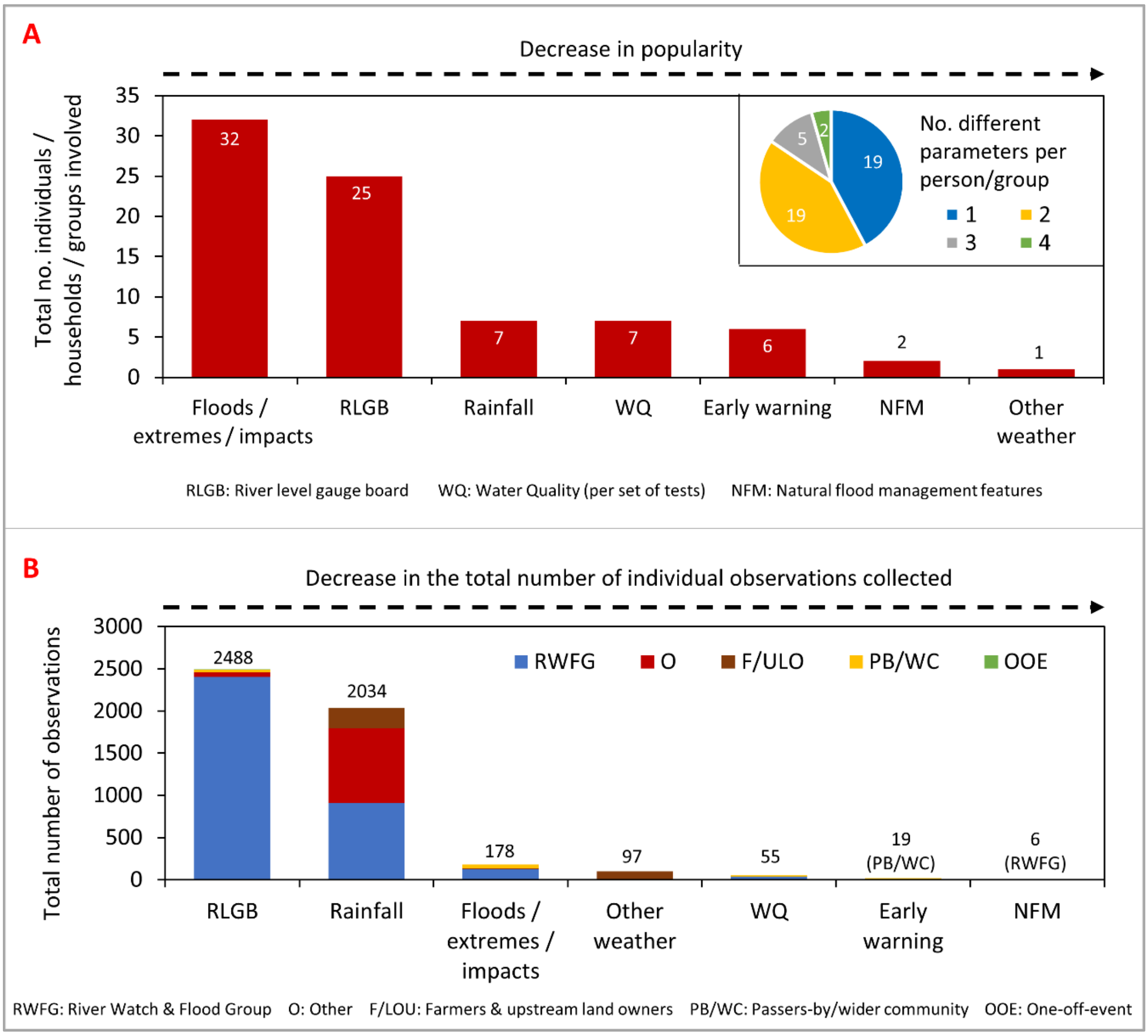


Figure 4.20. Graphs summarising (A) the total number of individuals/households/groups who have monitored each type of parameter at least once, (B) the total number of individual observations collected for each parameter.

4.7.4. How were observations captured and submitted?

Table 4.9 summarises the different data formats collected during the citizen science monitoring programme. Collectively, the community produced a set of quantitative, semi-qualitative and qualitative observations for the parameters of interest, involving direct or indirect monitoring methods, and thus the direct level of involvement and effort varied. Although quantitative observations were frequently submitted, it was found that many participants preferred to simply take a photograph (FPP), rather than a direct quantitative observation. There are many reasons for this tendency, including the simplicity, mobility, quickness and availability of smartphone cameras (*"actually it's easier for me to take a photo… saves me keeping a number in my head (which I'd probably forget by the time I got home)"*). Visual outputs also provide more meaningful and relatable information. On the other hand, participants sometimes preferred to avoid getting their personal smartphones damaged during the monitoring process (*"No pic today; too wet.*

#RiverLevel approx. 1.7 at 10.15am"). However, indirect monitoring methods, such as taking photographs and videos, induced an additional stage of processing (carried out manually by the researcher, not the community) in order to extract meaningful and useable catchment information. There are also consequences associated with relying on automatic sensors or data capturing devices as participants' physical involvement with the natural environment (monitoring experience) decreases compared with direct manual methods. Different data formats also induce variations in observer and instrumental error. Nevertheless, many of these community-based observations produced new types of data, particularly when multiple formats were submitted in one go (i.e. a combination of quantitative and visual information for the same observation).

Figure 4.21 and 4.22 summarise the different routes and tools adopted by participants when entering and submitting their catchment observations. The following points can be noted:

- A range of traditional (paper-/document-based) and web-based methods were adopted;
- Participants preferred to submit their data using tools that they favoured and were already familiar with (hence a broad range adopted across the community);
- Alternative methods were suggested and used by the community, including file sharing platforms such as GoogleDrive, YouTube and Dropbox, which are currently free to use and are interchangeable (for instance, YouTube files can also be shared on Twitter);
- Emailing electronic files and making use of the River Watch Photo Posts (therefore Twitter, Dropbox and the web form) dominated;
- The frequency of data submission varied significantly. Regular volunteers (particularly the RWFG) preferred to email their observations in monthly or quarterly batches. The photo posts permitted passers-by and the wider community to submit data immediately;
- Although most participants continued to use the same data submission tools over time, project involvement successfully encouraged individuals to capture and submit consistent electronic data;
- The Android app was significantly underused; it was trialled but never regularly adopted.

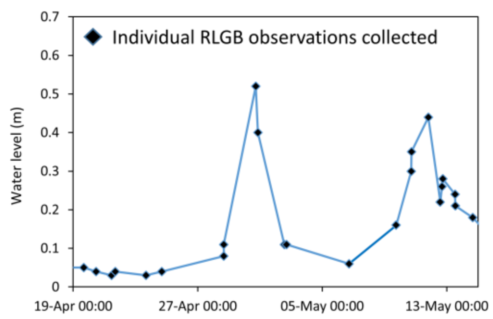
<table>
<tr><td>Monitoring approach</td><td colspan="2">‘Human’ sensor</td><td>‘Electronic’ sensor</td></tr>
<tr><td></td><td colspan="2">• Manual, direct and hands-on;
• Visual observations (the participant was the ‘sensor’), usually aided by relevant monitoring kit, e.g. rain gauge;
• Volunteer fully engaged and aware in order to capture the data.</td><td>• Manual but indirect and non-contact;
• Electronic (cameras & smartphones);
• Volunteer did not necessarily need to know what they were monitoring or why.</td></tr>
<tr><td>Output format</td><td>• Quantitative;
• Semi-quantitative;
• Comparable to traditional datasets.</td><td>• Qualitative;
• Anecdotal;
• Descriptive observations.</td><td>• Qualitative
• Photographs and videos (visual data) accompanied by date, time and locational information.</td></tr>
<tr><td>Parameters monitored</td><td>• Rainfall;
• River levels (RLGB);
• x7 water quality parameters;
• Other weather (temperature, wind speed).</td><td>• Flood events & impacts;
• Early warnings;
• Weather experienced;
• NFM performance;
• Metadata describing other datasets submitted.</td><td>• River levels (RLGB);
• Flood events, low flows, snow and associated impacts;
• Extreme weather experienced;
• NFM performance during high flow.</td></tr>
<tr><td>Post processing required</td><td>• Useable catchment data was provided directly.</td><td>• Descriptions used to supplement and interpret other observations.</td><td>• End user must extract meaningful information before use (e.g. extract quantitative river level data from photographs).</td></tr>
<tr><td>Examples (river level)</td><td colspan="2">“We must have had a lot of rain overnight, the Burn was well up this morning, on level 3”

</td><td>
River level at Broomshaw: 0.5m Date & time automatically stamped into photograph (26/01/2016 12:11).</td></tr>
</table>

Table 4.9. Community-based data captured for each parameter and associated information.

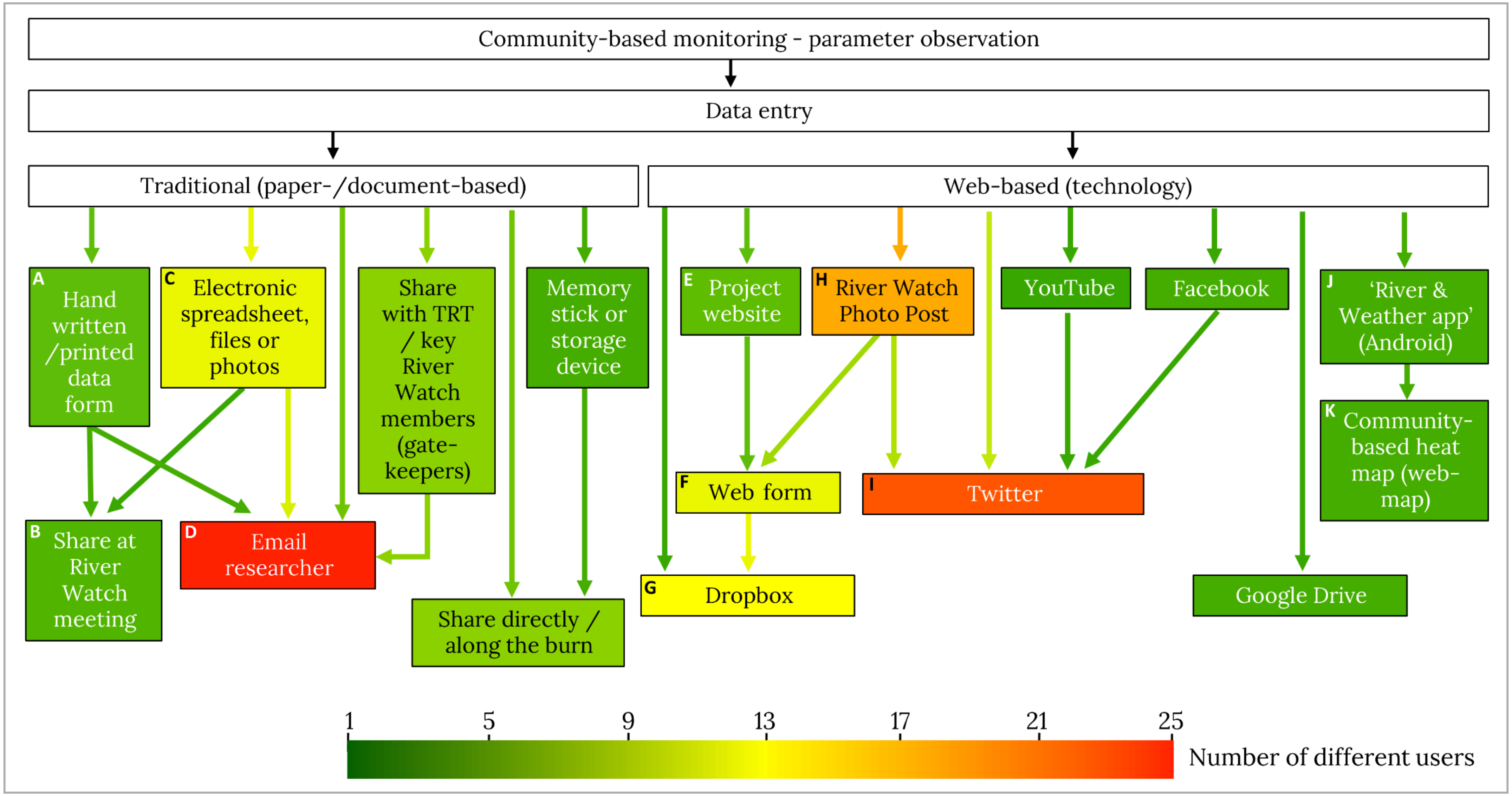


Figure 4.21. Community-based data entry and submission techniques used by the public over the monitoring period of interest – **all methods** (A-K were initially proposed in Figure 4.6). Colour scheme reflects the number of different users. Choice of data submission tools restricted or pre-determined data formats submitted.

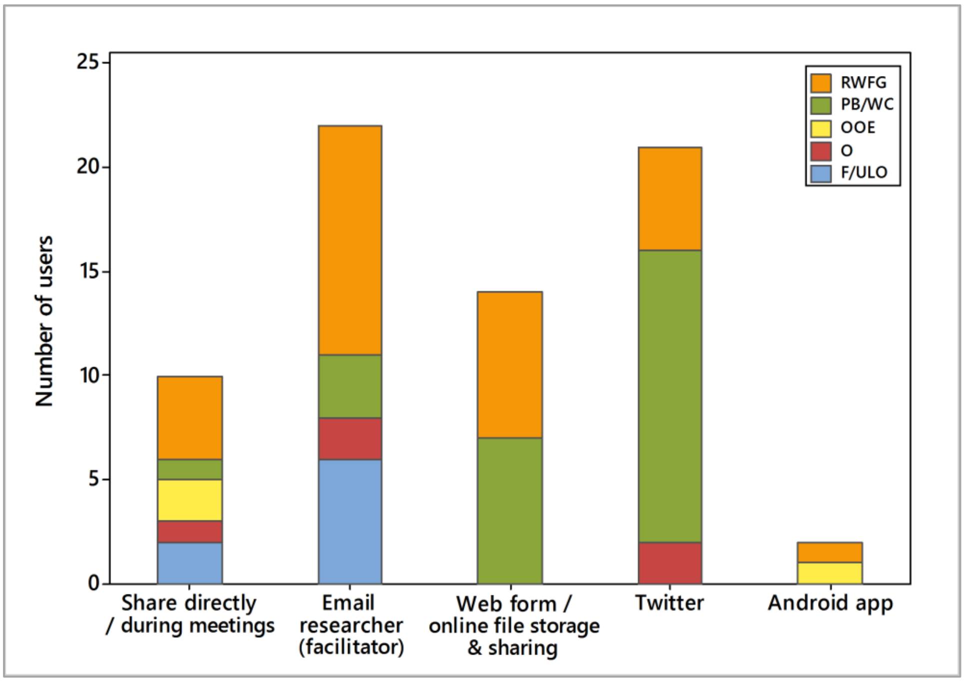


Figure 4.22. Community-based data entry and submission techniques used by the public – **broader categories**.

Results displayed in Figure 4.21 have been classified into five broader data submission categories within Figure 4.22. The need for direct contact with, and even feedback or reassurance from the facilitator is depicted by the high number of citizen scientists emailing data. Twitter has also proved to be a significant data submission and sharing tool within the Haltwhistle Burn community, primarily during extreme weather events. Alongside data submission, this free and universally available social media tool has provoked multiple applications, including the dissemination of early warnings, allowed key words or monitoring locations (hashtags '#') to be tracked, encouraged widespread community engagement, linked the public to the project website, and stimulated discussions in and around the Haltwhistle Burn community (Figure 4.23). On the other hand, the project-specific Android app was unfavourable, even for volunteers who received a free Android tablet. Valid reasons for underuse include the lack of internet coverage within the catchment, software compatibility, installation difficulties and technology failure (the app's server failed in 2015).

The heterogeneous range of data formats generated and data entry and submission methods employed meant that subsequent data sorting, anonymising, processing and analysing activities were complex compared with traditional monitoring programmes. Nevertheless, flexibility and choice were essential during this community-based monitoring scheme to avoid participation isolation, and to maximise data volumes. Results have also highlighted how different types of tools and the frequency of data submission dictate the ultimate value or practical application of the community-based observations, from early warnings and real-time flood risk information on Twitter, through to longer-term catchment characterisation and management activities using spreadsheets of data.

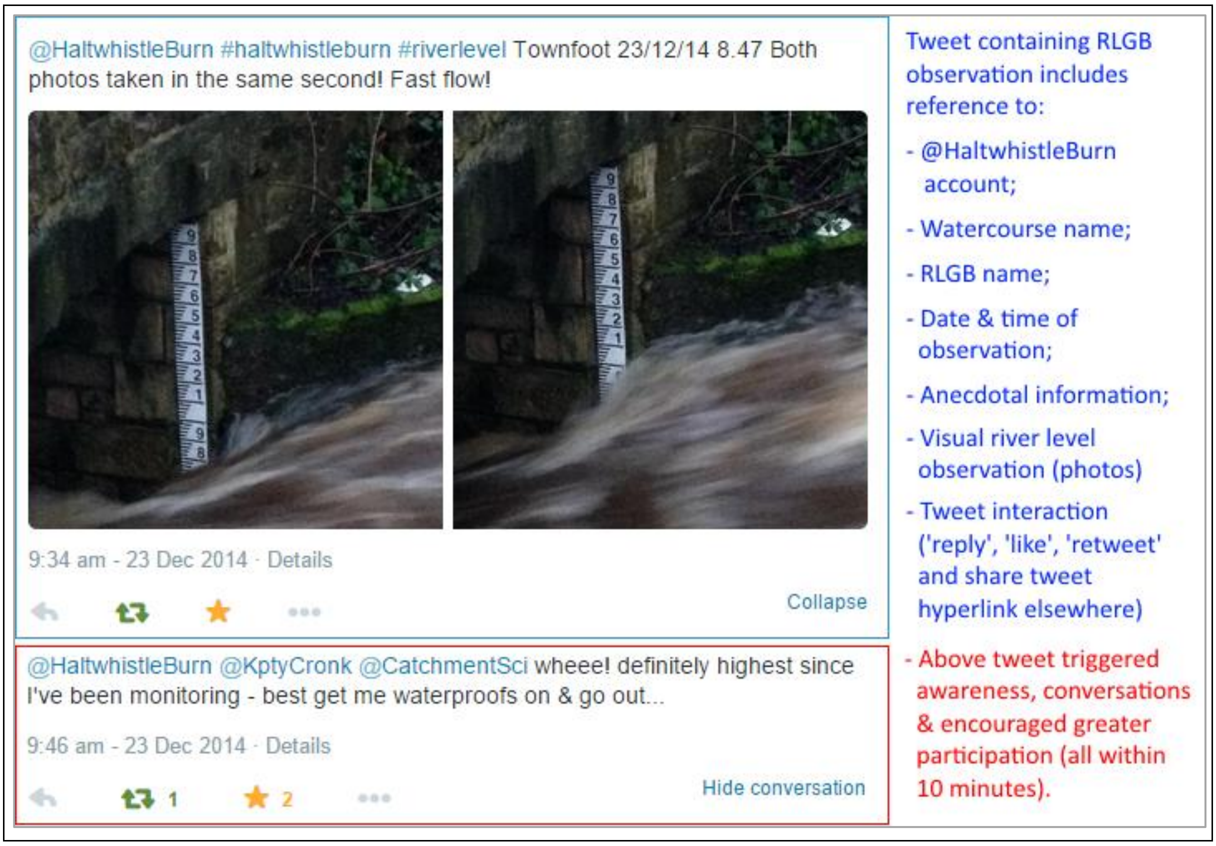


Figure 4.23. Example demonstrating how Twitter has provoked wider monitoring benefits and recognition, including *"Twitter really does seem like a useful tool for community endeavours like this eh. So immediate!"* (Member of the RWFG, 2014).

4.7.5. Spatial resolution: where did they monitor?

Citizen science schemes are increasingly being recognised as a source of environmental information across extensive spatial scales (Bonney *et al.* 2009; Tweddle *et al.*, 2012). Spatial coverage is one of the most attractive aspects of citizen science for catchment science too, as no two catchments are alike and professionals are unable to monitor ubiquitously. The spatial distribution of catchment observations have therefore been considered here for the Haltwhistle Burn catchment over the 29-month monitoring period. Figure 4.24 displays a set of catchment maps, illustrating the spatial distribution of all monitoring locations (maps i-ii) and the spread of each individual observation made (observation density maps iii-iv). Note that monitoring sites have been anonymised by removing detailed map backdrops. Table 4.10 presents results from a set of spatial analysis tests carried out using ArcGIS to illustrate the proximity of the community-based observations in relation to geographical features of interest.

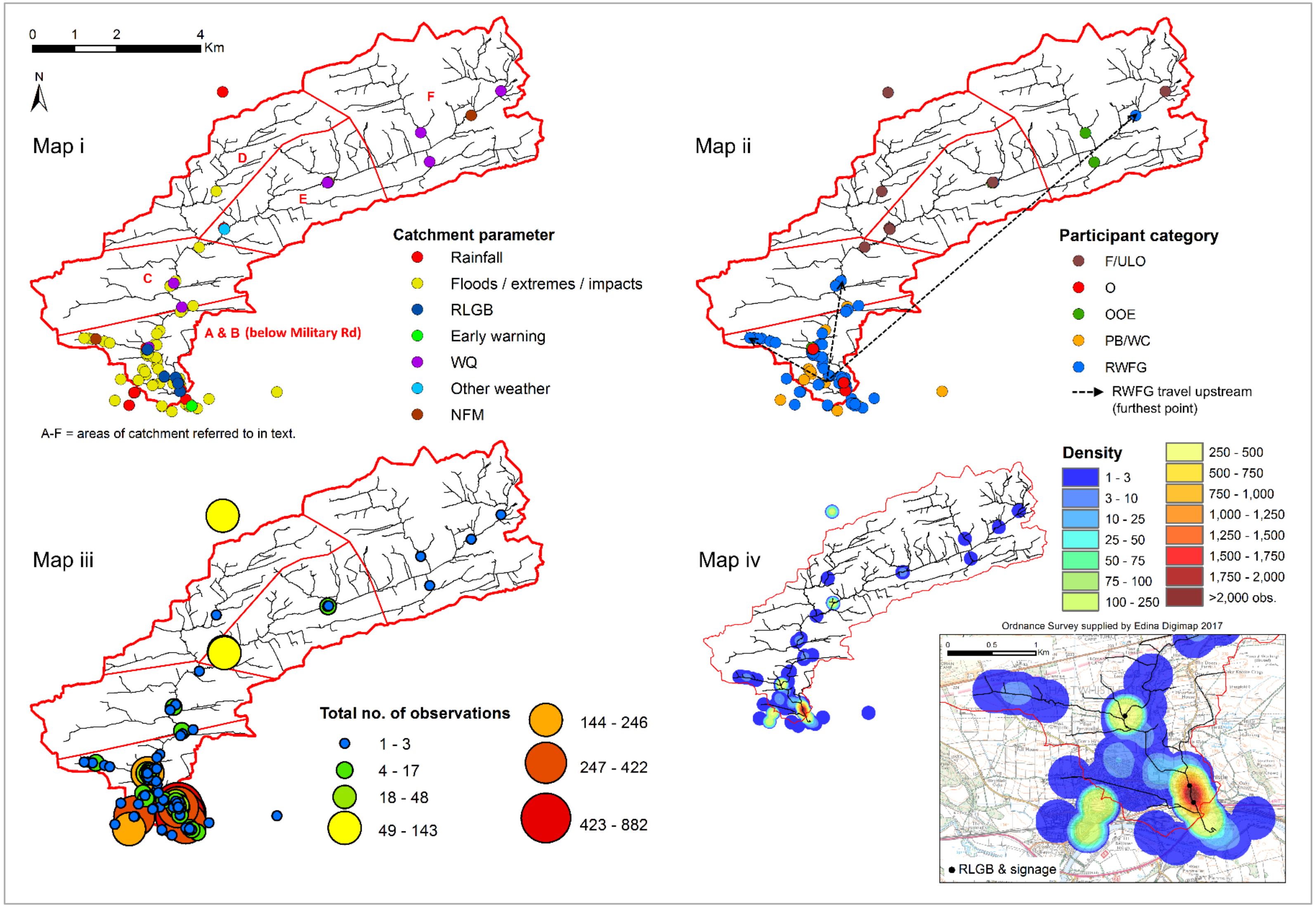


Figure 4.24. Spatial coverage of community-based observations in and around the Haltwhistle Burn catchment (Oct-2013 to Feb-2016). Maps i (parameter type) and ii (participant category) represent individual monitoring locations. Maps iii and iv illustrate total number of individual observations received.

	Intersects (%)	Proximity to / buffer distance (% of obs)				Description / boundary source
		5m	10m	50m	100m	
Areas A & B	73					Below / downstream of Military Road
Area C	0.3					Lower/middle catchment
Area D	0.02					Middle/upper catchment
Area E	4					Middle/upper catchment
Area F	0					Upper catchment
Catchment boundary	77					Within Haltwhistle Burn 42km² catchment
Town	63					Urban & sub-urban Land Cover Map 2007
RLGBs (x3)		42	43	70	71	RLGB at Broomshaw, Townfoot, Mill Bridge
Watercourse		56	59	87	90	All watercourses, includes loughs & South Tyne
Haltwhistle Burn		54	54	81	82	Haltwhistle Burn only (4.28km long)
Haltwhistle Burn tributaries		2	6	15	16	Haltwhistle Burn tributaries only (low order streams)
Buildings		18	22	73	85	OS Mastermap buildings
Roads		39	61	89	99	OS Mastermap roads (includes restricted/local roads)
Public footpaths		3	12	60	89	OS 1:25k marked public rights of way / other public access

Table 4.10. The intersection and proximity of community-based observations with geographical features of interest, in and around the catchment boundary (results presented as percentage (%) of the total number (4877) of observations collected). Tests have been carried out using the ArcGIS spatial analysis toolbox. Results are graded from yellow (low %) to red (high %).

Overall it can be noted that the Haltwhistle Burn community feasibly monitored a range of observations across the catchment. This in turn has connected the public to the wider catchment, rather than individual properties, gardens or nearby streets. It has already been highlighted that extreme (flood) events are favourably monitored, but they are generally clustered below the Military Road and within Areas A and B (areas delineated in Figure 4.24 and previously within Section 4.6). Water quality observations were positioned at fixed locations across the catchment, including Gibbs Hill and Greenlee Lough, as these comprise waterbodies failing to reach the EU WFD 'good' water quality status. A similar trend can also be noted for NFM monitoring, as they are dictated by the location of the NFM features from the onset. A number of observations were also made outside (but in close proximity to) the catchment boundary. This is generally as a result of surface water flooding incidents within the town itself following intense storms, as well as rain gauges located at volunteers' homes. 23% of the total observations were harvested outside the catchment boundary and are still valid because they add to the 'flood story', can potentially verify other community-based observations, and may be more applicable to use than those in other areas of the catchment (for instance, rain gauges at similar altitudes).

Although F/ULO were generally reluctant to take part in regular monitoring activities, they still provided useful one-off flood-related observations for a number of upstream locations. In many instances, upstream land owners provided alternative volunteers with permission to access and monitor their land, thus were still connected to the project and downstream community. Individuals from the RWFG did also make an effort to travel upstream (above the Military Road) at times to other parts of the catchment to monitor. Feedback from the community (Flood Group in particular) confirms that these deliberate monitoring trips were only prioritised when the town itself was not being affected by flooding. Nevertheless, results emphasise that it is possible for members of the community to monitor upstream, several kilometres away from their homes and provide their own transportation (or even walk).

Despite a broad range of monitoring locations across the catchment, it is clear that the total number of individual observations (includes repeat visits over time) generated specific monitoring hotspots (Figure 4.24, maps iii-iv). Spatial investigations confirm that 63% of the community-based observations were located within the catchment's urban and sub-urban land use areas. There is a strong spatial bias towards the town itself, therefore lower catchment, where participants (RWFG and PB/WC) generally live and walk. The Military Road acted as a prominent monitoring barrier, with 73% of the total observations being made solely within Areas

A and B, and as high as 96% being generated south of this transport corridor. This meant that only 4% of observations produced were within the middle and upper catchment regions. Only a small number of catchment observations were therefore obtained along first, second and third order upper-tributary streams, with 82% of the total number of individual observations being made within 100m of the Haltwhistle Burn itself. More detailed analyses relating to the proximity of relevant geographical features suggests that roads and public footpaths (therefore transport links) are essential for monitoring access. Unlike the Haltwhistle Burn itself, which has a dedicated footpath running in parallel, many upstream tributaries are isolated and located on private land.

A direct analysis concerning the RLGBs (Figure 4.24, map iv), which are located along the Haltwhistle Burn and within the urban areas of the catchment, confirms that these monitoring sites produced the highest density of observations. This suggests that the community were in favour of predefined monitoring locations, and that the RLGBs, accompanying signage and the proximity of the town had a major influence on the spatial distribution of catchment observations generated. When assessing the specific locations of the individual RGLB's and River Watch Photo Posts, it was clear that the Townfoot gauge board yielded a higher frequency of river level observations. Townfoot holds a prominent location within the town and is well connected by roads and public footpaths. However, the RLGB at Mill Bridge had a poor vantage point at the foot of a steep bank, on a culvert opening, and hence attracted a lower number of participants (*"I don't like that one very much"*, Member of RWFG).

4.7.6. Temporal resolution: when did they monitor?

As reported in Section 4.7.3, a total of 4877 observations were collected over the 29-month (882 day) period of interest in and around the Haltwhistle Burn catchment. This equated to 5.5 observations being generated on average per day, and 168 observations per month. However, these averages are not as straightforward in reality; the sporadic nature of volunteer-based data collection activities has meant that the temporal resolution of the catchment data varies significantly. As a result, the temporal resolution of community-based or citizen science data is known to be poor or biased when used alone, particularly in comparison to those generated using automatic hydrometric networks (Buytaert *et al.*, 2014; Roy *et al.*, 2012; Sene, 2016; Walker *et al.*, 2016). This then raises concerns over the quality, reliability and therefore value of community-based observations.

The temporal resolution of data collected within the Haltwhistle Burn catchment has been explored here, with focus on seasonal, monthly, weekly, daily and sub-daily data collection patterns. The 29-month period of interest offers a large window of data when assessing temporal coverage, which many citizen science projects struggle to accomplish (e.g. Breuer *et al.*, 2015). Out of the total quantity of observations collected and submitted by the public, over 98% (4801) of them contained date, time and locational information. This meant that nearly all of the observations received from the public were available for use during the forthcoming analyses and later applications. This monitoring programme can therefore be regarded as having an extremely low 'data discard' level, and hence a very high data availability rate. However, it is unknown whether any participants failed to submit and share their data to the project team, despite making an effort to make credible observations. Following an extensive citizen science review, West *et al.* (2016) found that there are a range of barriers to data submission, including participants forgetting or not having the time to submit, and some of these are likely to have occurred within the Haltwhistle Burn community.

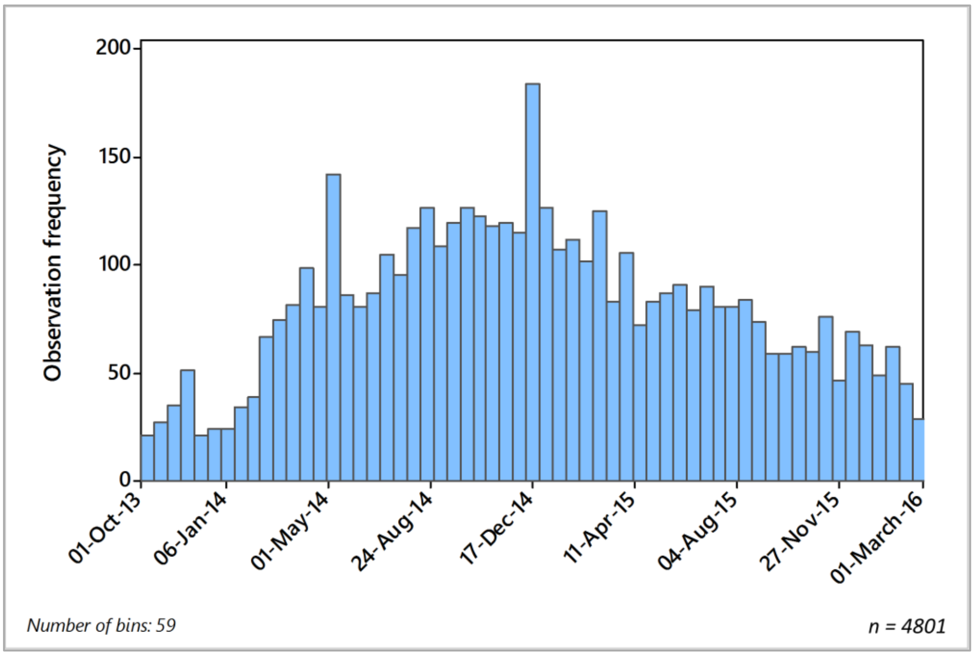


Figure 4.25. Histogram illustrating the frequency of community-based observations made over time, from 1st October 2013 to 29th February 2016.

The histogram presented in Figure 4.25 highlights how the frequency of observations has changed over the monitoring period of interest. Although affected by outliers, notably extreme events when multiple flood-related and low-flow observations were made, there was an initial growth in the number of observations collected, which then peaked mid-way through the monitoring project, followed by a gradual decline towards February 2016. Participation (therefore data collection) patterns for catchment science therefore echoed the same generic data collection concerns exhibited over time by other environmental citizen science projects (Science Communication Unit, 2013; Wentworth, 2014a; Geoghegan *et al.*, 2016). However, it can be noted that the rise in data collection is steeper than the decline phase. Chapter 7 explores the consequences of diminishing participation levels in relation to long-term catchment monitoring and management in more detail.

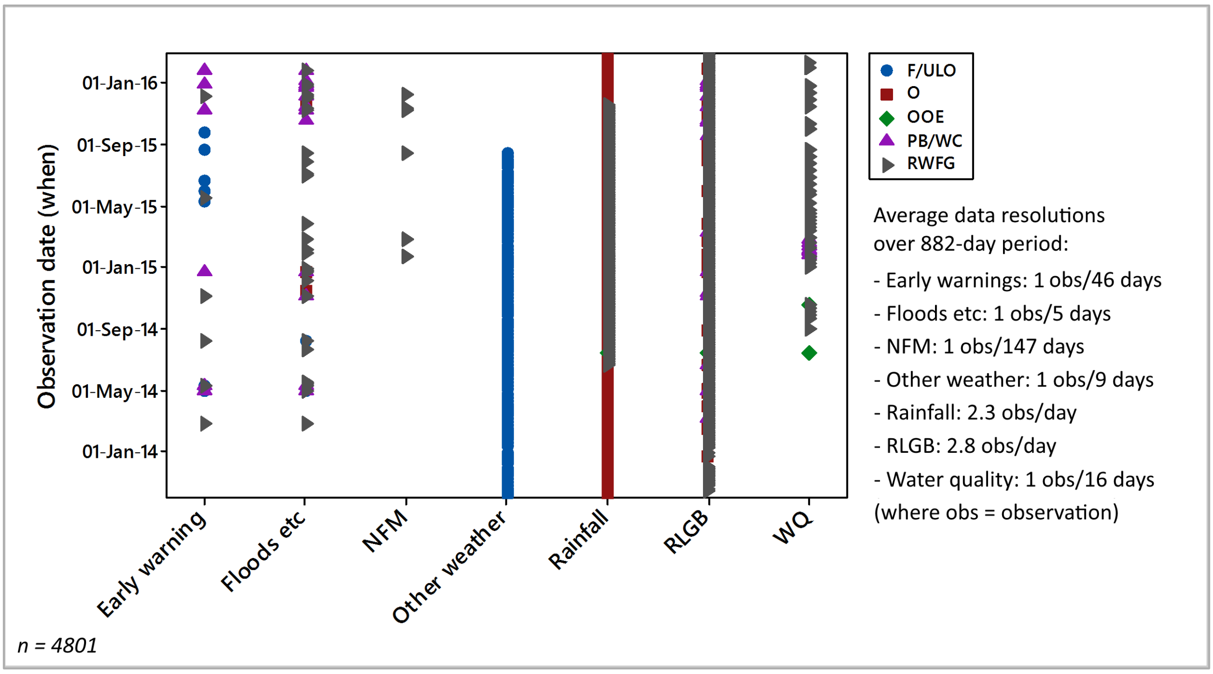


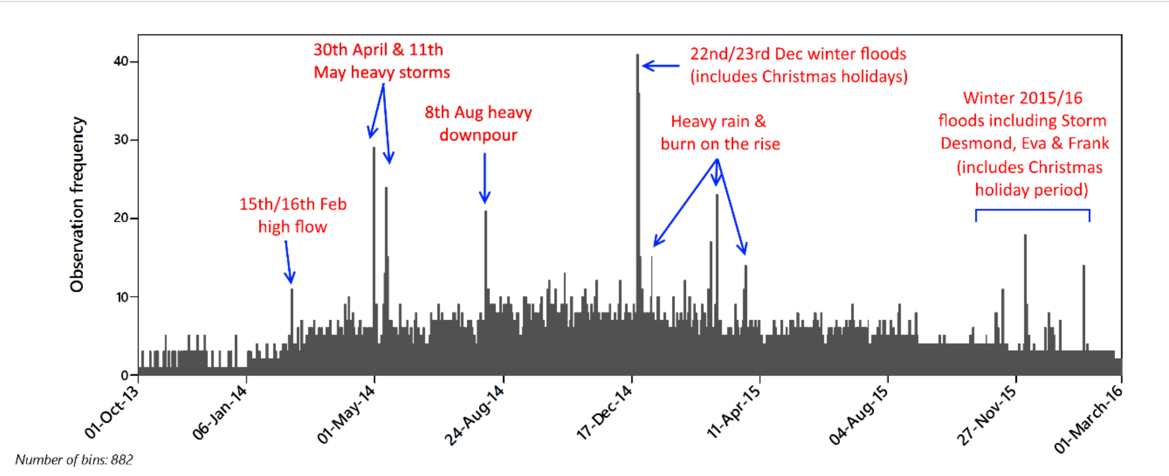
Figure 4.26. Total number of observations collected over time: grouped by parameter type (what) and volunteer (who) category. Average 882-day resolutions are listed for each parameter.

Whilst grouped by parameter type and the volunteer's role or position within the community, Figure 4.26 plots each individual observation made over the 29-month period of interest (who category). It is clear that the Haltwhistle Burn community were able to collect all types of observations over time (rather than in one go), and as already highlighted, the RWFG contributed the greatest. It is also apparent that early warnings, flood-related observations (extreme events and associated impacts) and NFM monitoring were sporadically observed over time, but were generally synchronised. Meteorological (rainfall and other weather) and RLGB observations have been observed on a more frequent basis (at least daily, with RLGB having an average resolution of 2.8 observations per day), thus are characterised by finer temporal resolutions. Catchment scientists would also expect to achieve these sporadic and regular datasets for the relevant parameters in question, however, it is yet to be determined whether the actual resolutions acquired here (see 882-day averages listed within Figure 4.26) were sufficient to characterise the catchment's local behaviour (see Chapter 5). Water quality observations were also produced over time, but at a coarser resolution (generally monthly or bimonthly, with gaps). Despite being encouraged to monitor on a weekly basis, one volunteer implementing the water quality test kits said that *"As nothing is changing much they are at two week intervals which fits in with [our] trips away"*. Other volunteers provided similar feedback (e.g. *"I must say, the results hardly seem to change, apart from, obviously, temperature & clarity"* and *"Just repetitive and not really showing much variation… a tad boring!"*), which detracted them from observing on a more frequent basis as they didn't feel as though they needed to. Rapid and visual changes across the catchment appear to fuel temporal monitoring efforts, especially flood events.

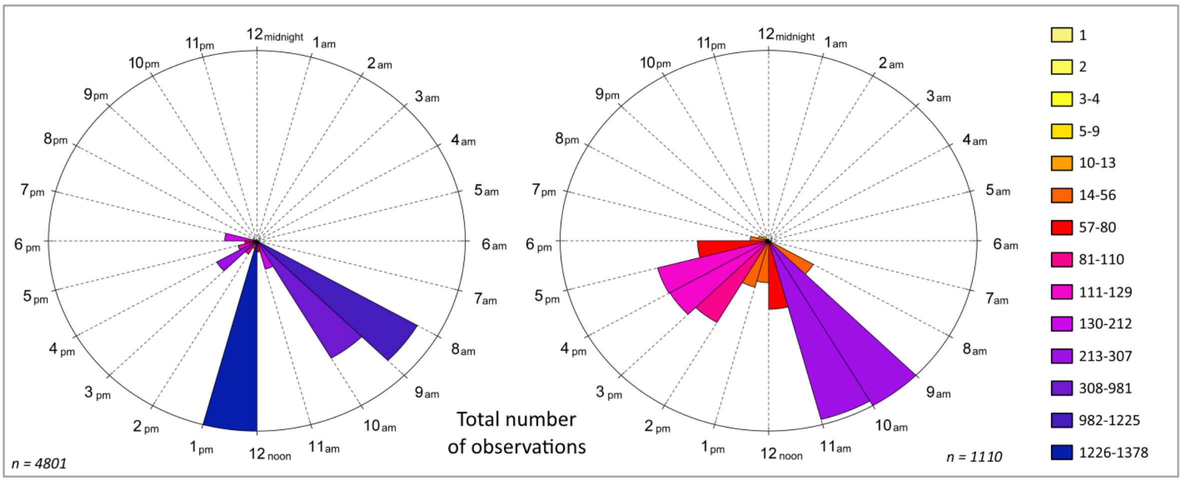
Tables 4.11A and 4.11B present findings relating to seasonal, monthly, weekly, daily and sub-daily community-based monitoring capabilities over the period of interest. Although longer data samples are required to fully investigate seasonal trends (Graph A), there appeared to be very little difference in the total number of winter and summer observations collected during the two-year period analysed. However, a slightly higher number of observations were collected during spring and summer. There are no clear trends arising from monthly observation totals (Graph B) as they are likely to be affected by the occurrence of flood events, which implies that the time of year (therefore weather and temperatures experienced whilst outdoor monitoring) did not hinder the publics monitoring capabilities. Weekly trends (Graphs C-D) do not advocate that monitoring efforts were restricted to either weekdays or weekends, particularly when 'regular' rainfall and river level observations are included within the analysis. When these regular observations are excluded (Graph D), there are still no clear data collection patterns, although Saturdays appeared to be more successful than Thursdays and Fridays.

Table 4.11A. Temporal coverage of community-based observations collected over the 29-month period of interest. Graphs illustrate (A) seasonal, (B) monthly and (C-D) weekly monitoring capabilities.

E) Daily (all observations and parameters plotted, with flood events and dates of interest annotated)



F) Hourly / sub-daily trends (left figure includes all 'regular' observers, right excludes them)



G) Hours of daylight (data sourced from UK HM Nautical Almanac Office for Haltwhistle postcode)

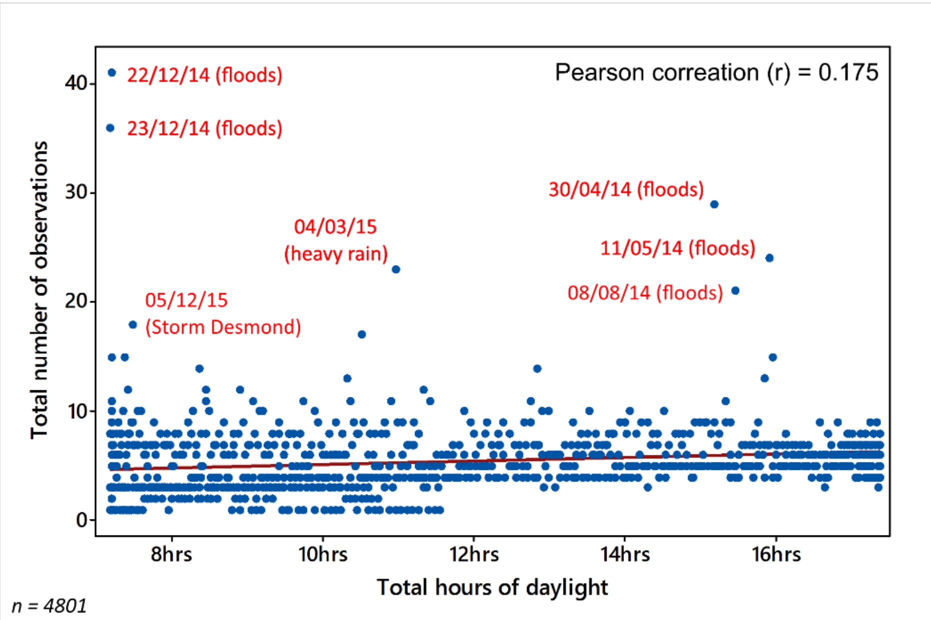


Table 4.11B. Temporal coverage of community-based observations collected over the 29-month period of interest. Graphs illustrate daily and hourly monitoring capabilities (E-F), and daily trends associated with total daylight hours experienced (G).

Once grouped into daily time steps (Table 4.11B), the rise, peak and fall in monitoring efforts over time is noticeable again. As annotations in Graphs E and G highlight, daily observation totals (therefore data resolutions) were significantly biased towards the occurrence of extreme hydrological events (heavy or prolonged rainfall and catchment flooding) within the Haltwhistle Burn community, a trend which even includes Christmas day. A set of clock charts (Graph F) have been used to illustrate how monitoring efforts were (as expected) largely restricted to mornings, afternoons and early evenings, with observations being completely absent between 11.30pm and 7am (7 ½ hour period) (*"#riverlevel Townfoot 8/6/14 9.43am Did I miss a deluge during the night?!"*). Prevailing monitoring times were 9-11am and 12noon-1pm in line with regular rainfall and river level observations. Once these regular observations were excluded from the analysis, monitoring activities still continued throughout the day, often in line with dog walking duties (Figure 4.27). Participants also commented that dark nights in winter restricted their observation window throughout the monitoring programme. Graph G illustrates how it is possible that the total number of observations collected in any one day are loosely correlated with the total daylight hours experienced on the ground. However, these trends were again overridden by the occurrence of extreme events. Evidence suggests that some monitoring activities were feasible in the dark though (Figure 4.27), including *"I got a torch for Christmas so that I can see the gauge board in the dark"* (member of RWFG, December 2014).

Based on the aforementioned findings, it is clear that the temporal resolutions of community-based data were influenced meteorologically (such as day-to-day variability in weather patterns and extreme events), as well as habitual factors affecting the practicality and availability of the volunteers themselves. This means that the temporal availability of observations has been significantly restricted by the number of daylight hours and the occurrence of hydrologically important events, rather than specific seasons, months, or days of the week. When considered in isolation, the community-based observations described here do not offer the same temporal resolutions captured by traditional hydrometric networks. Nevertheless, the snapshots of data acquired are important to this particular focus community and would not normally be available for a small rural catchment such as the Haltwhistle Burn.

RLGB at Broomshaw	Haltwhistle Burn flood-related observation
	

Figure 4.27. Examples where participants monitored in the dark or whilst walking their dog.

4.7.7. Additional findings affecting feasibility

Additional findings arose during the project whilst working directly with the public, which support the feasibility of a community-based monitoring approach. Whilst largely captured in the form of anecdotal (qualitative) information, these opportunistic findings are considered as valuable research outcomes, as summarised below:

- Regular volunteers started to purchase monitoring equipment using personal funds. For instance, one RWFG member bought a waterproof case for their smartphone so that they could continue to observe the Haltwhistle Burn during poor weather conditions (*"@HaltwhistleBurn #haltwhistleburn #riverlevel Townfoot 1/3/14 11.26am using my new waterproof case! "Looking forward to taking some rainy day photos"*). This level of effort suggests that the citizen science approach triggered enthusiasm amongst participants, and that partakers recognised the importance of capturing high flow and flood-related evidence, despite the rain;
- Many volunteers initially monitored river levels, rainfall or captured flood-related information, which are all related to water quantity. Once actively monitoring, interests

then expanded into other areas of catchment science, including water quality (*"I wouldn't mind trying out other types of monitoring"*);

- Regular RWFG volunteers began to appreciate the importance of complete datasets as they arranged 'monitoring cover' whilst they went away on holiday (*"[they] offered to do the readings at Townfoot at times when I can't, so that's good"*). However, lengthy holidays also affected the completeness, therefore temporal resolution, of ongoing datasets at times, particularly rainfall;

- Volunteers made additional observations during times of rapid change (i.e. during and after heavy rainfall). This emphasises that participants made an effort to better-capture these hydrological incidents (as desired by professionals, but is not always feasible) and subsequently realise the importance of doing this (Figure 4.28);

- Regular volunteers raised their concerns over situations affecting the quality of their catchment observations, including unclean RLGBs (Figure 4.28). Chapter 5 discusses data quality further;

- Due to restricted timescales, it was not possible to trial additional citizen science monitoring techniques relevant to hydrometeorology. For instance, float gauging (US EPA, 1997) would have been desirable for obtaining river discharge estimates. Health and safety also restricted the feasibility of some community-based monitoring activities, including float gauging during dangerous flows;

- There were a few occasions when the River Watch Photo Posts were vandalised, stolen or washed away by high flows. This temporarily interfered with passers-by interacting with the project. Careful considerations are therefore required during the design phase to rectify or minimise such impacts, including provisions for maintenance funds. Nevertheless, participants involved in the programme showed that they were proactively capable of reporting such issues, and thus can also safeguard equipment (*"the photo post went in the floods. It will be in the North Sea by now"* RWFG, December 2015);

- Although members of this particular RWFG were close-knit and did not restrain sharing their whereabouts, photographs or data with one another, ethical concerns were raised by some participants given that the project itself was shared online with the wider public. For instance, one observer said that they wanted to participate, but did not want *"a dot on the map showing that the data comes from my property, showing people where my* *instrument is kept*". Another participant queried whether they needed an alternative Twitter account setting up to keep personal interests and monitoring results separate. There are also risks associated with sharing exact monitoring locations (therefore real-time whereabouts) in the public domain.

Rain started at about 3.30pm on 08/08/2014	
River levels at Townfoot:	
08/08/2014 16:30	0.03m
08/08/2014 17:15	0.05m
08/08/2014 19:00	0.06m
08/08/2014 21:15	0.18m (max level)
09/08/2014 09:00	0.17m
09/08/2014 15:00	0.08m

@HaltwhistleBurn #haltwhistleburn #riverlevel Broomshaw 10/5/14 5.37pm - 38 mins later, gone up quick twitpic.com/e3guuy

"The board at the culvert is covered in black slime" Member of RWFG.

Figure 4.28. Examples where participants (left) made additional observations during high flows, (right) highlighted the provision for equipment maintenance to ensure trustworthy data.

4.8. Examples of ongoing feedback

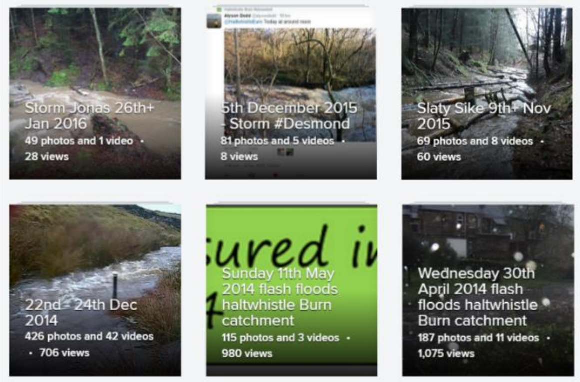
Unlike traditional studies which generally delay sharing any monitoring results or findings until formally published within peer-reviewed scientific publications, it is widely known that citizen scientists require ongoing and rapid feedback (Roy *et al.*, 2012; Tweddle *et al.*, 2012; Pocock *et al.*, 2014a; 2014b). Rapid feedback is often regarded as a challenging activity which may require additional IT infrastructure (Bonney *et al.*, 2009), whilst Silvertown (2009) and Tweddle *et al.* (2012) draw attention to it being an important reward, providing volunteers with a sense of achievement. Such activities are also pursued to reduce monitoring fatigue and avoid comments such as *"they take it [the data] from us and we never see any actions as a result of it"* (RWFG commenting on their experience with professional catchment stakeholders).

Feedback was provided to the Haltwhistle Burn community throughout the live phase of the monitoring programme, primarily to maintain motivation and participation levels, but also to engage with the wider community. Ongoing feedback did not involve disseminating final project results; a quicker method was necessary to keep the momentum going with the public, avoid clashes with the research projects timescales, and ensure that they were benefitting from the monitoring activities too. Snippets of community-based data were therefore used to emphasise the spatial and temporal variability across the Haltwhistle Burn catchment, with focus on the community's interests, including rainfall, river levels, flood events and catchment characterisation. Feedback has allowed participants to view and discuss community-based data collected, broaden their knowledge on catchment-wide response, gain a sense of ownership, maintain a two-way dialogue, and subsequently close the citizen science loop by being more than just data providers.

Table 4.12 provides examples of different feedback mechanisms employed during the live phase of the Haltwhistle Burn community-based monitoring programme (both periodic and instantaneous). Similar to the engagement process (Section 4.4), a range of methods were used in order to cater for different groups of people within the community. Simple and meaningful visualisations and use of lay language were vital. Alongside face-to-face meetings with the RWFG, which allowed direct interaction and discussions to unfold about the data, the use of technology and various online communication tools meant that feedback was also instantaneous and reached a wider audience (including those who did not monitor). Digital methods also permitted interaction levels to be monitored, such as the number of times a photograph had been viewed. Being immersed within the community as a researcher also made it easier to provide continuous feedback and be in regular contact with key volunteers. Similar to the data submission trends, it was evident that the regular volunteers preferred to receive feedback and be in regular contact with the facilitator themselves over time. Others preferred to catch up on feedback material in their own time, and appreciated being able to do this (for instance *"I had a look, very interesting! Think I'm starting to understand the bigger picture"*). Publications and media coverage also provided a useful way of disseminating project impact back to the community, for instance, the booklet written by Starkey and Parkin (2015), which TRT and some members of the community purchased (*"can we buy hard copies of the booklet? We would like to put them in the Haltwhistle library"*).

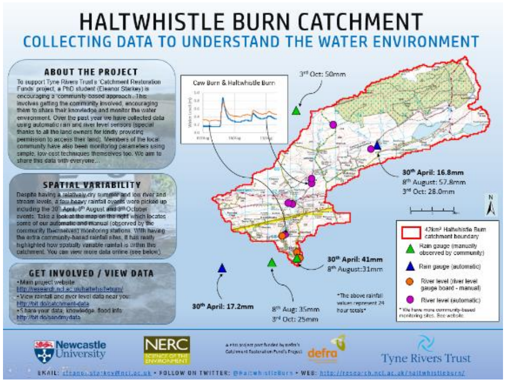
From a researchers' prospective, it was challenging to keep up with the demands and timescales of the community, which is common in Community-based PAR (Hacker, 2013). For instance, it was desirable to distribute monthly or quarterly newsletters to participants over time, but this never materialised. It also left the research project exposed given that methodologies, data and extracts of results were posted online, hence it has not followed the traditional research process.

Haltwhistle Burn Flickr photo albums
(e.g. individual flood event timelines)



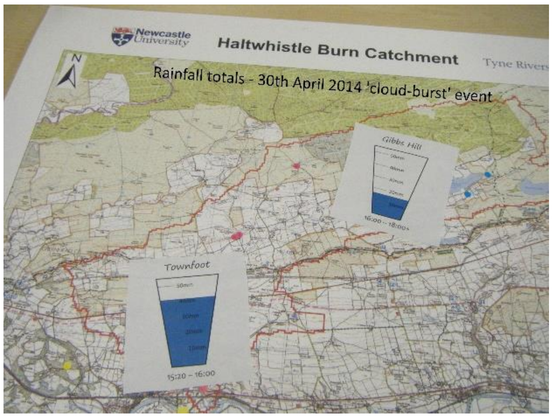
https://www.flickr.com/photos/114248420@N03/albums

Leaflets posted/distributed to engaged upstream farmers and land owners

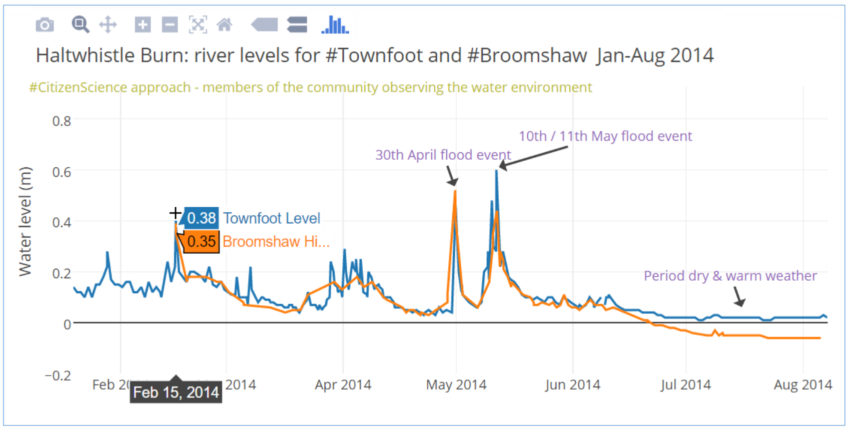


Twitter (real-time, same day or periodic)

RWFG meetings/workshops (e.g. leaflets, slideshows, visualisations and discussions)



Website (e.g. host news items, observations, interactive graphs, community-based heat map, links to Flickr data and Twitter timelines).



http://research.ncl.ac.uk/haltwhistleburn/newsevents/

Table 4.12. Examples of instant and periodic feedback mechanisms adopted.

4.9. Chapter discussion and summary

4.9.1. Discussion – feasibility of citizen science

Designing, implementing and facilitating a relevant citizen science monitoring scheme, with the support of simple training, data collection and data submission tools, has enabled a detailed assessment into the feasibility of community-based monitoring for catchment science. The Haltwhistle Burn catchment and focus community have been used to achieve this as it represents a typical rural UK catchment suffering from multiple pressures. Examples presented within this chapter illustrate how a community-based monitoring approach is feasible for a range of parameters within catchment science, evidence of which is largely absent within the literature. Other studies that have proved feasible generally relate to less developed locations, and thus the drivers, tools and participants involved are dissimilar (e.g. Gomani *et al.*, 2010; Buytaert *et al.*, 2014). The level of detail attained here has only been possible by working alongside the community as a researcher and facilitator to obtain a combination of quantitative and qualitative findings. It is clear that this proposed monitoring approach (including the design phase) differs from traditional, well-established and formal meteorological and hydrometric monitoring networks in several ways. The ultimate (yet obvious) disparity is that a community-based approach involves local people collecting simple observations about the weather and water environment. Feasibility is however distorted by current perceptions and expectations arising from traditional monitoring networks. This has naturally triggered various data quality and compatibility concerns as a result.

The 'total number of observations collected' has proved to be a useful proxy for feasibility by highlighting who participated, motivations, what was monitored and which tools were favourable. Additional qualitative findings have also taken participants' feedback and wider considerations into account. Although the majority of catchment observations were made by a small number of regular RWFG volunteers, the wider community were also required to fill these gaps and increase spatial resolutions during hydrologically important events. This is also important given that volunteers have their own individual monitoring preferences and capabilities. Regular and one-off (or 'event-based') observers delivered different types of data, creating a stronger patchwork of catchment information when combined. As Figure 4.29 summarises, it is clear that the type of parameter observed also affected the overall physical monitoring efforts required, and in turn the spatial and temporal availability of catchment observations. For instance, less readily observed parameters provided snapshots of data, whereas flood observations were event-based. River levels (via the RLGB) proved to be the most beneficial citizen science parameter here as it generated the greatest quantity of observations and involved the maximum number of people. Figure 4.29 offers a relatable diagram during the citizen science design phase when trying to streamline monitoring efforts and available resources.

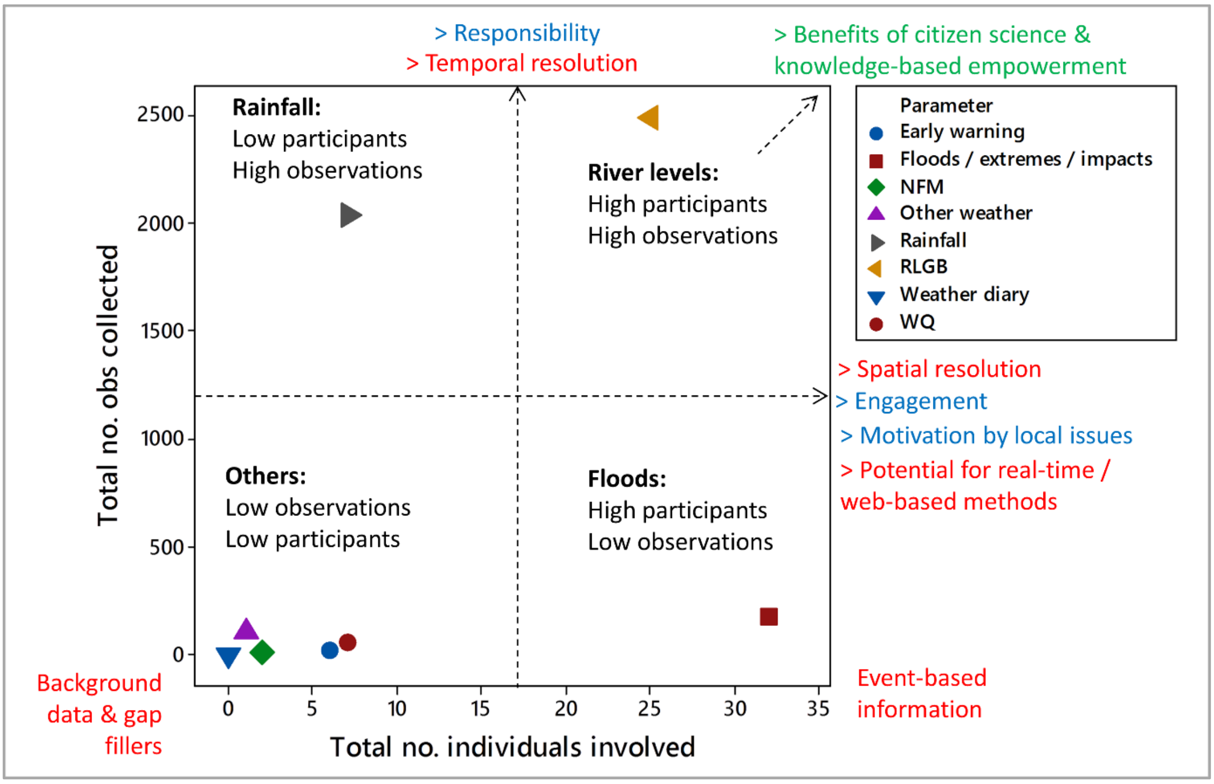


Figure 4.29. A community-based monitoring matrix summarising the relationship between the total number of observations collected with parameter type, data resolutions, overall monitoring efforts, and therefore summarises benefits to the citizen scientists and end data users.

Findings suggest that community-based data collection activities can significantly increase the spatial resolution of data in catchment science, notably during and immediately after heavy or prolonged rainfall events. For catchments similar to the Haltwhistle Burn, these observations would otherwise be absent, and key flood events would largely go unrecorded. However, volunteer-based monitoring is unpredictable, although results presented within Section 4.7.5 suggest that monitoring hotspots (such as RLGBs and River Watch Photo Posts located along prominent public footpaths) can be used to encourage data collection at predefined locations. Spatial analyses involving geographical features of interest can be used to model and locate these catchment-specific hotspots beforehand. Remote sensing (e.g. rainfall radar) offers an alternative to traditional ground-based gauges, providing data across large spatial scales. However, it is widely acknowledged that remote sensing is expensive and contains various sources of error as it is categorised as a non-contact monitoring method (Harrison *et al.*, 2000), the latter of which significantly contrasts citizen science, which offers a direct and hands-on monitoring experience.

Whilst relying on unpaid volunteers and manual data collection methods similar to those trialled within this study, it is also inevitable that this community-based approach will never match the high temporal resolutions exhibited by traditional automatic sensors. However, automatic sensors do not exist in every catchment or watercourse, hence the need for alternative local information. Some citizen science projects have already employed automatic sensors (particularly those branded as low-cost alternatives including Hut *et al.* (2014) and Castell *et al.* (2015)), but there are trade-offs associated with these methods as they considerably reduce the physical connection between the catchment itself and the data that participants are collecting. Sensors are also less likely to continue long-term as they will need maintaining, upgrading or replacing, unlike the ‘human sensor’. Demographics of the focus community will also dictate which route is more appropriate, although inexpensive sensors may be more suitable for busy farmers and upstream landowners in remote locations.

There are concerns that there are spatial, temporal and parameter bias as a result of community-based monitoring. Monitoring in daylight hours and along key watercourses in close proximity to urban areas will always be a priority for local communities. However, it can be argued that such outputs are not intending to replace or fully replicate traditional protocols, and that monitoring locations, times of day and parameters of interest are those which really matter to the public on a local level. This chapter has shown that it is feasible to monitor a range of catchment parameters using simple citizen science protocols (e.g. water quality) and in more remote locations upstream, but they have not been seen as a priority for the Haltwhistle Burn community. It is therefore apparent that perhaps the feasibility of community-based monitoring is governed by the purpose of the scheme and whether the data are fit for purpose. Regardless, the Haltwhistle Burn community focussed their monitoring efforts on flood risk management by empowering themselves with actionable local knowledge. These social benefits inspire ownership on a local level, which supports, for example, the CaBA and NFM success (Nesshöver *et al.*, 2017).

Heterogenic formats complicate the data collection process, as does the generation of videos and photographs which were readily produced by participants during this case study. The recent growth in digital camera ownership has created a surge in this new type of data, including unmanned aerial vehicles (UAVs). This has triggered an increase in hydrology-related image, video and structure-from-motion (photogrammetry) analysis techniques, making it simpler to extract quantifiable and meaningful information automatically (Perks *et al.*, 2016; James *et al.*, 2017; Tauro and Grimaldi, 2017). A single image or video collected by the community could therefore be used to extract multiple catchment parameters (e.g. river level, velocity, discharge and water quality), and reduce data compatibility issues associated with catchment applications. Such multimedia are also visually meaningful and contain transferable and relatable information suitable for the wider community ('a picture is worth a thousand words' as Xiao *et al.*, (2011) underlined). A similar outcome was also achieved by participants during this study using Twitter in real-time. User Generated Content and 'social sensors' have also been praised by McDougall (2011), Fohringer *et al.* (2015) and Tkachenko *et al.* (2017). Nevertheless, technological barriers evident within the Haltwhistle Burn community should still be respected.

It cannot be overlooked that the Haltwhistle Burn citizen science scheme required significant amounts of engagement, facilitation and resources in order to guide and fund the monitoring activities trialled. However, findings suggest that some enthusiastic volunteers are not just data collectors; many regular participants also proved to be gatekeepers, facilitators and collaborators themselves, which should to be explored further (see Chapter 7).

4.9.2. Summary – feasibility of citizen science

Chapter 4 has presented a novel community-based (citizen science) monitoring scheme that was designed, implemented and facilitated within the Haltwhistle Burn catchment and focus community (**Objectives 1A-1C**). Using a PAR approach to gather numerous quantitative and qualitative findings, it is clear that members of the community can (and want to) feasibly monitor their local catchment using a simple citizen science approach. In light of this monitoring programme, the following conclusions apply:

- Community-based monitoring for catchment science is feasible; this example has produced snapshots of heterogeneous data in a range of formats, and for a variety of parameters over the 29-month period of interest. The majority of observations were collected by a small number of regular volunteers (almost three quarters of the total observations submitted were generated by four participants). However, monitoring efforts are unpredictable and sporadic;
- Rainfall, river levels and flood-related observations were favoured by volunteers, and are directly linked to issues affecting the community on the ground. Web-based tools allow these observations to be shared in real-time with the wider community. However, spatial

and temporal monitoring efforts are biased towards individual capabilities and interests, hence they cannot replicate or replace traditional monitoring schemes;

- 'One size' does not fit all citizen scientists – participants have their own motivations, preferences and skills. The design phase is therefore crucial;
- Despite being regarded as simple and low-cost, community-based monitoring schemes are not free and they require well-connected gatekeepers and strong leadership in order to drive the scheme forward and maintain participation levels. Nevertheless, enthusiastic participants have the potential to be facilitators themselves.

The feasibility of the community-based monitoring scheme has been catchment- and community-specific, and participation levels have been affected by the occurrence and timing of the weather patterns experienced. It is also likely that some participants were reluctant to share flood-related information which entails their own property or business. However, this case study provides an insight into what is possible, and in doing so, it has raised questions relating to reliability (data quality – Chapter 5), usability (value – Chapter 6), as well as long-term sustainability of such schemes (Chapter 7). Volunteers must also be reassured that their monitoring efforts are worthwhile, and hence the data have been used to support real applications within Chapter 6.

Chapter 5. Evaluating the quality and reliability of community-based observations

"Looks like the stake holding the monitors may have been washed away and left the cable just trailing in the flow. I'll see if I can retrieve it safely."
(Member of RWFG, December 2014 during the winter high flows).

'There is a perception that the quality of research carried out by citizens does not match that of research carried out by scientists' (Science Communication Unit, 2013).

'As a discipline, hydrology and climatology have followed the "rules" of good science' (World Meteorological Organization (WMO), 2008)

Figure 5 (intro). *A comparison between traditional and community-based monitoring methods within this chapter emphasises that data quality is just one of many factors to consider.*

5.1. Chapter introduction

Findings presented within Chapter 4 demonstrated that community-based (citizen science) observations were feasibly collected within the Haltwhistle Burn catchment for a range of parameters. It was also acknowledged that community-based observations are dissimilar to those collected using traditional procedures; citizen scientists generated sporadic and heterogeneous datasets using simple monitoring equipment. Spatial and temporal biases were also induced given that unpaid volunteers were being relied upon to collect catchment observations manually, which then raised data quality (DQ) and reliability concerns. DQ is also frequently questioned in the citizen science literature as it is one of the main barriers to widespread uptake and data use (Tweddle *et al.*, 2012; Hunter *et al.*, 2013; Science Communication Unit, 2013; Buytaert *et al.*, 2014; Pocock *et al.*, 2014a; 2014b; Riesch and Potter, 2014; Cooper, 2016; Leibovici *et al.*, 2017). However, Roy *et al.* (2012) point out that DQ issues are not restricted to citizen science as hydrological monitoring methods are also vulnerable if they are not carefully managed by experts (Bren, 2015; Younos and Heyer, 2015; WMO, 2017). Quality assurance (QA) and quality control (QC) procedures can however be used to minimise error and bias, and provide data users with confidence (Bonter and Cooper, 2012; Tweddle *et al.*, 2012; Hunter *et al.*, 2013).

This chapter evaluates the reliability and quality of community-based monitoring for catchment science (**Objectives 2A-2C**), using observations introduced in Chapter 4. The following areas have been used to demonstrate this by:

- Comparing them against other community-based observations (QC checks);
- Comparing them against traditional (benchmark) datasets;
- Presenting case studies from the Haltwhistle Burn which infer reliability and quality;
- Using them to characterise the catchment as this also infers reliability and quality.

A traditional hydrometric monitoring network was therefore designed, installed and maintained in parallel to the community-based approach for the duration of the monitoring programme to achieve this. Traditional gauges provided scientifically robust datasets suitable for comparisons with community-based methods where possible. The same traditionally-derived datasets have also been used to demonstrate the value of community-based observations within Chapter 6.

Due to the high volume of data collected during this project, it has not been possible to assess all aspects of every dataset. However, DQ and reliability have been assessed statistically in places (where traditional and community-based datasets overlap), alongside knowledge from case-specific experiences. Other factors, such as costs involved, have also been considered.

5.2. Overview of the data quality (DQ) literature

Good quality data is of high importance and is a prerequisite across all scientific disciplines. As Figure 5.1A illustrates, catchment-related observations are inherent to random and systematic errors. Unlike laboratory experiments, which are carried out under controlled conditions, fieldwork is embedded within a complex, open and therefore interacting environment. The monitoring process also consists of a number of stages, including network design, installation and maintenance, followed by data downloading, archiving, processing, validation and analysis (Shaw *et al.*, 2011; Bren, 2015; Younos and Heyer, 2015; Sene, 2016). Consequently, the monitoring process is exposed to numerous sources of bias[19] and error[20], including spatial, temporal, observer and instrumental, which can in turn disturb the overall accuracy[21] and precision[22] of the environmental variable, as Figure 5.1B exemplifies (WMO, 2008; 2011; 2017). Although individual observations may contain negligible error, these can rapidly accumulate over time and through space, causing implications for end users (Environment Agency, 2004). It is also widely acknowledged that the 'true' value is never exactly known as all measurements are accompanied by a degree of uncertainty[23].

QA and QC procedures are routinely and systematically integrated into the traditional catchment measurement process to ensure robust datasets are available for use (WMO, 2011). Guidelines and manuals for such assessments are well-established for hydrological, meteorological and climatological monitoring networks (Gordon *et al.*, 2004; WMO, 2008; 2011; O'Donnell, 2012; WMO, 2017). Given that monitoring occurs worldwide, sources of bias and error are generally anticipated, and hence methods are advocated for prevention (QA) and correction (QC). A range of validation checks are typically encouraged, for instance, searching for incorrect formats (format tests), gaps in time series (completeness tests), unnatural trends (consistency checks) and unlikely or impossible measurements (tolerance tests). While the aforementioned QC checks have been specifically highlighted and categorised by the WMO (2011), the same principles are

[19] *Bias:* results from an unrepresentative or distorted sample of the total population, often arising from observer preferences.
[20] *Error*: a residual describing the difference between the measured and the true value.
[21] *Accuracy:* how well or close the measured sample represents the true value.
[22] *Precision:* the similarity between measurements observed multiple times.
[23] *Uncertainty*: a specified range within which the true value lies.
(Source: WMO, 2008).

published and adopted extensively by others (e.g. Hudson *et al.*, 1999; Gordon *et al.*, 2004; Shaw *et al.*, 2011; Blenkinsop *et al.*, 2017). Guidance is also available for specific catchment parameters. For instance, Gordon *et al.* (2004) describes the importance of 'getting to know your stream' to make it easier to detect problems in datasets after fieldwork (Figure 5.2). Blenkinsop *et al.* (2017) also describes a set of checks for rainfall time series.

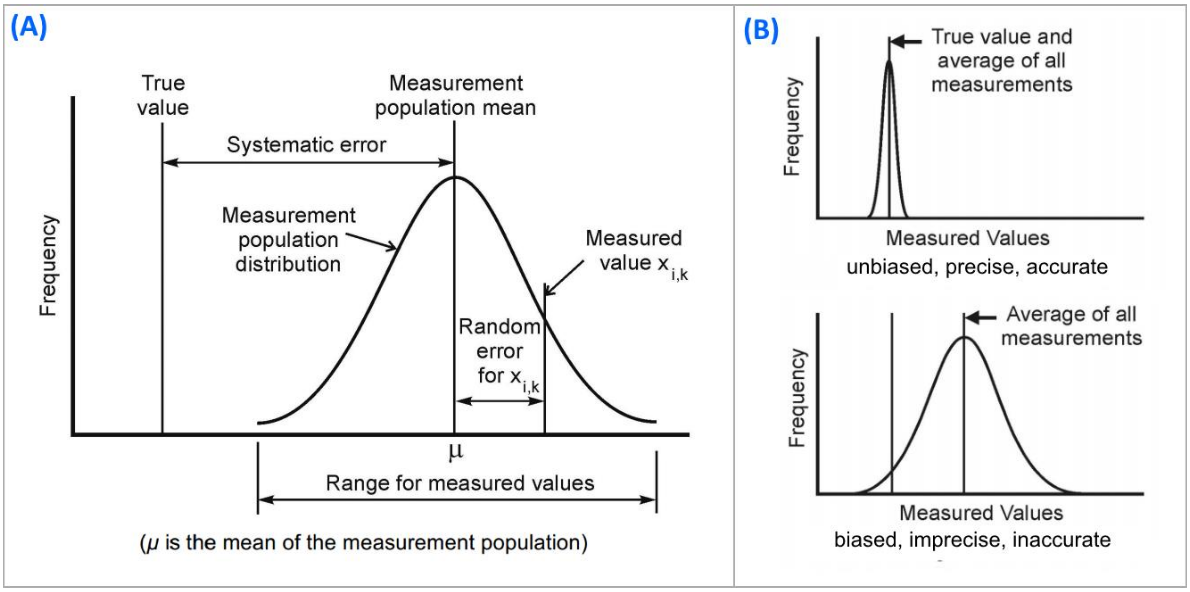


Figure 5.1. Schematics to illustrate the nature and effects of (A) random and systematic error and (B) accuracy, precision and bias, on fieldwork measurements (Source: WMO, 2017).

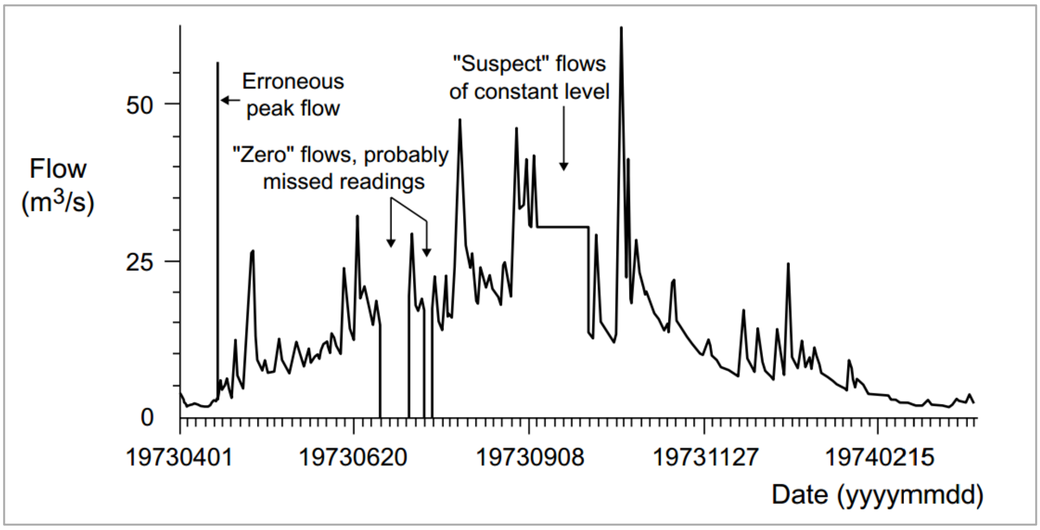


Figure 5.2. A time series containing artificial errors to illustrate some of the common problems encountered with traditional stage or discharge datasets (Source: Gordon *et al.*, 2004).

Large or long-standing organisations have well-developed QA and QC protocols in place for traditional practices. For instance, the UK's Met Office routinely carries out QA and QC activities on their meteorological and climatological datasets to reduce interferences before they are released (Blenkinsop *et al.*, 2017). Whilst checks were manually carried out in the past, improved processing power and finer resolution datasets have led to the development of algorithm-based systems which can accept, correct or flag up erroneous values automatically. Similar methods are also adopted by the Environment Agency, SEPA and CEH. However, it is difficult to control the citizen science monitoring process or to ‘get to know the monitoring site’ in this way, particularly as it relies on multiple (different) observers and simple monitoring methods. It is common for potential citizen science data users to associate untrained observers with being the main culprit for dataset error (Roy *et al.*, 2012). Others believe that the scheme’s design is the main cause (Wiggins *et al.*, 2011; Tweddle *et al.*, 2012; Kelling *et al.*, 2015). It is also common for traditional data users to assume that published measurements are completely free from error (Vidon, 2015).

The number of studies investigating the quality of citizen science data has grown in recent years (Crall *et al.*, 2011; Bonter and Cooper, 2012; Gollan *et al.*, 2012; Lukyanenko *et al.*, 2016; Leibovici *et al.*, 2017), but often correspond to disciplines where participants have been contributing for decades (e.g. ornithology). Many programmes have shown that citizen scientists are capable of collecting good quality measurements and can be of a similar standard to professional scientists (including Crall *et al.*, 2011; Gollan *et al.*, 2012). Some generic QA and QC frameworks for citizen science have been developed, including those documented by Wiggins *et al.* (2011), Bonter and Cooper (2012) and Hunter *et al.*, (2013). However, implementing generic QA and QC frameworks can be challenging because citizen science monitoring and data submission techniques are often project-specific within and outside disciplines of interest. Data accessibility, completeness, relevance and timeliness are commonly considered. Others rely heavily on participant training, use of online data filters and expert reviews (Riesch and Potter, 2014). Trust is also emerging as an important component of the citizen science QC criteria, as participants can often collect data over many years (Hunter *et al.*, 2013). A broader view of ‘DQ’ is therefore required when approving citizen science data (Lukyanenko *et al.*, 2016; Wiersma *et al.*, 2016).

To date, very little DQ investigations exist for catchment science or water resource management (Breuer *et al.*, 2015; Rose *et al.*, 2016; Walker *et al.*, 2016), and have yet to target the UK’s hydrological (flooding) context. Illingworth *et al.* (2014) for instance trialled a rain gauge network with schools in the Birmingham area, but claimed that ‘due to the non-standard nature of the collectors used’, scientific validation was not required. Unlike traditional methods, this means that QA and QC guidelines are absent for community-based monitoring activities relating to this study.

5.3. Traditional monitoring network

Traditional sources of catchment data were required to complete this chapter in order to a) characterise the catchment formally and b) validate the community-based data. 'Traditional' is referred to here as the monitoring protocols and subsequent data retrieved that are comparable to standards adopted or collected by professional catchment scientists (e.g. the Environment Agency and Met Office) and researchers. Owing to this, the data have been collected using well-established monitoring methodologies, equipment and standards, as the following sub-sections describe. While all environmental measurements are subject to error, multiple QA and QC procedures have been used here to provide high quality datasets.

5.3.1. Overview of all traditional monitoring sites

Over the duration of the project, a wide range of ground-based traditional datasets were collected directly from the field, or sourced from the Met Office and Environment Agency. Given that the citizen science monitoring methods covered a broad spectrum of variables, efforts have been made to ensure traditional datasets have covered as many of these as possible when assessing the quality and reliability of the community-based monitoring scheme.

Figure 5.3 provides a summary map of the Haltwhistle Burn study area, illustrating the spatial locations of all ground-based traditional monitoring sites used or discussed within Chapters 5-6. Equipment located at reference points A-H and Q comprise a detailed hydrometric monitoring network which was installed within the catchment boundary to support this study specifically. Table 5.1 describes each monitoring site and associated metadata, including data resolutions and temporal availability. All gauges listed were left in situ for the duration specified within Table 5.1. Gauges A-N have directly supported findings presented within this chapter; relevant data collection and processing methods are documented. In addition to the ground-based gauges, Met Office 1km gridded rainfall radar (5-minute resolution) data have been used to provide a remotely-sensed perspective within Chapter 6.

Whilst efforts have been made to ensure comparisons between traditional and community-based monitoring methods have taken place using co-located or closely located equipment, it has not always been possible to do this due to the unpredictable nature and whereabouts of citizen science. Nevertheless, the traditional monitoring network rationale took this into account from the onset by ensuring good spatial coverage across the catchment. Both community-based and scientific factors have therefore been considered during the design phase.

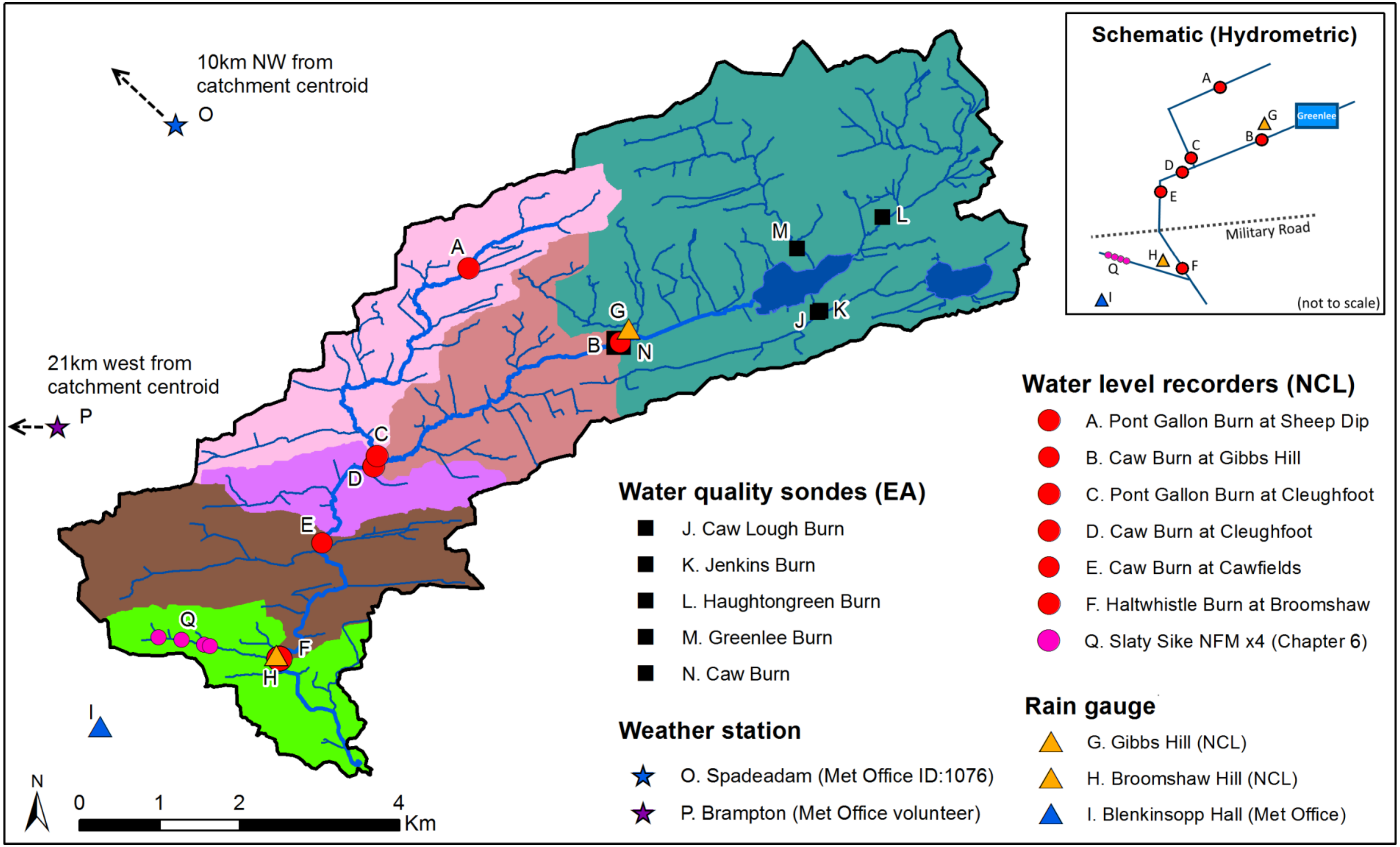


Figure 5.3. Location of all traditional ground-based monitoring gauges used or discussed during this chapter (and others). Note that the weather stations are located off the map extent displayed. Equipment owners are displayed in brackets (see metadata in Table 5.1 and sub-catchment names in Figure 3.2).

Map Ref.	Site name	British National Grid	Parameter	Equipment	Data resolution	Data availability		Site owner / source
						Data start	Data finish	
A	PGB at Sheep Dip	372956 569903	**Stage (water level)**	Diver (Schlumberger DI 240)	5-min	07/03/2014	31/05/2015	Newcastle University (NU)
B	CB at Gibbs Hill	374853 568980		Impress pressure transducer (IPT)	5-min	24/01/2014	Active	
C	PGB at Cleughfoot	371804 567553		Diver (Schlumberger DI 240)	5-min	28/01/2014	31/05/2015	
D	CB at Cleughfoot	371765 567428		IPT	5-min	28/01/2014	Active	
E	CB at Cawfields	371117 566466		IPT	5-min	28/01/2014	Active	
F	HB at Broomshaw	370687 565050		(1) Diver (Schlumberger DI 240) (2) IPT from Feb-2015	5-min	21/05/2014 13/02/2015	31/05/2015 Active	
G	Gibbs Hill	374963 569143	**Rainfall**	Tipping bucket rain (TBR) gauge (ARG100)	2-min	24/01/2014	Active	
H	Broomshaw Hill	370550 565056		TBR gauge (ARG100)	2-min	13/11/2014	Active	
I	Blenkinsopp Hall	368344 564166		TBR gauge	24-hour	01/02/1962	Active	Met Office (2016b) (ID: 1788)
J	Caw Lough Burn	377327 569356	**Water quality** (conductivity, dissolved oxygen, ammonia, pH, salinity, turbidity, temperature)	Sonde (continuous water quality monitoring – summary report also available)	30-min	April 2013	Aug 2014	Environment Agency (EA) (© Environment Agency and database right)
K	Jenkins Burn	377362 569374						
L	Haughtongreen Burn	378138 570545						
M	Greenlee Burn	377066 570148						
N	Caw Burn	374833 568973						
O	Spadeadam	364675 572995	**Weather / climate**	Automatic weather station (AWS)	Hourly / daily	1992 / 2003	Active	Met Office (2016b) (ID: 1076)
P	Brampton	353100 560300		Met Office approved equipment, includes Davis VP2 AWS	24-hour	2001	Active	Met Office volunteer (Brampton Weather, 2015)
Q	Slaty Sike	369373 565243	**Stage (water level)**	x4 Divers (Schlumberger DI 240 & CTD)	5-10 min	31/05/2015	01/03/2016	NU

Table 5.1. Traditional monitoring sites (and metadata) used or discussed within Chapters 5-6. A-H and Q have been specifically installed during this project. Sections 5.32-5.33 discuss these gauges further. Watercourse acronyms include PGB, Pont Gallon Burn; CB, Caw Burn; HB, Haltwhistle Burn.

5.3.2. Environment Agency and Met Office data availability (existing data)

As previously highlighted, there were no official automatic monitoring stations within the catchment prior to this or TRT's CRF project. The Environment Agency and Met Office were first consulted to check their availability for existing open access datasets, alongside the British Atmospheric Data Centre (BADC, Met Office, 2016b). Besides any habitat- or biodiversity-related spot samples which are carried out as part of the WFD assessment process (by the Environment Agency, TRT and RWFG volunteers), datasets were limited. However, the following were of interest to this study (map reference I-P):

- **Spadeadam AWS:** Provided appropriate (daily) weather variables for Chapter 6. This station was not used to support this chapter due to proximity and elevation issues, which would have induced additional error during rain gauge analyses;

- **Blenkinsopp Hall daily rain gauge:** This long-standing gauge is located immediately outside the catchment (122m AOD) but was used to represent the western areas of Haltwhistle and lower catchment. Observations are recorded at 09:00 GMT each day, and hence provided useful measurements for nearby community-based comparisons;

- **Brampton volunteer-led AWS (Brampton Weather, 2015)**: Despite being 'volunteer-led', this Met Office approved AWS site provided daily variables for Chapter 6. Again, due to proximity issues and spatial variability in rainfall measurements, this station was not used to support DQ activities within this chapter. However, it is important to highlight that this station has been in operation since 1999, has submitted data to the Met Office WOW since 2012, and did not contain any gaps in the datasets used. The observer has subsequently received several 'gold' awards from the Met Office to praise reliability and consistency;

- **Greenlee Lough water quality sondes:** Running in parallel to TRT's CRF project, the Environment Agency ran a temporary water quality project in the Greenlee Lough area during 2013 and 2014. Responding to a degraded WFD status, the 'Roman Wall Loughs' diffuse pollution project provided snapshots of the chemical and physical properties at Greenlee's main inlets and outlet (CB). To accompany this, the Environment Agency also authored an unpublished summary report (Environment Agency, 2014), which highlights the main pollution concerns following monitoring activities;

- **1km NIMROD rainfall radar (Met Office, 2003):** gridded rainfall totals were downloaded from the BADC for the UK and extracted for the Haltwhistle Burn catchment. This provided spatial rainfall data which overlapped all other ground-based rain gauges.

Although the aforementioned datasets were subject to QC checks by the site owner before being released, they were checked here for format, consistency and completeness issues, both visually and graphically. Where possible, cumulative plots and expert knowledge were also used to validate the data and rule out the possibility of missed erroneous measurements. No changes were made to the original datasets following this brief validation phase. This outcome was useful as all datasets were identical to those used by catchment stakeholders for operational duties.

All datasets were aggregated or disaggregated into relevant resolutions required for each analysis. In some cases, spot measurements at specific timestamps were also extracted for direct analysis, particularly those which overlapped the presence of community-based data.

The Environment Agency also monitors water level on the 'River Tyne at Haltwhistle'[24], adjacent to the town for flood warning purposes. However, this gauge was not explored here as this main river has a very different hydrological regime to the Haltwhistle Burn.

5.3.3. Project-specific hydrometric network installed

5.3.3.1. Traditional monitoring process and DQ framework

The flow chart in Figure 5.4 summarises the monitoring and DQ framework adopted during the Haltwhistle Burn traditional data collection process. The purpose of this framework was to ensure high quality, spatial and temporal, rainfall and river level observations were available for use. QA and QC steps have been implemented throughout to achieve this. All processes and products have been controlled by the Ph.D. researcher to ensure consistency and gain hands-on catchment knowledge. Consent was required to install equipment on private land, which provided farmers and upstream land owners with an additional element of engagement and involvement. January 2014 to February 2016 datasets have been prioritised here as this mirrors the period during which community-based observations were analysed. All traditional datasets were captured using GMT time-stamps.

[24] River level gauge map https://flood-warning-information.service.gov.uk/station/8356?direction=u

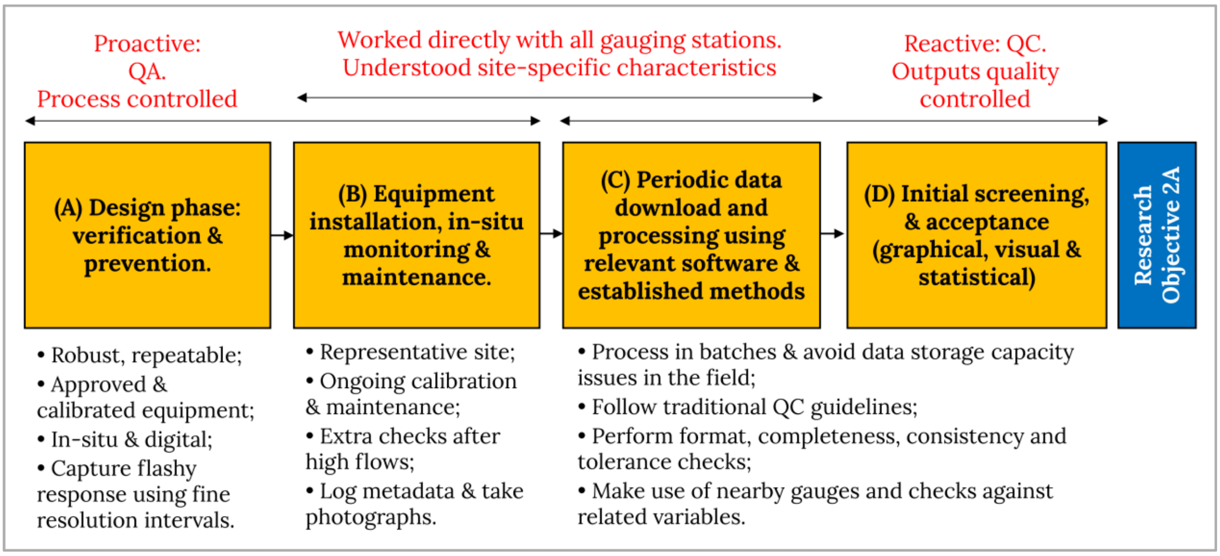


Figure 5.4. Traditional monitoring process and DQ framework adopted. Established guidance documents were consulted beforehand (e.g. WMO, 2008; 2011; 2017).

5.3.3.2. *Rain gauge network*

Aerodynamic TBR gauges (ARG100) were installed at Gibbs Hill and Broomshaw Hill to provide high resolution precipitation data in the upper and lower regions of the catchment. Located on the ground (therefore an orifice elevated by 30cm), TBR gauges allow precipitation to enter the funnel, pass through a filter and fill a plastic bucket. Once full, the bucket tips and a signal is detected and logged electronically. Refer to Appendix 5A for specific gauge summary sheets.

Various sources of error are possible when observing precipitation, including gauge design issues, catch errors and instrumental exposure, which can be eliminated or reduced through careful equipment and site selection (Environment Agency, 2004; Villarini *et al.*, 2008). Both gauges were therefore located, installed and maintained following WMO (2008) and Shaw *et al.* (2011) guidelines. This included building enclosures around each gauge to protect against cattle damage, regular visits to remove vegetation and debris, and maintaining the same gauge position over time (aided by a gauge baseplate, spirit level and pins). The buckets were also calibrated by the supplier immediately before installation. According to the Environment Agency (2004) and Pollock *et al.* (2014), wind-induced errors dominate. However, the TBR's 'champagne glass' shape is designed to minimise wind exposure and are known to provide better catch estimates than straight-sided gauges. TBR gauges are approved and used by the Environment Agency (2004) and Met Office (Blenkinsop *et al.*, 2017).

TinyTag loggers were used here to provide internal data storage capacity; periodic data downloading was therefore required out in the field using TinyTag Explorer software and a waterproof laptop. To avoid saturated logging space and losing succeeding observations, the gauges were typically downloaded every two months. Once downloaded, the number of tips were converted to rainfall totals using the gauge-specific calibrated bucket capacities (either 0.201mm or 0.202mm). Datasets were then initially QC checked for gaps, format issues, offsets and any erroneous spikes or prolonged dry periods. Rainfall totals were also checked against expected trends and other gauges, including the Met Office gauge at Blenkinsopp Hall (Figure 5.5). Specific attention was also paid during the Met Office named storms (e.g. Storm Desmond, Eva and Frank (Marsh *et al.*, 2016)). Double-mass (cumulative regressions) plots and summation checks were then used to finalise the validation checks and accept the data (Figure 5.5). Other than test tips (which were replaced with 0mm), there were no suspicious measurements found. Wind corrections were not applied to any rainfall datasets as guidelines are still unclear and likely to induced additional error (Pollock *et al.*, 2014). Where necessary, rainfall datasets were aggregated to an appropriate resolution (e.g. 5-minute, hourly or daily totals). Lastly, although there were no major snow events over the duration of the monitoring period, rain gauges were left to observe snow melt during light snow cover which may have caused a delay in precipitation being logged.

Broomshaw Hill was later telemetered to provide real-time rainfall information. However, due to signal, power and cattle intrusion issues, it was not fully operational until February 2015. Appendix 5A provides further details about this cross-over period, including QC checks.

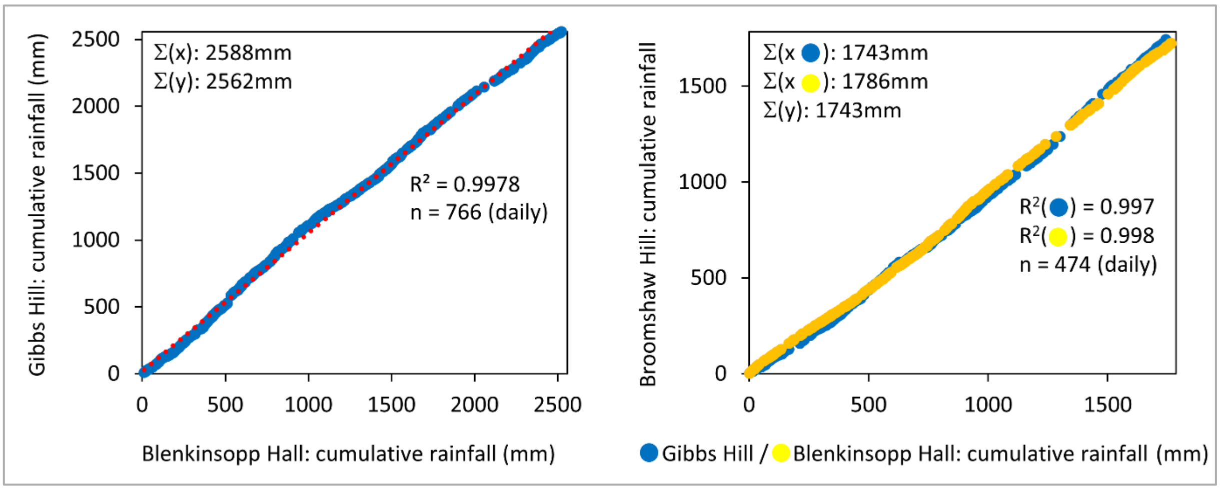


Figure 5.5. Double-mass plots of daily rainfall totals (9am-9am) used to validate the NU rain gauges. A Met Office gauge (Blenkinsopp Hall) was used to check Gibbs Hill (left) and Broomshaw (right). Strong relationships and summation checks permitted dataset acceptance.

5.3.3.3. River level (stage) gauges

Six water level recorders (WLR's) were installed and left in-situ along the backbone of the Haltwhistle Burn river network, within the 3rd and 4th order streams (HB, CB and PGB). The WLR's were required to capture the catchment's response and characterise peaks and troughs, as well as baseflow over the duration of the community-based monitoring scheme. Water level (stage) time series were also required to develop stage-discharge rating curves at each gauging station (Section 5.3.3.4). The Broomshaw WLR was specifically co-located beside the community-based RLGB to allow for direct comparisons within this chapter (see photograph in Figure 5 *intro*). The Broomshaw site was most suited for this comparison due to its prominent position along the Haltwhistle Burn footpath. A further four WLR's were installed along the Slaty Sike at a later date (but are not discussed here, see Chapter 6).

Water level has been observed by hydrologists using a variety of manual and automatic methods over time (Gordon *et al.*, 2004; Younos and Heyer, 2015; Sene, 2016), including the graduated RLGB's used by the Haltwhistle community. However, submerged pressure transducers are used extensively today as they are relatively cheap, streamlined, robust and easy to use. They also provide continuous measurements efficiently, and at resolutions which are capable of capturing a flashy river response. Pressure transducers are typically installed at a fixed position within the water column, and left to observe pressure and temperature over time. Working on the principle that depth is proportional to the pressure observed (Herschy, 2009; Shaw *et al.*, 2011; Sene, 2016), direct and continuous pressure and temperature observations are simple to observe, unlike water level or discharge. Pressure sensors are accompanied by a power supply and data logger, allowing for manual or automatic (telemetered) data downloading.

Submersible pressure transducers were used to monitor water level over time within the Haltwhistle Burn catchment and care was taken to ensure that they were installed appropriately, following relevant technical guidance documents (WMO, 2008). The sensors were located along clear, representative, safe and accessible stretches of the river network, away from obstructions, backwater effects, and morphological activity, and were secured to the river bed (perpendicular to the flow) at well-defined cross-sections. The sensors themselves were submerged into plastic pipes to protect them from debris-, flood- and ice-related damage, which also helped to maintain a constant datum over time. It was important that the sensor's position remained unchanged as water level was observed relative to the base of the sensor itself, rather than the river bed. Where possible, sensors were also located within water columns that were not expected to run dry (i.e. avoid negative readings) and where flow gauging activities were supported. All pressure transducers were programmed to log observations every 5-minutes.

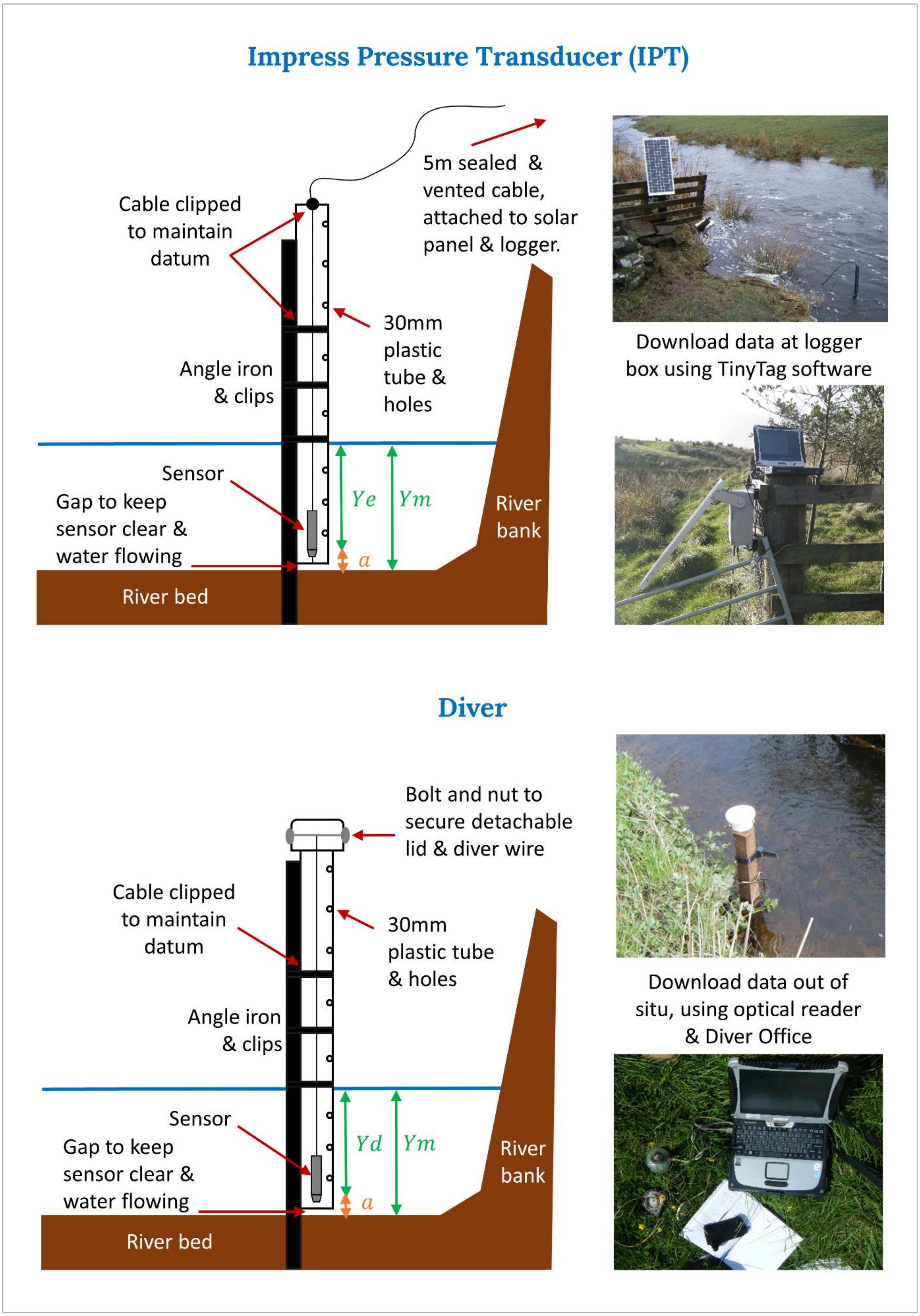


Figure 5.6. Schematic of a typical 'IPT' and 'Diver' gauging station installed within the catchment for water level monitoring. Photographs also illustrate the data downloading process required.

Isolating pressure exerted on the water column (Pwc) only	**Equation 5.1.**
$Pwc = Pd - Pb$	
Where Pd = Absolute pressure observed by the Diver. Pb = Atmospheric pressure observed by the barometer.	

Due to resource availability, both 'vented' (Impress Pressure Transducers (IPT)) and 'absolute' (Schlumberger Divers) pressure transducers were employed across the catchment (see Figure 5.3 and Table 5.1 for locations and metadata), thus required slightly different installation and data downloading procedures (Figure 5.6). As Equation 5.1 demonstrates, in order to isolate pressure exerting on the water column (Pwc) only, a reference to the atmospheric pressure (Pb) is required (Herschy, 2009; Younos and Heyer, 2015). This isolation process is the significant difference between the two types of sensors:

- **Vented IPTs (x4)**

Although more costly, the vented IPT automatically compensated for atmospheric pressure over time as it incorporated a vent pipe into its cable design. The sensor and cable was attached to a logger box and solar panel which was mounted above the highest expected water mark. Similar to the TBR gauges, and whilst the sensor remained in situ, TinyTag Explorer was used to download batches of data approximately every two months (although these particular gauges were capable of storing over a seven-month period). IPTs automatically convert pressure into an electrical signal (Ye), therefore upon receipt of the data, raw time series were provided in milliamps (mA) and had to be converted to water level using a linear relationship (Equation 5.2).

Converting raw IPT's outputs into water level	**Equation 5.2.**
$Y = (0.3125 \cdot Ye) - 1.25$	(sensor-specific calibrated equation provided by the equipment supplier)
Where Y = resulting water level or depth (m) of the water column Ye = raw IPT electrical signal (mA)	

Over the duration of the monitoring period, all IPTs provided reliable, consistent and easy-to-use datasets which were generally error-free, correctly time-stamped, and benefitted from a sensor accuracy of <±0.1% (confirmed by the manufacturer). However, gaps were present within two of the four IPT datasets (CB at Cawfields and HB at Broomshaw) as these gauges were disturbed during the 2014/15 and 2015/16 floods. Nevertheless, and similar to examples previously presented by Gordon *et al.*, (2004) in Figure 5.2, these invalid periods were easily identified. To eliminate the risk of inducing additional uncertainty, gaps were not interpolated during periods of high flows or change.

Manual stage measurements (Ym) were made during each site visit to check that the sensor's datum remained constant over time. Although this provided reassurance (see example in Figure 5.7), datum corrections were not applied as the IPT readings were likely to be more accurate than Ym. The RLGB delivered additional confidence at the Broomshaw site.

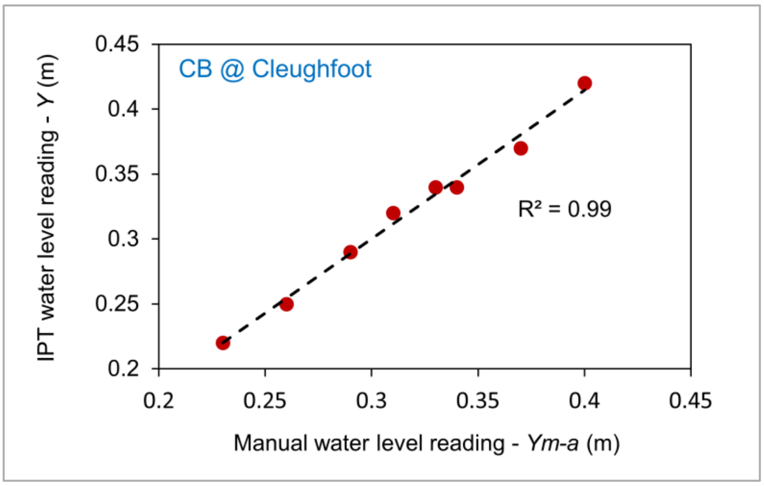


Figure 5.7. Example of QC check involving IPT (Y) and manual (Ym) river level observations for the CB at Cleughfoot. Note that Ym is shown here as Ym-a (a = 0.02m). See Figure 5.6 for notations.

When the Broomshaw Hill site was later telemetered and operational by February 2015, the IPT at Broomshaw also benefitted from this facility. As a result, there was a cross-over period (similar to the Broomshaw rain gauge) from February to May 2015. Appendix 5A provides further details about this cross-over period, including QC checks.

- **Absolute Divers (x3 - includes an extra temporary sensor at the Broomshaw site)**

All Divers used here were unvented and consequently required a Schlumberger Diver-barometer in the catchment to observe and isolate Pwc. One barometer was sufficient for a study area of this size and was installed close to the CB at Cawfields in a dry location. The barometer operated in the same manner as the Divers by observing temperature and pressure every 5-minutes. Divers and the barometer provided three months of data storage space before requiring manual data downloading using Diver Office software whilst out in the field. However, data downloads occurred approximately every two-months in line with other equipment. The manufacturer confirm that these particular Divers are capable of deriving an accuracy of ±0.1% (pressure) and ±0.1°C (temperature) whilst operating within the calibrated range.

Equation 5.3 justifies the relationship between the Divers and water level, a conversion which was automatically calculated within Diver Office upon retrieval of all raw data. This software delivered a consistent and quick solution to barometric compensations and eliminated any potential human (calculation) errors. Diver Office also corrected for drifting sensor clocks.

Converting raw Diver outputs into initial water level* **Equation 5.3.**

$$Yd = 9806.6\left(\frac{Pd - Pb}{n.g}\right)$$

(Van Essen Instruments, 2004)

Where Yd = initial water level obtained from the Diver (cm)
P = pressure in cmH_2O
g = acceleration due to gravity ($9.81 m/s^2$)
n = density of water ($1000 kg/m^3$)
*Note that temperature (T) is not required here, it is used within the manufacturers calibration procedures and forthcoming temperature corrections.

Once Yd time series were derived, initial format, completeness and consistency checks were carried out. Despite the Divers being undisturbed during high flow (therefore did not contain any gaps), four issues still needed to be investigated further, which are also common in other fieldwork studies (e.g. Ewen *et al.*, 2010):

1. *Occasional spikes in the data due to Diver malfunctions*: these were automatically highlighted by Diver Office but were manually deleted using tolerance checks. Resulting gaps were generally very small (often just one five-minute observation) and hence water level was assumed to remain constant during these periods. Linear interpolation filled these gaps using data points on either side;

2. *Incorrect readings during and immediately after data downloading*: given that the Divers had to be removed from the water column briefly during downloading activities, incorrect water levels were logged for a number of very short periods. Linear interpolation filled these gaps using data points on either side;

3. *Negative readings*: despite trying to avoid this, two of the Divers were located on the smaller PGB tributary, and although it never completely dried up, the pressure sensors were elevated out of the water at times of low flow. See below for datum corrections (a);

4. *Datasets contained unwanted diurnal cycles*: these cycles are amplified during the summer months, can be affected by sensor and stream orientation, and occur because the sensors are confined within protective tubes. They arise because Divers are slightly sensitive to

temperature, and the manufacturer has only calibrated these instruments between 15 and 35°C (Van Essen Instruments, 2004). However, temperatures fall below 15°C for a large proportion of the time within the Haltwhistle Burn catchment (annual average of 10.7°C at Spadeadam – see Figure 3.4) and thus the Divers were corrected for this. See below for temperature corrections (b).

Despite having already attained an initial water level (Yd) using Equation 5.3, an additional calibration procedure was required to correct datum and diurnal temperature issues. An approach documented by Ewen *et al.* (2010) was applied to obtain a final set of water level time series, Y (Equation 5.4). Manual water level measurements were obtained at each Diver site over the duration of the monitoring programme to acquire a set of reference points ('true' stage, Ym), which were then used to calibrate each Diver. The datum offset (a simple measurement from the river bed to the base of the sensor) was first applied to address component a within the equation. Any remaining error was attributed to b, the diurnal temperature effect which was obtained through trial and error, by improving the relationship (R^2 value) between the paired reference points and the Diver data. Figure 5.8 presents the final results applied to each of the three Divers following this correction process. The final calibration equations were applied to individual Diver time series (Yd) to obtain Y. However, error cannot be eliminated completely due to the nature of hydrometric monitoring. It is acknowledged that manual measurements are subject to error too; Ewen *et al.* (2010) estimated this to be around ±5mm, which is negligible considering the end application of the data. The original diurnal temperature errors were minor in comparison to the broader dataset, and were overridden when water levels were changing.

Final Diver datum & temperature correction/calibration equation* **Equation 5.4.**

$$Y = a + (0.01 \cdot Yd) - (b \cdot Td)$$

(Ewen *et al.*, 2010)

Where Y = resulting water level or depth (m) of the water column
a = a constant datum correction
Yd = the initial water level obtained from the Diver
0.01 converts Yd(m) into Yd(cm)
Td = temperature of the Diver
b = a constant temperature correction
*Individually applied to each Diver, calibrated against a set of manual measurements, Ym.

Diver site	Number of Ym obs.*	Calibration equation to obtain Y	R^2 (Ym & Y)	Average error (mm) ($Y - Ym$)**	Site information
PGB at Sheep Dip	10	$0.07 + (0.01 \cdot Yd) - (-0.0019 \cdot Td)$	0.98	4	Exposed to sunlight. Limited shade from river bank
PGB at Cleughfoot	8	$0.07 + (0.01 \cdot Yd) - (0.0015 \cdot Td)$	0.96	9	
HB at Broomshaw	12	$-0.02 + (0.01 \cdot Yd) - (-0.0014 \cdot Td)$	0.97	1	In gorge area, shaded by canopy.

*Note that manual measurements were made across all seasons to capture temperature changes.
**Error decreases with a greater number of manual measurements, larger catchment area (e.g. Broomshaw) and available shade during the summer months (which reduces thermal expansion within the protective tube). The effects are overridden when water levels are rising or falling.

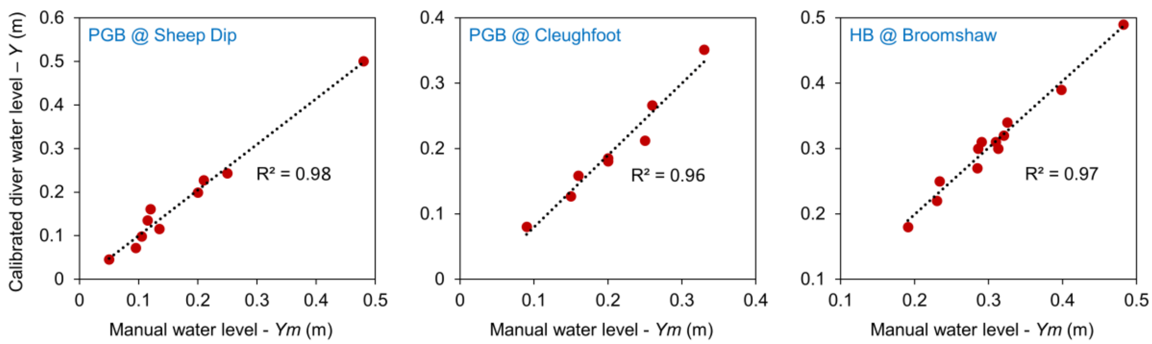


Figure 5.8. Top: Final diver calibration equations used at each site and errors obtained between all pairs of Ym and Y. Bottom: calibration results plotted for all three Divers.

- **IPT and Diver maintenance, processing and final QC checks.**

WLR maintenance involved taking manual water level measurements over time to ensure that the sensor or its tube had not moved (Ym previously discussed), removing debris entangled around sensor cables (especially post-flood event), keeping solar panels clean, and ensuring sufficient water movement around the pressure sensor. Due to its vented properties, IPT's are considered to be more accurate and reliable than the Divers in this study. Direct involvement with each gauging station and site-specific knowledge has also significantly supported the derivation of carefully controlled datasets.

Initial QC WLR checks have already been described above, which ensured consistent, realistic, and correctly formatted datasets. All IPTs and Divers recorded observations once every 5-minutes which made it simple to prepare datasets. Most WLR datasets had already attained whole 5-minute timestamps (5, 10, 15 etc.); those that did not were assigned to the nearest, allowing for direct 5-minute resolution comparisons. Final QC checks then entailed the following:

- Tolerance checks: flagging up and manually checking the timing of river levels that were <0.05m, <0.10m, >1.00m and >2.00m (depending on stream order);

- Visually checking and graphically plotting the timing and alignment of peaks and troughs with photographic evidence (those collected during traditional fieldwork), fieldwork notebooks, physical relationships with other parameters (rainfall datasets), and documented Met Office storms (Marsh *et al.*, 2016);

- Overplotting water level datasets from nearby gauges to check alignments, looking for expected trends, and carrying out double-mass checks using other gauges across the catchment (Figure 5.9). The Broomshaw cross-over period also provided a useful Diver-IPT cross-check which revealed a very close match (direct comparison yielded an R^2 value of 0.98, see Appendix 5A).

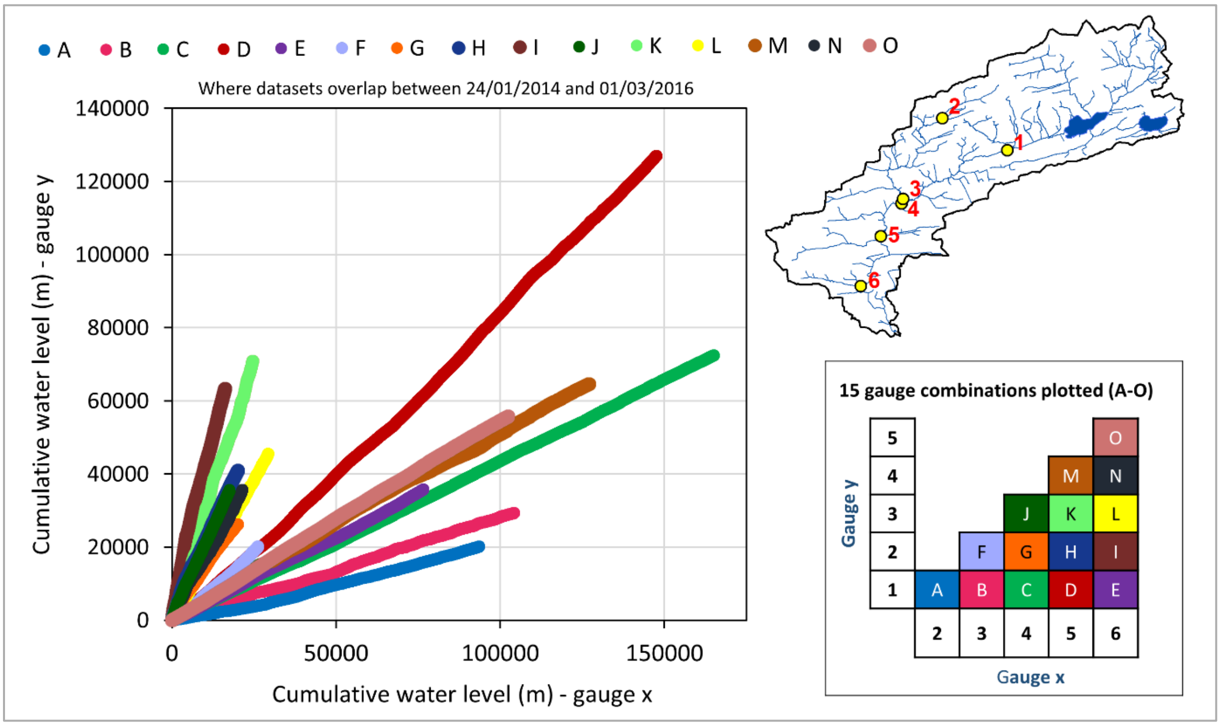


Figure 5.9. Final IPT and Diver QC checks: double-mass curves involving all 15 possible gauge combinations. Plots entail 5-minute data from different gauges within the catchment. A perfect match (straight line and x=y) was not necessarily anticipated at all sites due to spatial variability.

Although community-based observations (especially photographs taken during extreme events) are likely to be extremely valuable during these QC steps, they have not been used here to quality control the traditional datasets to avoid invalidating forthcoming analyses.

- **Temporal availability following all QA and QC stages**

Figure 5.10 summarises the temporal availability of river level data for the Haltwhistle Burn catchment between October 2013 and February 2016 (same 29-month period as the community-based programme). These datasets were also available to support discharge estimations. Site-specific gauge summary sheets are provided in Appendix 5A.

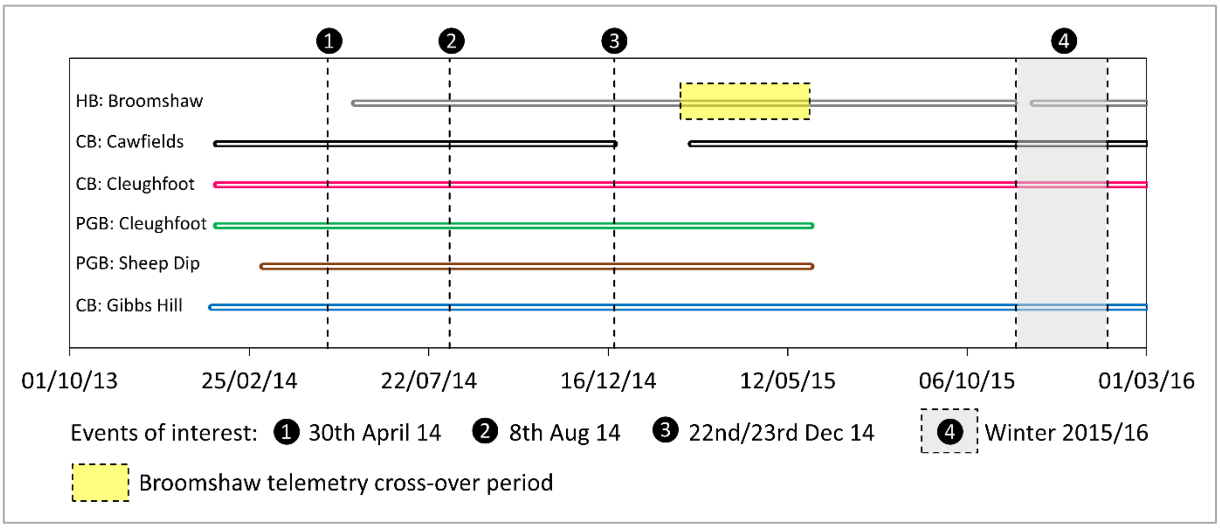


Figure 5.10. Temporal availability of river level data, with key events of interest highlighted. Divers were decommissioned in May-2015 and moved to the Slaty Sike NFM scheme.

5.3.3.4. *Discharge estimation*

Flow rate or discharge (Q) measurements provide valuable water quantity information which is required for a range of hydrological applications, including hydrological and hydrodynamic modelling (Sene, 2016). Q was required for the Haltwhistle Burn catchment to characterise catchment response and then drive the modelling activities summarised within Chapter 6.

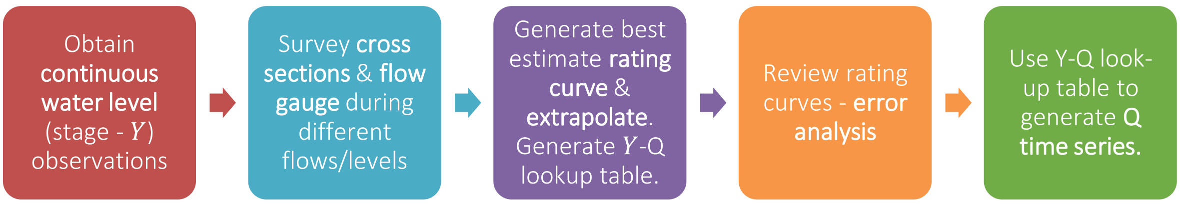


Figure 5.11. Key steps implemented to derive discharge (Q) from water level measurements.

Despite being an important component of the water balance equation, direct and continuous discharge measurements are still rarely made today. It is expensive, dangerous and physically challenging to obtain reliable Q datasets, and thus in-situ flow equipment do not usually contribute to the hydrometric monitoring network. Owing to the difficulties of observing continuous Q measurements in open channels, rating curves were required to convert water level (stage – Y) into Q across the Haltwhistle Burn catchment. Given that Q is a function of Y (Shaw *et al.* 2011), stage-discharge rating curves are unique to individual stretches or cross-sections along the river network, and hence six rating curves were derived following relevant fieldwork activities. The flow chart in Figure 5.11 summarises the key steps taken to derive Q, and subsequent observed Q time series.

The fundamental velocity-area equation used to derive discharge (Q)	**Equation 5.5.**
$\mathrm{Q} = \mathrm{V} \cdot \mathrm{A}$ Where Q is expressed as $\mathrm{m^3/s}$, velocity (V) as $\mathrm{m/s}$ and area (A) as $\mathrm{m^2}$.	(Davie, 2008; Herschy, 2009)

Calculating cross-sectional Q	**Equation 5.6.**
$$\mathrm{Q} = \sum_{i=1}^{n} q_i = \sum_{i=1}^{n} \overline{v_i} \cdot a_i$$ Assumes that v and a measurements are available for each panel within the cross-section, where n = number of panels, $\overline{v_i}$ = mean velocity at each panel taken at 0.6 of the depth, a_i = area of each panel, and therefore qi = discharge within a single panel. A sufficient number of panels must be used to characterise the cross-section.	(Shaw *et al.*, 2011; Le Coz *et al.*, 2012)

Using the well-established velocity-area method (Equation 5.5), a Valeport impellor flow meter (‘8011 series high impact styrene impellor’, model 001) was used to obtain flow measurements manually, an instrument which is reported by the manufacturer to have an accuracy of ±1.5%. Although there are other velocity and flow measurement techniques, including the modern Acoustic Doppler Current Profiler (Sene, 2016), the velocity-area method was more appropriate and feasible given the characteristics of the Haltwhistle Burn catchment (small, narrow, vegetated, bedrock outcrops and shallow in places). It is also a method which is frequently used worldwide (Shaw *et al.*, 2011; Le Coz *et al.*, 2012). Cross-sections were divided into small and regular segments in the vicinity of each WLR gauging station, where individual velocity, depth and width measurements were taken. Given that velocity varies vertically within the water column, the flow meter was placed at 0.6 of depth from the water surface in order to obtain representative (average) velocity readings (Herschy, 2009; Shaw *et al.*, 2011). Equation 5.6 was then used to combine results from each segment and obtain an overall Q spot measurement for each cross section. Spot measurements were repeated over time; between 6 and 11 (average of 8) Y-Q points were obtained at each individual gauging site, covering 95% of the January-2014 to

May-2015 observed water levels. Cross-sections were located next to each WLR, at uninterrupted, uniform and representative stretches of the watercourse.

Despite efforts to flow gauge during low to high flows, it is both difficult and dangerous to capture high, flashy and out-of-bank flows. There are also risks associated with simple linear extrapolations as the behaviour of Y-Q alters once out of bank. The stage-velocity-area (SVA) method described by many (including Ramsbottom and Whitlow, 2003; Shaw *et al.*, 2011, Herschy, 2009) was used to generate a rating curve for each monitoring site, which was then extrapolated to account for out-of-bank flow. The SVA method is popular as it makes use of observed, therefore catchment-specific, data. However, a more sophisticated SVA approach, described and successfully used by Ewen *et al.* (2010), was adopted to provide additional confidence when extrapolating each rating curve. This method is based around physical assumptions and mass (water) balance calibration adjustments to ensure that the extrapolation method does not under- or over-estimate Q. The main assumption is that, at higher stages (including floods), the maximum velocity of UK upland streams is typically 1.5-2.0m/s (Bathurst, 1998). This means that velocity diminishes and asymptotes towards this peak value, and can be represented by a site-specific sigmoid curve.

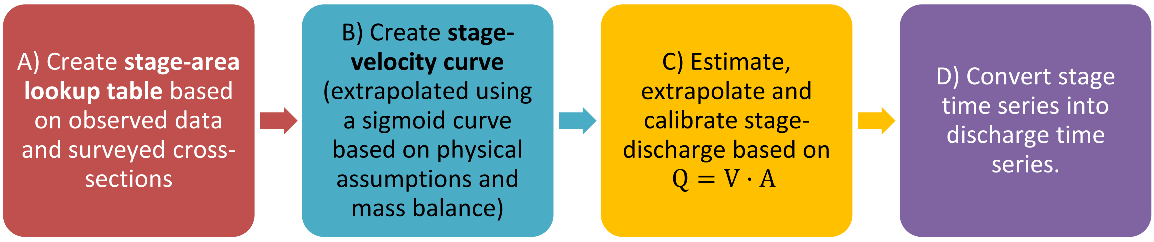


Figure 5.12. A summary of the modified SVA method (Ewen *et al.*, 2010) used to produce, extrapolate and calibrate the six rating curves. Note that final Q time series were only calibrated for January-2014 to May-2015 datasets (making use of the available data at the time).

Figure 5.12 summarises the SVA process, which subsequently offered a robust QC check on all discharge data. More details regarding the modified SVA method implemented can be found in:

- Appendix 5B - a worked example, including equations used, and QA measurements;
- Appendix 5A – all surveyed cross-sections and resulting rating curves.

Once the process outlined within Figure 5.12 had been completed, both observed (obtained through flow gauging whilst out in the catchment) and estimated (derived from the rating curve) pairs of Q were available to use, which offered a final validation check. Table 5.2 summarises the results for each WLR across the catchment, including how many Y-Q points were obtained and the resulting quantitative error analysis. All six rating curves were accepted for use following strong correlations obtained between pairs of Q. Given that the winter 2015/16 widespread floods occurred towards the very end of the monitoring period, it was not feasible to flow gauge, and hence the rating curves have not been calibrated for these events of interest. As a result, Q has not been derived beyond 1st-November 2015 to eliminate additional uncertainty when extrapolating extreme out-of-bank flows.

Gauging station name	Number of flow gauging points (Y-Q)	Error analysis (Q flow gauging & rating curve)	
		R^2	ANOVA (Significance F)
CB at Gibbs Hill	9 (8 used)	0.97	$1.1\text{x}10^{-5}$
PGB at Sheep Dip	9 (8 used)	0.98	$1.4\text{x}10^{-6}$
PGB at Cleughfoot	6	0.94	$1.2\text{x}10^{-3}$
CB at Cleughfoot	6	0.94	$1.4\text{x}10^{-3}$
CB at Cawfields	10 (9 used)	0.91	$6.8\text{x}10^{-5}$
HB at Broomshaw	11 (10 used)	0.97	$7.0\text{x}10^{-7}$

Table 5.2. Number of Y-Q points obtained for each monitored site are shown. An error analysis was completed for each rating curve by comparing pairs of Q (derived directly through flow gauging and also the rating curve). This includes R^2 and analysis of variance (ANOVA) F tests.

5.3.3.5. *Broomshaw telemetry*

Hydrometric monitoring networks are now taking advantage of real-time communication systems by linking in-situ sensors to the internet or mobile phone network (Younos and Heyer, 2015). As part of the CRF project, TRT funded a telemetry system which was installed at the Broomshaw monitoring site, immediately above the town of Haltwhistle. The system enabled the site's IPT and TBR gauge to be logged and transmitted using the mobile phone network (see schematic in Figure 5.13). Given that the system was being developed as part of another research project, and due to technical difficulties (e.g. damage from cattle, power issues and vandalism), it was not operational until February-2015. As a result, the telemetered system was not officially adopted by the community and nor was it intended to replace the community-based approach. It did however provide TRT and the research team with access to relevant data remotely, and also receive the following email alerts (which were based on catchment-specific knowledge and experience from other catchment monitoring systems);

- Rainfall alert: if ≥3mm precipitation was logged within any 15-minute period;
- River level alert: when the IPT reached 0.7m and 0.8m (equated to 0.3m and 0.4m on the Broomshaw RLGB).

Due to sim card and server costs, it was only possible to download data remotely between 10am and 12-noon. Batches of rainfall and river level data were downloaded on a regular basis.

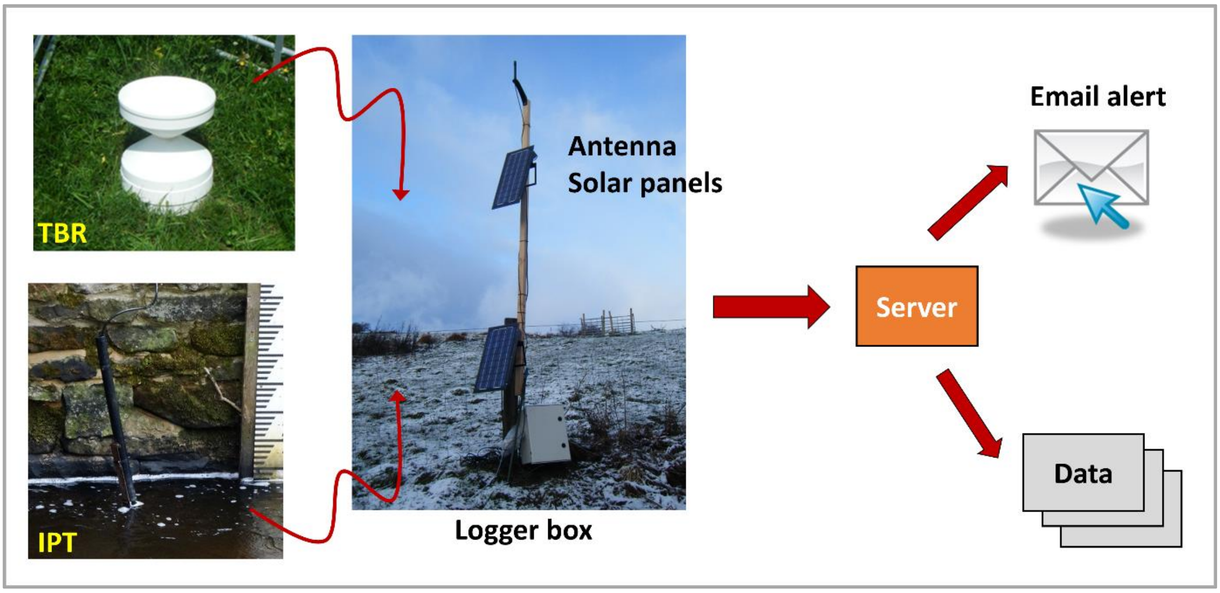


Figure 5.13. A schematic of the telemetry system installed at the Broomshaw monitoring site.

5.3.3.6. *Fieldwork limitations*

Despite carrying out consistent and representative fieldwork, which was subject to various QA/QC measures, errors can never be truly eliminated (Beven and Westerberg, 2011). Fieldwork has also been restricted by the available resources, time, travelling required and catchment-specific weather and hydrological conditions experienced during the project. Monitoring of flash floods has always been a challenge to hydrologists, including flow gauging activities during rapid and out-of-bank-flows (Le Coz *et al.*, 2012). Consequently, the Haltwhistle Burn hydrometric network would have benefitted from a greater number and range of Y-Q rating curve points. Diver data is also regarded as being less accurate than the high-precision IPTs used, and the TBR gauges will have been affected by wind-induced errors and ability to log high-intensity rainfall accurately (Villarini *et al.*, 2008). Davie (2008) also argues that it is impossible for cross-sections at gauging stations to remain constant over time (especially if they have experienced a number of high flows). Furthermore, gauging stations, which are essentially point measurements, have represented an entire sub-catchment area or river network (Beven and Westerberg, 2011). Nevertheless, a wide range of hydrological conditions were experienced over the duration of the monitoring period and QC checks have confirmed that data are of a high, therefore acceptable, quality. Although fieldwork has entailed a large amount of travelling, and often at short notice, key members of the RWFG also checked on the traditional equipment over time when passing, including potential damage as a result of vandalism or high flows. The latter point has helped to reduce the number of gaps in the datasets, and is a clear benefit of having the public involved.

5.3.4. Results: catchment characterisation (with focus on 2014 and winter 2015/2016 floods)

This sub-section describes and analyses the hydrological and meteorological response of the Haltwhistle Burn catchment, with focus on the NU hydrometric network and the Met Office Blenkinsopp rain gauge (until the end of February-2016 where datasets overlap). Particular attention has been paid towards extreme rainfall and high river levels or flows, given that this was what the community-based monitoring scheme focussed upon. Water quality is discussed later within Sections 5.4-5.5.

5.3.4.1. Overview of catchment response

Rainfall, water (river) levels and subsequent discharge (Q) time series are available for all six traditional gauging stations. Such data have been plotted to provide an overview of the catchment's response over the duration of the monitoring period, as Figure 5.14 (CB at Gibbs Hill) and Appendix 5C (all remaining gauges) illustrate. Note that these plots:

- Make use of the catchment's 24-hour areal rainfall, derived using Thiessen polygons (Shaw *et al.*, 2011) and the Gibbs Hill, Broomshaw and Blenkinsopp Hall rain gauges;
- Only include Q where Y-Q falls within the calibrated limits (as Section 5.3.3.4 discussed).

Datasets reveal that the Haltwhistle Burn was susceptible to a range of high and low flows from January-2014 to February-2016. Prevailing winds from the south west and the presence of the Pennine Hills encouraged this catchment to experience frontal and orographic rainfall events, which then instigated wide-spread fluvial response (e.g. 22nd/23rd December 2014 and the winter 2015/16 storms). In contrast, the catchment also witnessed a number of heavy downpours, which then activated a localised and flashy response (e.g. 30th April 2014 and 8th August 2014). The Haltwhistle Burn can be regarded as a responsive and saturated catchment, meaning that its high-order stream network rises and falls quickly in response to precipitation. As expected, the winter 2015/16 high flows were the largest/highest recorded at all sites, which correlates well with the Met Office documenting this period as being the UK's wettest and warmest winter on record (Marsh *et al.*, 2016). Conversely, it was noticeable that many high rainfall totals and river levels observed within the Haltwhistle Burn catchment were not observed or discussed elsewhere. Table 5.3 provides photographic evidence of contrasting high and low flows experienced as a result of inter-annual variability.

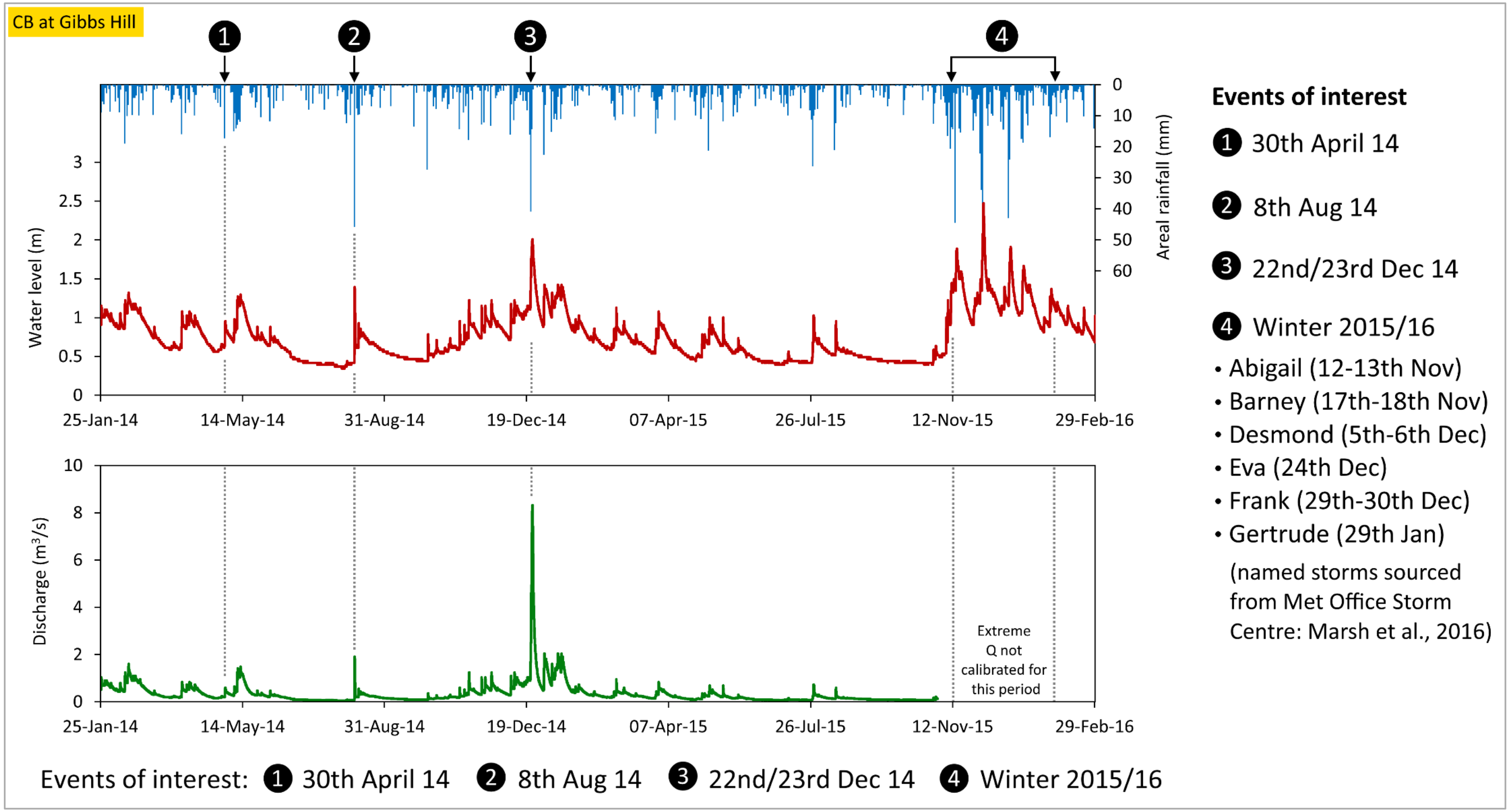


Figure 5.14. Overview of the catchment's response during the monitoring period of interest for the CB at Gibbs Hill. Includes site-specific river levels, estimated Q, and areal rainfall (derived from Thissen polygons). Hydrological events of interst are highlighted. All other gauges are plotted in Appendix 5C.

Table 5.3 Examples of high (left) and low (right) flow conditions within the Haltwhistle Burn (photographs captured during fieldwork, not by the community).

Despite only monitoring for a relatively short period of time, hydrologically, the Haltwhistle Burn and its tributaries peaked on a number of occasions. This exemplifies the importance of localised monitoring and that low return period events are also significant in this catchment.

5.3.4.2. Rainfall analysis

Figures 5.15 to 5.18 characterise the Haltwhistle Burn's rainfall regime, including spatial and temporal response, rainfall frequencies and rainfall maxima experienced under a range of durations.

Figure 5.15 presents areal monthly and seasonal rainfall totals for the monitoring period of interest. Results confirm that a typical UK or European precipitation regime dominated; wetter winters and drier summers were generally experienced, with precipitation occurring in all months observed. The months of February-2014 to August-2015 were fairly regular, which was followed by two drier months, and a prolonged period of extreme rainfall totals from November-2015 to January-2016. The latter therefore shaped an annual areal rainfall total of 1289mm, which is significantly (31%) higher than the catchment's 1961-1990 average of 983mm (FEH 2013) or 800-1250mm (Kay *et al.*, 2013; TRT, 2015). In contrast, the 2014 annual total reached 1055mm at the Blenkinsopp Hall gauge.

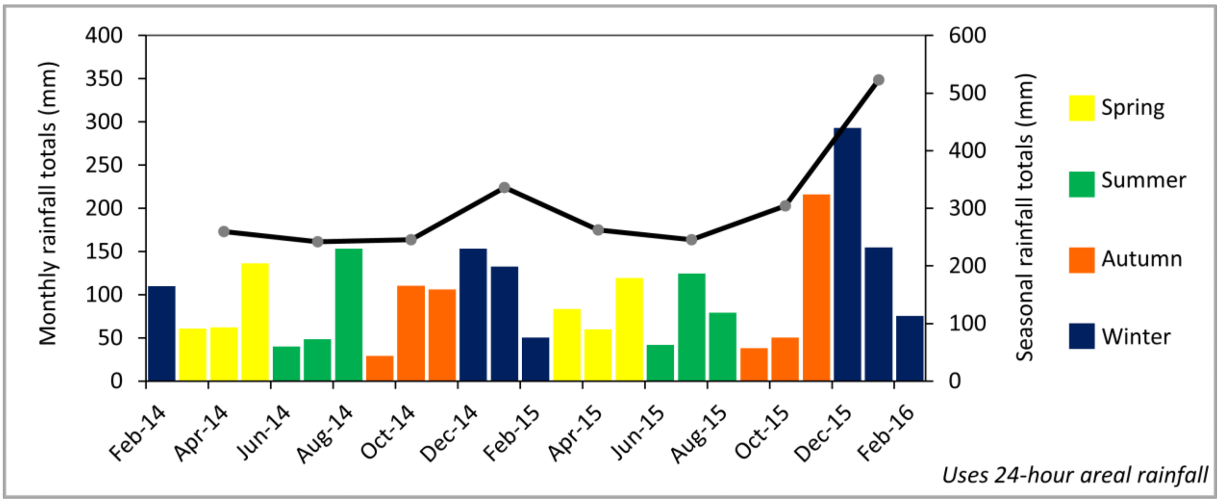


Figure 5.15. Temporal variability: Areal monthly (bars) and seasonal (black line) rainfall totals.

As expected, the 24-hour (daily) rainfall frequency plot exhibits a J-distribution (Shaw *et al.*, 2011) within Figure 5.16, as data are positively skewed towards lower rainfall totals. Extreme (therefore rarer) 24-hour totals are denoted by the histogram's tail (~20-48mm). The monthly frequency plot demonstrates that rainfall totals vary on a monthly basis (101mm on average) and are significantly affected by infrequent high rainfall accumulations. A greater sample of data are required to analyse seasonal and annual totals with sufficient confidence. However, based on the data captured, totals generally fell below 350mm each month and it is clear that the catchment's rainfall regime was dominated by the reoccurring winter 2015/15 storms (523mm). It is also apparent that rainfall was logged by the rain gauges on 623 of the 767 days (81%), which confirms that the Haltwhistle Burn exhibits a typical northern England precipitation regime.

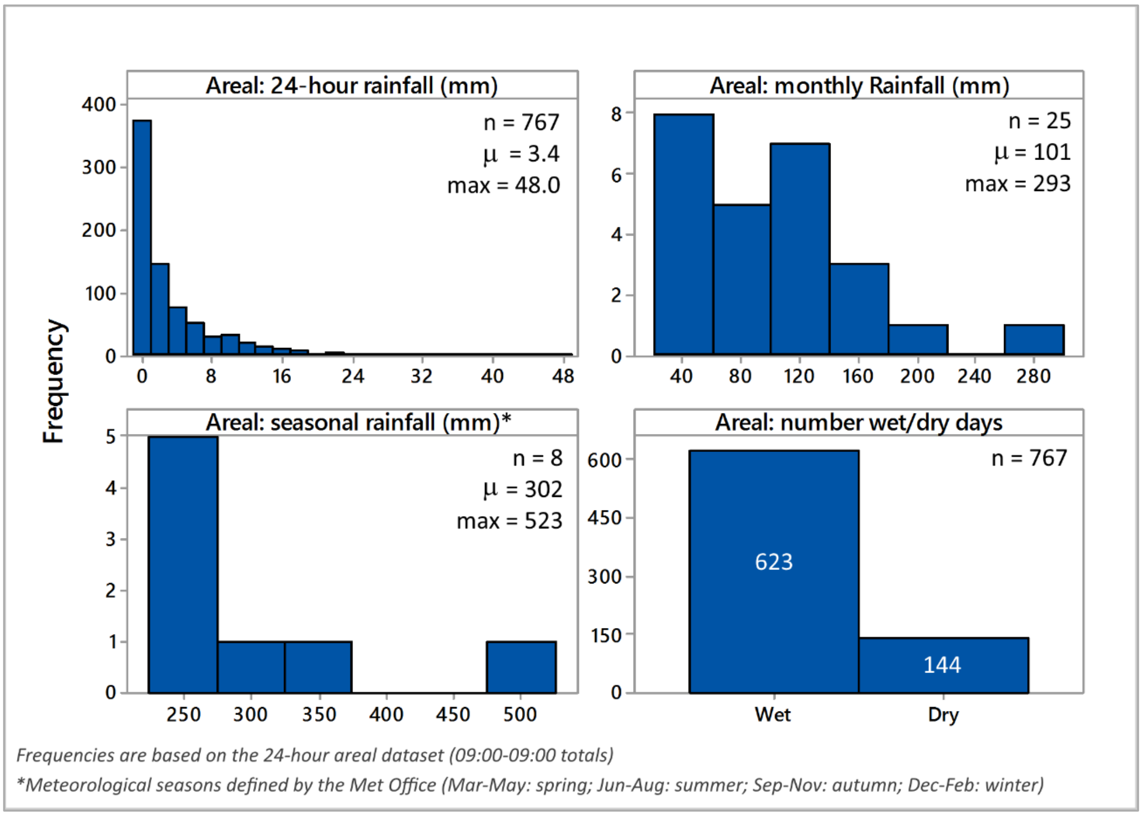


Figure 5.16. Frequency: areal frequency plots used to characterise the Haltwhistle Burn's precipitation regime. See text in figure for season boundaries.

The spatial distribution of rainfall has also been investigated in relation to extreme rainfall (Figure 5.17), cumulative rainfall totals over time, and the hydrological events of interest (Figure 5.18). Rainfall maximums from each gauge (and areal rainfall) have been extracted for a range of durations of interest (where resolutions allow, e.g. 2-min, 30-min, 1-hour and 24-hours). Such durations are important as they induce short and intense rainfall, or prolonged periods of wet weather, both of which can activate flooding. A clear relationship is portrayed between duration and rainfall maxima (highest recorded rainfall total during the monitoring scheme), which denotes that the Haltwhistle Burn experienced a number of short-duration events in the summer and autumn months, whereas prolonged rainfall totals were restricted to winter, and spring was generally less active. These trends are mirrored spatially across each monitoring site. Longer-term (15-month) cumulative rainfall totals (Figure 5.18) were also similar, with Gibbs Hill and

Broomshaw rainfall totals being within 98% of the Met Office Blenkinsopp Hall gauge. This generated a Pearson's correlation coefficient of 0.92 (Gibbs Hill) and 0.98 (Broomshaw) when compared with Blenkinsopp Hall. This means that rainfall regimes in the upper and lower catchment are comparable, and are not significantly dictated by topography.

A closer inspection of event-based rainfall totals (Figure 5.18) indicates that:

- There are no clear patterns between the upper and lower catchment (i.e. the upper catchment does not necessarily experience higher rainfall totals each time);
- Rainfall totals can vary considerably during individual events, emphasising the importance of localised data. Observed totals are affected by the type, strength, direction and position of individual event-based weather systems. For instance, a rainfall rarity assessment (using FEH 2013) estimated that 36-hour rainfall totals on 5th-6th December 2015 had a 1 in 263 year return period (RP) at Broomshaw, yet this was only a 1 in 36 year event at Gibbs Hill;
- The Broomshaw gauge often experienced higher or lower rainfall totals compared with the other two gauges. It is likely that the catchment's gorge feature either traps or shelters the Broomshaw area from event-based precipitation.

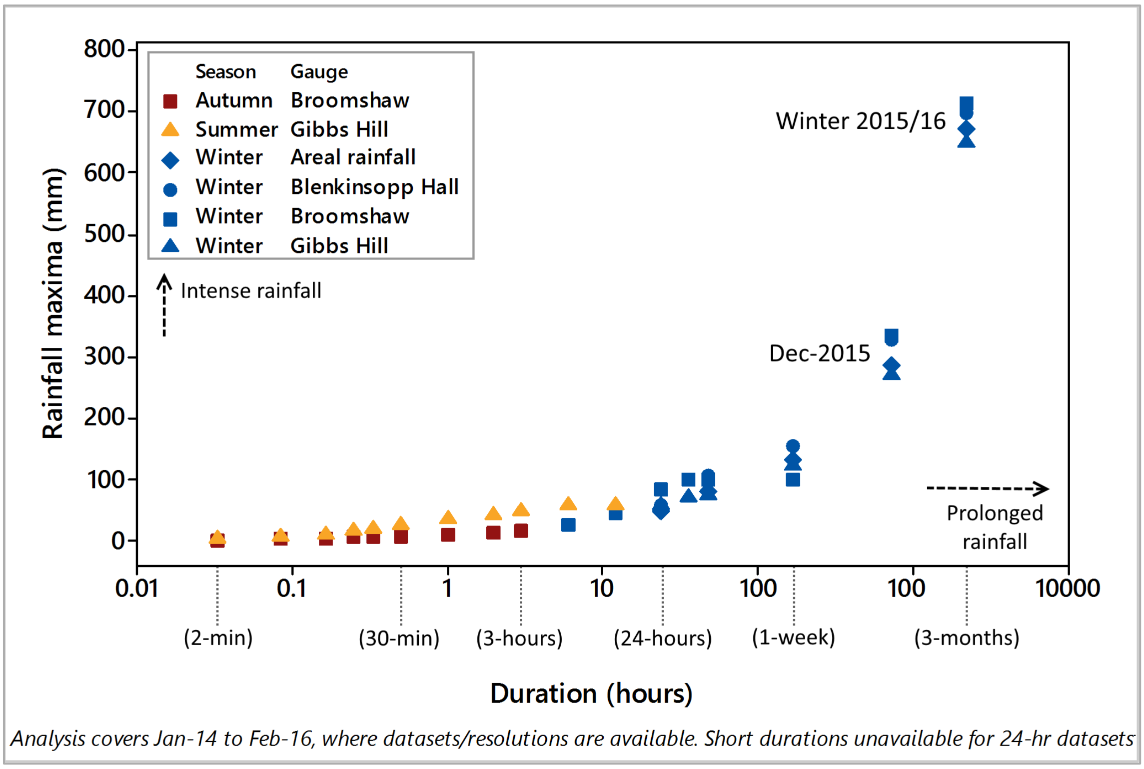


Figure 5.17. Extreme rainfall durations: maximums for each duration specified. Short-duration values are limited due to missing data (Broomshaw) and 24-hour datasets (Blenkinsopp Hall).

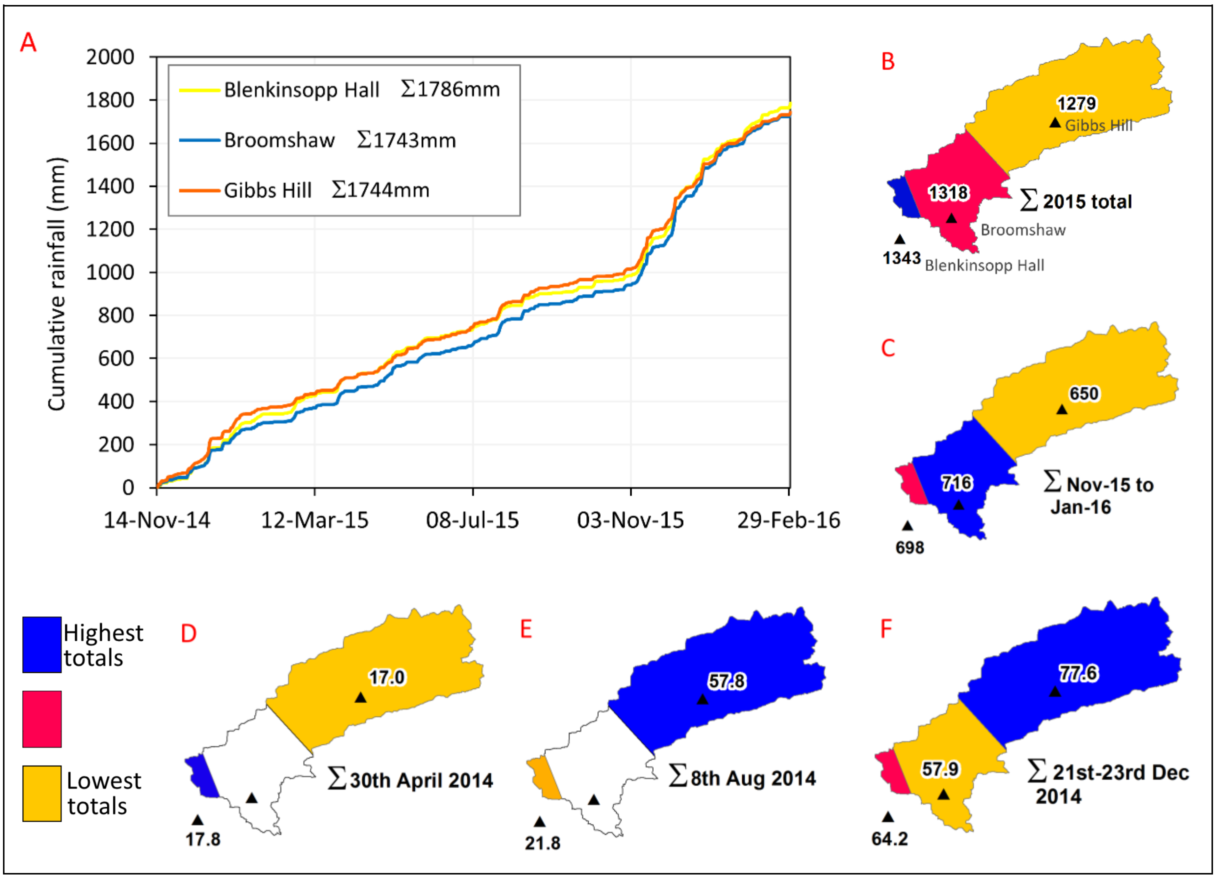


Figure 5.18. Spatial variability: cumulative rainfall totals for each rain gauge (A) and spatial rainfall totals for the events of interest are also highlighted on each Thiessen polygon map (B-F). These are the same polygons used to derive areal rainfall.

Area / region of interest	Nov-15 to Jan-16 rainfall total (mm)	Rank	Source
Solway	919	Wettest	Marsh *et al.*, 2016
North-west England	783		
Tweed	708		
Haltwhistle Burn catchment	**664**		Haltwhistle Burn (areal)
UK	571		Marsh *et al.*, 2016
Yorkshire	444		
England	376	Driest	

Table 5.4. Comparison between winter 2015/16 extreme rainfall totals: national, regional and Haltwhistle Burn figures.

Given the hydrological importance of November-2015 to January-2016, the Haltwhistle Burn rainfall totals have been compared with regional and national figures (see Table 5.4). In summary, the Haltwhistle Burn experienced an exceptionally wet 2015/16 winter, totals which were above the UK, England, Yorkshire and Northumbrian averages. However, rainfall totals were not as severe as those in the neighbouring north-west England, Tweed and Solway regions.

5.3.4.3. *River level and flow analysis*

As expected, rainfall frequencies previously described have dictated river levels experienced across the catchment, therefore temporal discharge patterns. However, as Shaw *et al.* (2011) point out, many factors affect river regimes, including antecedent conditions and land use. Since rainfall is frequent within the Haltwhistle Burn catchment, soils are often saturated, which generates a flashier response. The Haltwhistle Burn's runoff regime has been characterised by Figures 5.19-5.23. The CB at Cleughfoot has been used in many analyses to represent the catchment's response as it is located downstream of the two main tributaries (CB and PGB), and continuous and lengthy datasets exist. Given that Q is directly related to water level, the latter has been included to ensure the winter 2015/16 high flows are covered.

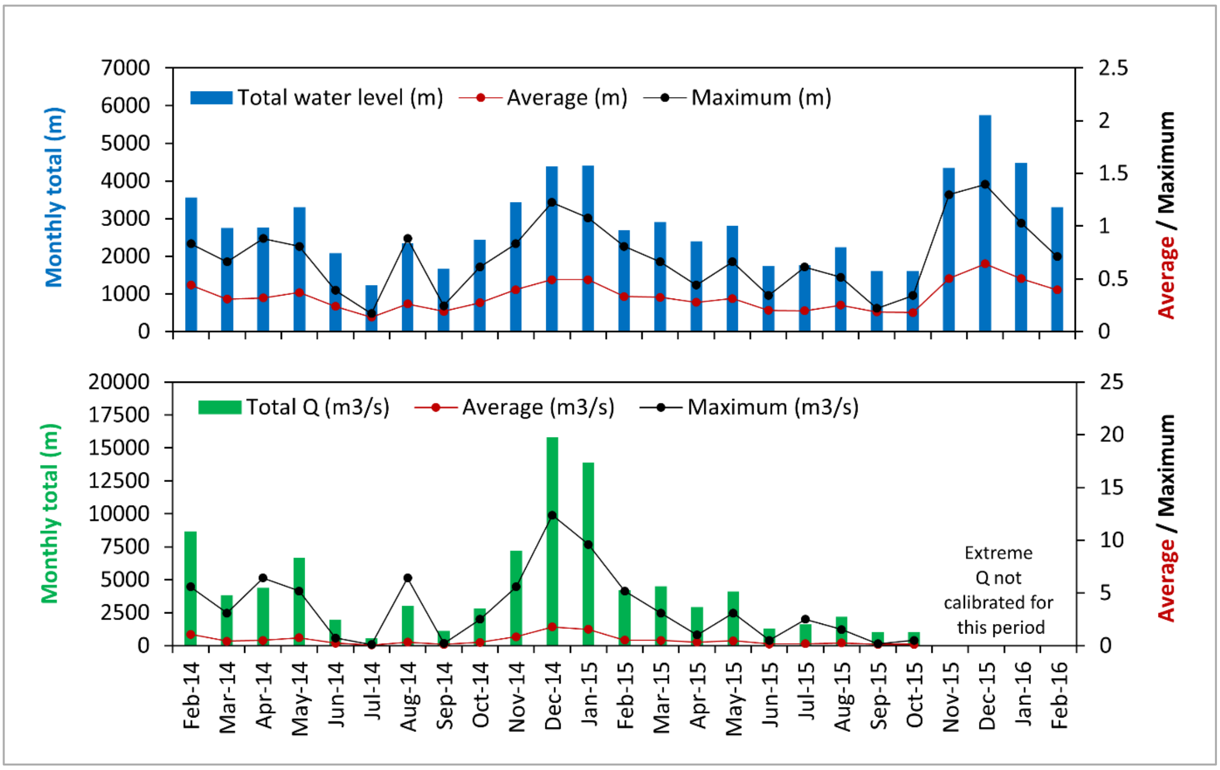


Figure 5.19. Temporal variability: monthly river levels (top) and Q (bottom) for the CB at Cleughfoot. Includes monthly totals, averages and maximums (peaks).

Monthly water (river) level and Q patterns are presented for the CB at Cleughfoot in Figure 5.19. It is clear that levels and flow increased during the winter months, which then declined throughout summer. This created a cyclical pattern which is common across the UK. Substantial peak flows were captured in December-2015, whilst those observed in July-2014 were extremely low. Although monthly averages remained fairly constant throughout the monitoring period, greatest variability stems from peak water levels and Q. Peak water levels (therefore peak flows - Q*peak*) have been investigated further within Figure 5.20, which highlights the top 30 high flow events experienced by the CB at Cleughfoot. Most Q*peak* events materialised during the winter months, and are predominantly biased towards winter 2015/16, including Storm Desmond (5th/6th December). However, a few high magnitude events were associated with spring and summer (30th April and 8th August 2014). It is also noticeable that considerably high flows were experienced on 15th November 2015, which were similar in magnitude to those observed during Storm Desmond.

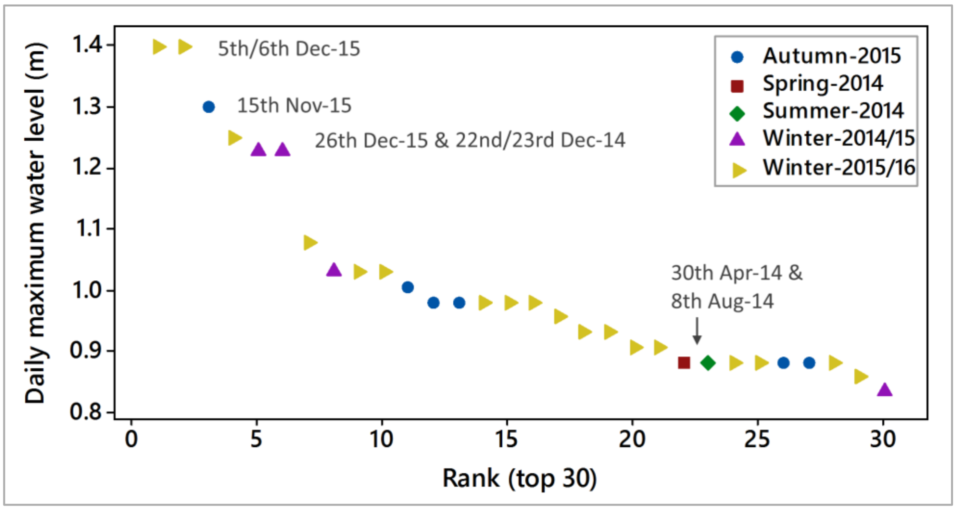


Figure 5.20. Temporal extremes: peak water levels for the CB at Cawfields over the Jan-14 to Feb-16 monitoring period. Top 30 daily maximums are reported.

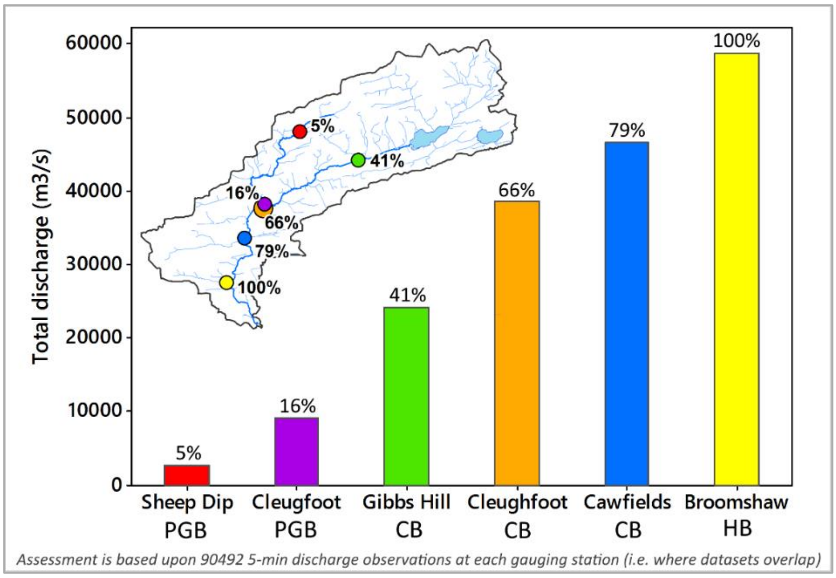


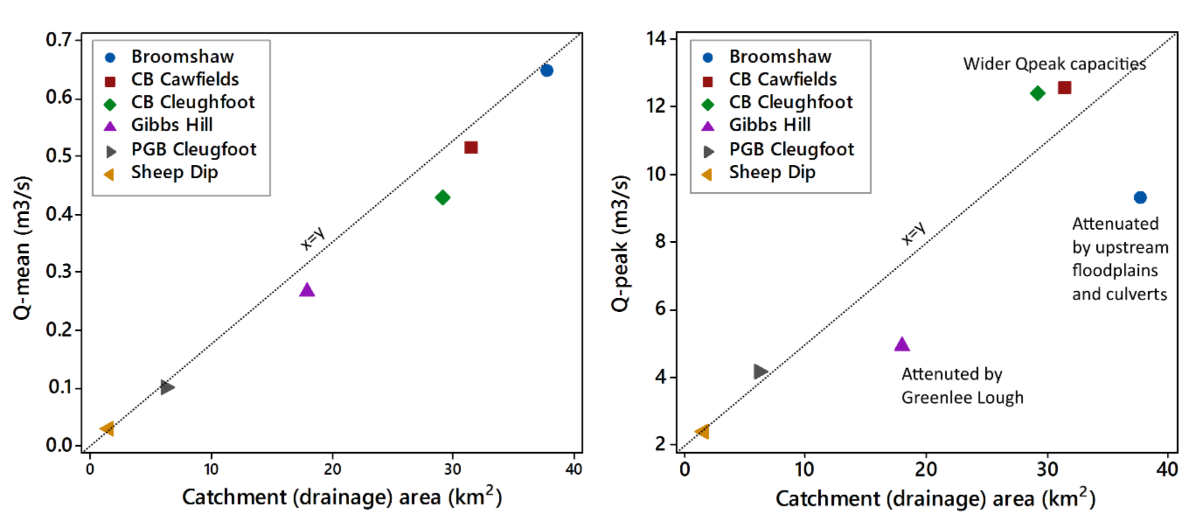
Figure 5.21. Spatial contribution of discharge at a sub-catchment level, relative to Broomshaw. Assessment includes all six gauges where datasets overlap.

Figure 5.21 presents the spatial contribution of discharge throughout the catchment, relative to Broomshaw (labelled as 100%, representing the 'outlet' gauging station). This figure highlights where Q originates from at a sub-catchment level. As much as 41% of the catchments total Q is sourced upstream of Gibbs Hill, and the CB (approximately 50% at the PGB confluence) provides a much greater contribution to downstream flows than the PGB (16%).

Given that discharge contributions (total Q over time) increases with distance downstream, this also advocates that average Q values grow with distance downstream (Figure 5.22). As expected, the highest flows (totals and averages) are therefore experienced at Broomshaw. It would also be reasonable to assume that, as catchment area increases, Q*peak* increases. However, this is not the case within the Haltwhistle Burn catchment (Figure 5.22). Due to the presence of multiple upstream floodplains, subdued elevations in the mid-catchment region, loughs, and various man-made culverts, the HB at Broomshaw experiences lower Q*peaks* than those at the nearest upstream gauge (Cawfields). Whilst this trend could initially suggest that there are errors present within the Broomshaw data, the following points strongly confirm that this phenomenon is an important characteristic of this catchment, which plays a significant role in storing and attenuating Q*peak* upstream of the town during high flow events:

- Elevation data (Figure 3.2) clearly illustrates how there are multiple upstream floodplains and that the Broomshaw gorge area is restricted;
- Based on evidence collected (e.g. flood photographs in Table 5.3) and fieldwork experience, the HB did not flow out-of-bank at Broomshaw (including during Storm Desmond). However, levels frequently spread across the Greenlee Lough, Cawfields and Cleughfoot floodplains, causing widespread flooding;
- Total and average Q values reported for the HB at Broomshaw are still higher (as expected) over time than all upstream gauges, including hydrograph recessions;
- The presence of the Military Road culvert, downstream of the Cawfields floodplain, acts as a hydrological control.

Figure 5.22 confirms that there is a strong linear relationship between the size of the catchment and the average flows experienced, which is then interrupted when attenuation comes into force during high flows. Figure 5.23 reinforces these catchment characteristics.



Assessment is based upon 90492 5-min discharge observations at each gauging station (i.e. where datasets overlap)

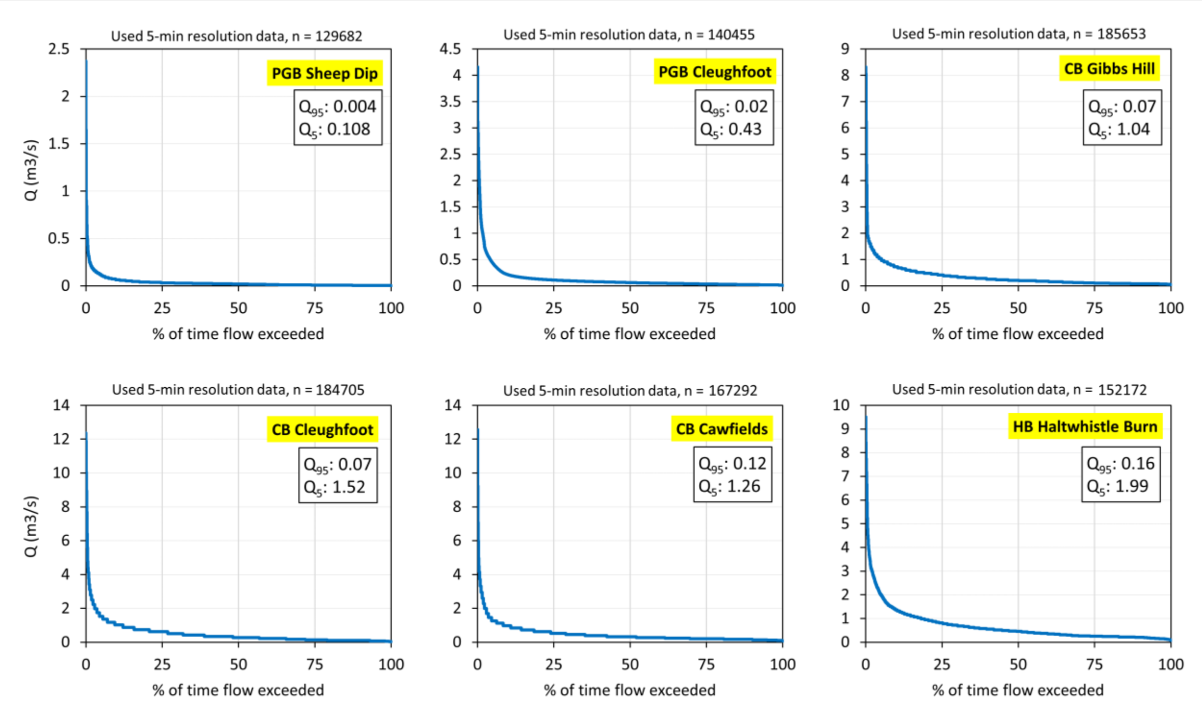
Figure 5.22. Relationship between catchment area, and mean observed Q (left) and maximum observed Q (right) at each gauging station.

Exceedance Probability (Pr): **Equation 5.7.**

$$Pr = 100 \cdot \left[\frac{M}{n+1}\right]$$

(Davie, 2008 Shaw *et al.*, 2011)

Where M is the ranked position of the discharge value and n is the total number of discharge observations (either observed or simulated).



Uses datasets where available between Jan-14 and Oct-15. The winter 2015/16 extremes are not included due to absence of Q datasets.

Figure 5.23. Spatial and temporal: flow duration curves summarising flow frequency signatures at each gauging station. Low (Q_{95}) and high (Q_5) magnitude flows are specified. Note that these extreme percentiles are higher at Broomshaw than all upstream gauges.

Flow duration curves have been created for each gauge to identify flow frequency signatures (Figure 5.23). As Gordon *et al.* (2004) and Davie (2008) describe, flow duration curves are used to characterise how often (percentage of time) a certain flow is exceeded and are particularly useful for identifying high and low magnitude flows (see Q_{95} and Q_5 values on each curve). This 'exceedance probability' (P*r*) has been derived using Equation 5.7 for each individual gauging station. Note that the datasets used to develop these flow duration curves vary in length, and do not contain the winter 2015/16 peak flows due to the absence of Q data (hence peak flow durations are underestimated). In summary, the flow duration curves emphasise how flashy the PGB is and that both the CB at Gibbs Hill and the HB at Broomshaw are more attenuated than other sites. Nevertheless, all six curves suggest that flows are very low for the majority (95-99%) of the time. The Haltwhistle Burn's runoff regime is therefore susceptible to rarer high-intensity and prolonged precipitation events.

5.3.4.4. *Rainfall-runoff*

Rainfall-runoff (RR) coefficients have been calculated for the CB at Cleughfoot using Equation 5.8 to quantify the relationship between precipitation inputs and resulting Q (Table 5.5). Although derived using a different methodology (involving soil categories), the FEH (2013) SPRHOST (standard percentage runoff) catchment descriptor of 0.4788 has also been used to provide an indication of the catchment's observed RR, relative to this estimated catchment descriptor.

Results ascertain how high runoff rates dominate in the winter months, with winter 2015/16 experiencing 215% of the SPRHOST average. This confirms that persistent rainfall and a saturated catchment influenced runoff patterns. Evaporation, interception and storage (e.g. Greenlee Lough area) also dictated summer flows, which were low in both 2014 and 2015. The Haltwhistle Burn's runoff regime therefore experiences clear seasonal trends, with Spring-2014 to Summer-2015 seeing higher runoff rates in comparison to the estimated average (121% for the full 2014/2015 hydrological year). Isolated peak Qs experienced in the spring and summer (e.g. 30th and 8th August 2014) are therefore heavily influenced by the short-duration and high-intensity nature of convective storms, which encourages shorter lag times.

Rainfall runoff (RR) coefficient **Equation 5.8**.

$$RR = \frac{\Sigma Q}{\Sigma P}$$

Where Q is the total discharge (mm) over the period of interest, and P is the total precipitation (mm) over the same period.

Time period	Q (mm)	Areal P (mm)	RR coefficient	% of FEH 2013 SPRHOST (0.4788)
Spring-2014	153	259	**0.59**	123%
Summer-2014	57	244	**0.24**	50%
Autumn-2014	114	244	**0.47**	98%
Winter-2014/15	348	339	**1.03**	215%
Spring-2015	119	262	**0.45**	94%
Summer-2015	53	244	**0.22**	46%
Hydrological Year Oct-14 to Sep-15	633	1099	**0.58**	121%
Total 640 days of data	961	1790	**0.54**	113%

Table 5.5. Rainfall runoff (RR) coefficients for the CB at Cleughfoot.

5.3.4.5. *Summary of catchment characteristics and controls*

Figure 5.24 summarises the characteristics and controls discussed during the former hydro-meteorological analyses. It is important to point out that characterisation has only been possible here because this project specially installed a hydrometric monitoring network; without it, data would not have been available. Trends highlighted throughout Section 5.3.4, such as the occurrence of heavy rain and high flow events, are those which the community-based monitoring scheme should be compared with.

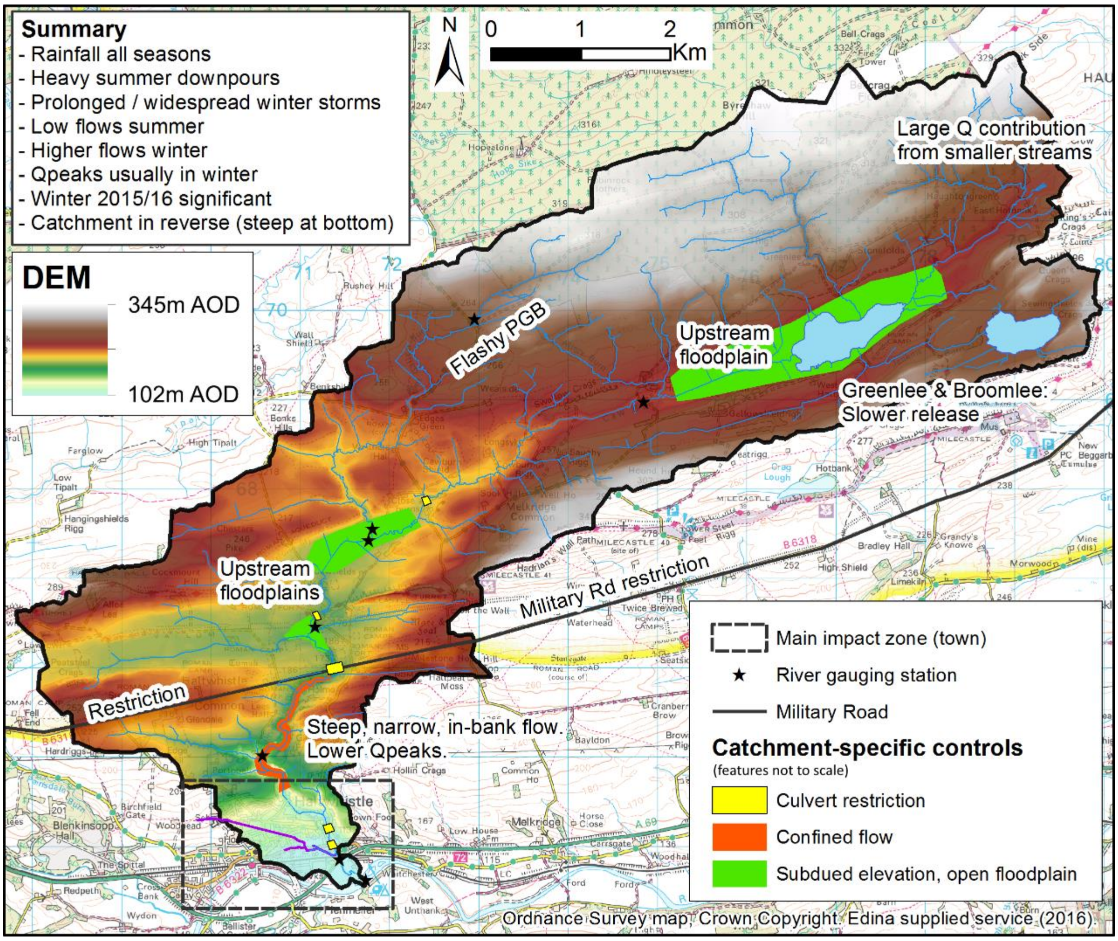


Figure 5.24. Summary of the Haltwhistle Burn's characteristics and hydrological controls.

Feedback and visualisation has already been highlighted as being an important aspect of citizen science. As a result, traditional data summary sheets were handed out or posted to all upstream farmers and land owners involved (who permitted regular fieldwork access and equipment installation on their land) on a seasonal or bi-annual basis.

5.4. Ensuring reliable community-based observations are available for use

5.4.1. Overview - feasibility and availability do not imply reliability

The availability of community-based observations has already been introduced within Chapter 4 during the feasibility assessment. It was highlighted that a heterogeneous set of catchment data was successfully collected and submitted by the Haltwhistle Burn community over the duration of the 29-month monitoring scheme. Rainfall, river level, water quality, sediment (morphological) and extreme weather/flood-related observations now exist for this catchment.

Although a large number of community-based observations were shared by the community, and aspects such as parameter type, spatial and temporal trends, and data resolutions were assessed in Chapter 4, it is important to stress that feasible citizen science monitoring activities and readily available catchment observations do not automatically imply that datasets are reliable or useful. The DQ argument surfaced numerous times during the feasibility assessment, principally because traditional protocols are well-established (as Section 5.3 demonstrated). The main issue is that data users have little control over the monitoring protocols actually implemented; they are relying on the public to accurately represent the catchment environment (Kelling *et al.*, 2015).

5.4.2. Expectations: how do community-based observations differ from traditional data?

Community-based (Chapter 4) and traditional (Section 5.3) datasets have both been individually presented in the context of catchment science, and it is clear that they have their own qualities. Based on direct experience, the two sources of catchment data have been compared with each other in relation to factors which can or will affect DQ (Table 5.6).

An appreciation of the two data types is important at this stage because:

- It affects how data users store, process, analyse and use the data, and how they are able to assess the overall quality and reliability of the data;
- Traditional QA and QC protocols are well-established; it may be appropriate to adopt or adapt existing methods to suit the nature of community-based datasets;

- Community-based data does not need to be kept in isolation. It is possible that the data can be integrated with traditional datasets where appropriate.

Factors which can affect DQ	Traditional (ground-based)	Community-based
Type of data & format	Quantitative, fixed, electronic. Various stages of processing involved.	Quantitative, semi-quantitative and qualitative. Heterogeneous, but mostly electronic. Often direct observations in correct format (except RLGB photos).
Temporal resolution (recording)	Fixed, user-defined, reliable. Lengthy gaps possible due to equipment malfunction, vandalism or theft.	Sporadic, flexible, observer-defined.
Temporal resolution (reporting)	Can be real-time, likely to be in daily/monthly/quarterly batches. But consistent.	A mixture of real-time, daily, monthly, quarterly batches. Some data will not be submitted (generates gaps).
Spatial resolution	Fixed, point-based, predictable but limited coverage.	Mass data, wide coverage, cross-overs (patchwork), private land, unique locations.
Location of observation	Known.	Some are known automatically (e.g. RLGBs), others may be incorrect, unknown or anonymised.
Key sources of error and bias	Instrumental (but sophisticated equipment used), transmission.	Observer, instrumental (simple methods used), data entry, potential sabotage.
Network resilience	'Eggs in one basket' approach – solely relying on a single gauge or piece of equipment.	Accumulation of multiple observations through space and time. Less reliant on specific gauges or observers.
Analysis – compatibility with existing methods	High compatibility.	Potentially low compatibility.
End application (e.g. ability to characterise catchment)	High temporal resolution allows 'regular' and 'extreme' events to be captured, but spatially limited.	Often limited to 'extreme' observations (i.e. interesting events), but benefit from spatial coverage.
Overall expectation	Predictable, consistent. Should ultimately align with equipment specification and intentional network design.	Unpredictable, variable (fuzzy) but potentially unique. Should in theory achieve requirements specified during training phase.

Table 5.6. Factors affecting DQ: comparison between community-based and traditional.

5.4.3. Next steps: QA and QC framework for community-based observations

It has already been highlighted that the quality of hydrological and meteorological data can be controlled both before (QA) and after (QC) the data collection phase (WMO, 2008; 2011; 2017). As there are no specific guidelines to follow for citizen science projects operating in within this discipline (and because most citizen science projects pursue different and innovative collection methodologies), traditional protocols and generic citizen science frameworks were used to develop a project-specific QA/QC framework. The framework (Figure 5.25) has been tailored by taking expectations and experiences outlined in Table 5.6 into account. The framework also summarises four DQ outcomes, which together provide a robust analysis into the reliability of the community-based observations collected (**Research Question 2**). This means that this DQ assessment extends beyond just data 'accuracy', and thus incorporates the fact that the data can hold multiple qualities. This multidimensional concept of DQ is discussed in the traditional and community-based literature (Wang and Strong, 1996; Hunter *et al.*, 2013; Lukyanenko *et al.*, 2016; Leibovici *et al.*, 2017). Wiggins *et al.* (2011) reviewed around 130 citizen science projects and found that 17% only used one validation procedure, and 75% used an average of just 2.5 methods. The Haltwhistle Burn datasets have been quality checked using a wide range of methods; this is important if citizen science observations are to support real catchment applications.

After comparing both the traditional (Figure 5.4) and community-based (Figure 5.25) QA/QC frameworks applied to the Haltwhistle Burn catchment, it is apparent that the mechanisms used to control the quality of data are very alike in places. Both have mechanisms in place to ensure accuracy, precision, consistency, validity, timeliness, correct format and completeness. This is convenient given that (for example) Lukyanenko *et al.* (2016) stress that citizen science observations must meet the standards for professional science. Additional measures were required for the community-based observations though (such as trust, expert reviews and believability), as direct and paired comparisons are not always possible between datasets, and because there are uncertainties arising from not knowing exactly how the data were collected. It is also acknowledged that citizen science projects are typically implemented to obtain data where traditional data are absent. As a result, simple comparisons against traditional datasets are not always possible (Hunter *et al.*, 2013). QA/QC procedures have therefore taken this into account by allowing stages A-D of the framework to be implemented and the community-based data to be accepted first without any traditional information.

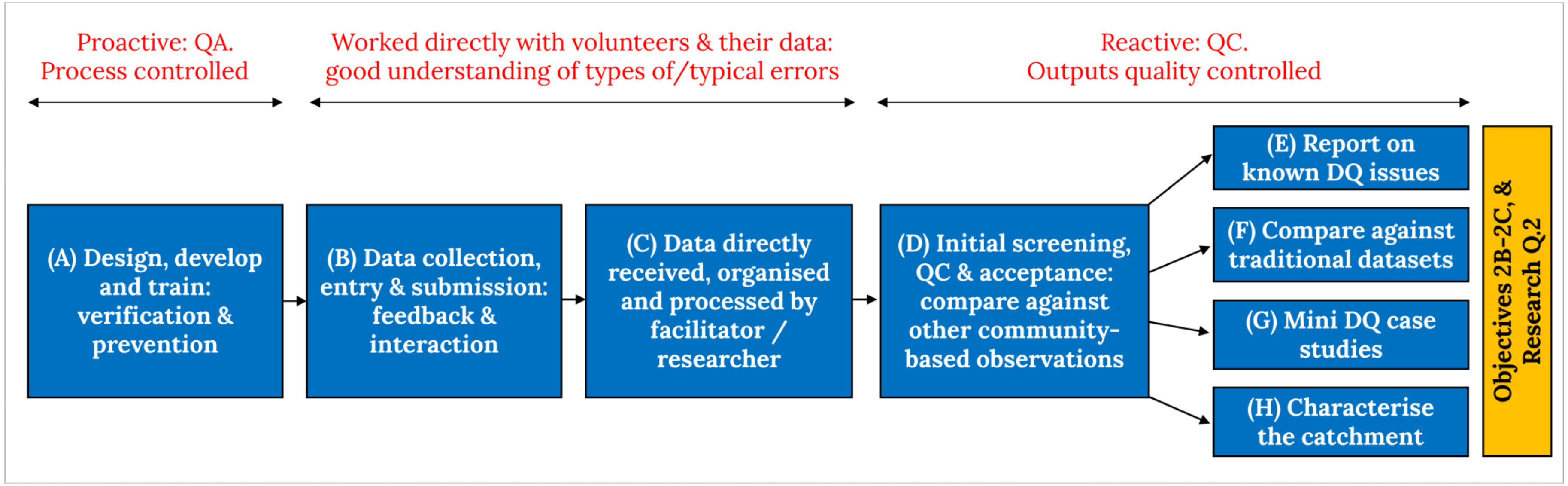


Figure 5.25. Community-based DQ framework adopted (stages A-D) and additional activities implemented to demonstrate the reliability of the data further (stages D-H).

The individual components of this framework are documented within the following sections:

- A-C are summarised below within Table 5.7. They are not discussed here in detail as they have already been introduced during the design and implementation phase (Chapter 4.5);
- D-E are presented within Section 5.4.4-5.4.5;
- F-H are demonstrated separately within Section 5.5.

As Table 5.7 implies, the monitoring scheme was designed with consistency and reliability in mind, and to make the QC process compatible with existing methods. Volunteers were therefore trained and encouraged from an early stage. Receiving data from multiple sources and in multiple formats can easily induce DQ issues. Many of the QA mechanisms were therefore required to ensure mixed observations were managed and stored in a clear and logical way. For instance, all individual observations were paired with date and locational information by including them within the file name (e.g. '2015-12-23 1248*hrs Haltwhistle Burn Broomshaw*'). This was particularly important for flood photographs and videos.

Stage	Mechanisms used to reduce community-based DQ concerns
A) Design, develop & train	To encourage relevant and reliable observations: • Used pre-defined monitoring activities with simple protocols; • Quantitative data to be collected where possible, by multiple observers; • Training: face-to-face, website material and training cards used; • Encouraged correct, consistent, complete and electronic observations to be collected e.g. using web-forms which pre-define data formats and mandatory fields; • Where possible, consistent equipment used, and correct siting and usage. This was supported further by using RLGBs and fixed-point photo posts; • Volunteers encouraged to submit anecdotal information, photographs and/or videos alongside quantitative data, especially when unusual or extreme conditions were experienced; • Encouraged data quality issues to be logged e.g. using the 'rate the quality of your observation' web-form function and within the 'notes' section on data forms; • Ensuring all observations were submitted with date, time and locational metadata information.
B) Data collection, entry and submission	To encourage trustworthy and relevant observations over time, and increase volunteers' confidence: • Kept in contact with regular volunteers throughout the data collection and submission phase, which also allowed participants to ask questions; • Interim feedback using a variety of methods (e.g. during workshops, leaflets, social media and project website); • Adjusted the monitoring scheme based on feedback from initial participants.
C) Data directly received, organised & processed by the facilitator / researcher	Whilst managing and organising observations upon receipt from multiple sources: • Saved observations on receipt (used '*yyyy-mm-dd*' & location in file name); • Adopted a logical file and folder structure; • Kept a copy of raw files and restricted access; • Converted data to usable format where necessary (e.g. RLGB photographs); • Ensured all BST timestamps were available in GMT format; • Compiled observations into databases/spreadsheets & summarised availability; • Followed up any unclear observations with the volunteers themselves, or asked for additional metadata if absent (this was rarely required though); • Hands-on experience with observations as a facilitator - became familiar with regular observers and their data over time, bringing 'trust' into the DQ process.

Table 5.7. Summary of the DQ controls put in place during steps A (before monitoring) and B-C (during and after monitoring) of the DQ framework.

All observations required locations and the observer's name to be anonymised. The location aspect largely applied to the rain gauges as they were situated in private back gardens. Monitoring sites were subsequently renamed (generic but recognisable area) and provided with new coordinates (nearest street/road). Other than observations sourced from social media, it was imperative to anonymise observer names. Participants were assigned an observer number for research and facilitation purposes here (as used in Chapter 4), although end data users would not typically need to know who submitted the data. Although changes to gauge location can induce error, they were regarded as negligible here due to being in close proximity to their original position.

Unlike the traditional hydrometric network presented within Section 5.3, there are limited processing steps required to obtain a final and usable catchment observation. Other than RLGB photographs, all other community-based observations were ready for the initial QC phase. River levels were manually extracted from the RLGB photographs by the researcher, and not the community. This was only applicable where observers did not provide a quantitative estimate themselves. The graduated RLGBs allowed observations to be made to the nearest centimetre.

It can be argued that the design and development stages were more important within the community-based scheme (as oppose to the traditional) because this is when the facilitator or professional has an element of control over the scheme. It is much easier for traditional schemes to be amended or tweaked once the network is live. The post-processing phase is less demanding however for a community-based methodology as the recorded format is generally more direct and meaningful, and hence often in its final format already.

5.4.4. *Initial data screening (QC checks) and acceptance*

The first opportunity to assess the quality and reliability of the community-based observations has been possible here by carrying out an initial data screening and acceptance phase (stage D in Figure 5.25). Data screening and QC checks are mandatory for any traditional monitoring scheme as it is not possible to eliminate or avoid error completely during the data collection phase. For community-based or citizen science data, the following DQ concerns arise:

- Different people are observing the environment and potentially using diverse equipment and/or monitoring protocols (if they do not implement protocols documented during the training phase);
- Monitoring methods themselves are very simple regardless of who implements them;

- The natural world is extremely variable – it is difficult to know what the accurate ('true') observation is;
- Citizen science is adopted to encourage rare or extreme sightings that would otherwise be unaccounted for. QC checks can easily discard unusual reports like these.

A set of initial screening and QC checks were carried here on the community-based data. Checks involved a two-tier procedure; those which were applicable to all, and those which were parameter and data submission technique specific, as described below. Expert judgement, trust, expectations, validity, format and precision have been heavily replied upon.

5.4.4.1. *Screening and QC checks applicable and applied to all observations*

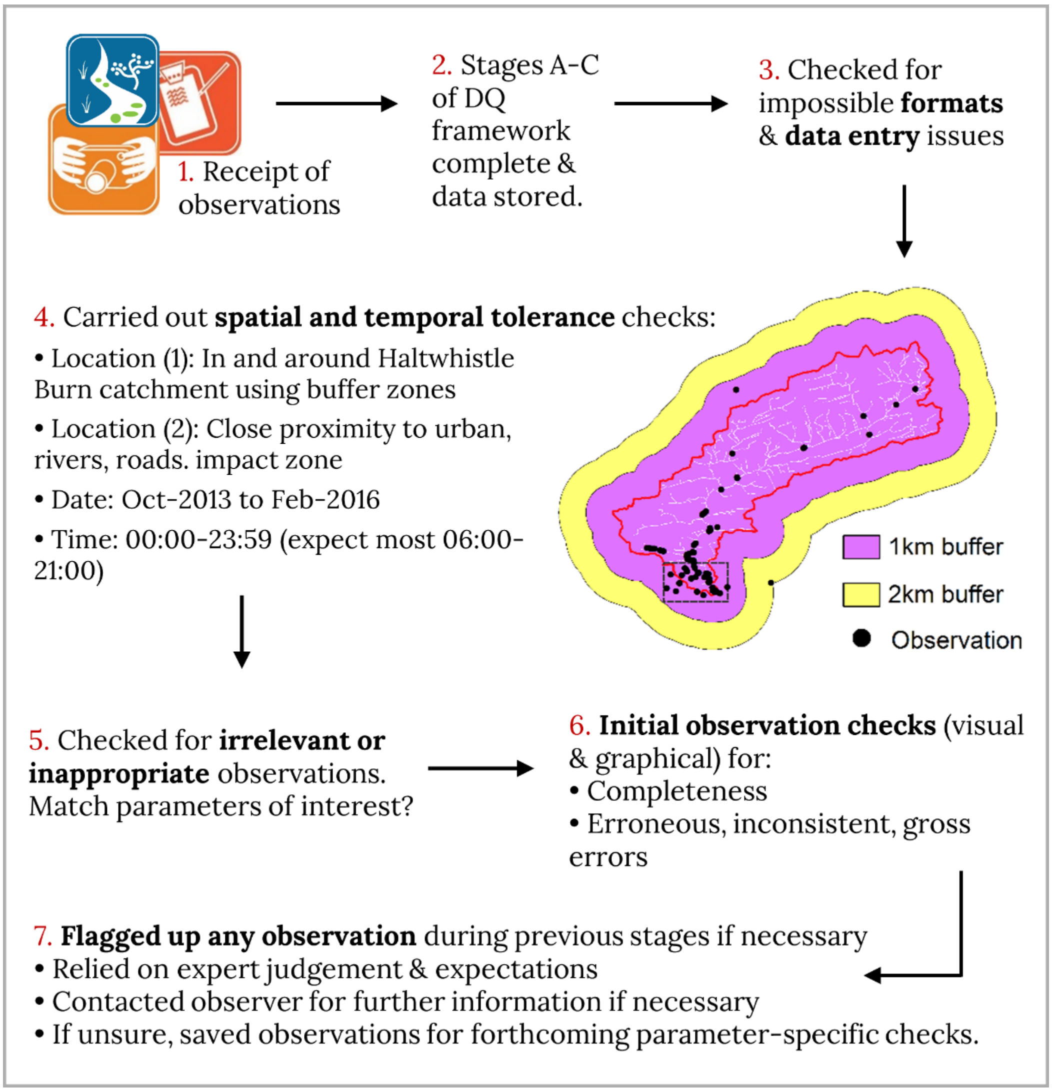


Figure 5.26. Initial data screening and generic community-based QC checks applied.

Figure 5.26 outlines all of the generic screening and QC checks applied to the community-based observations, including catchment-specific tolerance checks. These checks were appropriate for all parameter types and data formats received. The steps outlined in Figure 5.26 essentially created a checklist for incoming observations, before the parameter-specific QC phase. Expert judgement and expectations enabled most observations to pass this initial screening phase. Any problems encountered are summarised below (detailed examples contribute to Section 5.4.5):

- Most observations sourced from the community were in a correct, usable and adaptable format. They were easily identified (e.g. using Excel's data validation tool) and manually corrected if not;
- Although they could have failed initial spatial tolerance checks, it was important to remember that not all observations needed to be contained within the catchment boundary;
- Most (>98%) observations were accompanied with date, time and locational information. Some suspicious locations could also be validated using desk-based and open access tools such as Google Street View. On a few occasions the RLGB observations were not accompanied by location (usually because passers-by submitted them), but because they were collected at fixed and identifiable locations, they were simply assigned a RLGB name;
- All submissions were relevant and aligned with the parameters of interest;
- There were only a few occasions where additional information was requested from an observer. For example, one observer was contacted following the 30th April 2014 flash flood to check whether their camera timestamp was set to BST or GMT. It was noticed because their photographs were offset against all other submissions. Another observer was contacted because a batch of data were missing (created a large gap) during their extended holiday.

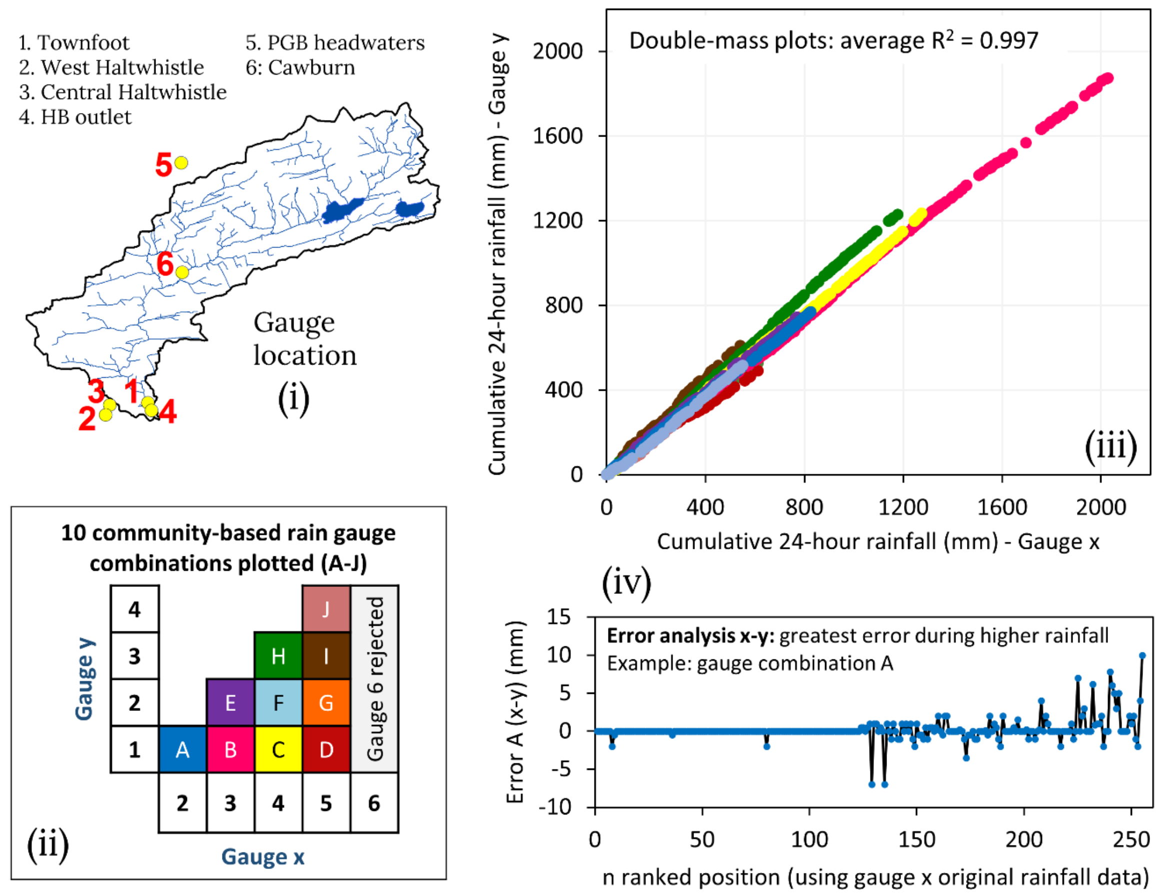
5.4.4.2. *Specific QC checks for each parameter and data submission technique*

Provided that a wide range of parameters had been monitored, it was important to apply specific QC checks to each. These checks were largely based upon the expectation that good quality observations should fall within physical and realistic limits, as defined during the scheme's design phase. Each monitoring method therefore had a finite number of possibilities, many of which fell into a set of pre-defined categories (e.g. the water quality test kits). All parameter-specific QC checks that were applied are described below (i-iii) and in Appendix 5D:

(i) Rainfall (largely quantitative with anecdotes/descriptions)

The following list of bullet points were applied or considered:

- *Temporal* – data should normally fall between 9am-9am (±1 hour), and at the same time each day. This was true for all but the Cawburn gauge, which provided weekly totals;
- *Tolerance and format* – maximum gauge capacity is 50mm, therefore reported values were restricted to 0-50mm, and observed to the nearest millimetre. However, some observers attained extra rainfall readings during storm events (e.g. 4th and 5th December 2015 *'Storm Desmond. The first time my rain gauge in the garden has reached this high!'*);
- *Tolerance and expectations* – timing of extreme rainfall totals (>20mm/24 hours) and number of consecutive dry days (>5 days) were checked to confirm that they are unusual, yet valid;
- *Tolerance and expectations* – monthly rainfall totals should be lower in summer and higher in winter. Annual totals were expected to lie close to a benchmark (average annual totals);
- *Completeness* – checked for gaps (no data) when observers went on holiday. Nevertheless, observers were still able to submit extended rainfall accumulations, which could then be disaggregated based on 24-hour patterns exhibited by nearby gauges. A few gaps existed in some datasets, but were infilled using nearby gauges. Disaggregation and infilling was possible because there were multiple gauges in close proximity to each other;
- *Trust, reliability and consistency* – added confidence that only regular and committed volunteers could observe rainfall over time, which increased consistency. Gauges were also checked and maintained on a regular/daily basis;
- *Cross-checks, triangulation, expectations and expert judgement* – used anecdotal weather descriptions and other parameters (river level) to approve trends and extremes, and check for offsets;
- *Precision and expectations* – visually, graphically and statistically checked data against all other community-based rain gauges (Figure 5.27-5.28 and 5.31). Expected some variability as none of the rain gauges were co-located;
- *Sources of error* – gauges can overflow during intense or prolonged storms. They will also lose some precipitation to evaporation, splash and wind effects, leading to under-catch issues. Although not a major issue here, severe winter ice and snow may cause confusion or induce inconsistencies.



(v)

	A	B	C	D	E	F	G	H	I	J
Close proximity?	✓	✓	✓	×	✓	✓	×	✓	×	×
No. data pairs (n)	255	524	447	147	213	186	147	406	147	79
R^2 (x-y)	0.93	0.95	0.93	0.86	0.94	0.89	0.84	095	0.85	0.81
Pearson's x-y correlation (r)	**0.96**	**0.97**	**0.97**	**0.93**	**0.97**	**0.95**	**0.92**	**0.97**	**0.92**	**0.90**
ΣRainfall - x (mm)	823	2027	1235	612	771	516	612	1178	612	281
ΣRainfall - y (mm)	771	1876	1275	491	746	550	530	1230	541	247
No. wet days - x	133	290	210	103	122	92	103	198	103	48
No. dry days - y	122	261	202	75	118	87	85	194	87	41
Mean - x (mm)	3.24	3.87	2.76	4.16	3.62	2.78	4.16	2.90	4.16	3.56
Mean - y (mm)	3.02	3.58	2.85	3.34	3.50	2.96	3.60	3.03	3.68	3.13
Max – x (mm)	40	60	58	42	35	30	42	49	42	40
Max – y (mm)	31	65	46	31	40	35	40	46	35	30
***Difference* x-y (mm)**	0.21	0.29	0.09	0.82	0.12	0.18	0.56	0.13	0.48	0.43

● A ● B ● C ● D ● E ● F ● G ● H ● I ● J

Some variation expected as community-based gauges were not co-located and were observed by volunteers at different times (between 8-9am)

(vi)

Event of interest	Gauge: 1*
30th April 2014	41
8th Aug 2014	31
Σ 21-23rd Dec 2014	61
Σ Nov-15 to Jan-16	709
Σ 2015	1331

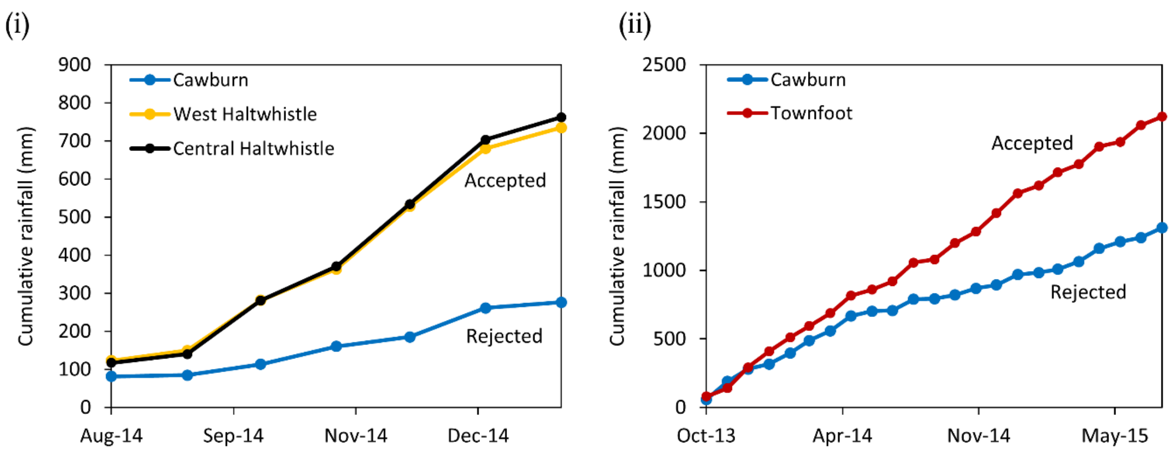
*Where rainfall totals are in mm. 24-hour totals relate to 8.30am on date specified to the following 8.30am.

Figure 5.27. Precision checks: comparing community-based rain gauges against each other. Includes (i) rain gauge locations, (ii) paired gauge combinations, (iii) double-mass plots for each combination, (iv) error plot example (combination A) to illustrate that discrepancies are more noticeable during higher rainfall totals, (v) statistics for each gauge combination, (vi) rainfall totals extracted for the events of interest for the longest running gauge (1 - Townfoot).

Following the aforementioned checks, considerations, and statistical summaries (Figure 5.27 i-vi), gauges 1-5 were accepted for use. Some error was evident given that observed pairs of data did not yield an R^2 or correlation coefficient (r) value of +1. However this was to be expected given that the gauges were located at different sites and were observed at different times (between 8am-9am) by multiple participants, using simple measuring cylinders. Despite these issues, very strong and positive correlations were portrayed during this multi-gauge comparison exercise. Close agreements were evident for nearby gauges within the town (particularly combinations B and E) which deteriorated to some extent when compared with the PGB rainfall totals in the upper catchment. Located at a much higher elevation (264m AOD), this PGB headwater gauge generated greater rainfall totals over time. The double-mass plots (Figure 5.27 iii) suggest that volunteers were able to monitor consistently and precisely, even if they were affected by site-specific variations. It is also apparent that rainfall observations were less precise when larger rainfall totals were experienced (see graph iv). This issue is also inherent with traditional rainfall monitoring schemes, particularly when using different gauge designs (Environment Agency, 2004; Pollock *et al.*, 2014). Nevertheless, where data were available, the community-based rain gauges captured the events of interest (vi). When assessing discrepancies between each pair of x-y rainfall data (v), an average difference of 0.12mm was obtained for gauge combination E, which is remarkably low.

Apart from gauge 4, all datasets were complete and formatted correctly. Gauge 4's observer confirmed that they had a two-month gap in their data because they misplaced their readings. The same observer submitted their data in multiple formats; this caused a transcription error on one occasion, but was easily detected and corrected during this QC process. For instance, rainfall maxima were particularly useful for checking that datasets aligned with each other. Anecdotal notes (such as '*rain most of the day and heavy overnight*' and '*it woke me up*') were abundant when these extremes occurred, providing an additional source of validation material.

QC checks immediately highlighted how gauge 6 (Cawburn) did not yielded reliable results, and has thus been rejected. As Figure 5.28 illustrates, cumulative and annual total checks suggest that this gauge has significantly underestimated rainfall. Nevertheless, the observer highlighted during the submission phase that they were concerned about the quality of their data due to gauge maintenance issues. This indicates that volunteers are aware of DQ and that their supporting anecdotes are useful for detecting problems. This observer also monitored rainfall on a weekly basis and was the only participant involved who did not receive any training (they were monitoring already prior to the project). Cawburn was the only gauge rejected.



Gauge	7-month rainfall total (mm)
Cawburn	276 ← too low
West Haltwhistle	736
Central Haltwhistle	763

Gauge / rainfall estimate	Rainfall (mm)
Cawburn (2014)	613 ← too low
Townfoot (2014)	1125
Average annual rainfall (AAR) (FEH 2013)	983
AAR (TRT, 2015)	800-1250

Figure 5.28. QC checks used to reject gauge 6 (Cawburn), including cumulative plots containing accepted and rejected data, and associated rainfall totals.

(ii) River levels (x3 RLGBs – quantitative or photographs/videos)

The following list were either applied or considered:

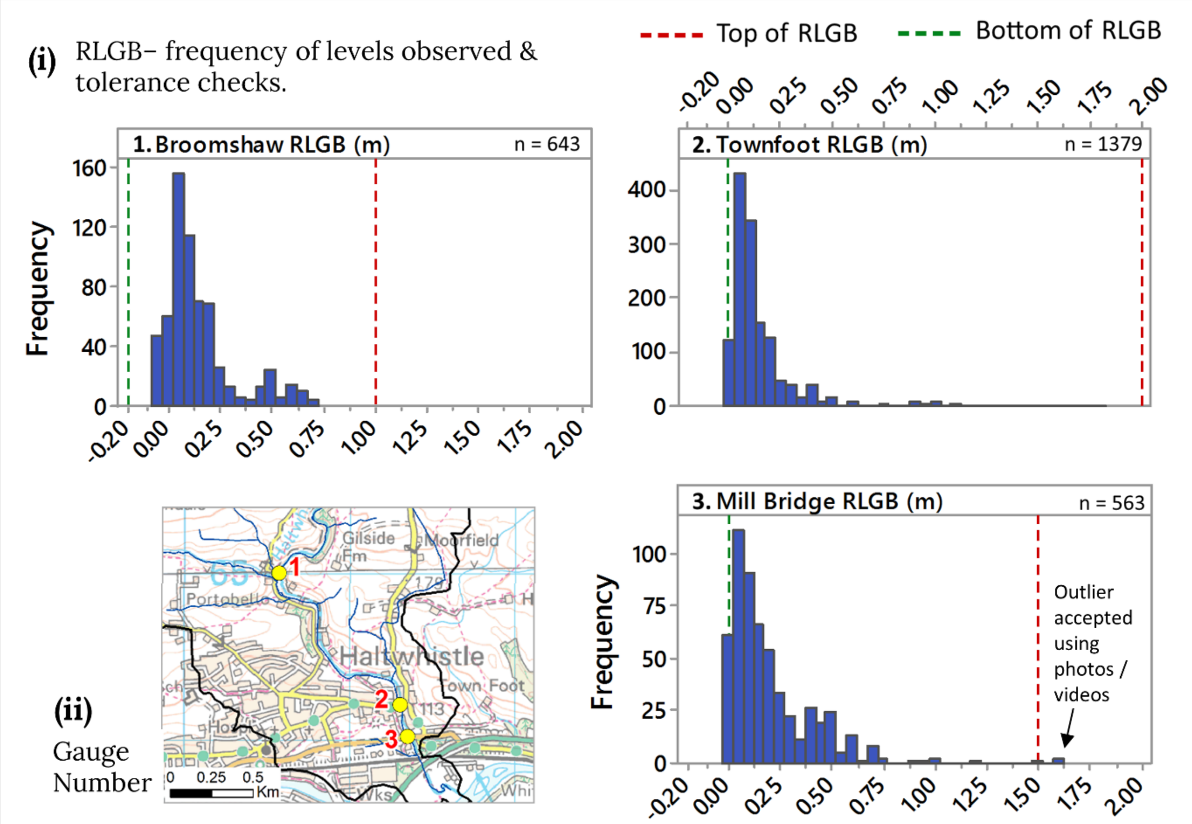
- *Temporal and completeness* – river levels were observed sporadically, hence gaps were expected. Observation completeness was essential (date, time, location and water level);
- *Tolerance and format* - precise 24-hour time-stamp required. Photographs, tweets and web-forms embedded this information automatically;
- *Spatial and consistency* – river levels should only relate to the three RLGB locations where photo posts were erected. RLGB's remained in a fixed position overtime;
- *Tolerance* – all river levels should have been reported to the nearest 0.01m. Site-specific RLGBs dictated possible minimum and maximum water levels (-0.20m ≤ Broomshaw ≤ 1.00m; 0.00m ≤ Townfoot ≤ 2.00m; 0.00m ≤ Mill Bridge ≤ 1.50m).
- *Trust, reliability and consistency* – some volunteers observed on a daily/regular basis which then encouraged consistency. However, one-off observers (e.g. passers-by) always submitted photographs with their observation, a data type which self-verifies;

- *Cross-checks, triangulation, expectations and expert judgement* – used anecdotal weather descriptions, flood photographs/videos and other weather parameters (rainfall) to approve trends and extremes (peaks and troughs), and check for offsets;
- *Precision and expectations* – visually, graphically and statistically checked trends across all three RLGBs (Figures 5.29-5.31). Similar trends were anticipated, but some variability was expected as gauges were not co-located and were affected by site-specific characteristics (e.g. nature of the RLGB cross-section and morphological activity);
- *Sources of error* – only provides 'spot' levels and peaks are missed during high flows. River level photographs vary in quality. River level also naturally fluctuates over the timeframe of a single observation.

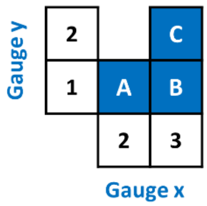
Following the QC checks, including graphical and statistical summaries (Figure 5.29 i-iv), all RLGB observations were accepted for use. It has been a greater challenge to cross-check RLGB observations (as oppose to rainfall) because the data are not paired or logged at regular intervals, the RLGBs have different scales, and each gauge board site has its own set of cross-sectional characteristics. Nevertheless, QC checks have taken into account that the Haltwhistle Burn at Broomshaw, Townfoot and Mill Bridge would typically behave in a similar manner throughout the year, and hence they should correlate reasonably well. It was found that monthly comparisons (e.g. monthly maximum, minimum and average levels, where data points were available) were valuable during this process as it generated pairs of data with respect to extremes and regular baseflow. Other than a few typing/transcription errors, there were no erroneous data points.

Strong and positive correlations (many are over 0.9) were achieved during gauge comparisons when considering maximum and average river level observations, particularly for Broomshaw and Townfoot (iii), which demonstrates precision. Frequency plots (i) and an analysis into the occurrence of peak river levels (iv) also emphasise that observations are relevant, realistic, and aligned within the specified gauge scales. Conversely, correlations deteriorated when minimum levels were assessed, and when Mill Bridge was included in the analysis. A closer examination reveals the following:

- The R^2 and Pearson product-moment correlation coefficients (r) improve as the number of RLGB observations increase. The Townfoot RLGB therefore captured the range of levels experienced more accurately over time, as well as individual peaks;

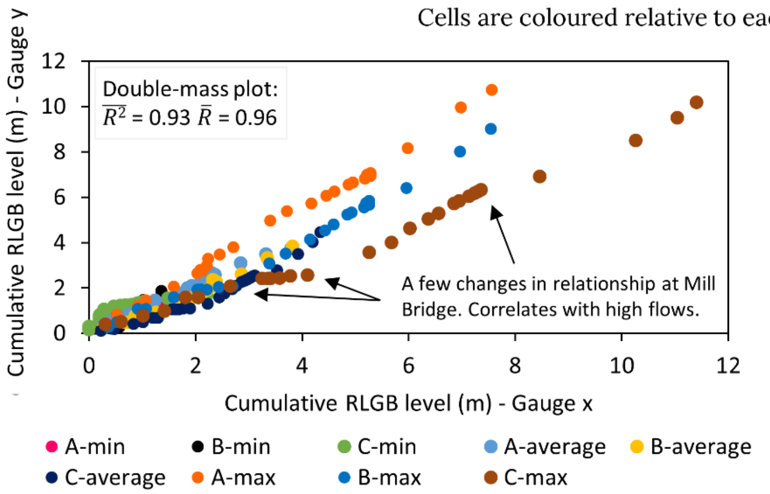


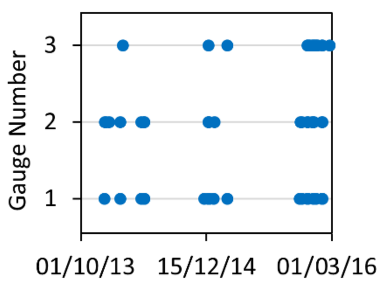
(iii) Cross-checks against each RLGB combination (A-C) using monthly data.



RLGB combination	No. of monthly x-y pairs	x-y		Cumulative x - Cumulative y	
		Correlation r	R^2	Correlation r	R^2
A-maximum	26	0.87	0.76	0.996	0.991
B-maximum	25	0.85	0.72	0.989	0.978
C-maximum	28	0.88	0.77	0.993	0.985
A-average	26	0.94	0.88	0.996	0.993
B-average	25	0.73	0.53	0.986	0.973
C-average	28	0.65	0.42	0.98	0.96
B-minimum	26	0.65	0.42	0.932	0.869
A-minimum	25	0.32	0.57	0.923	0.852
C-minimum	28	0.36	0.13	0.873	0.762

Cells are coloured relative to each other (low = red, high = green)





(iv) Timing of data: top 20 max daily RLGB observations

Figure 5.29. Precision checks: comparing RLGB data against each other. Includes (i) frequency plots and river level tolerance checks, (ii) gauge location, (iii) graphical and statistical (correlation) cross-checks against each gauge combination using maximum, average and minimum levels observed, (iv) temporal checks involving the top 20 daily maximum levels observed.

- Even though it is very unlikely that actual Q*peaks* were accounted for, high flows have been represented at all three sites and they aligned with each other, as have seasonal highs and lows (iv and Figure 5.30). Low and 'normal' flows were less frequently observed as they are not as appealing to the community, and they cannot be monitored continuously;

- The specific location of the RLGB is important; if it is installed within shallow flow or within morphologically active reaches, the cross-section is likely to change over time (particularly following high flows – *"… caused a change in the readings"*). This has been the case at Mill Bridge, and to a lesser extent, Townfoot, as they are located within narrow and culverted stretches of the Burn. Although QC checks highlighted a change in relationship at times (iii), community-based quotes have firmly validated this point and provided an explanation (e.g. *"Burn is now in a narrower channel due to build-up of rocks […] brought down by heavy rain"*);

- When water levels dropped below the level of the RLGB, participants logged this as '0m' or left it blank (*"No water running past board"*), and consequently river behaviour was observed as a straight line during these periods.

Despite the problems noted above, it is still important to stress that individual observations appeared reliable and consistent across all three RLGB sites. The irregular nature of community-based monitoring will inevitably create gaps, which in turn affects any trend analyses. Anecdotes, photographs and videos have been essential during this validation phase.

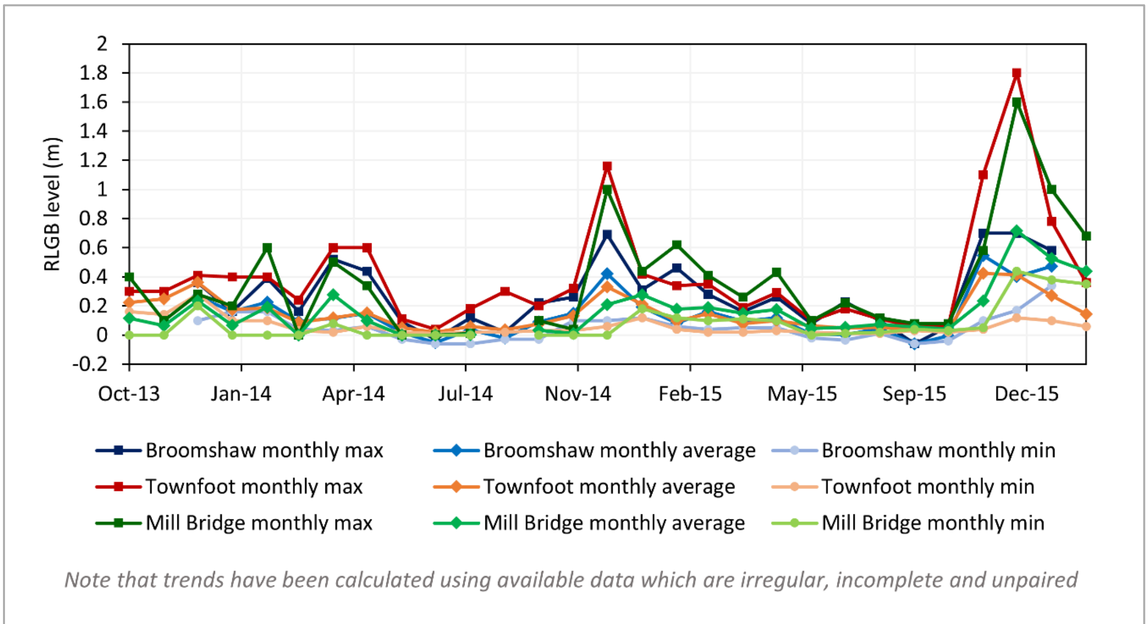


Figure 5.30. Monthly maximum, average and minimum river level observations captured by the community at the three RLGB sites over time. Clear peaks and troughs are visible.

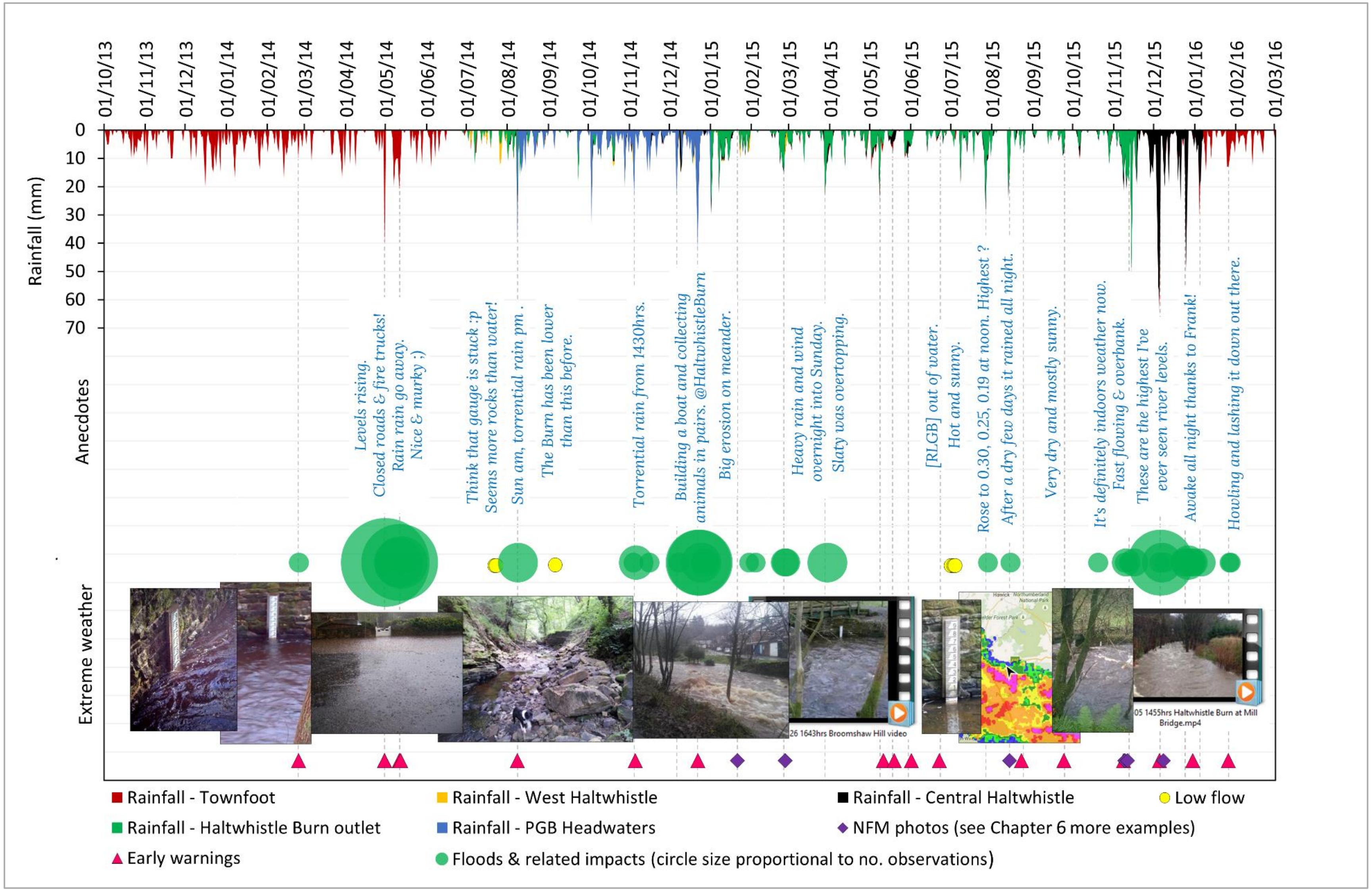
(iii) Photographs, videos, anecdotes (includes NFM and early warnings)

These observations generally provided qualitative river level, NFM and extreme weather related information. Due to the nature of such observations, if they were incorrect, irrelevant or inappropriate, it was not possible to manipulate them for use. The following checks were applicable:

- *Relevance, reliability and expectations* - photographs and videos were self-verifying. Concerns related to whether content was relevant, clear and useable. Good quality images were required, an aspect which appeared to improve over time in line with increased smartphone ownership and improved camera specifications. There were no inappropriate submissions identified; members of the community used these observation techniques as an opportunity to capture extreme weather and river events. Multiple observations were received during 'extremes' which increased their reliability;
- *Completeness* – date, time and locational information were imperative. Over 98% of the observations submitted provided this, others were kept on file but had limited use;
- *Cross-checks, triangulation, expert judgement and precision* – the timing and feasibility of these qualitative observations were assessed during a multi-triangulation approach (see Figure 5.31);
- *Sources of error* – image quality and the exact time of observation.

Despite concerns over the quality of citizen science data, the Haltwhistle Burn observations were largely reliable, complete, precise, realistic, consistent, formatted corrected and trustworthy. Original observations required limited processing and outliers were competently identified. Although many believe that mass data collection reduces consistency and hampers DQ, community-based QC checks benefitted from having multiple observers and parameters involved here as they were used to cross-check or triangulate observations (Wiggins *et al.*, 2011; Bryman, 2016). Photographs and videos are readily seen to be self-verifying, and even well-documented protocols encourage these qualitative observations to be collected for validation purposes (WMO, 2008; Wiggins *et al.*, 2011; Tweddle *et al.*, 2012; Wentworth, 2014a). Hydrological expectations also played an important role in the QC process, particularly the hydrological cycle and catchment connectivity, as rainfall, river levels, water quality, morphology and extreme events are closely related and are expected to converge towards the same conclusions. Since the Haltwhistle Burn community-based scheme provided a patchwork of observations, a final multi-triangulation QC approach was applied before accepting the data (Figure 5.31). This robust approach was not possible during the traditional validation phase due to the lack of qualitative observations. However, it must be iterated that the community-based monitoring methods are simple compared with traditional methods (e.g. semi-quantitative and categorical), and spatial and temporal bias is induced when relying on unpaid volunteers.

Besides being used to cross-check all community-based observations, Figure 5.31 is useful for appreciating that a patchwork of community-based observations (in a variety data formats) are essential for providing a detailed and reliable picture of the catchment's response. Whilst most major 'peaks' were captured by one or more parameters or data format types, the community have still underestimated or missed some (particularly at Broomshaw because it is located north of the town). This is certainly the case for water quality outputs as they were only intended to provide temporal snapshots (similar to Rose *et al.*, 2016), although some clear hydrological trends have been captured (e.g. lower clarity following greater rainfall totals). The water quality tests are also clearly limited by the subjective colorimetric approach and their calibrated quantities, as many readings remained stable over time. Nevertheless, they were still able to represent discrete events.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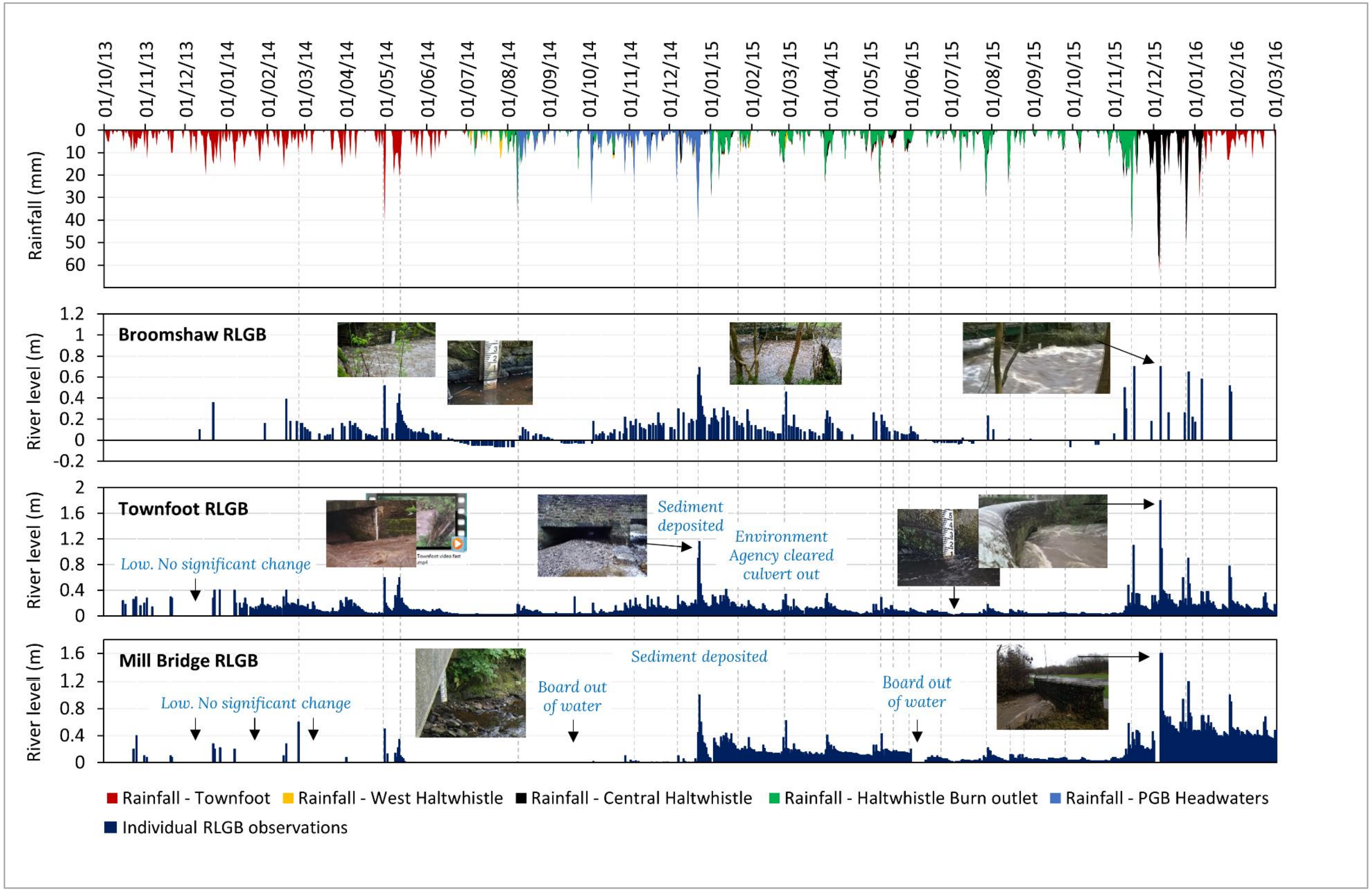
01/07/15
01/08/15
01/09/15
01/10/15
01/11/15
01/12/15
01/01/16
01/02/16
01/03/16
Rainfall (mm)
0
10
20
30
40
50
60
70
Anecdotes
Levels rising.
Closed roads & fire trucks!
Rain rain go away.
Nice & murky ;)
Think that gauge is stuck :p
Seems more rocks than water!
Sun am, torrential rain pm .
The Burn has been lower than this before.
Torrential rain from 1430hrs.
Building a boat and collecting animals in pairs. @HaltwhistleBurn
Big erosion on meander.
Heavy rain and wind overnight into Sunday.
Slaty was overtopping.
[RLGB] out of water.
Hot and sunny.
Rose to 0.30, 0.25, 0.19 at noon. Highest ?
After a dry few days it rained all night.
Very dry and mostly sunny.
It's definitely indoors weather now.
Fast flowing & overbank.
These are the highest I've ever seen river levels.
Awake all night thanks to Frank!
Howling and lashing it down out there.
Extreme weather
26 1643hrs Broomshaw Hill video
05 1455hrs Haltwhistle Burn at Mill Bridge.mp4
Rainfall - Townfoot
Rainfall - West Haltwhistle
Rainfall - Central Haltwhistle
Low flow
Rainfall - Haltwhistle Burn outlet
Rainfall - PGB Headwaters
NFM photos (see Chapter 6 more examples)
Early warnings
Floods & related impacts (circle size proportional to no. observations)

Figure 5.31(A).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01/07/15
01/08/15
01/09/15
01/10/15
01/11/15
01/12/15
01/01/16
01/02/16
01/03/16
Rainfall (mm)
River level (m)
Broomshaw RLGB
Townfoot RLGB
Low. No significant change
Sediment deposited
Environment Agency cleared culvert out
Mill Bridge RLGB
Board out of water
Rainfall - Townfoot
Rainfall - West Haltwhistle
Rainfall - Central Haltwhistle
Rainfall - Haltwhistle Burn outlet
Rainfall - PGB Headwaters
Individual RLGB observations

Figure 5.31(B).

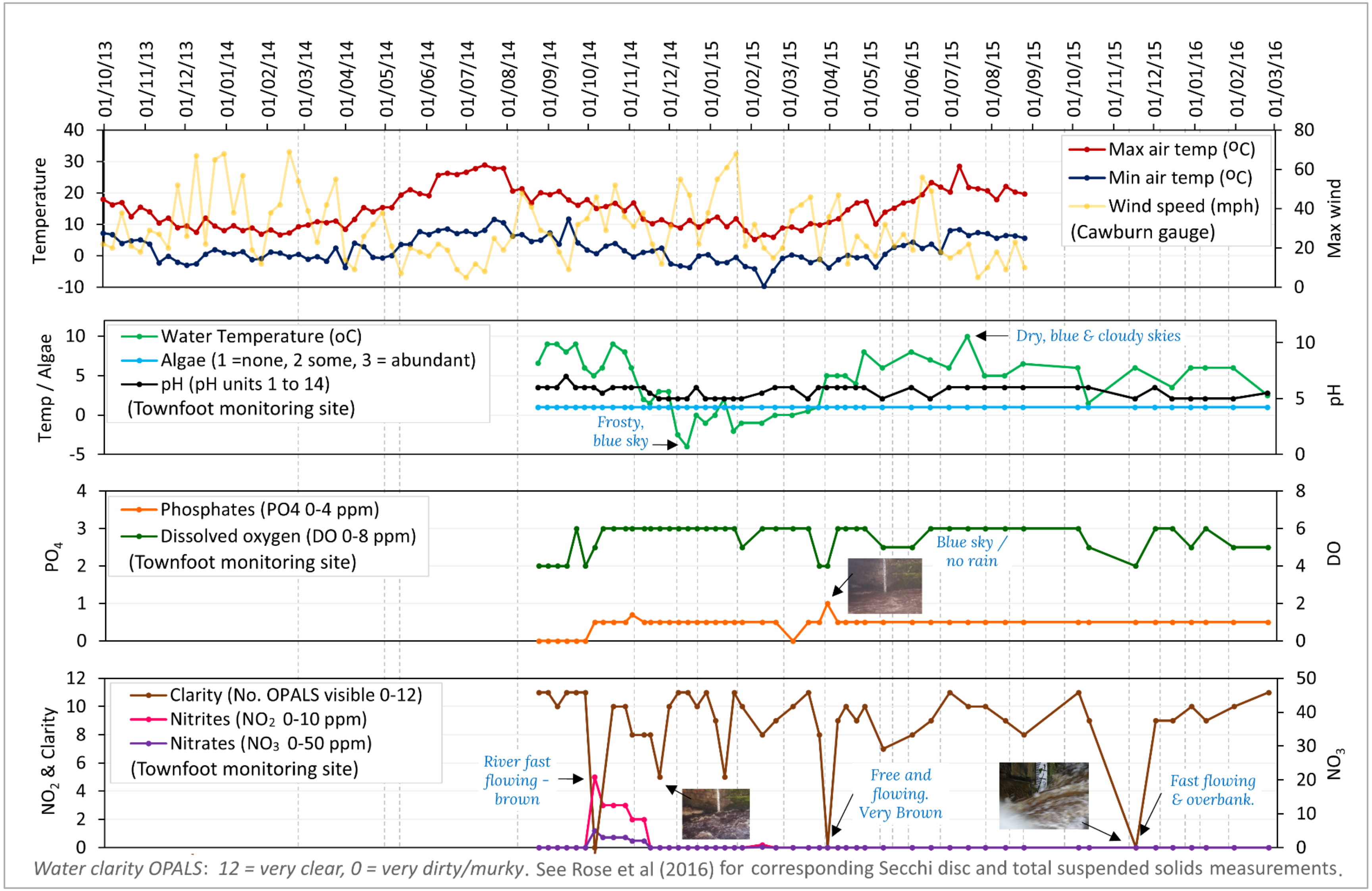


Figure 5.31(C). Multi-triangulation QC approach: includes all datasets and data types collected by the community. Final (accepted) data are plotted across graphs A-C. Appendix 5E contains an extended list of anecdotes used. Dashed grey lines help to illustrate that different data types closely align.

5.4.5. Common issues affecting DQ: what to look out for based on experience

Tweddle *et al.* (2012) argues the importance of pre-defining and understanding DQ issues before launching citizen science schemes. Such knowledge can be used to control the nature of the data collected, manage expectations and reduce errors before and after the data collection phase. The following list of DQ issues have been compiled following the Haltwhistle Burn scheme (see Table 5.8 for specific examples):

- Colour charts (e.g. water quality kits) are affected by printing quality, which disturbs the observation process. Original equipment supplier/manufacturer charts should be used;
- Rain gauges clog easily if they are not maintained regularly, are vulnerable during gardening activities (e.g. grass cutting) and can be disturbed by animals (*"Our dogs will get it if we leave it on the ground." "Will make sure we don't affect the readings when watering the plants"*);
- 'Early warning' data can still be valid even if a hydrological event does not materialise after;
- Parallax errors or inability to extract quantitative information from the RLGB when/if:
    - sunlight reflects off the board, poor visibility persist or when daylight is limited (*"It is dangerous going out at 4am in the middle of the night to check the gauge board"*; *"Too bright for a good photo!"*);
    - vegetation blocks the observer's line-of-sight;
    - the RLGB is located too far away from the designated photo post;
    - dirt, debris and sediment adheres to the board over time;
    - the gauge board is affected by cross-sectional issues and non-uniform flow;
    - the width of the river channel reduces during low flow conditions, leaving the board to dry up and gaps to appear in datasets (*"There is only a trickle"*);
    - Camera specifications vary between devices (applies to any photographic observation or video, although quality has significantly improved over the project's lifetime);

    The above issues impede the end users ability to extract meaningful information manually or automatically using image processing and analysis techniques. Careful site selection is essential;
- Observers may switch or take turns over time, which reduces dataset consistency;

- Regular observers go on holiday which can generate gaps in datasets. Gaps can also be mistaken for 0mm (rainfall) or portray a phenomenon to be absent. A similar issue arises when the community focus their efforts on capturing unusual events, rather than reporting regular or absent sightings;
- It is possible for inappropriate text and images to be submitted. Some members of the public may also want to avoid sharing flood related information ("*Would be reluctant to talk on camera about flooding […] for insurance reasons!*");
- Similar to findings by Rose *et al.* (2016), passers-by are less likely to submit correct and complete observations, compared with regulars who are fully engaged and received training;
- Careful QC checks are necessarily to ensure erroneous data are highlighted for further review. There is a risk of discarding unusual (therefore valuable) sightings during this process (Riesch and Potter, 2014; Lukyanenko *et al.*, 2016), as the 30th April 2014 rainfall totals exemplify (Section 5.5.1.1, Starkey *et al.* (2017) and Chapter 6 have investigated this further);
- Submissions may be accompanied by sarcastic or colloquial language, particularly on social media (e.g. "*Nice & murky [river water] ;)*" and "*Just a bit soggy on @HaltwhistleBurn today [during Storm Desmond]*"). Although this approach supports the engagement process, the full context of the observation must be taken into account when interpreted as hydrological data;
- Data entry, submission and transcription errors cause most problems, including:
    - GMT and BST timestamps; most observers submit their data with local timestamps but end data users may not be aware of this;
    - Date/time of the submission versus date/time of the actual observation. This is common for rainfall observations or when data are submitted retrospectively (e.g. delayed submission on social media). Cameras and social media date/time settings can also be incorrect;
    - Typing and transcriptional errors are induced when data are submitted in invalid or different formats. Walker *et al.* (2016) also describe these issues;
    - When observations are submitted without any (or different) units.

Owing to the abovementioned issues, a monitoring network can be designed to improve the quality, reliability and value of community-based observations by learning from experience gained here.

Variation in photograph/video quality

Automatic time-stamps sometimes incorrect

Unclean RLGB

Incorrect/missing units, dissimilar data formats and typing errors (highlighted red)

@HaltwhistleBurn #haltwhistleburn #riverlevek Townfoot 15/7/14 8.53am

Observation Type	Rainfall
When were your observation(s) taken?	26/09/2015 to 02/19/2015 8 30 am NIL
Rate the quality of your observation(s)	★★★★★

Sunday		0.06
Monday	0,08	
Tuesday		0.12
Wednesday		0.08
Thursday		0.06
Friday		0.08
Saturday		0.06

Day	Rain
1	8.0
2	0mm?
3	Or no
4	data?
5	1.5
6	5.0

Site-specific variations affecting observations (turbulent and sloping stage)

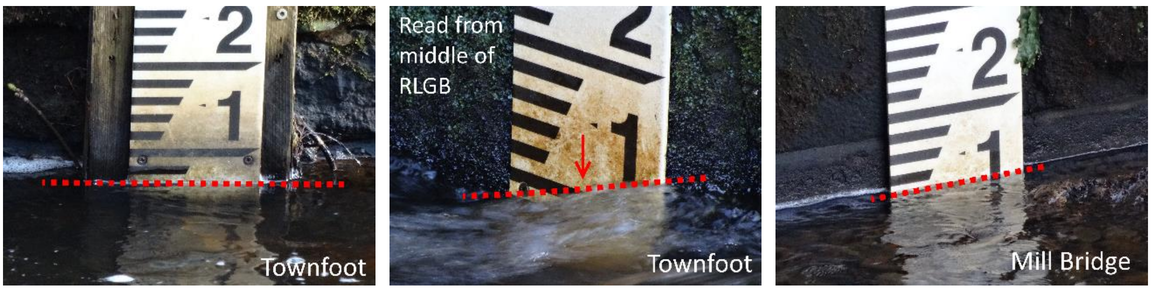


Table 5.8. Examples of data DQ issues encountered during the community-based scheme which can be managed during the QA/QC process.

5.5. Is community-based data reliable?

5.5.1. A comparison against traditional datasets

The accuracy of community-based data have been explored by comparing observations against traditional datasets. Graphical and statistical methods have been implemented to accomplish this, with focus on rainfall, river level and flood data. Graphical techniques largely mirror those previously used during the QA/QC procedures, as promoted by the WMO (2008; 2011; 2017) and O'Donnell (2012), including regression, mass-balance, time-series and spatial plots. Various statistical techniques have been applied, including the coefficient of determination (R^2), Pearson product-moment correlation coefficient (r), percentage bias (PBIAS) and average difference ($\overline{Difference}$), to quantify error and bias (Equations 5.9-5.12, which have been calculated automatically using Microsoft Excel and Minitab 17). These outcomes have been particularly useful for examining paired data (x = traditional, y = community-based, both with a GMT time-stamp), offering direct comparisons against different gauges and parameters, and have been used elsewhere to evaluate other community-based projects (Gollan *et al.*, 2012; Rose *et al.*, 2016; Storey *et al.*, 2016).

Coefficient of determination (R^2): **Equation 5.9.** (Krause *et al.*, 2005)

$$R^2 = \left[\frac{[\sum_{i=1}^{n}(T_i - \overline{T})\,(CB_i - \overline{CB})]}{\sqrt{\sum_{i=1}^{n}(T_i - \overline{T})^2\,(CB_i - \overline{CB})^2}}\right]^2$$

Where T = Traditional data point and CB = Community-based data point. n = total number of observations. Pairs of T and CB data are evaluated across the same time period/step. Provides an R^2 value between 0 to +1 to describe the degree of collinearity.

Pearson product-moment correlation coefficient (r): **Equation 5.10.** (Krause *et al.*, 2005)

$$r = \left[\frac{[\sum_{i=1}^{n}(T_i - \overline{T})\,(CB_i - \overline{CB})]}{\sqrt{\sum_{i=1}^{n}(T_i - \overline{T})^2\,(CB_i - \overline{CB})^2}}\right]$$

Output value between -1 and +1 as an index of the degree linear relationship.

Percentage Bias (PBIAS): **Equation 5.11.** (Moriasi *et al.*, 2007)

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(T_i - CB_i)\cdot 100}{\sum_{i=1}^{n}(T_i)}\right]$$

Output as a percentage (%) to describe the overall magnitude of the CB data against T (+'ve = underestimation, -'ve = overestimation).

Average difference ($\overline{Difference}$) of all x-y pairs in the dataset **Equation 5.12.**

$$\overline{Difference} = \frac{\sum_{i=1}^{n}(CB_i - T_i)}{n}$$

Output presented in the units of the variable being observed (+'ve = over-estimation, -'ve = underestimation).

As already mentioned, it has not been possible to assess every DQ aspect due to high volumes of community-based data being submitted, and because it was unfeasible to co-locate all monitoring sites with traditional monitoring devices. It is also difficult to carry out direct comparisons when data formats and measurements do not necessarily align, which Storey *et al.* (2016) also found. However, prominent examples are presented to illustrate concordance and reliability of quantitative observations where possible.

5.5.1.1. *Rainfall comparisons*

Community-based rainfall data introduced within Section 5.4.4 have been directly compared against nearby traditional gauges where datasets overlap. Figure 5.32 illustrates how a multi-gauge comparison has been carried out; 14 combinations (paired x-y data) have been used to demonstrate reliability at 24-hour, monthly and seasonal resolutions. Regression (direct x-y comparison) and double-mass plots (cumulative x-y comparison) can be found in Figure 5.33 for each gauge combination, accompanied by relevant summary and correlation statistics in Tables 5.9-5.11. Monthly and seasonal datasets have been created by aggregating 24-hour observations.

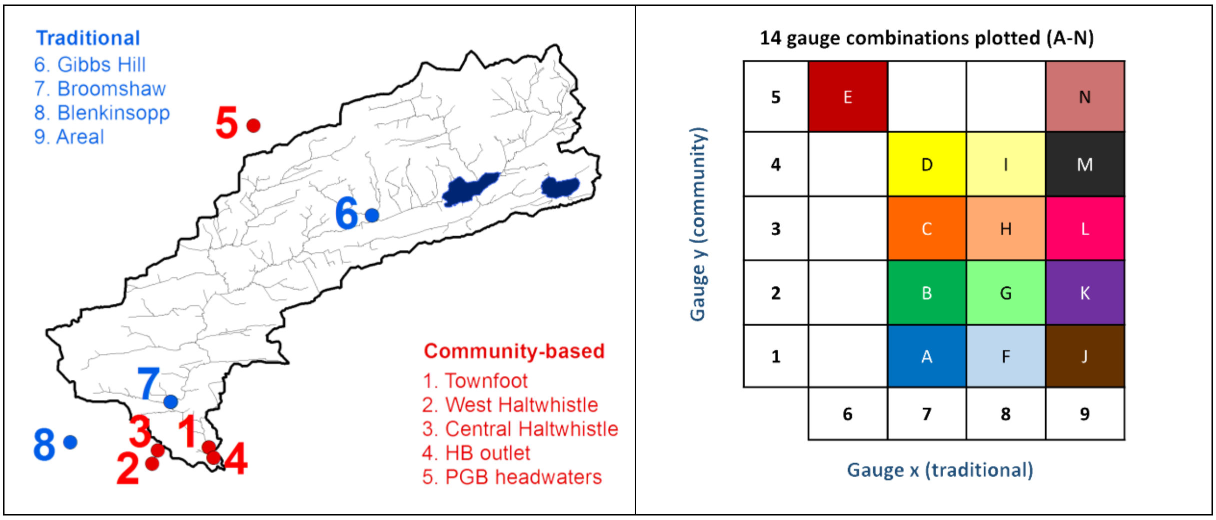


Figure 5.32. Spatial combination of all traditional (x) and community-based (y) gauges analysed. Combinations were dictated by availability and resolution of the datasets.

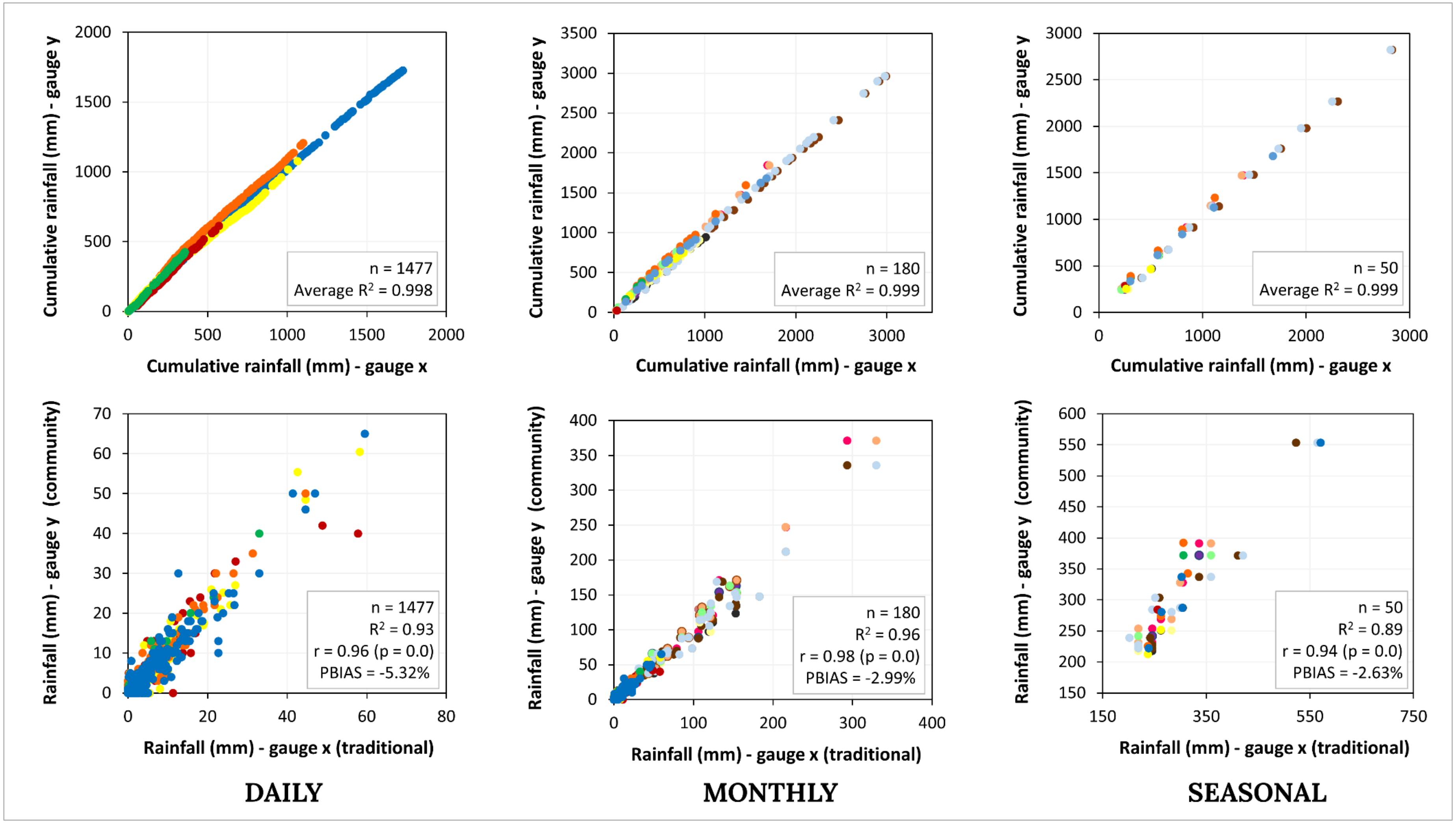


Figure 5.33. Double-mass (cumulative x-y) and regression (direct x-y) plots for each rain gauge combination using daily, monthly and seasonal data. Colours relate to gauge combinations in Figure 5.32.

Daily					
	A	B	C	D	E
n (no. of pairs of daily data)	473	110	421	326	147
R^2 (x-y)	0.92	0.90	0.95	0.95	0.86
r (x-y)	**0.96**	**0.95**	**0.98**	**0.97**	**0.93**
PBIAS (%)	0.08	-18.86	-10.42	-1.20	-7.04
ΣRainfall (mm) – x	1727	358	1548	1064	571
ΣRainfall (mm) – y	1726	426	1709	1077	612
Wet days – x	353	85	310	226	122
Wet days – y	240	63	234	157	103
Mean (mm) – x	3.65	3.25	3.68	3.27	3.89
Mean (mm) – y	3.65	3.87	4.06	3.00	4.16
Max (mm) – x	59	33	58	58	58
Max (mm) – y	65	40	60	60	42
$\overline{Difference}$ x-y (mm)	-0.003	0.6	0.4	0.04	0.3

Table 5.9. Correlation and summary statistics for each gauge combination: **daily rainfall**

Monthly														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
n (monthly)	15	3	13	10	4	29	8	16	12	29	8	16	13	4
R^2 (x-y)	0.99	0.99.	0.98	0.90	0.97	0.96	0.97	0.99	0.96	0.94	0.91	0.98	0.91	0.99
r (x-y)	**0.99**	**0.99.**	**0.99**	**0.94**	**0.99**	**0.98**	**0.99**	**0.99.**	**0.98**	**0.97**	**0.95**	**0.99**	**0.95**	**0.99**
PBIAS (%)	-0.06	-21.68	-10.16	2.32	-8.07	0.53	-8.98	-8.00	3.45	0.98	-3.97	-9.30	6.66	-13.90
ΣRainfall - x	1679	306	1449	765	421	2979	747	1708	938	2992	783	1688	1010	399
ΣRainfall - y	1681	372	1597	747	455	2963	815	1845	905	2963	815	1845	943	455
Mean – x	112	102	111	76	105	103	93	107	78	103	98	105	78	100
Mean – y	112	124	123	75	114	102	102	115	75	102	102	115	73	114
Max – x	330	131	330	127	165	330	154	330	154	293	154	293	153	154
Max – y	325	165	362	152	170	336	163	371	152	336	163	371	152	170
$\overline{Difference}$ x-y (mm)	0.07	22	11	-2	8	-0.5	8	9	-3	-1	4	10	-5	15

Table 5.10. Correlation and summary statistics for each gauge combination: **monthly rainfall**

Seasonal														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
n (seasonal)	5	1	4	2	1	9	2	5	2	9	2	5	2	1
R^2 (x-y)	0.97		0.87			0.94		0.90		0.93		0.98		
r (x-y)	**0.98**		**0.93**			**0.97**		**0.95**		**0.96**		**0.99**		
PBIAS (%)	-0.06		-10.30			-0.22		-6.93		0.26		-5.68		
ΣRainfall - x	1679	306	1119	499	256	2816	577	1378	501	2829	582	1394	508	245
ΣRainfall - y	1681	372	1235	465	285	2822	614	1474	469	2822	614	1474	469	285
Mean – x	336		280	250		313	289	276	251	314	291	279	254	
Mean – y	336		309	232		314	307	295	234	314	307	295	234	
Max – x	571		314	263		564	359	359	283	523	336	336	262	
Max – y	554		392	252		534	372	391	251	554	372	391	251	
$\overline{Difference}$ x-y (mm)	0.2		29	-17		0.7	18	19	-16	-0.8	16	16	-20	

Table 5.11. Correlation and summary statistics for each gauge combination: **seasonal rainfall** (analysis limited by availability of data at this resolution). Seasons are defined in Figure 5.16.

Results presented so far clearly demonstrate how community-based rainfall observations collected within the Haltwhistle Burn catchment are strongly (and positively) correlated with nearby traditional ground-based gauges. Consistently high R^2 and Pearson correlation coefficients suggest that community-based data can be as reliable and accurate as traditional data sources under the resolutions explored. This outcome does however assume that the traditional gauges are 'accurate' (accepted during the QC process). There are no significant or obvious outliers visible, although greater variability is (as expected) exhibited at higher rainfall totals. Regression and correlation analyses are heavily affected by outliers, but they remain high across all gauge combinations, which supports the previous point made. Individually (Tables 5.9-5.11), all gauge correlation coefficients (r) lie above 0.9 (i.e. very strong relationships). When all datasets are combined (Figure 5.33), correlation coefficients are as high as 0.96 (daily), 0.98 (monthly) and 0.94 (seasonal), which is exceptionally high considering that none of the gauge combinations were co-located side-by-side. These correlation coefficients are also accompanied by p-values of 0.0, meaning that the results presented are significant and reliable. One of the 'best' performing gauges was Townfoot (Figure 5.34) which closely correlates with the traditional gauges at Broomshaw and Blenkinsopp Hall (e.g. Townfoot has a PBIAS of -0.06% and $\overline{Difference}$ of 0.07mm because it only overestimated the 15-monthly rainfall total by 2mm). On the other hand, the PGB Headwater gauge is regarded as one of the 'worst' performing gauges as it exhibits most scatter (Figure 5.35), yet regression (0.86) and correlation (0.93) values are still strong and significant. This gauge also coincides with being at the highest elevation within the catchment and it is located the furthest away from its traditional counterpart (3.3km from Gibbs Hill).

PBIAS results suggest that some gauges over-estimated rainfall, and others underestimated. Variability can be associated with site-specific, observational, and gauge-specific installation inconsistencies. While many of these errors are inevitable, they could be minimised further by enforcing stricter monitoring protocols (which could then reduce the number of participants involved, hence a careful balance is required). However, when assessing all datasets together, daily, monthly and seasonal rainfall totals are over-estimating rainfall slightly (by 5.32%, 2.99% and 2.63% respectively). Although these PBIAS results are still remarkably low, errors can be generically assigned to the monitoring method itself (i.e. volunteers using a simple gauge). Nevertheless, these percentages are lower or similar to those discussed within the traditional rain gauge literature. For instance, an Environment Agency (2004) study found that the TBR gauge caught at least 5% less precipitation than the standard 5" Met Office gauge. The same study also claims that the TBR gauge could have a 10-30% error when observing intense rainfall.

Pollock *et al.* (2014) also found that traditional straight-sided TBR gauges observed 15% less precipitation than the aerodynamic design. Gauge design can also explain why the community-based gauges did not observe identical maximum rainfall totals.

Data are better correlated when analysed at monthly resolutions as this reduces the influence of daily/sub-daily variability (which is naturally anticipated). Correlation was expected to improve further when analysing seasonal trends. However, the latter are affected by the limited number of data points available for analysis. Nevertheless, acceptable results are obtained across the daily, monthly and seasonal multi-gauge comparisons. This means that this catchment's rainfall regime was reliably represented using volunteers and simple manual rain gauges.

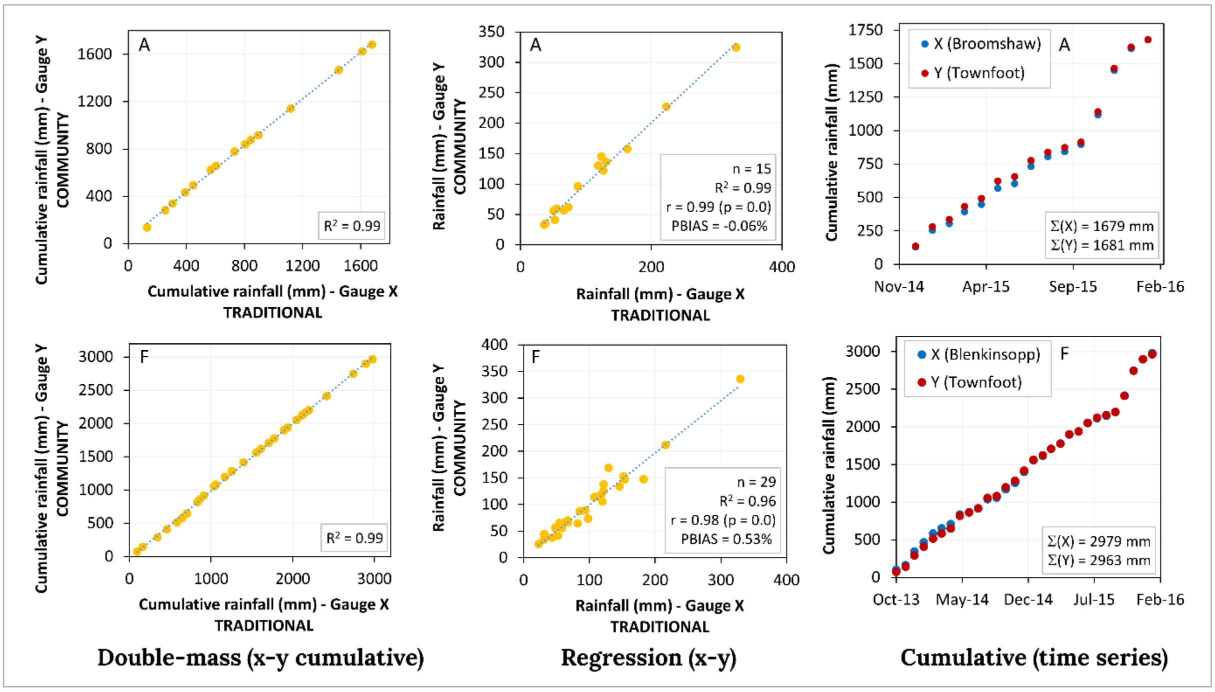


Figure 5.34. Double-mass, regression and cumulative plots for one of the 'best' performing community-based rain gauges (Townfoot – gauge combinations A & F using monthly data).

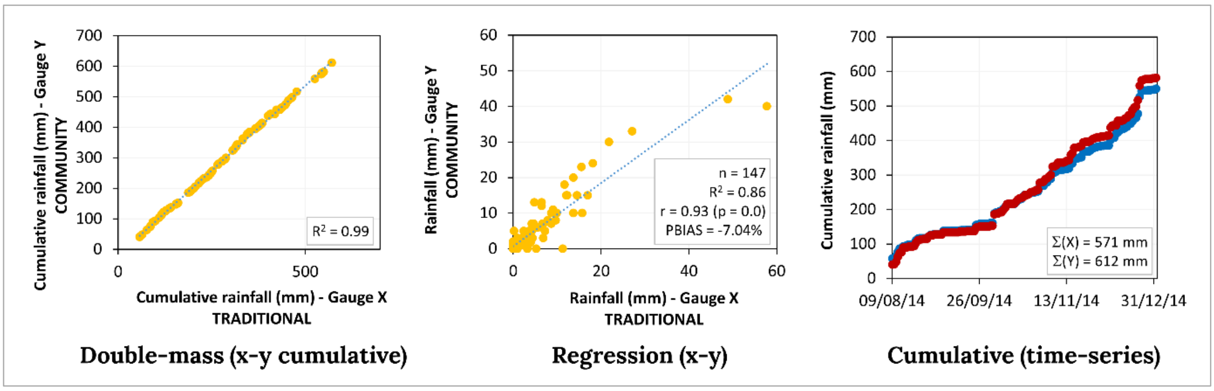


Figure 5.35. Double-mass, regression and cumulative plots for one of the 'least' performing community-based rain gauges (PGB Headwaters – gauge combination E using daily data).

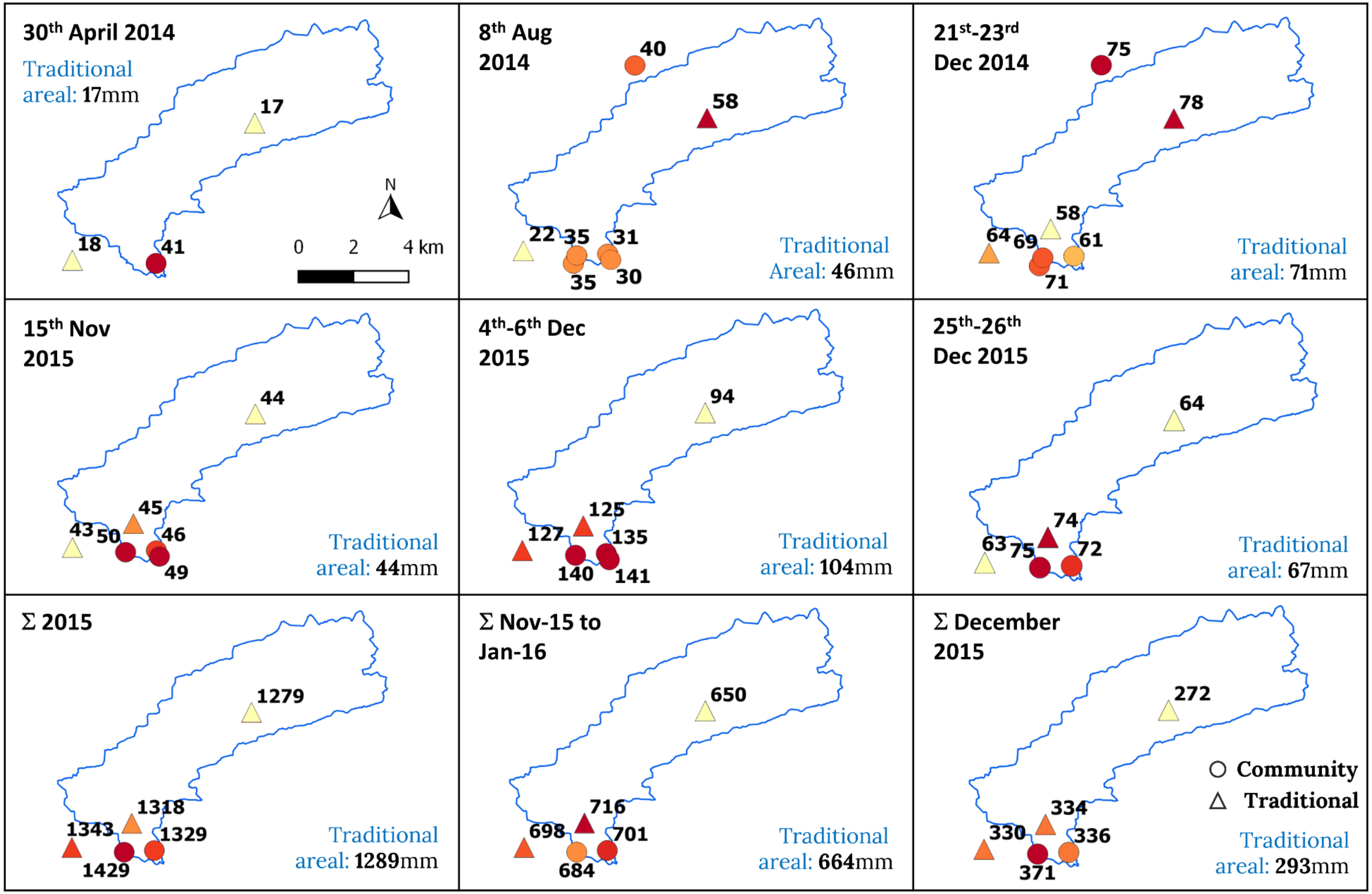


Figure 5.36. Spatial extremes: maps illustrating rainfall totals observed by all traditional and community-based gauges during events/periods of interest. Graduated colours are proportional to rainfall totals (light yellow = lowest, dark red = highest).

Since this study has focused on flooding as a hazard to the community, extreme rainfall totals have been individually analysed (Figure 5.36-5.38 and Table 5.12). Given that simple gauges have been used, equipment are not co-located, and because the catchment naturally exhibits spatially variable rainfall (particularly during localised events), identical rainfall totals were not expected. However, the spatial plots in Figure 5.36 illustrate how all community-based rainfall totals are well-placed and of a realistic magnitude, given their position within the catchment and proximity to the three traditional rain gauges. A graduated colour scheme has been used within each plot to emphasise how the community-based data are precise and that Blenkinsopp Hall and/or Broomshaw are of a similar magnitude. For instance, Townfoot (community-based) observed 61mm and Broomshaw (traditional) observed 58mm during the 21st-23rd December 2014 event. The same two gauges observed 336mm (Townfoot) and 334mm (Broomshaw) in December 2015 (one of the wettest Decembers on record). Above-average annual rainfall totals were also shown by each gauge in 2015, with Townfoot totals being within 0.8% of Broomshaw.

The only visible outlier in Figure 5.36 is that on the 30th April 2014, when one community-based rain gauge observed 41mm. Participation levels were low at this point within the project, hence only one gauge was available for examination. This example demonstrates how the 41mm observed by the community should be questioned over its reliability, given that both Blenkinsopp Hall (19mm) and Gibbs Hill (17mm) observed much lower totals on either side. However, Chapter 6 (Starkey *et al.* 2017) explores this specific event in more detail (through hydrological modelling) to illustrate how this rainfall total is authentic; an intense and localised storm occurred over the town of Haltwhistle. While additional rain gauges within the town would have been advantageous during this particular circumstance, a patchwork of qualitative and quantitative data support this conclusion. It is therefore essential to point out that community-based observations can reliably observe hydrologically important (extreme and isolated) events which would otherwise be missed. Care should therefore be taken to ensure rare observations are not discarded during QC checks. It should also be kept in mind that differences in extreme rainfall totals can easily cause discrepancies and offsets during rain gauge comparisons (e.g. Figure 5.35).

Due to the hydrological and meteorological significance of November-15 to January-16 (Marsh *et al.*, 2016), both community-based (where available) and traditional rainfall totals have been ranked against published regional and national figures. As Table 5.12 highlights, the two community-based rain gauges sit realistically between neighbouring regions and Haltwhistle's traditional gauges. They also fall below north-west England and Solway as anticipated. The community have therefore reliably observed the UK's wettest three month period on record.

Area / region of interest	Nov-15 to Jan-16 rainfall total (mm)	Rank	Source
Solway	919	Wettest	Marsh *et al.*, 2016
North-west England	783		
Broomshaw	**716**		**Traditional**
Tweed	708		Marsh *et al.*, 2016
Townfoot	**701**		**Community-based**
Blenkinsopp Hall	**698**		**Traditional**
Central Haltwhistle	**684**		**Community-based**
Areal	**664**		**Traditional**
UK	571		Marsh *et al.*, 2016
Gibbs Hill	**650**		**Traditional**
Yorkshire	444		Marsh *et al.*, 2016
England	376	Driest	

Table 5.12. Comparison between winter 2015/16 extreme rainfall totals (red = community-based, blue = traditional, black = published national/regional figures). Data covers Nov-15 to Jan-16.

Extreme rainfall totals have also been assessed in terms of magnitude (top 30 daily maxima in Figure 5.37) and timing (Figure 5.38). Similar to the above findings, the wettest days observed are realistic and in line with nearby traditional gauges. Figure 5.37 also specifically demonstrates how Townfoot and Central Haltwhistle extremes lie between Broomshaw and Blenkinsopp Hall. While magnitude (therefore peak rainfall regime) has been characterised, this does not mean that the same events are ranked in an identical order (although the 5th/6th December 2015 is systematically higher across all gauges). Nevertheless, Figure 5.38 illustrates how Townfoot (which can be assessed in this way because it covers the full monitoring period) has generally observed the same top 30 wettest days as the traditional sources, regardless of which order they appear. These top 30 maxima also include all of the key hydrological events of interest previously described.

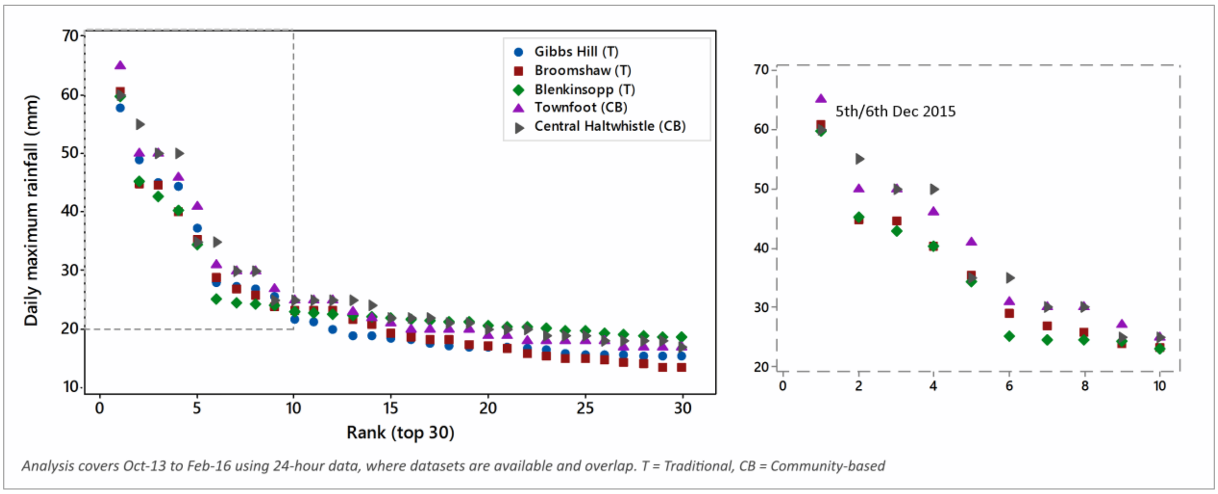


Figure 5.37. Extreme rainfall totals: wettest 30 days ranked and plotted for gauges where data is available (left). Top 10 wettest days are also revealed for gauges in the lower catchment (right).

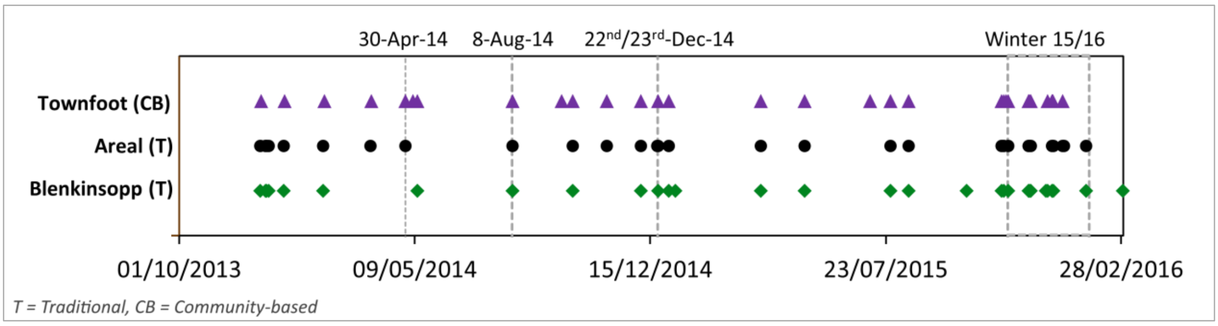


Figure 5.38. Timing of the top 30 wettest days observed. Townfoot is compared with Blenkinsopp Hall and Areal totals as they cover the full period interest, and are located in close proximity.

Whilst community-based rainfall observations appear reliable here, there are still limitations:

- Without interpreting other sources of community-based data (e.g. weather descriptions and photographs) in order to depict the exact timing and magnitude of rainfall at a sub-daily resolution (see Starkey *et al.* (2017), therefore Chapter 6), it is not feasible for the public to provide the high temporal resolutions observed by traditional gauges (e.g. Gibbs Hill). However, some participants did empty their gauge and observe rainfall at a sub-daily resolution during extreme events, such as Storm Desmond;

- Community-based data are limited by the type of rain gauges used. Here simple, inexpensive and manual recording cylinders were used and are affected by wind, splash, evaporation and gauge capacity issues. Nonetheless, traditional (more expensive) gauges are still heavily restricted by their design and it is still unclear to the hydrological community which is best to use (Environment Agency, 2004, Pollock *et al.*, 2014). Nevertheless, a greater number of low-cost and reasonably sophisticated designs are becoming more readily available to 'amateur' meteorologists;

- Spatial and temporal gaps are inevitable in community-based datasets due to the nature of relying on unpaid volunteers over time;

- It is not always possible to analyse community-based rainfall data in the same way as traditional. For instance, rainfall maxima are limited to 24-hour totals (or coarser) and are assessed at fixed intervals over time, rather than running totals. This also means that resolutions will affect the data's end application.

- The above findings are only valid following careful QA/QC procedures.

5.5.1.2. River level (stage) comparisons

Community-based river level data introduced within Section 5.4.4 (RLGBs at Broomshaw, Townfoot and Mill Bridge) have been compared directly against the traditional WLR located at Broomshaw. The Broomshaw gauges have been focused upon as they have been deliberately co-located in order to isolate discrepancies associate with the two gauge types or monitoring methods, rather than spatial and temporal variability. Nevertheless, Townfoot and Mill Bridge RLGBs have also been considered in places as they are located along the same watercourse. All data have been graphically and statistically analysed using methods implemented during the rain gauge analyses.

River level data have been more difficult to analyse than rainfall given their sporadic nature. As a result, river level comparisons involved:

A) A paired (x-y) analysis involving individual RLGB observations collected by the community and those observed by the traditional WLR, but only where time-stamps overlapped (Figures 5.39-5.40). This approach enabled the accuracy and reliability of individual community-based observations to be assessed directly. Since all community-based observations were observed to the nearest minute, they were paired with the closest 5-minute data logged by the traditional sensor (look-up tables paired them automatically). This generated 561 pairs of co-located data ready for comparison;

B) All available data points observed traditionally, and by the RLGBs (Figures 5.41-5.46 and Table 5.13). This generated unpaired and uneven samples, allowing the sporadic nature of community-based data to be analysed across the full monitoring period (i.e. ability to temporally characterise the Haltwhistle Burn, both long-term and event-based). Statistical analyses involving both sets of data would inevitably reveal that community-based data are 'poor' quality because they cannot capture river levels at regular and fine resolutions. As a result, the data have been manipulated to ensure that they are paired. To do this, monthly and seasonal maximum, average and minimum river levels have been calculated for both sets of data. River level duration curves have also been generated as they have allowed the data to be categorised into comparable percentiles or quartiles.

Figure 5.39 presents a set of outputs following the paired investigation at Broomshaw. The regression analysis (Plot A) initially demonstrates how the 561 individual RLGB observations are in almost perfect agreement with their traditional counterparts. R^2 and r values of 0.99 have been acquired; on an individual basis, these results suggest that community-based RLGB observations are accurate and reliable. A PBIAS of 4.25% is also very low, confirming that the gauge board observations collectively underestimated river level by only a small margin. The double-mass plot (B) exhibits a perfect straight line, which suggests that there are no obvious changes in relationship between the two data sources over time. River level totals (81m and 77m) again confirm that the observations are very similar, but are not identical. Plot A illustrates how variability is greater during high flows. This is understandable given that river levels naturally and rapidly fluctuate during these times due to non-uniform and turbulent flow. Unlike traditional sensors, which can account for short-term fluctuations by recording averages, it is impossible for the community to manually capture an accurate river level observation during these occasions. Nevertheless, traditional WLRs can still under- or over-estimate river level during times of high flow. Plot C is useful for comparing how similar the two monitoring methods are. The first half of the data appear more accurate than the second half, and can be attributed to the fact that river levels are lower, there are more community-based observations available, and because a greater number of 'regular' volunteers took part in the monitoring programme during 2015. Nevertheless, the two monitoring methods are remarkably similar and verify that the public can collect credible river levels.

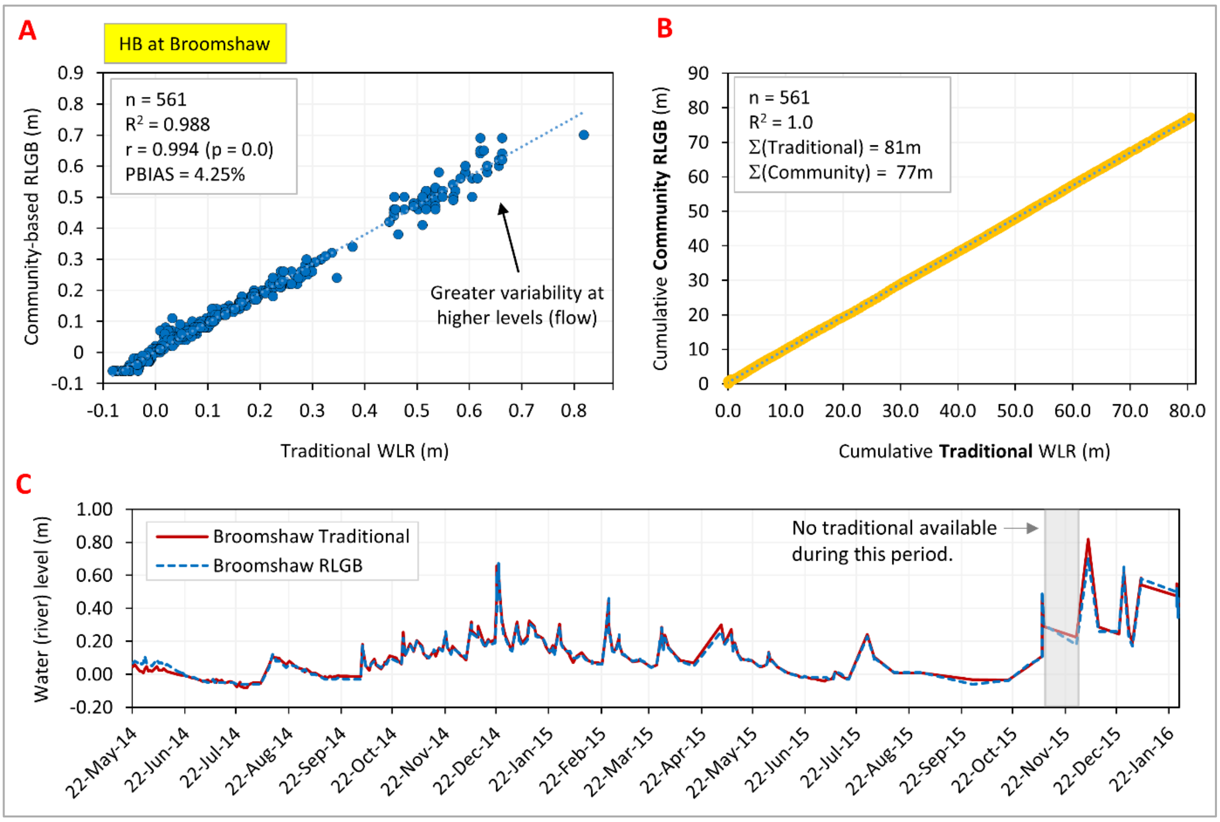


Figure 5.39. A direct comparison against paired traditional and community-based river level observations at Broomshaw, where datasets overlap with the same time-stamp. Includes x-y regression (A), double-mass cumulative (B), and time series (C) plots.

Figure 5.40A shows the difference between each pair of data after they have been subject to Equation 5.12. Results confirm that the average difference (error) between the RLGB and traditional sensor is just 0.01m – this equates to just one mark (or bar) on the gauge board. After ranking these errors, it was found that 95% of the observations assessed here fell within -0.056m and +0.036m of the traditional benchmarks. The 5% that fell outside these limits are not associated with erroneous data. For instance, the maximum difference between the two data sources was just -0.12m, which relates to the 5th December 2015 when Storm Desmond arrived. This particular RLGB observation was submitted in the form of the photograph which clearly illustrates the difficulties of extracting quantitative values during turbulent conditions (Figure 5.40B). Since these types of events are short-lived, 57% of the public's river level observations still fell within ±0.01m of the traditional sensor. Very low river levels are also difficult to observe or photograph as parallax errors increase, and the gauge boards are usually stained at lower levels. Cleaner gauge boards and multiple high flow photographs would help to improve DQ further.

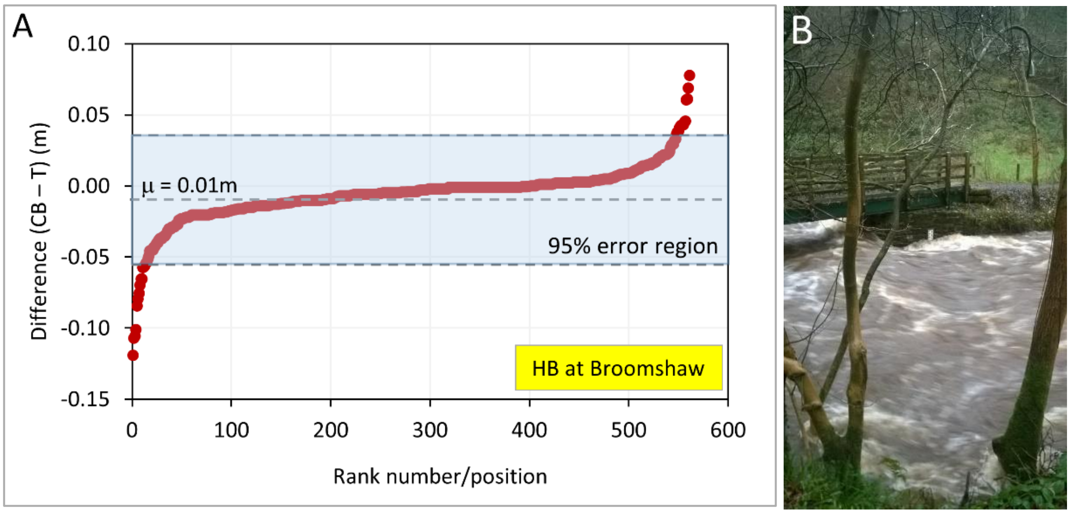


Figure 5.40. A: Error plot illustrating the difference between each pair of traditional and community-based river level observations shown in Figure 5.39 (A). RLGB observation submitted on the 5th December 2015 during high flows (B).

Despite the quality of individual river level observations, catchment scientists are usually concerned with time series, rather than single snapshots of data (unless it is a rare peak). As a result, the full set of community-based RLGB observations have been compared with the full set of traditional data. Figure 5.41 presents a histogram for each of the two data sources at Broomshaw. The obvious difference is that the traditional 5-minute resolution sensor observed 183179 individual data points over the duration of the monitoring period, as oppose to 643 by the community. However, a similar river level regime can still be depicted from these plots, even if the two sample means disagree (traditional: 0.09m, community-based: 0.15m). Although RLGB observations have missed some of the very high and low flows, outputs are still realistic for the flashy Haltwhistle Burn which predominantly experiences lower flows.

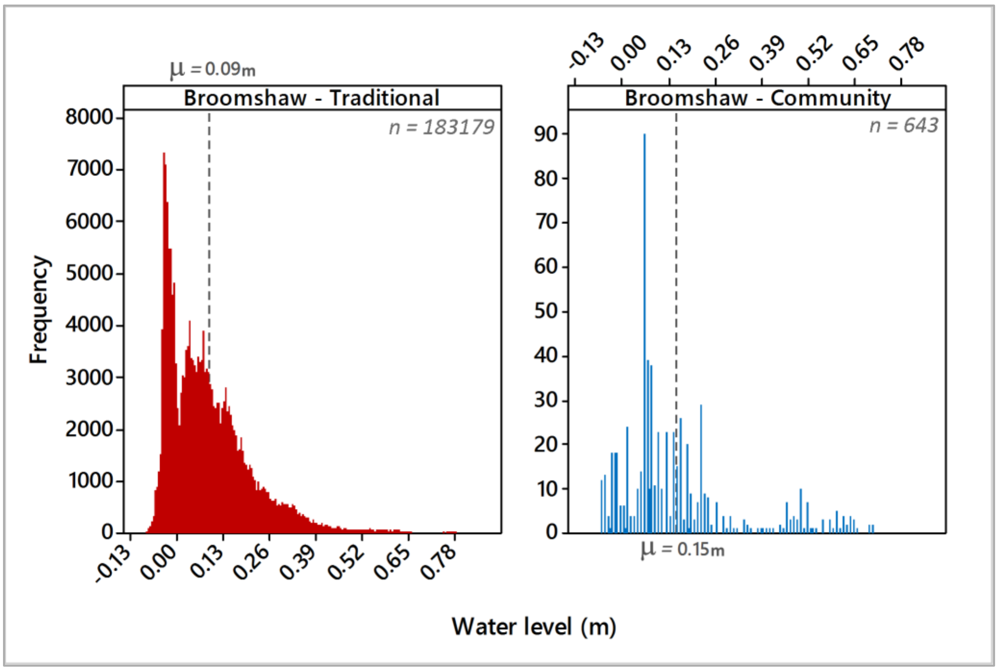


Figure 5.41. Histograms containing all individual river level observations collected at Broomshaw (left: traditional, right: community) over the duration of the 29-month monitoring period.

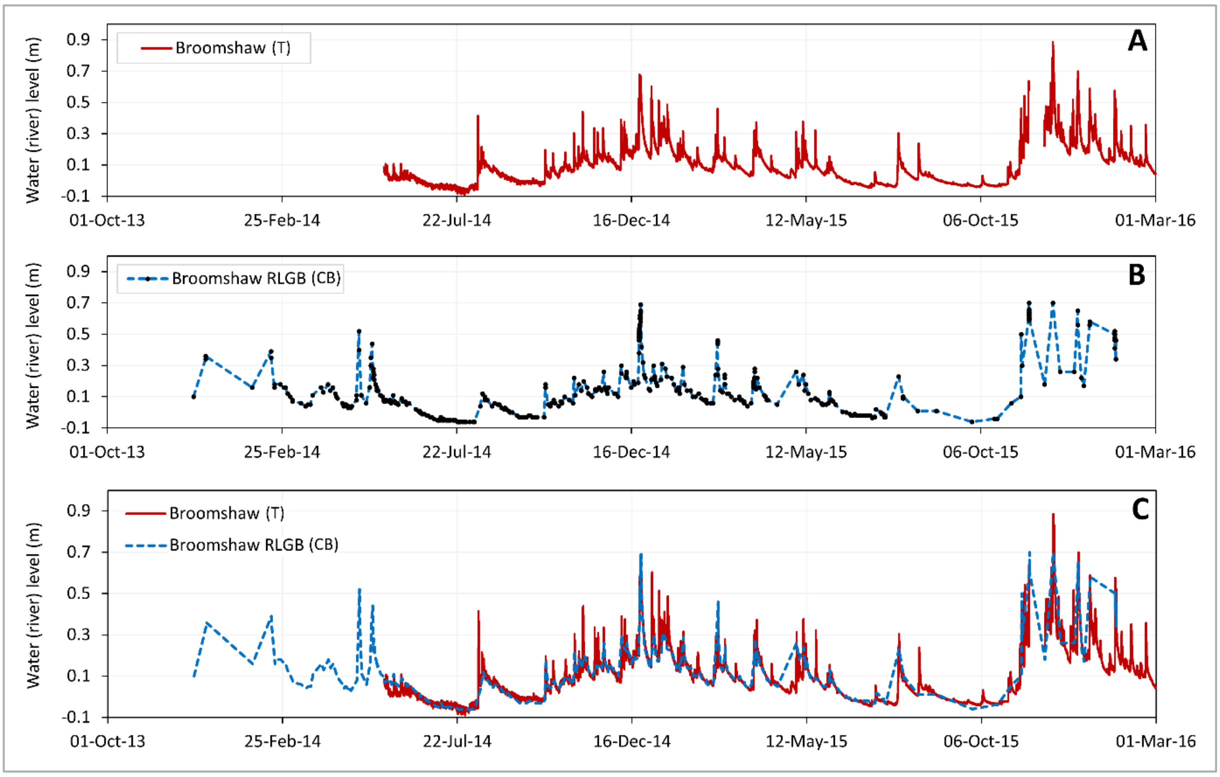


Figure 5.42. Time-series of all individual river level observations collected at Broomshaw (A: traditional, B: community, C: both) previously introduced within Figure 5.41.

The same datasets from Figure 5.41 have been presented as time-series plots in Figure 5.42. Although there are significant temporal gaps between some of the RLGB observations, individual data points have been joined by line segments to give a better appreciation of how the Haltwhistle community managed to observe the Burn over time (note that this is simply for visual purposes and have not been interpolated between data points or included in any statistical analyses). These plots illustrate how the community-based data can collectively observe:

- Winter highs – including 22nd/23rd December 2014 and the series of winter 2015/16 storms;
- Summer lows – including July 2014 when the Haltwhistle Burn was at its lowest levels, which the traditional sensor also observed;
- Some of the flashy events – including 30th April 2014.

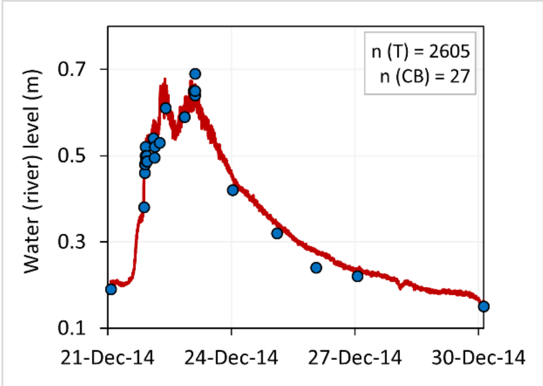
Although these 'events' were captured by the community to some degree, many peaks were significantly underestimated. Peak underestimation does not account for why the community have overestimated river levels on average; it can be explained by the fact that the community focussed their monitoring efforts on high flow events over time, rather than low flows.

Evaluations have demonstrated that individual RLGB observations are reliable, but monitoring efforts are still intermittent and unpredictable. Based on the Haltwhistle Burn experience, Table 5.13 presents a set of typical RLGB scenarios when relying on unpaid volunteers to manually monitor a rural headwater catchment. A closer look at these individual scenarios confirms that:

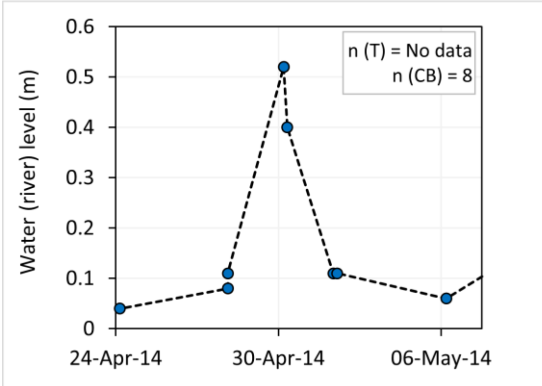
- The community have the potential to capture peak river level observations. For instance, the rise, peak and recession of the December 2014 event was captured by the community using just 27 data points (equivalent to 1% of the traditional data);
- When river levels stabilise (summer low flows), a very small number of RLGB observations are able to characterise the Burn's response with confidence (e.g. 8 compared with 2593);
- Community-based observations are able to capture valuable information which would otherwise be missed by traditional sensors;
- It is likely that peak levels will be missed or underestimated if they occur during the night;

- Even if participation levels are low, concerned locals or passers-by are likely to observe some data during prolonged or extreme hydrological events.

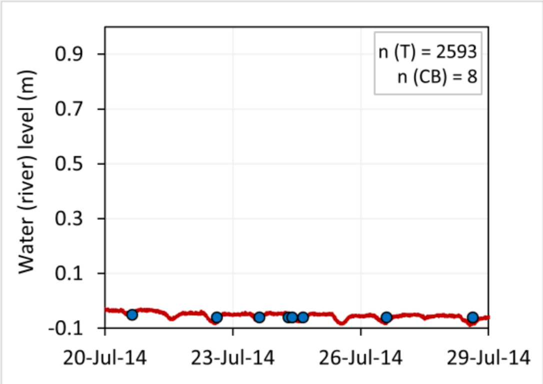
A) Peak captured well – just 27 data points (1%)



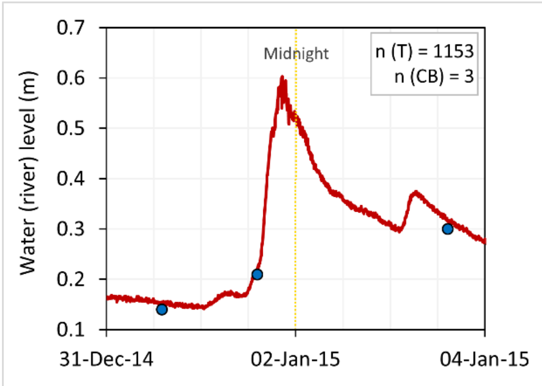
B) No traditional data – otherwise be missed.



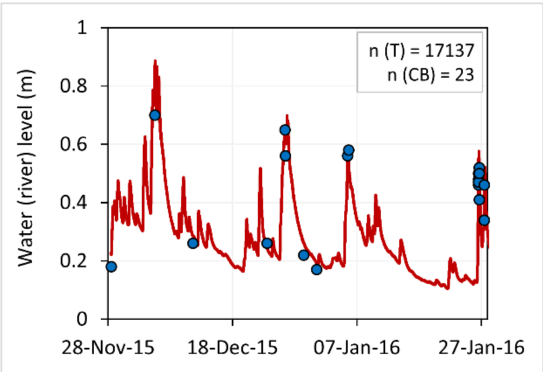
C) Summer low flows – just 8 data points (0.3%)



D) Peak arrives in the night – rise not recorded



E) Winter floods documented – peaks underestimated but have focussed on high flows.



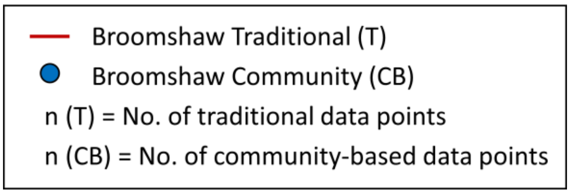
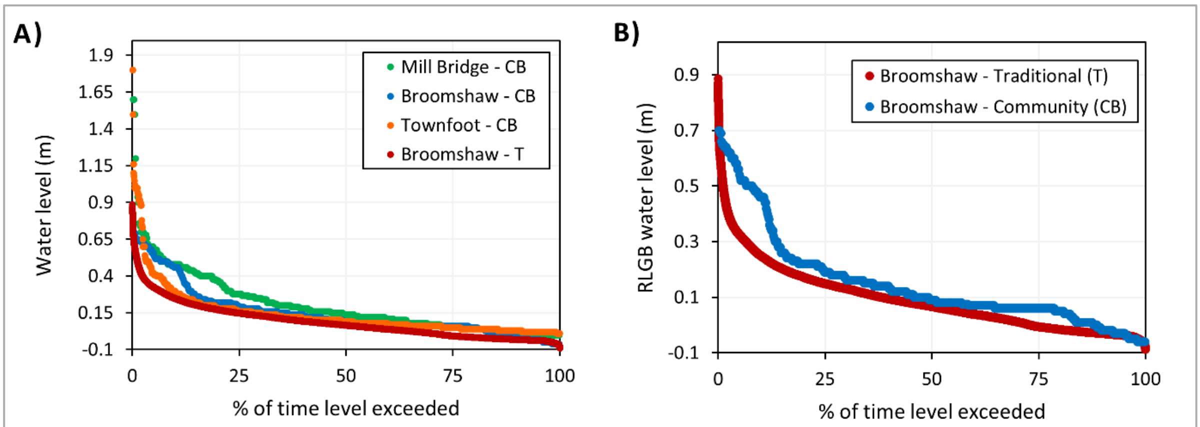


Table 5.13. Extracts of data collected by the community at Broomshaw to illustrate typical RLGB scenarios and the public's monitoring capabilities within a flood-rich and flashy catchment.

The full sets of unpaired data captured by the community and automatic WLR have been used to construct a set of river level duration curves (using Equation 5.7). This has allowed paired data to be generated in a catchment characterisation context, and hence has adopted a well-established hydrological technique. The original river levels have therefore been ranked, quartiles calculated and then compared with each other. Resulting duration plots (Figure 5.43) specifically highlight the consequences associated with not being able to feasibly monitor at high temporal and sub-daily resolutions. While the RLGB duration curves are realistic, do not contain any significant outliers, and generally contour the traditional Broomshaw benchmark, they are useful for highlighting (again) how the community were unable to capture extreme river level durations accurately. The duration curves and percentiles therefore illustrate how a more subdued catchment response is generated by the community. A direct comparison against Broomshaw generated quartiles 1-99 (n=99) reveal how the community-based duration curve depicts a reliable shape (r = 0.97), but the magnitude is incorrect (PBIAS = -66%). Townfoot and Mill Bridge are included within Plot A (Figure 5.43) to demonstrate how river behaviour is however characterised more accurately when larger RLGB sample sizes are available. For instance, a total of 1379 observations were available for Townfoot (Broomshaw: 643, Mill Bridge: 563) and have generated a reasonable river level duration curve.



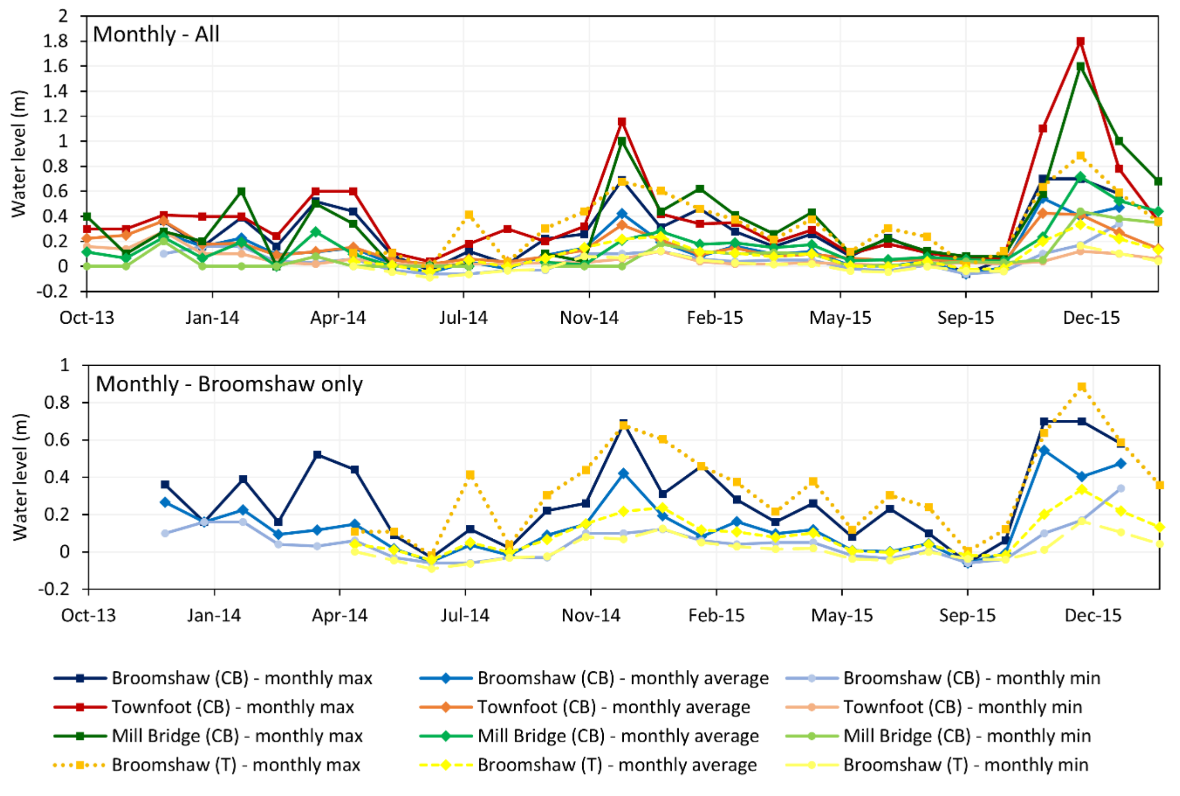
C)

Quartile	Broomshaw T	Broomshaw CB
Q99	-0.06	-0.06
Q95	-0.04	-0.03
Q75	-0.007	0.06
Q50	0.07	0.09
Q25	0.15	0.19
Q5	0.32	0.70
Q1	0.52	0.70

Figure 5.43. 'River level' duration curves for the traditional sensor located at Broomshaw and for each of the three RLGBs (A). Broomshaw gauges are plotted individually and relevant quartiles extracted to allow for direct comparisons (B-C).

Maximum, average and minimum river level observations have been extracted from all available data and plotted to demonstrate that monthly and seasonal trends can be represented using the RLGBs (Figures 5.44-5.45). Whilst the accompanying statistics (Figure 5.46) confirm that these trends are not in perfect agreement with the traditional sensor at Broomshaw (r ranges from

0.72-0.84), they are realistic and provide an indication of catchment response over time. Since data gaps exist, temporal resolutions are irregular, peaks are often underestimated, and average river level estimations are over-estimated, community-generated river level data collected in this way cannot be used to perform detailed hydrological analyses alone (for instance, calculating return periods and the water balance). They could however be used to accomplish this alongside traditional data sources given that individual RLGB observations are accurate. Participants can obviously be encouraged to monitor more frequently or regularly, but their capabilities will always be limited by the fact that they are unpaid volunteers carrying out manual monitoring methods in their own time. One volunteer specifically emphasised that they cannot get out quickly enough to capture the evidence because the Haltwhistle Burn rises so rapidly (*"I can't get my camera quick enough"*).



Note that statistics/trends have been calculated using uneven and unpaired datasets.

Figure 5.44. Monthly maximum, average and minimum river level observations captured by the traditional sensor (T) and by the community at the three RLGB sites (CB).

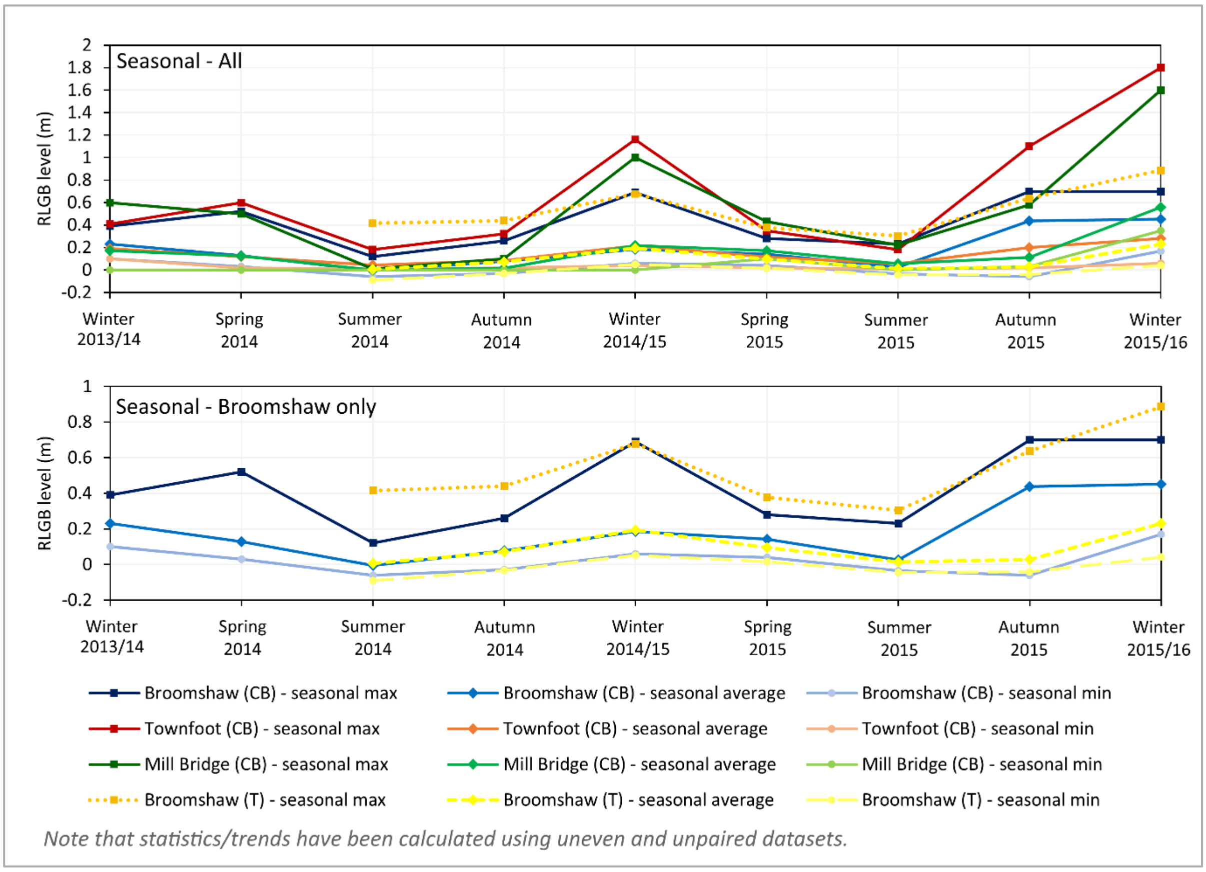


Figure 5.45. Seasonal maximum, average and minimum river level observations captured by the traditional sensor (T) and by the community at the three RLGB sites (CB).

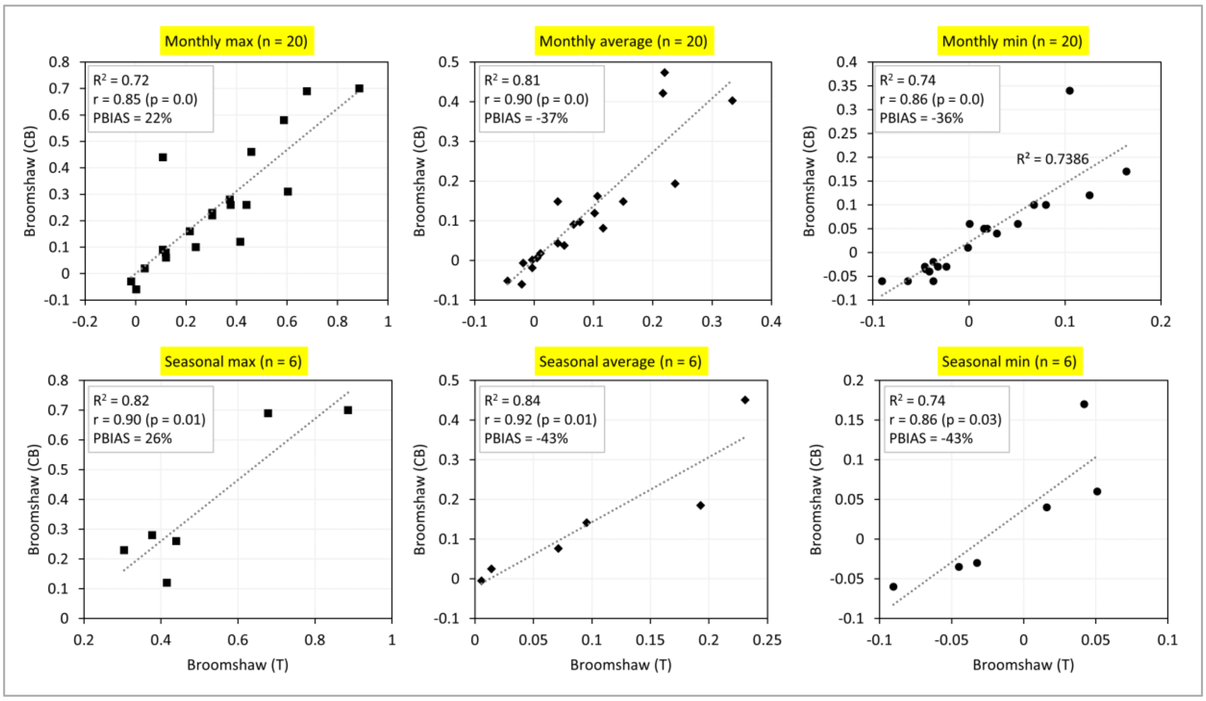


Figure 5.46. Monthly and seasonal regression plots summarising the relationship between traditional (x-axis) and community-based (y-axis) river level data (m) collected at Broomshaw.

A final investigation into daily river level maxima has been conducted to demonstrate how many top 30 peak river levels were captured by the community at each of the three RLGBs (Table 5.14).

Broomshaw (T)		Broomshaw (CB)		Mill Bridge (CB)		Townfoot (CB)		Any/All (CB)	
No.	Date of maxima	Any obs?	Top 30?	Any obs?	Top 30?	Any obs?	Top 30?	Any obs?	Top 30?
1	05/12/15								
2	06/12/15								
3	26/12/15								
4	22/12/14								
5	23/12/14								
6	15/11/15								
7	03/12/15								
8	27/12/15								
9	04/12/15								
10	01/01/15								
11	05/01/16								
12	26/01/16								
13	24/12/14								
14	11/11/15								
15	14/11/15								
16	07/12/15								
17	02/01/15								
18	27/01/16								
19	22/12/15								
20	07/01/15								
21	25/12/15								
22	15/01/15								
23	10/12/15								
24	29/11/15								
25	08/01/15								
26	01/12/15								
27	08/11/15								
28	26/02/15								
29	06/01/16								
30	05/11/14								

'T' = Traditional sensor. 'CB' = Community-based RLGB observation. 'Any/All' = any or all of the three RLGBs.
'Any obs' = at least one river level was observed by the community on the same day (not necessarily a peak level)
'Top 30' = also registered by the community as being a top 30 river level (magnitude not necessarily the same)

Table 5.14. Dates when the top 30 daily river level maxima were observed by the traditional Broomshaw gauge. Coloured cells confirm when one or more RLGB observations were captured by the community on the same day (where data overlap with the traditional sensor only).

The following apply when assessing daily river level maxima observed by traditional sensor:

- At least one or more RLGB observation were captured by the community on each of the 30 days listed;
- Two thirds of the top 30 traditional peaks were registered as a top 30 by the community;
- 12 of the largest 15 traditional peaks were registered as a top 30 by the community;
- All six of the largest peaks observed by the traditional gauge were registered as a top 30 by the community;
- River levels were observed at all three RLGBs during Storm Desmond (5^{th} December 2015);

- RLGB observations underestimate most peaks, which means that magnitude and timing misalign with those observed by the traditional sensor. Night-time peaks are completely missed by the community;
- A greater number of observations were collected (therefore peaks captured) at the RLGBs closer to the town centre;
- When all three RLGB observations are combined, they provide a more reliable representation.

5.5.2. *Data quality case studies*

The following short case studies are presented to further emphasise the nature, quality and reliability of community-based observations (stage H in the community-based DQ framework, Figure 5.25).

- **The 'wave effect' (RLGBs) and evidence of DQ concerns**

After the first few high flow events in 2014, the community began to notice the difficulties of observing accurate RLGB observations, whether as a quantitative estimate, or just a photograph. For example, some participants proactively included multiple (2+) RLGB photographs in their submission to highlight this issue (Figure 5.47). This phenomenon became known by the community as the 'wave effect' and is, as expected, generally amplified when greater flow depths and discharge are experienced (Nichols *et al.*, 2016). Turbulence explains why there are increased discrepancies between the community-based RLGB and traditional observations at higher levels (Figure 5.39 and 5.42). Wind can also influence turbulence on a local scale (Herschy, 2009).

Figure 5.47. Examples where the community captured the 'wave effect'.

Traditional sensors can account for the wave effect to some degree by recording average levels, although a closer look at the traditional WLR (Diver) at Broomshaw illustrates how automatic sensors can also be affected by this issue (Figure 5.48A). The more sophisticated IPT later used at

Broomshaw was programmed to observe temperature and pressure (therefore river level) once every 30 seconds, which then logged a 5-minute average (Figure 5.48B).

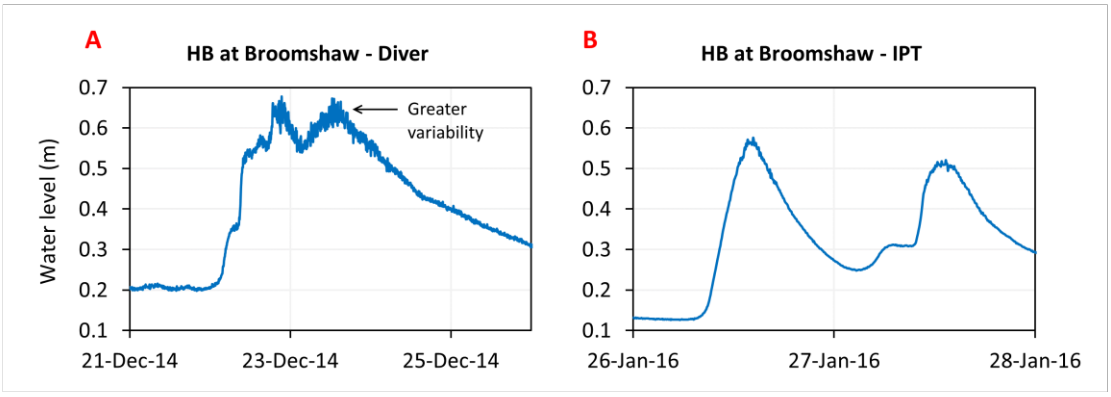


Figure 5.48. Observing water level during turbulent flow conditions using traditional sensors.

With respect to community-based monitoring, it is virtually impossible to manually observe the wave effect consistently, either visually or by taking a single photograph. This prompted further monitoring investigations by taking multi-burst images of the RLGBs. This investigation was carried out as a research activity, and not by the community. A Sony DSC-HX50 camera was set to 'multi-burst' (continuous shooting) mode to allow ten still images to be captured within one second. By doing this, the wave effect could be captured over a very short period of time, and under different flow depth conditions. Figure 5.49 presents examples of the RLGB obtained.

It was found that the wave effect appeared to increase with flow depth, but it also varied depending on which RLGB was being observed. Nevertheless, this case study demonstrates that regular volunteers are aware of these RLGB errors. It also provides a potential monitoring solution which could feasibly be adopted by citizen scientists during turbulent flow conditions. Multi-burst, continuous shooting, live video streaming, and even 'slow-mo' camera modes are becoming increasingly available to the average and everyday camera user, including on smart-phones and time-lapse/action cameras. Shaw *et al* (2011) documents that RLGB observations usually harvest an accuracy of ±3mm. Batches of multi-burst images and the like can assist with achieving this level of accuracy during turbulent conditions, along with River Watch Photo Posts. It can also be argued that the level of error attained as a result of the wave effect is not important to some RLGB data applications.

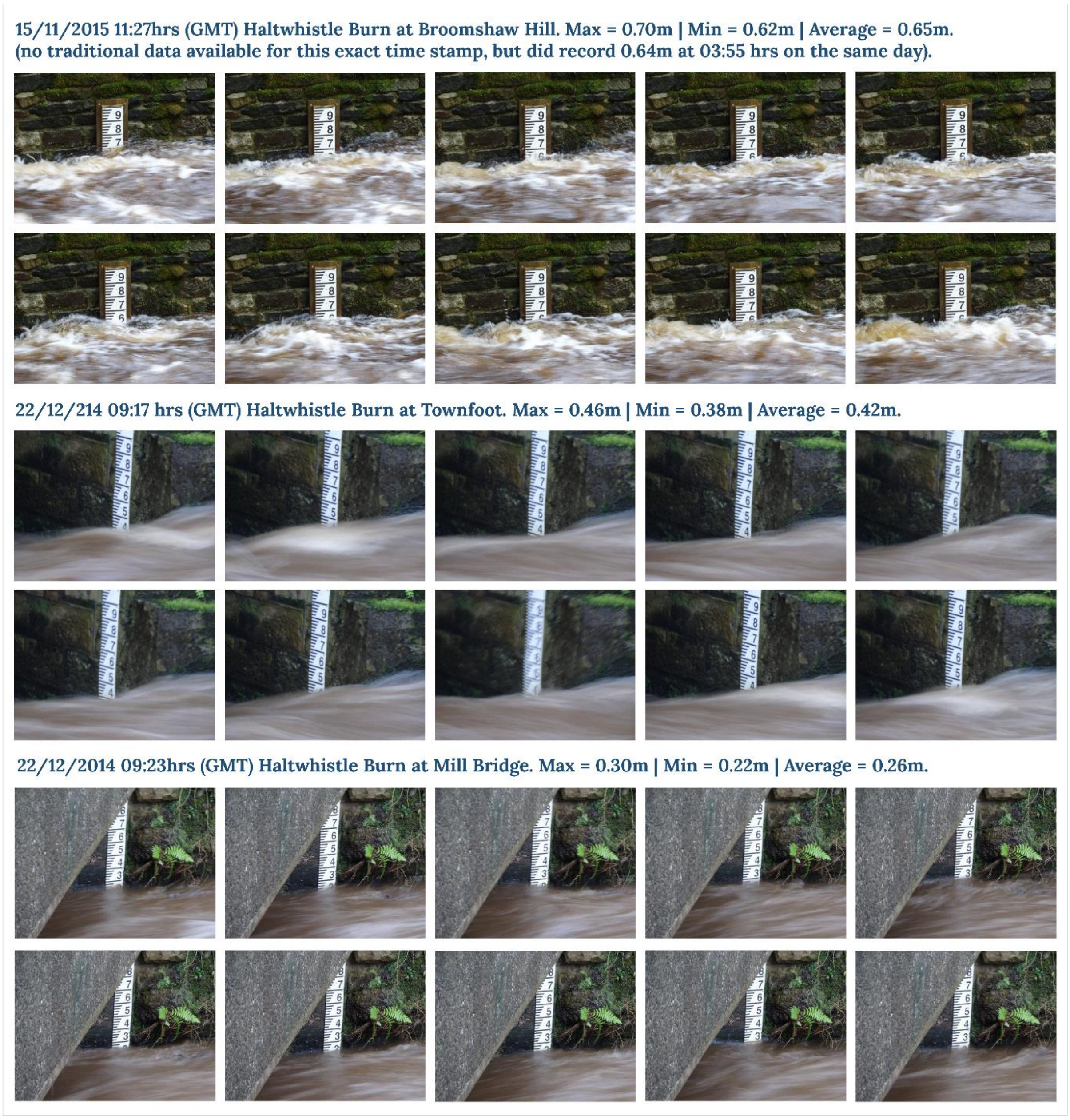


Figure 5.49. RLGB observations obtained during turbulent flows whilst using the camera's multi-burst mode. See Appendix 5F for low flow examples.

Image analysis techniques can be used to standardise the quantitative data extraction process from RLGB photographs, particularly if multiple images exist for the same observation timestep.

- **One community-based RLGB observation versus the traditional equivalent**

It has been widely demonstrated that community-based monitoring offers a patchwork of observations in a variety of non-traditional formats. Figure 5.50 illustrates how one qualitative RLGB observation can be used to extract, communicate and utilise a range of information by a wide audience, including the public. This contrasts the traditional equivalent; one quantitative river level observation which offers limited information. Whilst some data users may regard the traditional sensor as being more reliable, the RLGB photograph is self-verifying and can provide relevant catchment information (assuming the date/time stamp is correct).

One community-based river level observation:

- Check: equipment still in place
- Check: flood risk (no overtopping or debris)
- Check: no damage
- River level: 0.41m
- Discharge / velocity: possible to estimate if video supplied
- Water quality: indication of clarity / turbidity / colour
- Metadata: embedded automatically (date/time)
- Data quality: self-verifying
- Check: general weather conditions

Traditional equivalent:
26/01/2016 11:45 = 0.44m

- Unknown quality without full QC investigation.
- Limited value when used alone by most stakeholders (unless it represents Q*peak*).
- Not normally available to the public in real-time.

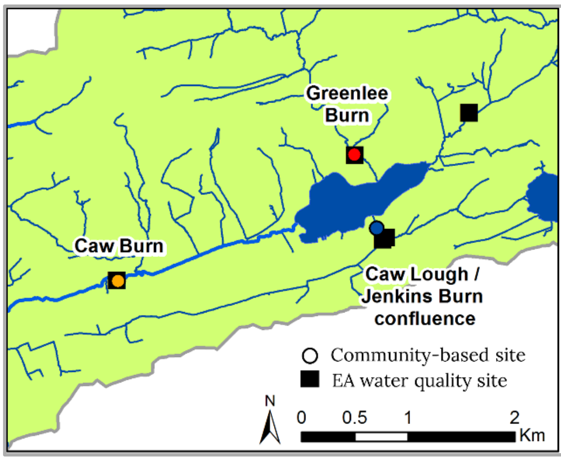
Figure 5.50. A comparison between one RLGB observation and its traditional equivalent. Example emphasises how multiple attributes can be extracted from a single qualitative photograph.

- **Water quality around Greenlee Lough**

The community-based water quality data have not been assessed in detail within this chapter as simple, low-cost and non-scientific test kits have already been explored by others, including the OPALometer for water clarity, pH, DO, temperature, nitrate and phosphate dip strips (Environment Agency, 2012c; Rose *et al.*, 2016; Storey *et al.*, 2016). These studies generally conclude that most parameters are in close agreement with professionals, but are limited by the tests themselves and the ability to detect low concentration levels. Citizen science has supported water quality monitoring for many years, and has reliably supported the US Environmental Protection Agency and the World Water Challenge by providing snapshots of valuable data (US EPA, 1997). Although a detailed water quality analysis is beyond the scope (and budget) of this study, a small case study is presented here to emphasise that these snapshots can provide an indication of water quality. As Chapter 2 highlighted, water quality, particularly nitrates and phosphates, are a concern in rural catchments due to agricultural intensification.

The Environment Agency monitored water quality within the Greenlee Lough area as part of the Roman Wall Loughs project (Section 5.3.2 introduced). Traditional water quality monitoring have therefore characterised a variety of biological and chemical parameters of interest using continuous sensors and spot samples (see locations and metadata in Figure 5.3 and Table 5.1). In the vicinity, community-based water quality monitoring took place as a one-off event during the Haltwhistle Walking Festival (18th October 2014). While the latter was designed to overlap some of the same monitoring locations focussed upon by the Environment Agency, no time-stamps overlapped any of the datasets mentioned as the traditional monitoring sites were terminated earlier than expected. This does however emphasise the difficulties around monitoring remote locations, acquiring long-term traditional monitoring sites, and getting members of the community to regularly monitor water quality in a remote location. Nevertheless, the Environment Agency:

- Classified Greenlee Lough with a 'moderate' WFD status in 2009 and 2012 (hence the Roman Wall Loughs project initiated);
- Created a report (Environment Agency, 2014) to summarise key monitoring findings in the context of rural diffuse pollution, mitigation measures and any implications associated with the EU WFD targets. This report has concluded that total phosphorus is the only element worse than 'good'. While concentrations were not extreme at the time (hence 'moderate' status for Greenlee Lough), there are concerns that the ecological quality of the lake will deteriorate. Nitrate concentrations have not been highlighted as an issue.



Group 1 results	WQ parameter	Site 1:	Site 2:	Site 3:
	Water temperature (ºC)	13.5	11	10.5
	Dissolved Oxygen (ppm)	4	4	3.5
	Phosphates (ppm)	**1**	**0.5**	**0.5**
	Nitrites (ppm)	**0**	**0**	**0**
	Nitrates (ppm)	**0**	**0**	**0**
	pH	6	6	6
	Algae	None	None	None
	Water clarity (Opals)	10	9	10

Group 2 results	WQ parameter	Site 1:	Site 2:	Site 3:
	Water temperature (ºC)	13	12	11
	Dissolved Oxygen (ppm)	2	4	2
	Phosphates (ppm)	**0.25**	**1.5**	**0.75**
	Nitrites (ppm)	**0**	**0**	**0**
	Nitrates (ppm)	**0**	**0**	**0**
	pH	6.5	6	6.5
	Algae	None	None	None
	Water clarity (Opals)	11	10	10.5

Figure 5.51. Community-based water quality monitoring locations and results from two groups during the walking festival (18/10/2014).

Figure 5.51 presents the community-based water quality results at three monitoring sites around Greenlee Lough which were captured during the walking festival. A very simple comparison between these results and outcomes from the Environment Agency report confirms that the low-cost colorimetric test kits also detected the presence of phosphates, but not nitrates or nitrites. To accompany this, DO levels were not depleted, water clarity was high, algae was not detected and pH levels were realistic across all sites. Whilst these tests are subjective (creating discrepancies between observers) and results presented were controlled by a number of factors (e.g. antecedent conditions, recent farming activities, time of year and the simplicity of the tests themselves), they have been used here to provide an indication of water quality in the Greenlee

Lough area which feasibly supports the Environment Agency's project conclusions. Repeat community-based water quality monitoring at Townfoot (outputs shown in Figure 5.31C) also proves that nutrient and sediment fluxes can be detected during high flow conditions. In conclusion, the water quality tests can at least be used to detect the presence of parameters and provide an indication of magnitude.

5.5.3. Catchment characterisation using community-based observations

The Haltwhistle Burn catchment was previously characterised and hydrological controls depicted using the traditional datasets, as Figure 5.24 summarised. Community-based data have since been presented and DQ checks have confirmed its reliability; it can therefore be argued that the catchment has already been characterised in detail during this process. Nevertheless, Stage H of the DQ framework (Section 5.4.3) is finalised here by presenting a summary of the catchment characteristics derived from the Haltwhistle Burn community and their data. Figure 5.24 has been used during the direct comparison involving traditional and community-based data. Catchment characterisation is important as it gives citizen scientists and their data a purpose, and it demonstrates its value to stakeholders (including the community).

Table 5.15 presents a list of catchment characteristics previously highlighted during the traditional monitoring process. Evidence has been recorded alongside to demonstrate that the same generic conclusions have also been attained through the community-based monitoring scheme. While there are issues associated with generating continuous datasets, those which are required for executing well-established hydrological analyses, Table 5.15 demonstrates how the patchwork of quantitative and qualitative citizen science data was sufficient for drawing the same conclusions about this catchment's regime, and provided real ground-based evidence to support them. In some cases, the community were able to provide new or more detailed information. For instance, observations highlighted that the catchment suffers from sediment issues, the Slaty Sike responds rapidly and overtops regularly, and that the Hemmel Burn is a major issue within the town itself. These additional pieces of catchment information are often more reliably captured by citizen scientists because:

- 'Human sensors' are not static; they can monitor anywhere, anytime depending on the situation;
- As Figure 5.50 demonstrated, multiple conclusions can be drawn from a single observation.

Traditional summary (from Figure 5.24)	Characterised by community-based data?	Evidence / figure reference	Evidence / examples
Rainfall in all seasons	Qualitative and quantitative data directly demonstrated this, including continuous 24-hour rainfall data.	Figure 5.27, 5.31A, 5.33. Table 5.11. Appendix 5E.	
Heavy summer downpours	Qualitative data has proved this alone, particularly local knowledge shared during community meetings. However, strong quantitative datasets exists. Heavy downpours have resulted in localised flash flooding, which has been observed by many participants.	Figure 5.31A, 5.31B, 5.36, 5.37, 5.38. Appendix 5E.	*"Some heavy rain nearby. #Haltwhistle looks to be getting a hammering"* *"Wow! Heavens just opened. Gone from calm to monsoon like in a second!"* *"Sun am, torrential rain pm"*
Prolonged / widespread winter storms	Both winters (2014/15 and 2015/16) have seen significant rainfall totals observed.	Figure 5.29-5.31, 5.36, 5.38. Table 5.12.	*"Horrid day, rained continually"* *"Horrible wet day"* *"Building a boat and collecting animals in pairs... @HaltwhistleBurn #rain #RainInDecember"*
Low flows in summer	River levels indicate flow. Quantitative and photographic evidence confirm summer low flows. Anecdotes specifically reference this phenomenon.	Figure 5.30, 5.31B, 5.39, 5.42, 5.44, 5.45, Table 5.13, Appendix 5E.	*"I've seen it [Haltwhistle Burn] lower than this before... not for a while though"* *"Dry with Sunny Periods"*
Higher flows in winter	River levels indicate flows. Quantitative and photographic evidence confirm winter high flows. Anecdotes specifically reference this phenomenon.	Figure 5.29-5.31, 5.39, 5.42, 5.44, 5.45. Table 5.13-5.14, Appendix 5E.	*"Lots of water in the @HaltwhistleBurn today!"* *"HaltwhistleBurn already higher than 15 Nov and rising steadily"* *"HaltwhistleBurn yesterday it was on number 1, today it on 5"* *"These are the highest I've ever seen river levels around here"* *"#StormDesmond is reaching its peak"*
***Qpeaks* usually in winter**	Peak river levels suggest *Qpeak* are clustered to winter 2014/15 and 2015/16. Monthly and seasonal maximum levels also display this pattern.		
Winter 2015/16 hydrologically significant	Maximum rainfall totals and peak river levels relate to this period (notably Nov-15 to Jan-16). Passers-by also collected vital observations e.g. during Storm Desmond.	Figure 5.30-5.31, 5.37-5.39, 5.42, 5.44-5.45, Appendix 5E.	
Catchment response in reverse: in-bank flow at Broomshaw, upstream floodplains.	Lengthy record of data confirms that even during record-breaking floods, levels did not come out of bank at Broomshaw. Photographs and videos confirm that flood water spreads across Greenlee, Cleughfoot and Cawfields floodplains.	Figure 5.29(i), 5.31B, 5.40B, 5.47, 5.49-5.50.	 

Table 5.15 (A). Characterising the Haltwhistle Burn catchment using community-based data, which further demonstrates reliability and quality.

Traditional summary (from Figure 5.24)	Characterised by community-based data?	Evidence / examples
Larger Q contribution from smaller headwater streams	This has been harder to depict from the community's data given that they did not monitor headwater streams in the upper catchment. However, they have shown that (for example) Slaty Sike is a significant contributor to flood risk and sediment issues within the town of Haltwhistle, particularly under the road culverts. Slaty Sike is a first and second order stream which, according to the community and their data, has overtopped and blocked with sediment on a number of occasions. This was not picked up by the traditional monitoring network.	*"[The Slaty Sike] was overtopping and running down the road"*   
Flashy PGB. Slower release for Greenlee & Broomlee.	Upstream farmers and land owners have supplied anecdotal and photographic evidence to indicate that the PGB is very flashy. Limited data exists for Greenlee & Broomlee, but anecdotal information has been shared at times. Lack of data in the Greenlee area also indicates that it is not a concern or priority to locals.	  *"The [PGB] floods looked like they had been and gone"*
Military Road flow restriction	Direct evidence collected during the 22nd/23rd December 2014 flood event (in the form on photographs and videos) confirms that the Military Road acts as a hydrological control during high flow conditions. Whilst this conclusion was also drawn from the traditional data, there were no photographs or videos to verify it.	  *"Video taken from the culvert [downstream end]. Wow! Really going for it."*

Table 5.15 (B). Characterising the Haltwhistle Burn catchment using community-based data, which further demonstrates reliability and quality.

5.5.4. Other factors/issues to consider

It is widely documented that DQ is a concern when citizen science supports environmental monitoring activities (Buytaert *et al.*, 2014; Blaney *et al.*, 2016). Many believe that accuracy and precision should not be the only restraining factors as data can hold many qualities, such as ease of understanding, traceability, relevance, cost and timeliness (Wang and Strong, 1996; Lukyanenko *et al.*, 2016; Wiersma *et al.*, 2016).

Based on experiences from the Haltwhistle Burn catchment, additional factors affecting the uptake of citizen science are presented within this section. These considerations are important because budgets, resources, proposed impacts, intended outcomes, scales and end applications vary significantly, by project and by data consumer.

- **Cost:**

In many cases, citizen science is considered as an appropriate data collection activity because it is widely known for being inexpensive, allowing traditional scientists and environmental stakeholders to collect vast amounts of data over a wide area, with 'very little effort' (Science Communication Unit, 2013; Breuer *et al.*, 2015; Kelling *et al.*, 2015; Miskell *et al.*, 2017). This is often the case because they do not have the time or budget to collect the data alone, even if they want to. This argument is plausible for citizen science in catchment science as it is costly to monitor every catchment parameter on a local scale.

The Haltwhistle Burn citizen science monitoring scheme was explicitly designed to ensure low-cost monitoring tools were adopted. This meant that a greater number of participants could become involved (therefore collect more data), and if necessary, equipment can still be replaced or purchased easily by the community in the future. Many data collection and submission techniques made use of existing or open source tools, such as social media and smartphones. For the cost of every traditional aerodynamic TBR gauge used (approximately £600/gauge), around 110 plastic manual gauges (£5.50/gauge) could have been purchased instead. The one-off cost of around £30/RLGB is also significantly cheaper than any automatic WLR (£100s-£1000s, a cost which depends on the sensor's specification and whether it is telemetered). Furthermore, it cost approximately £73 per water quality test kit (enough to carry out each test 100 times, which then costs less to replace), as oppose to traditional water quality monitoring, which is again in the order of £100s-£1000s, especially when laboratory tests are involved. These examples disregard additional cost incurred during the traditional monitoring process as a result of field visits (travel), maintenance, laptops required for data downloading and so on. Despite being high cost, this does not mean that traditional gauges or sensors have a longer life expectancy as many are damaged during storms, run out of battery, or need to be replaced within 5-10 years. Wrage *et al.* (1994), Lowry and Fienen (2012), Buytaert *et al.* (2014), Breuer *et al.* (2015) and Storey *et al.* (2016) all discuss monitoring costs in a similar way, and argue that citizen science can offer a low-cost alternative for river, rainfall and water quality monitoring. Blaney *et al.* (2016) argue that the cost-effectiveness of citizen science is governed by how it is implemented.

- **Skills:**

Citizen science projects are successful if they promote simple monitoring methods (Bonney *et al.*, 2009). User friendly protocols were used by the Haltwhistle community to increase participation levels and encourage repeat or long-term monitoring. Experts typically carry out traditional monitoring methods because they demand very specific knowledge and skills in order to design, install, manage and extract reliable information from a traditional monitoring programme. Facilitation and communication skills are however required to drive community-based schemes.

- **Ongoing maintenance:**

All monitoring methods require some form of maintenance, regardless of whether it is a formal or informal scheme. For instance, rain gauges become blocked over time, or gauges located within a watercourse may become damaged by high flows. Maintenance plans are an essential part of any QA/QC procedure. However, the community-based scheme in Haltwhistle demonstrated how members of the public regularly (daily) checked their own or communal equipment, and were subsequently able to highlight or rectify any issues occurring soon after. In-channel maintenance activities may be dangerous for communities. Traditional monitoring equipment are subject to uncertainty unless they are maintained on a regular basis.

- **Ease of installation, data collection, processing and correction:**

This chapter has demonstrated that robust QA/QC procedures are required to ensure good quality data are available for use. Examples presented have demonstrated that community-based methods are simple to install and collect data, particularly as many rely on visual sightings or photographs being taken. Most observations are direct as they are already in a desirable and extractable format. However, traditional monitoring protocols frequently observe parameters indirectly (e.g. water level is observed using temperature and pressure, which is later used to estimate discharge) and subsequently require significant amounts of post-processing and conversion. Both types of data do however require similar QC checks being applied. QC checks are better established for traditional methods, and hence are easier to apply. Datasets are also easier to check and correct when they are complete and observed at regular intervals.

- **Equipment lifetime – is it future-proof?**

Equipment lifetime has already been touched upon. Unless funding is available to keep traditional monitoring networks in operation, they are not future-proof. Citizen science monitoring methods themselves are regarded as being more sustainable due to their simplicity, but long-term retention of volunteers is problematic (Pocock *et al.*, 2014a; 2014b; Wentworth, 2014a).

- **Directly & indirectly measuring water level:**

RLGBs allow members of the public to directly observe water level and provide direct quantitative estimates. See 'ease of installation, data collection, processing and correction' above.

- **Open access - data availability:**

Sharing knowledge with others is a fundamental concept of citizen science. It allows non-professionals to become involved in the monitoring process and use the data collected, even if they are not a 'contributor'. Social media, file sharing facilities and free website hosting are just a few examples of how citizen science supports an open source or open access approach to environment data. While the UK government is encouraging traditional environmental datasets to become open access (e.g. through the Urban Observatory: http://uoweb1.ncl.ac.uk/), they are generally unavailable to wider catchment stakeholders and the public. If they are available, they are not user friendly.

- **Social benefits and knowledge gained:**

Various social benefits, such as environmental democracy, ownership, empowerment and education are just a few examples which can arise when actively involving the public in citizen science (Tweddle *et al.*, 2012; Science Communication Unit, 2013; Socientize Consortium, 2013; 2014; Blaney *et al.* 2016). Professionals have traditionally used an isolated approach, which restricts the benefits gained through environmental monitoring. This aspect is discussed further within Chapter 7.

- **Resolution:**

It is well-known that traditional automatic sensors are capable of creating high temporal resolution datasets. However, citizen scientists are able to focus (and mobilise) their efforts on events or locations of interest over time. Citizen science also supports mass data collection, which encourages multiple observations to be collected over a wide area. Nevertheless, traditional sensors provide regular and known resolutions over time.

- **Qualitative descriptions:**

While professionals can easily record qualitative observations alongside their quantitative datasets, their presence within the catchment is often very limited. When hydrological events of interest occur, notably flash flood events, they come and go very quickly, and experts are unable to witness them on the ground. This chapter has demonstrated how community-based observations form a patchwork of data which contains a significant number of qualitative data. This alternative source of information is extremely useful for verifying quantitative datasets, outliers and rare events.

5.6. Chapter discussion and summary

5.6.1. Discussion – reliability of citizen science

The quality and reliability of community-based observations have been demonstrated throughout this chapter and in a number of ways, including comparisons against each other, and alongside those collected using carefully controlled traditional monitoring protocols. Additional DQ case studies and catchment characterisation activities have also been presented to demonstrate the reliability of citizen science observations further. This extensive assessment has in turn shown that community-based data collection methods have the potential to deliver meaningful information to a wide catchment audience.

Whilst it is difficult to summarise the quality of citizen science in one statement, examples presented collectively suggest that members of the public have the potential to collect high quality and reliable data pertinent to the weather and water environment. Even though it is impractical for unpaid volunteers to provide uninterrupted datasets at high temporal resolutions, individual observations were of a similar standard to those collected by traditional sensors during paired analyses. This is an important finding given that hydrology and climatology are known for following the "rules" of good science (WMO, 2008), and hence the reliability of citizen science has been questioned by many to date (Buytaert *et al.*, 2014). Despite this outcome being specific to the catchment science sector, the same conclusions have been attained from DQ-related citizen science studies across other environmental disciplines (e.g. Crall *et al.*, 2011; Gollan *et al.*, 2012; Miskell *et al.*, 2017). Even though participants were paid to record regular observations, Walker *et* *al.* (2016) also drew a similar conclusion from a community-based project in Ethiopia, where participants successfully observed meteorological and groundwater-related parameters.

A closer inspection reveals that the Haltwhistle Burn community has achieved similar outcomes to other inexpensive monitoring activities in the literature:

- Wrage *et al.* (1994) and Illingworth *et al.* (2014) assessed manual rainfall monitoring methods, including homemade gauges that were constructed using recyclable drinking bottles. Wrage *et al.* (1994) describe how they provided accurate and reliable data. Illingworth *et al.* (2014) found resulting data in close agreement with formal sites nearby and were able to identify spatial rainfall patterns;
- Environment Agency (2012C), Breuer *et al.* (2015), Rose *et al.* (2016) and Storey *et al.* (2016) investigated simple water quality monitoring kits, including OPALometers, temperature and various colorimetric test strips. All of these studies conclude, similarly to the Haltwhistle Burn trials, that these simple tests provide a snap-shot and an indication of WQ status. There are still concerns over the simplicity of the tests, which appears to restrict participants' ability to collect high quality data, rather than their own skills;
- Lowry and Fienen (2012) have also investigated the accuracy of RLGB observations submitted by passers-by in Western New York. They conclude that high quality data can be collected in this way at a minimal cost.

Since citizen scientists have the potential to collect high quality catchment observations on an individual basis, the final reliability and 'fitness of the data for an intended purpose' (Wiggins *et al.*, 2011) are dictated by the desired formats and resolutions required to carry out the task at hand. In most cases, very detailed datasets are required by professionals to carry out hydrological analyses, although this does not imply that the data cannot be used to fill traditional data gaps (as Chapter 6 summarises). Communities themselves are interested in characterising (or providing an indication of) their catchment's regime and response to heavy or prolonged periods of rainfall, a task which has been feasible here using community-based data. Observations must therefore be meaningful and attractive to the public (as Chapter 6 demonstrates), and this is likely to be achieved using qualitative data (especially photographs and videos). Sporadic data collection is also better-suited to flood mapping and modelling by indicating the presence of rare hydrological events. It is also well-suited to flash flood events and sub-hourly extremes, which are known to occur during the summer months and in the late afternoon (Blenkinsop *et al.*, 2017). The timing of such events coincide with when the public most frequently observed the Haltwhistle Burn catchment (Table 4.11B).

Despite citizen scientists being capable of collecting high quality observations, robust QA and QC protocols must be put in place in order to minimise error and bias, and detect erroneous data. Like many (Wiggins *et al.*, 2011; Gollan *et al.*, 2012; Kelling *et al.*,2015), the Haltwhistle Burn project has demonstrated the importance of carefully designing the data collection and submission process in order to minimise or eradicate error beforehand (QA). Likewise, volunteer training and facilitation has been an essential component of the citizen science process, as the rejected rain gauge example (Cawburn) clearly illustrates. It is imperative that end data users are aware of any QC outcomes as they will automatically assume that the data are accurate and precise (Gordon *et al.*, 2004).

Regardless of community-based data being irregular and heterogeneous, existing traditional QA/QC frameworks (written by reputable organisations) have been implemented with ease, including those published by the WMO (2008; 2011; 2017). 'Checking manual data collected', 'digitising of records', 'guidelines for hydrological data rescue' and 'filling complete and accurate returns' are just a few examples of relevant DQ protocols already documented by the WMO. In many cases, the WMO brand human checks as being prestigious, claim that 'digital photography are important' and encourage professionals to take more 'frequent readings during storm and flood periods'. All of these requirements listed are inherently provided by volunteers, alongside regular equipment checks and daily anecdotes. Double-mass plots, correlation coefficients, PBIAS and over-plots for instance have proved to be effective methods for communicating DQ in citizen science. Simple tests, such as completeness and tolerance checks, are applicable and valuable to both traditional and community-based datasets. However, these QC techniques may overwhelm community-groups themselves if they are interested in the quality of their own data, although some citizen science projects already involve validation and verification tasks (Tweddle *et al.*, 2012). Wiggins *et al.* (2011) conclude that the QA/QC process is dictated by project budgets. Automated QA/QC checks may also be required for larger projects, including those discussed by Wiggins *et al.* (2011) and Bonter and Cooper (2012).

Given that vast quantities of community-based data have been supplied in a variety of quantitative and qualitative formats, a multi-dimensional QC approach is crucial. Generic citizen science guidelines exist in the literature (Riesch and Potter, 2014; Lukyanenko *et al.*, 2016; Wiersma *et al.*, 2016), and after successfully applying them to the Haltwhistle Burn datasets, it is clear that expectations (e.g. hydrological patterns and relationships expected to occur), cross-checks and triangulation activities are particularly useful. This is because they allow mass datasets, containing multiple parameters and monitoring stations, and in the format of videos, photographs, anecdotes and quantitative estimates, to be assessed and aligned against each other. Although the Haltwhistle Burn's patchwork of data had been collected by multiple observers, which is traditionally seen as being an inconsistent data collection approach, involving large numbers of participants improved the QC process here. It is therefore no surprised that greater numbers of community-based observations support a stronger QC process. For instance, if multiple rain gauges or flood photographs are located in close proximity, monitoring efforts are not 'wasted' as they are valuable during the verification process.

It is acknowledged that the traditional datasets used within this chapter are unlikely to represent the 'true' values when assessing accuracy, as traditional fieldwork methods are also susceptible to error (Environment Agency 2004; Beven, 2007; Villarini *et al.*, 2008). Nevertheless, this study has validated community-based observations against traditional gauges to demonstrate that monitoring efforts are in line with acceptable scientific standards. Findings have also been heavily dictated by the case study site used, the level of facilitation and resources provided, and the volunteers who became involved. Greater efforts are also required to co-locate community-based and traditional monitoring methods. Nevertheless, findings are significant because high quality data has the potential to support applications relating to the flood risk and catchment management process.

5.6.2. Summary – reliability of citizen science

Following the implementation of a successful community-based monitoring scheme (Chapter 4), this chapter has focussed on demonstrating the quality and reliability of the data generated. This was necessary as data users are sceptical about using data collected by members of the public for scientific applications. An indication of DQ allows data users to assess whether citizen science observations are fit for purpose and whether they are meaningful to catchment stakeholders. Community-based datasets have therefore been evaluated statistically and graphically against each other, against a carefully controlled traditional hydrometric monitoring network, through informative case studies, and by using them to characterise the Haltwhistle Burn catchment. Assessments have specifically focussed around spatial and temporal qualities and hydrological events of interest.

The traditional hydrometric monitoring process has streamlined over the years and is renowned for creating high quality and reliable datasets ready for high profile applications. A set of rain gauges and WLRs were installed across the catchment to allow for a direct comparison against the more cost-effective citizen science approach. Whilst this created high quality data at fine temporal resolutions, no traditional hydrometric datasets would have been available for use without this project. It is costly to monitor every parameter of interest on a local level and has therefore represented a typical rural UK scenario.

Community-based datasets are inherently different to traditional counterparts; they are heterogeneous, irregular and unpredictable which affects DQ. After various assessments, it can be concluded that:

- Citizen scientists can manually collect high quality and reliable observations which would otherwise be missed. Examples presented here illustrate how rainfall and river level observations can be of a similar scientific standard to those collected using automatic sensors. Datasets have also been used to characterise the catchment successfully, including key flood events of interest. However, it cannot be guaranteed that every observation will be reliable or that regular volunteers will continue to collect high quality data over time;
- High quality datasets can only be attained if they are subject to a robust QA/QC process, including a carefully designed monitoring scheme which contains training and facilitation. This provides data users with confidence, allowing them to conclude whether datasets are fit for purpose;
- Well-established traditional QA/QC guidelines (published by reputable organisations) have been applied to the community-based datasets successfully. Efforts must also extend beyond this to take into account that citizen science data holds multiple qualities. Expectations, cross-checks and data triangulation are particularly useful;
- Multiple observations collected during hydrological events of interest are required to capture rapid changes or verify unusual sightings;
- Evidence suggests that citizen scientists are conscious of collecting good quality data.

These outcomes suggest that:

- If the citizen science data have been accepted during the QA/QC process, and are of a high quality, further research is required to demonstrate the spatial and temporal value of these quantitative and qualitative observations, and their ability to support real catchment management applications (Chapter 6). Data must be used in order to retain participation levels and recognise community-based monitoring efforts;
- Securing good quality data is not always a priority. Other benefits and challenges exist and may dictate whether citizen science is an appropriate monitoring method;
- Long-term participation and data collection is a prominent challenge (Chapter 7).

Chapter 6. Demonstrating the value and integration of community-based observations in catchment science

Figure 6 (intro). *This chapter demonstrates how citizen science offers an important tool to support the catchment modelling and management process. Alongside a catchment-wide modelling case study which was published in the Journal of Hydrology, the 'Slaty Sike NFM scheme' (above) is presented within this chapter. This NFM scheme appeared in the media many times during 2015/16.*

6.1. Chapter introduction

Following a successful citizen science monitoring scheme, the value of the community-based observations has been explored here by integrating them into the catchment modelling and management process. This chapter therefore addresses **Research Question 3** (Can community-based data be used to model, characterise catchment response and be integrated into the management process?), by completing **Objectives 3A-3C**. After having many people involved in a participatory study like this, it is important to use the data so that participants recognise that their observations and monitoring efforts are worthwhile.

Following collection and quality-checking activities, community-based rainfall, river level and flood observations have been successfully used to build and run a physically-based, spatially-distributed catchment model (SHETRAN), alongside other traditional sources of data. Model outputs are directly compared when using traditional only (including rainfall radar), community-based only and a combination of both types of observations. A high-level summary of the findings are provided here.

This chapter also demonstrates how citizen science can be integrated into the (longer-term) catchment management process. The NFM scheme relates to a series of ponds and a novel log structure which were constructed in 2015 within the Slaty Sike, a small tributary of the Haltwhistle Burn. The scheme proved to be a popular demonstration as it featured in the media several times during 2015/16 (Figure 6 *intro*).

6.2. Adding value to the catchment modelling process

One of the main arguments for initiating community-based (citizen science) monitoring schemes within catchment science is that it has the potential to **generate** new knowledge about the weather and water environment, which can then be **used** to support the catchment management process. Earlier chapters have stressed how modelling activities are particularly restricted by the availability of input, calibration and validation information. As a result, this thesis has regularly highlighted the importance of going beyond the citizen science data collection phase. Evidence is required to demonstrate whether this new source of catchment data is **valuable** and provide stakeholders with **confidence** when using it. Studies of this nature are limited to date.

This section presents a short summary of a modelling study which has specifically addressed Research Question 3 (Objectives 3A-3B). Following data collection and quality-checking activities, community-based rainfall, river level and flood observations (previously described in

Chapters 4 and 5) have been successfully used to build and run a physically-based, spatially-distributed hydrological catchment model (SHETRAN), alongside other traditional sources of data. Using different combinations of rainfall observations (community-based only, traditional only, a combination of both and rainfall radar) and a 'leave-one-out' methodology, model performance has been tested against traditionally-derived hydrographs for demonstrating the spatial and temporal value of citizen science data. As the SHETRAN modelling process was fairly extensive, content within this section is focussed around the high-level results and conclusions attained which are relevant to a wider audience and the broader citizen science debate.

Specific information about the modelling framework, research gaps, SHETRAN itself and the modelling methodology (model set-up, calibration and validation) can be found within Appendix 6A-6C. In order to make the most of the available community-based data and ensure each of the three rainfall events of interest were covered, three sets of SHETRAN models were set up. The final modelled scenarios, where results have informed the overall conclusions, are as follows:

- **Models 1A-1H** with focus on the 30th April 2014 event. The overarching SHETRAN methodology and results are published within Starkey *et al.* (2017) (copy in Appendix 6C);
- **Models 2A-2I** with focus on the 8th August 2014 event (see Appendix 6D);
- **Models 3A-3H** with focus on the 22nd-23rd December event (see Appendix 6D).

The above sets of models have been simulated and output results (Q) have been analysed using various visual, graphical and statistical performance indicators, including the Nash Sutcliffe Efficiency (NSE) coefficient (see Appendix 6B for equations). Figure 6.1 presents average NSE values for each scenario and has ranked them in order of performance, and hence provides a summary of all modelled results. Alongside outputs in Appendix 6C, it is clear that community-based observations can be included within the catchment modelling process. Results demonstrate that models containing a combination of traditional and community-based input data perform 'best', or are in line with ground-based traditional gauges. Models containing rejected community-based data or rainfall radar generated the least reliable models. The broader modelling work (Appendix 6) indicates that community-based observations are relevant and can add value in a variety of ways. However, it is stressed that community-based data can only add value to models and be used with confidence if they pass appropriate QC checks.

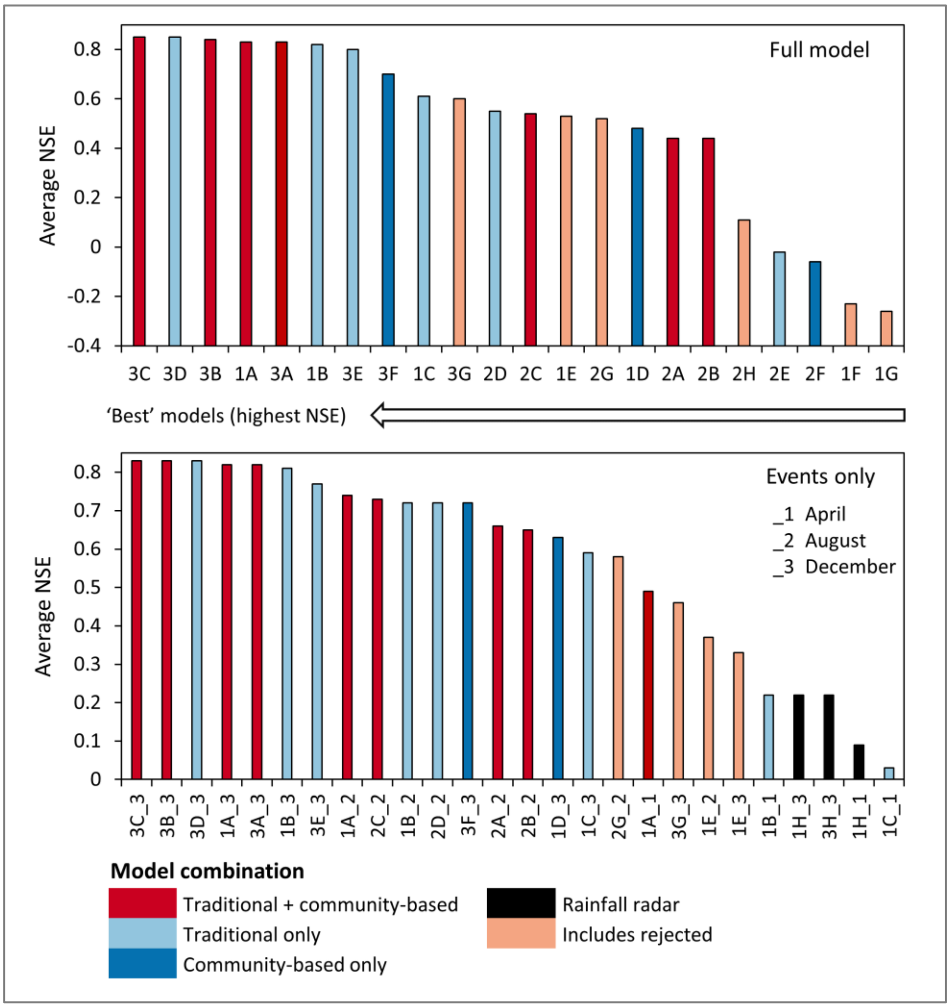


Figure 6.1. All NSE results ranked to highlight model performance (where 'best' relates to the highest NSE value), statistically, for each **full model** (top) and the **events of interest** (bottom, when NSE≥0). Each NSE value represents an average across all six gauging stations. Refer to Appendix 6C-6D for input rain gauge combinations and output locations.

Overall, the SHETRAN modelling study highlighted two fundamental findings:

- A patchwork of quantitative and qualitative community-based observations are required alongside traditional sources of hydro-information in order to fill spatial and temporal data gaps, and characterise local catchment response more accurately than when using traditional data alone. This includes the behaviour, timing and magnitude of river response during and after floods;

- Modelling has confirmed that community-based rainfall observations are most valuable during and immediately after local flash flood events. This information would otherwise often be missed, be unrecorded by existing ground-based gauges, or else be significantly underestimated by rainfall radar. Community-based observations are less valuable during prolonged and widespread floods, or over longer hydrological periods.

Figure 6.2 summarises the potential value of community-based observations in relation to the existing traditional sources of catchment observations following this SHETRAN study. It demonstrates how catchment stakeholders and communities themselves can harness and combine community-based observations with traditional datasets in order to ground-truth and fill data gaps, which in turn provides more spatially detailed information on a local level. This modelling study therefore significantly expands on existing participatory, citizen science or crowd-sourcing studies to date in hydrology (e.g. Kutija *et al.*, 2014; Fohringer *et al.*, 2015; Mazzoleni *et al.*, 2015; Smith *et al.*, 2015; Walker *et al.*, 2016).

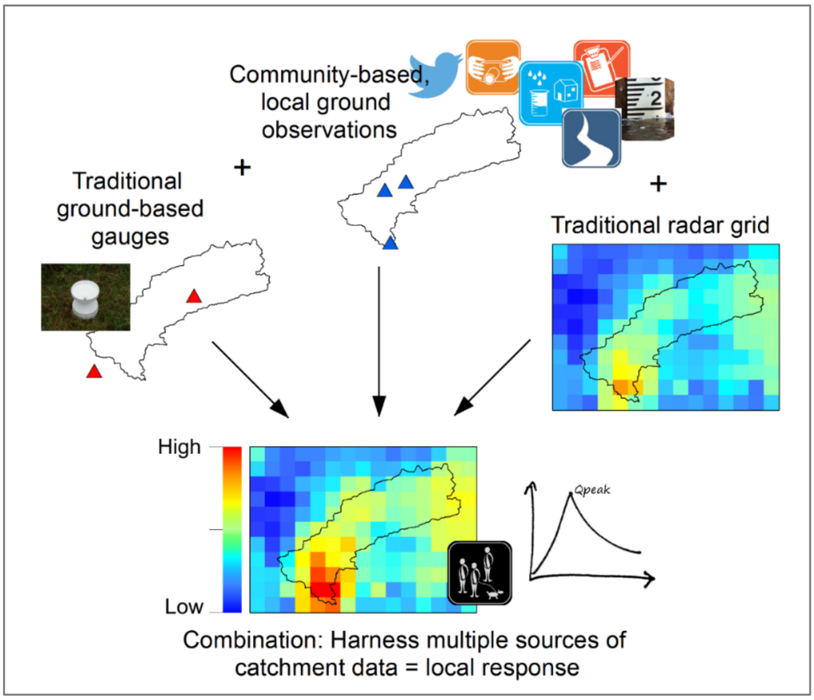


Figure 6.2. A schematic summarising the potential value of community-based observations in relation to the existing traditional sources of catchment observations (in this case rainfall), following this SHETRAN modelling study.

6.3. Integrating community-based monitoring into the catchment management process

6.3.1. The importance of integrating citizen science into the catchment management process

The literature review (Chapter 2) introduced catchment management from an integrated perspective, an approach which now prevails across the UK and EU. Integrated catchment management and the CaBA are encouraging:

- Multiple catchment issues to be considered and addressed together;
- Evidence-based science, therefore evidence-based policies;

- Involvement of all catchment stakeholders;
- Engagement, involvement and ownership of local issues using a bottom-up and partnership approach;
- Where appropriate, make use of nature-based solutions (NBS), work with natural processes (WwNP) and include natural flood management (NFM).

NBS, WwNP and NFM aim to enhance, restore and/or use the landscape by working with natural processes, and are now a major component of the catchment management procedure (Wentworth, 2011; Norbury *et al.*, 2015; SEPA, 2015; Defra, 2016; Metcalfe *et al.*, 2017). Interventions typically slow, store and filter runoff within the landscape, targeting sources and pathways, rather than receptors. In turn, multiple catchment issues can be addressed together, including flooding, erosion, diffuse pollution and ecosystem degradation.

Chapter 2 introduced NFM and established that previous schemes performed well and were cost-effective on a local scale (Nicholson *et al.*, 2012; Wilkinson *et al.*, 2014b; Defra, 2016), however there are still a number of barriers and negative perceptions preventing widespread uptake (Waylen *et al.*, 2017). In particular, there are uncertainties around the effectiveness of schemes during extreme events (locally, downstream and catchment-wide), and over longer periods of time (SEPA, 2015; Defra, 2016; Dadson *et al.*, 2017; Quinn *et al.*, 2017). Stakeholders are therefore repeating similar concerns, and are questioning what NFM features entail, what they will look like, and whether they will withstand high flows.

Howgate and Kenyon (2009), Bracken *et al.* (2016), Cook *et al.* (2016) and Moon *et al.* (2017) all stress the importance of including local communities in the catchment management process. While many NFM schemes have been praised for engaging with local residents (e.g. Wilkinson *et al.*, 2014b), public participation has not been explored or used to its full potential. Bracken *et al.* (2016) conclude that more effective and novel NFM monitoring methods are required, and Verbrugge *et al.* (2017) imply that public participation could support river management activities when demonstrating project success. Engagement, visualisation and decision support tools have been trialled (Wilkinson *et al.*, 2013; Hewett *et al.*, 2016) as a way to involve and communicate catchment management scenarios, but citizen science remains unexplored.

Chapter 4 has already illustrated how the community were able to monitor the Slaty Sike NFM features successfully (Figures 4.20, 4.24, 4.26 and 4.29). NFM-related monitoring was carried out less frequently than other parameters, although observations did closely align with heavy rainfall and high flows, and examples demonstrated how the community made targeted efforts to travel upstream for monitoring purposes. Observations were submitted as photographs and anecdotes (qualitative), and were deemed reliable after carrying out appropriate QC checks within Chapter 5 (e.g. Figure 5.31). Such observations have been assessed in more detail within this chapter, along with the Slaty Sike Divers (traditional monitoring), and two new qualitative monitoring techniques which also have the potential to be used by non-specialist audiences.

Regarding short-term catchment management, the Haltwhistle Burn examples have already illustrated how citizen science data are extremely valuable before and during flood events. Early warnings and flood-related observations helped to activate people within the community quickly, raised awareness and triggered action on the ground, especially when observations were shared online. Some participants have also used knowledge gained from monitoring activities in the Townfoot area to progress flooding discussions with the Local Authority and Environment Agency. For instance, the Environment Agency cleared out the blocked Townfoot culvert after the December 2014 high flows because members of the community informed them about it ("*I wonder if it's time to start making noises with a view to getting it cleared?*"). Citizen science observations are therefore important to the local community for short-term flood risk management.

6.3.2. Overview of the Slaty Sike NFM scheme

Funded by TRT's CRF project, a set of NFM measures were located, designed, constructed and monitored along the Slaty Sike watercourse. This pilot scheme was officially funded to target water quality issues and rapid erosion, but owing to NFM's multiple-benefit capabilities, flood risk also became a key component. NU was involved in the design phase, and this Ph.D. project was responsible for monitoring feature performance in a low-cost/cost-effective and participatory way. Figure 6.3 summarises the NFM process adopted (therefore the structure of this chapter) and highlights where the community and their observations played an important role. The scheme's design appreciated the values of NFM and best practice gained from previous interventions piloted around the UK, including those from the Belford Burn (NU and Environment Agency, 2011).

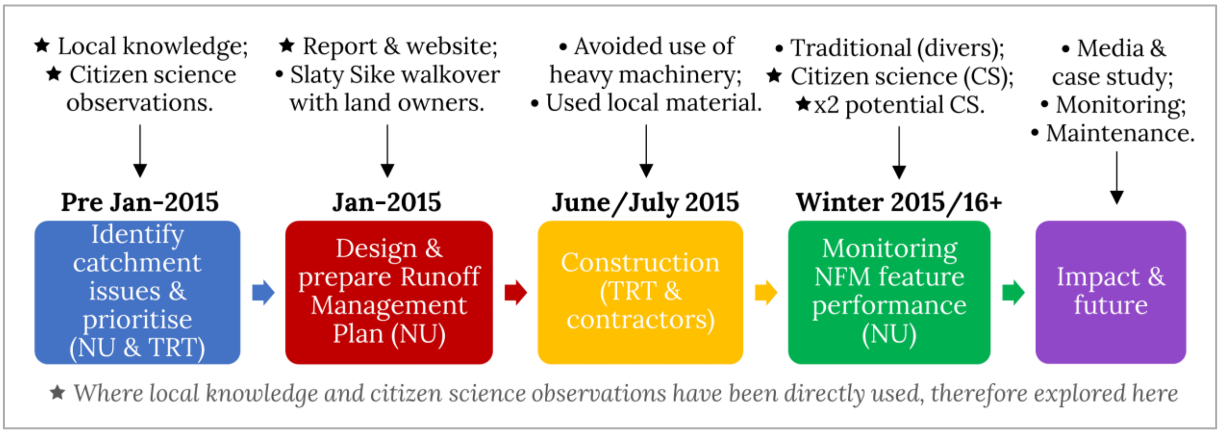


Figure 6.3. Summary and timeline of the Slaty Sike NFM process.

6.3.3. Local knowledge & community-based observations: identifying the catchment issues

The Slaty Sike was unmonitored and undocumented until the citizen science scheme commenced, and until the community shared their concerns during River Watch meetings. While the Haltwhistle Burn was known to be affected by multiple catchment issues, the following were regularly raised or observed by the community (see examples in Table 6.1):

- Townfoot and Mill Bridge RLGB observations are affected by the build-up of sediment and stones. The morphology along this stretch of the Haltwhistle Burn can alter rapidly, even after one short-lived high flow event (*"It all happens in one night." "Waterway filling up [with sediment] quick"*). Townfoot residents were concerned that sudden shifts and deposition of material would continue to undercut garden walls, completely block nearby culverts, and increase flood risk within the town;

- Small tributaries, including the Slaty Sike, regularly overtop and block with sediment in the vicinity of Willia Road and Broomshaw Hill (not the Haltwhistle Burn itself). This leaves a number of isolated properties and a business at risk of flooding, and they have been inundated in recent years;

- A member of the RWFG photographed overland flow occurring within the Slaty Sike sub-catchment which formed quickly following intense rainfall;

- The Slaty Sike, and nearby tributaries, contribute to water quality degradation within the Haltwhistle Burn itself and has been a primary concern for TRT.

Table 6.1. Community-based observations relating to Slaty Sike, Willia Road and downstream sediment issues.

The Haltwhistle Burn's water quality and flood risk issues were therefore closely related to rapid movement and deposition of silt, gravel and stones. Community-based evidence suggests that this material is sourced from upstream tributaries such as the Slaty Sike. This sub-catchment was therefore targeted as a NFM demonstration site where full scale interventions could be piloted to target sediment issues and attenuate peak flows. It was anticipated that slowing the flow and trapping silt, gravel and stones upstream during high flow events would relieve catchment issues downstream. It is important to note that the Slaty Sike NFM initiative was not intending to solve all water quality, erosion, and flood risk related issues as there are many contributory headwater streams; a scheme like this would need to be scaled up (Quinn *et al.*,

2017) across the Haltwhistle Burn catchment before witnessing any significant improvements at Townfoot.

6.3.4. Slaty Sike: location and catchment characteristics

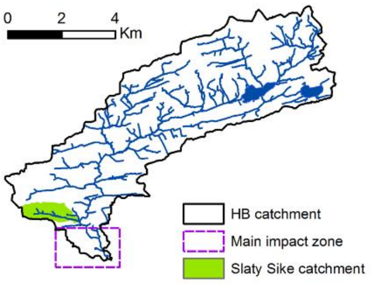
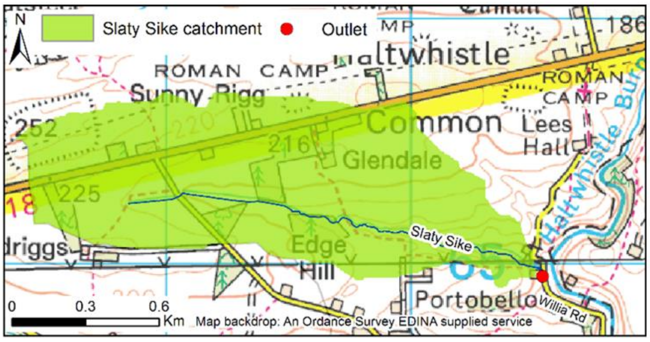
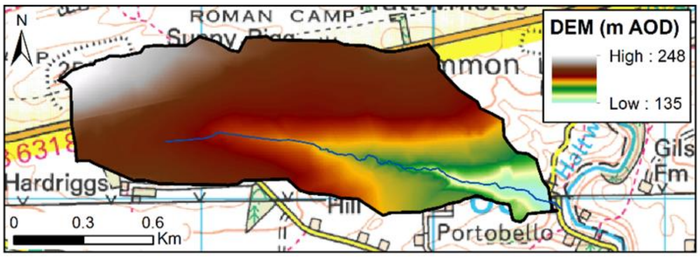
<table>
<tr><td>Location:

</td><td>
</td></tr>
<tr><td>Name of watercourse</td><td>Slaty Sike (1.8km long)</td></tr>
<tr><td>Sub-catchment area</td><td>1.13 km^2</td></tr>
<tr><td>Topography
(flow direction: west to east)</td><td>248m AOD (west) to 135m AOD (east).

</td></tr>
<tr><td>Bedrock geology:</td><td>Mudstone, sandstone and limestone</td></tr>
<tr><td>Soil</td><td>Loamy and clayey (slowly permeable, seasonally wet)</td></tr>
<tr><td>Dominant land cover / use</td><td>Improved grassland (agricultural use)</td></tr>
<tr><td>Strahler stream order</td><td>1 and 2</td></tr>
<tr><td>Monitoring</td><td>Completely unmonitored watercourse until 2015 (traditional and community-based methods – see below).</td></tr>
<tr><td>Runoff notes</td><td>Contains numerous gullies which activate quickly following heavy or prolonged rain. An active knickpoint is also present.</td></tr>
</table>

Table 6.2. The Slaty Sike NFM demonstration site.

Table 6.2 locates the Slaty Sike watercourse and its boundary with respect to the wider Haltwhistle Burn catchment, which is immediately north of the town and main impact zone. While the Slaty Sike is located within the lower Haltwhistle Burn catchment and drains directly into the Haltwhistle Burn itself, it is still a typical first and second order headwater stream which drains an area of 1.13km^2. This sub-catchment is rural, is covered by improved grassland, and is used for agricultural activities. Large open fields drain directly into the 1.8km long Slaty Sike, which becomes steep and narrow as it approaches Broomshaw Hill Farm (where it is culverted), before passing beneath Willia Road and into the main Burn.

6.3.5. Design: runoff management plan & land owner consultation

Following the aforementioned concerns, a draft runoff management plan was created by NU (Starkey *et al.*, 2015) which TRT then used to work with relevant stakeholders. This plan originally identified two NFM demonstration sites (Slaty Sike and another north of Cawfields Quarry), but due to time and funding constraints, only the Slaty Sike was feasible. The following sub-catchment criteria was used to select the Slaty Sike:

- Strahler stream order: 1st and 2nd orders are likely to yield most benefits from NFM;
- General topography, geology, land cover and soil type which favour attenuation;
- Size and shape of the sub-catchment: small and elongated;
- There are known catchment issues;
- Willingness of land owners to be involved with this pilot;
- Proximity to Haltwhistle town centre;
- Suitability for adopting different NFM features;
- An area where the RWFG had already expressed an interest in community-based monitoring activities (Figure 4.14).

The plan made use of the community-based data, characterised the Haltwhistle Burn and Slaty Sike catchments, and then located and described the NFM interventions proposed. Given that every NFM site is unique, it was difficult for stakeholders to visualise what the features would entail. Hosted on the NU project website, the report and an accompanying interactive map[25] therefore provided schematics and examples to aid discussions (Figure 6.4). The runoff management plan was discussed with the RWFG during a meeting. The plan was also shared with relevant farmers, land owners and land managers during a Slaty Sike walkover in January-2015 (Figure 6.4). TRT subsequently used the report to negotiate and agree on the final design with land owners and contractors.

Catchment walkovers revealed an active knickpoint which sits within the Slaty Sike itself. This geomorphological exposure was regarded as a typical upland sediment source which constantly erodes. The final NFM design took this into account; four attenuation ponds and a 60m long leaky

[25] Runoff Management Plan - interactive map created using ArcGIS online
http://research.ncl.ac.uk/haltwhistleburn/communityhub/catchmentmanagement/

dam were then installed. The ponds were expected to slow the flow upstream and reduce the Slaty Sike's erosive power before entering the knickpoint. Any material transported would then become trapped within the dam structure. These features significantly contrast traditional ('hard') defences, such as flood walls and barriers, which usually work against natural processes and are expensive to construct, maintain and monitor.

"I think it's just lovely working with nature like this. It's a great compromise" (land owner, 2015)

Figure 6.4. Sharing the runoff management plan with relevant stakeholders: using an interactive map (left) and land owner discussions (right).

6.3.6. Construction

TRT and an external contractor constructed the features in June/July 2015. Work was carried out in the summer months and was aided by traditional horse power to minimise impact on the landscape. A final description of the features are as follows:

Online runoff attenuation ponds (x4): as the first line of defence, this network of ponds was constructed to capture overland flow within an open field, store high flows and release runoff slowly during peak events. This attenuation method has been used in other NFM schemes to slow the rate of flow travelling downstream (e.g. Nicholson *et al.*, 2012). Slowing and blocking the flow using a series of depressions and soil bunds allows the Slaty Sike's power to diminish, and finer sediment to settle out. 'Online' means that these features are located within the drainage channel, therefore an outlet pipe was required at the downstream end of each pond to allow water to pass through the bund. Under low and baseflow conditions, the ponds encourage the Slaty Sike to behave normally and merge into the landscape (vegetate over). The bunds are wide enough for the farmer's quad bike and animals to pass over, and rock armour was placed downstream of each pipe to prevent erosion. The ponds cost £5k to construct and each have a 100-200m^3 capacity.

60m long leaky dam: this feature consists of a criss-crossed network of timber logs which were pinned in place across the Slaty Sike channel. While 'woody debris' type dams and other wooden structures have been placed perpendicular to flow in other locations across the UK (SEPA, 2015), this intervention is the longest of its kind and was carefully constructed to ensure the logs were secured to the stream bed and banks. Although some logs were felled within a few meters of the Slaty Sike, the majority were externally sourced. A logging horse pulled the timber into place within a small plantation, where the banks of the stream were steep and uneven. Smaller logs were positioned within the stream itself, while those longer in length were positioned on top, rested on the banks and extended onto the narrow floodplain. The layout of the logs was intended to reduce the force of the water, create a more torturous flow path (increase hydraulic roughness), push water out of bank, and subsequently encourage sediment (particularly gravel and stones) to trap within the structure. This trapping process resulted in the feature being compared with the children's game 'Kerplunk', with the straws and marbles representing the logs and stones within the Slaty Sike. This analogy proved to be a successful way of communicating this intervention to a lay audience. The feature cost £8k to construct.

All features and the knickpoint were surveyed during this Ph.D. project so that they could be mapped to scale (Figure 6.5).

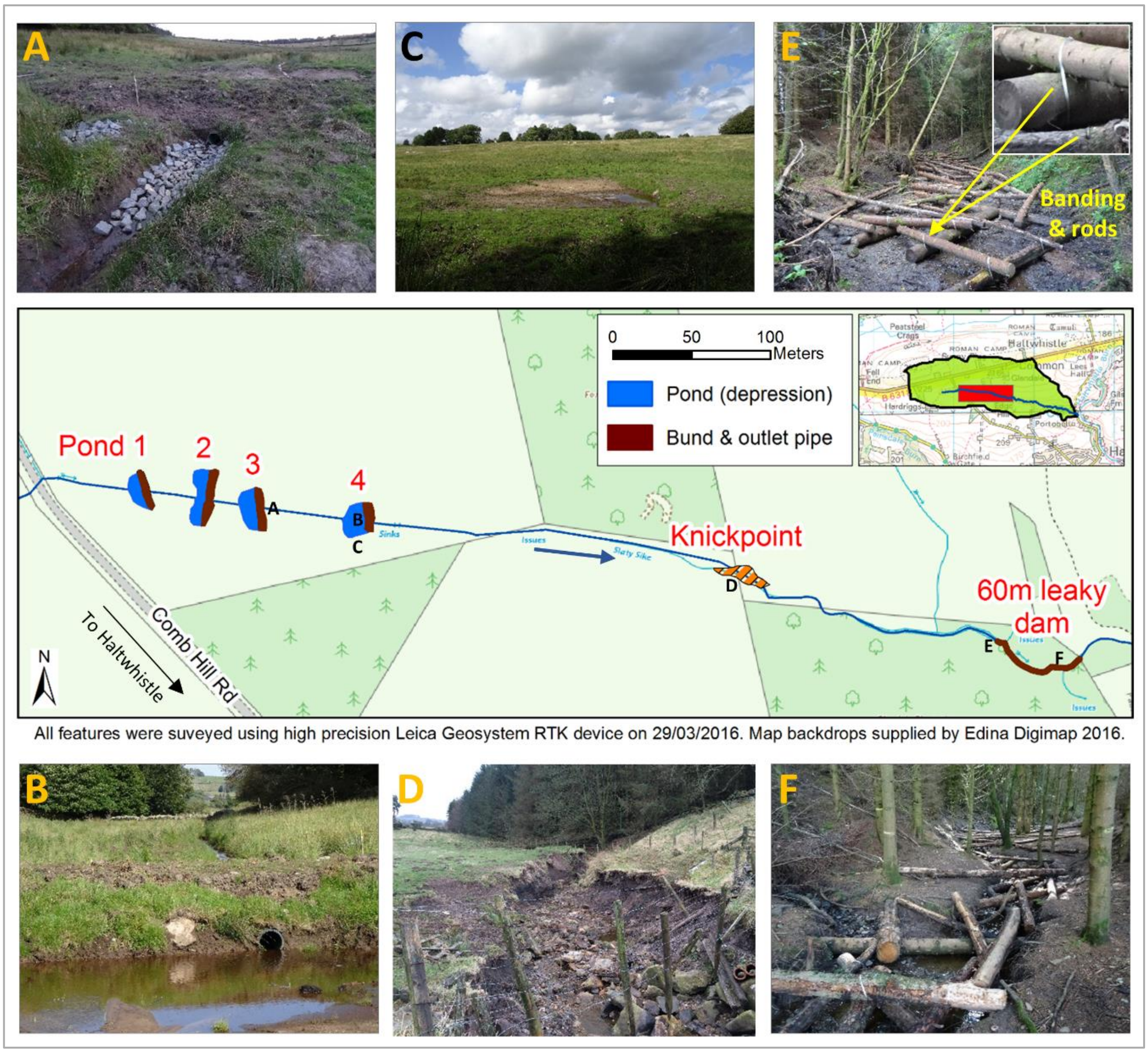


Figure 6.5. Map locating all of the Slaty Sike NFM demonstration features (following surveying activities) and photographs taken soon after construction.

6.3.7. Monitoring feature performance (with focus on winter 2015/16 floods)

- ***NFM monitoring – overview***

Monitoring the Slaty Sike NFM measures was required to demonstrate the scheme's performance to TRT's CRF project funders (Defra and Environment Agency), capture evidence for research purposes, and inform the local community (particularly land owners and the RWFG). It was essential to understand how the interventions behaved during high flow events and over longer periods of time. Given that the features were fully installed by July 2015, they were operational during the record-breaking winter 2015/16 floods, and thus were tested under extreme conditions. SEPA (2015) presents case studies where expensive monitoring networks have been used to appraise the performance of various schemes. However, many NFM schemes are installed and remain unmonitored, primarily because projects and accompanying funds terminate soon after the construction phase. Cost-effective yet insightful monitoring methods are therefore important.

The Slaty Sike was monitored using four key methods:

1. Traditional WLRs (Divers) installed within the network of NFM features (along with Broomshaw rainfall data already discussed);
2. Community-based monitoring: photographs and anecdotes, along with nearby rain gauge data (previously discussed in Chapter 5).
3. Qualitative monitoring method (1): Cost-effective time-lapse cameras (a **potential** community-based monitoring approach);
4. Qualitative monitoring method (2): 'kite-cam' involving an old camera strapped to a low-cost kite (a **potential** community-based monitoring approach);

Figure 6.6 presents a schematic of the NFM monitoring scheme. The following sub-sections describe each method.

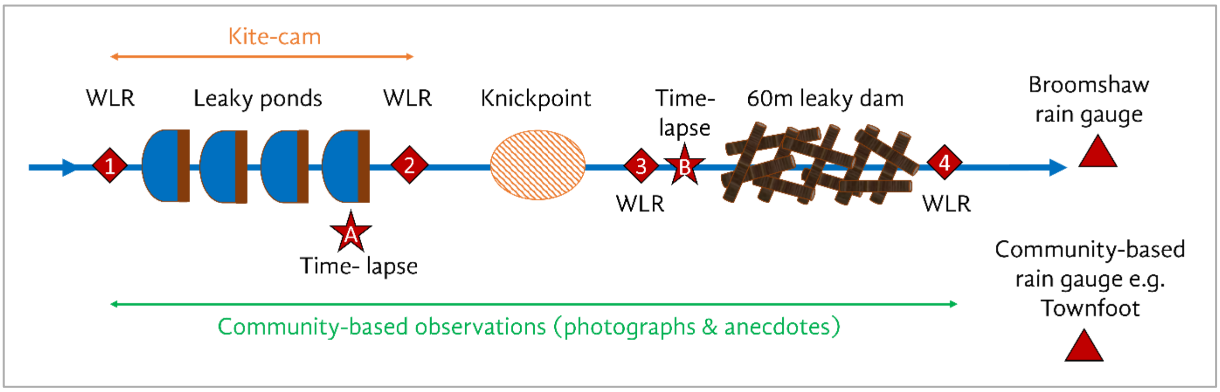


Figure 6.6. Schematic of the Slaty Sike NFM monitoring scheme.

- ***Traditional monitoring***

Four automatic WLRs (Divers) were installed within the Slaty Sike NFM catchment to capture the stream's response both upstream and downstream of the ponds and leaky dam feature (see Figure 5.3 and 6.6, and Table 5.1 for sensor locations and metadata). Divers were originally intended to observe pre- and post-construction conditions. However, stream levels remained extremely low between June-2015 (equipment installation) and July-2015 (NFM construction), offering limited information. Owing to the difficulties of traditional monitoring, there were also numerous gaps in the datasets following equipment failure, and Diver 4 (downstream of the logs) did not yield any useable data (battery failure and the gauge was damaged by cattle). As a result, WLR data have been assessed here between October-2015 and Febraury-2016. This period provides data from three Divers and contains the winter 2016/16 storms. These storms were significant to the UK (Marsh *et al.*, 2016; Parry *et al.*, 2016) and thus have tested the NFM measures under severe conditions. To accompany water level, the Broomshaw TBR gauge (QC checked in Chapter 5) provided the nearest set of traditional rainfall data.

Divers were installed, maintained and raw data processed using the same techniques described within Section 5.3.3.3. Appendix 6E provides a gauge summary sheet for each WLR and appropriate QC checks. It was found that Divers 1 and 2 (monitoring the pond field) were reliable for use. Diver 3 (upstream of the leaky dam) contained a number of offsets in the data because water level drifted over time. This data has been left unchanged because it contains valuable information relating to sediment deposition within the log structure.

Given the short monitoring timeframe, Q was not obtained for the Slaty Sike. It is acknowledged that there are many benefits associated with having Q estimates for NFM schemes (e.g. it can be used to carry out direct analyses between gauging stations), yet water level can still be used to understand runoff attenuation effects over short distances (as Norbury *et al.* (2015) illustrate).

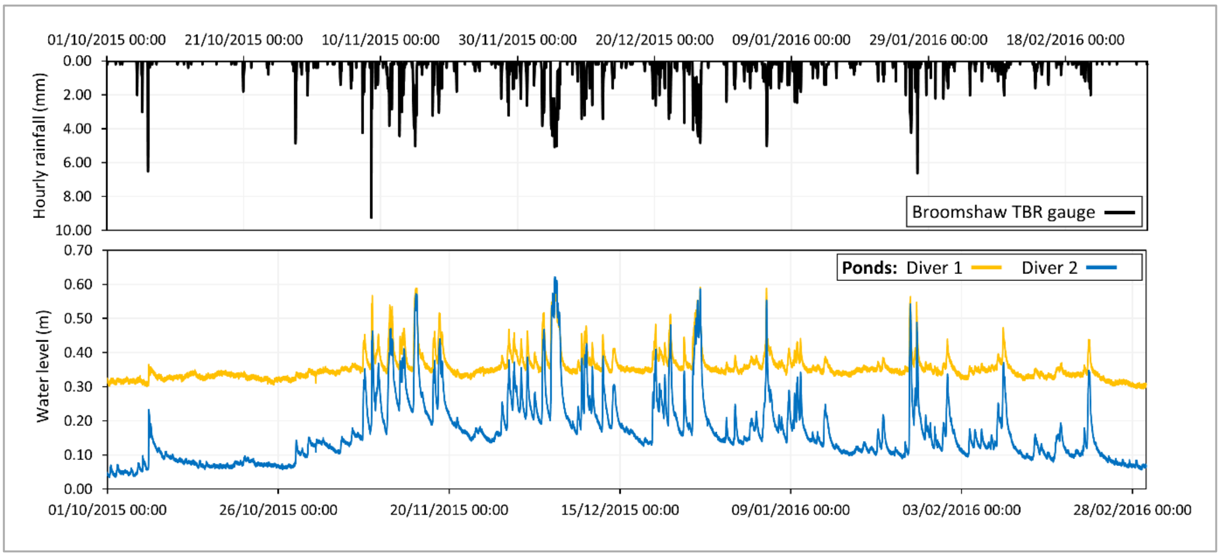


Figure 6.7. WLR data retrieved from Slaty Sike Divers 1 (upstream of ponds) and 2 (downstream of ponds). Hourly rainfall data also included.

Figure 6.7 presents the WLR data for Slaty Sike Divers 1 and 2. As expected, the Slaty Sike was active between October-2015 and Janaury-2016; summer baseflow prevailed until the end of October-2015, then a number of rapid response peaks were experienced. Diver 1 shows the Slaty Sike to be less responsive to rainfall than Diver 2. This effect can be attributed to the channel at

Diver 1 being controlled by the road culvert immediately upstream, and it also drains an area of land (0.25km^2) which is almost half the size of that drained by Diver 2 (0.48km^2 - downstream of the ponds and open field). It is also noticeable that the majority of extreme peaks observed by Diver 2 were of a similar magnitude, despite displaying greater variations elsewhere in the Haltwhistle Burn catchment (Figure 5.14 and Appendix 5C). It is possible that the ponds lowered water level to some extent as Diver 2's Storm Desmond peak (5th December 2015) was not significantly higher than other peaks observed (as would be expected).

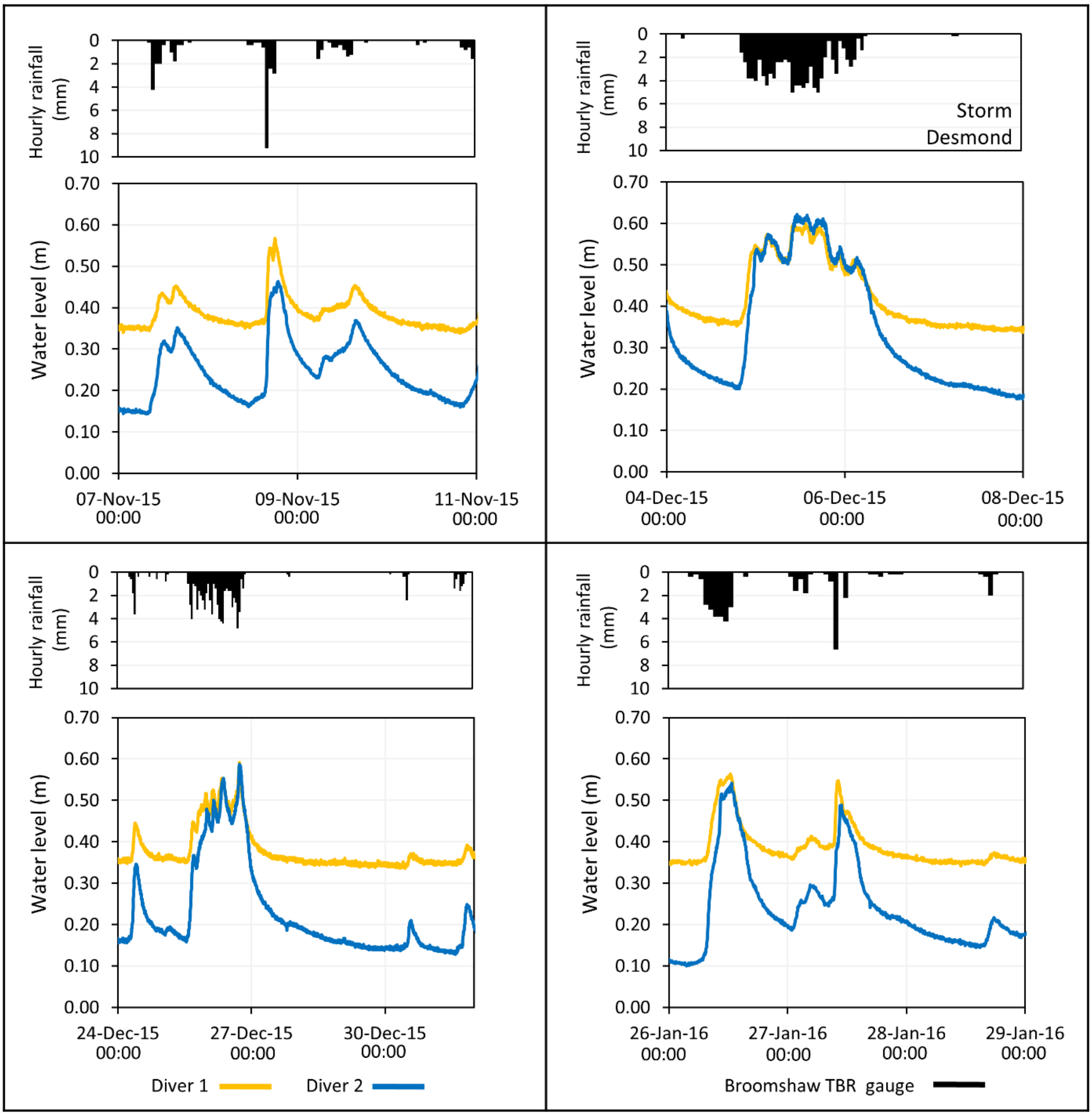


Figure 6.8. Event-based WLR data retrieved from Slaty Sike Divers 1 (upstream of ponds) and 2 (downstream of ponds). Hourly rainfall data also included.

Given that the ponds were designed to work on an event-based scale, it is difficult to assess performance from Figure 6.7. A series of event-based plots are therefore presented in Figure 6.8

to represent catchment response immediately upstream and downstream of the four ponds. These plots (which include Storm Desmond) do not show any clear indications of feature performance or attenuation. This finding is valid because on the whole, Divers 1 and 2 rise and fall in a similar manner. The only clear difference is that Diver 1 did not rise and fall to the same extent (magnitude) as Diver 2. While it is possible that Diver 1 was simply installed within a wider channel that was less responsive, or that the ponds did not work at all, it is more realistic to assume that Diver 2 experienced greater magnitudes because the catchment area is twice the size. Overland flow will contribute to the hydrological response observed by Diver 2, making it difficult to compare catchment response across the two Divers. However, it can be concluded that the ponds have been located in a beneficial location as they are able to intercept a significant contribution of flow at this point within the sub-catchment, but the divers were unable to provide evidence of feature performance (attenuation).

Limited information can be extracted about sediment accumulation within the ponds without regular site visits, water quality sampling or use of sediment traps. A complex network of pressure transducers located within and downstream of each pond (and accompanying Q data) would also be required to quantify attenuation capabilities (similar to Nicholson *et al.*, 2012). These methods were beyond the scope of this study.

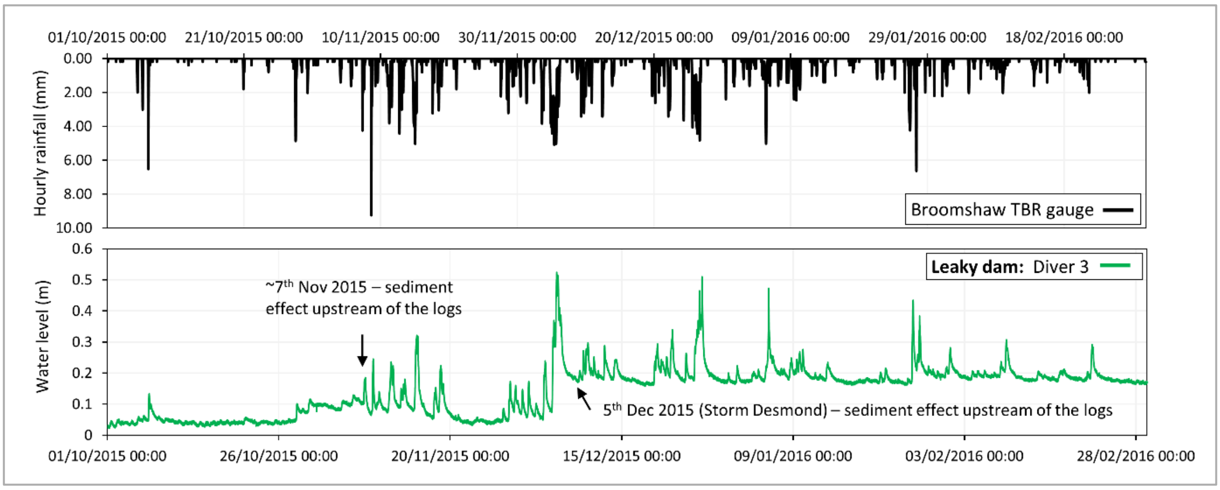


Figure 6.9. WLR data retrieved from Slaty Sike Diver 3 (upstream of the leaky dam). Hourly rainfall data also included.

Figure 6.9 presents the WLR data for Slaty Sike Diver 3 which was located approximately 20m upstream of the 60m long leaky dam. While Diver 3 has responded in a similar manner to Diver 2 (as expected as there are no major inlets or outlets in between), there are noticeable shifts in the data, particularly during Storm Desmond. QC checks also revealed a smaller step following high flows experienced at the beginning of November 2015. This water level data therefore indicates that significant sediment shifts are occurring in the vicinity of the log system, and that very large flows, such as Storm Desmond, are required to activate these changes. However, site visits were required to visually confirm that sediment was accumulating and backing up (22m) behind the leaky dam itself, as well as within the logs (for the first 25m). Other than discovering rapid shifts within the Diver data, this example demonstrates the difficulties of understanding how the log structure performed over time using the traditional hydrometric monitoring equipment. Regular site visits and monitoring schemes involving sediment traps, detailed laser scans, topographic surveys and/or morphological mapping would be required immediately before and after high flows (and repeated over time) to fully understand and quantify feature performance, as Addy and Wilkinson (2016) demonstrate.

This basic traditional monitoring scheme involving ponds and a leaky log structure highlights how complex it is to hydrologically monitor NFM features. While it is likely that the ponds have locally intercepted overland flow and the logs have trapped sediment during extreme conditions, many assumptions have been made. Lengthy pre-construction monitoring is required to take changes in catchment response into account as a result of feature installation. Such monitoring programmes are often impractical for most management and restoration projects, and it is financially impossible to monitor and establish stage-discharge rating curves upstream and downstream of every feature installed.

Similar to the Slaty Sike scheme, Podolak (2014) refers to restoration monitoring activities as being complex and costly. Podolak also implies that a multi-year monitoring effort is required, but desired datasets are not normally collected, and thus efforts should focus on maximising the value of available data. Modelling has also been applied to some NFM studies to date, but Metcalfe *et al.* (2017) accentuate that outputs are generalised and unrealistic. Equally, it can be argued that these traditional and sophisticated methods do not provide cost-effect summaries of feature performance which are useful to local communities, despite being the target audience in this study, and in many others.

- ***Community-based monitoring***

Community-based observations previously outlined and QC checked within Chapters 4 and 5 have been used here to understand how the Slaty Sike scheme performed. Figure 4.20 showed that six batches of NFM-related observations were collected by two members of the RWFG over the duration of the 29-month monitoring period. Out of these six, one set of observations were collected in February-2015 following the design phase of the scheme, which clearly demonstrate how overland flow generates and contributes to the sub-catchment's response where the ponds have now been installed (Figure 6.10). Another set of observations relate to restoration work carried out by TRT upstream of Greenlee Lough. This leaves four sets of observations concerning the Slaty Sike's post-construction performance. While the number of NFM observations received from the community were low, they still relate to important hydrological events, and realistically align with community-based rainfall data (Figure 6.11). Members of the RWFG were also interested to find out how the features performed over time (*"It will be interesting to see how they work and given my particular self-interest I am happy to try to keep an eye on what goes on there under different conditions"*).

Figure 6.10. Photographs taken by the community which demonstrate how overland flow contributes to the Slaty Sike ponds. Images taken prior to pond construction (26/02/2015).

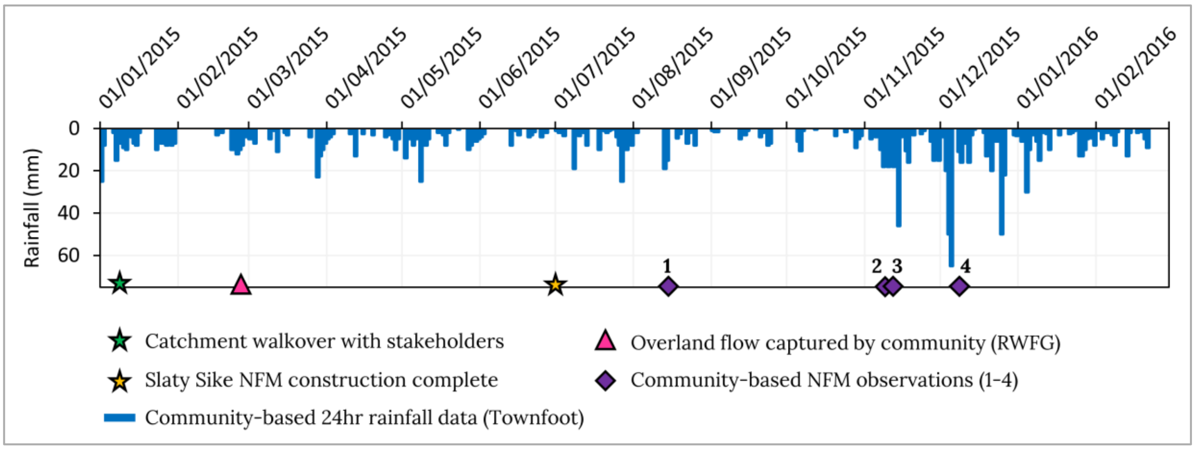


Figure 6.11. A timeline illustrating when the community monitored the NFM scheme (1-4). Note that these observations correlate well with high rainfall totals.

The four sets of community-based observations are summarised in Figures 6.12-6.15 and illustrate how the logs and ponds performed under a range of events. The following findings are therefore applicable as a result of integrating community-based monitoring into the catchment management process:

- Visually meaningful (yet simple) snapshots of NFM data are captured that would otherwise be missed, and can be used to validate formal sources of data (such as WLRs);
- While it is difficult to scientifically determine how quickly the ponds fill and empty under different rainfall scenarios, accurately quantify attenuation and sedimentation rates, or appreciate downstream impacts, the community-based observations indicated that the Slaty Sike features:
    - Were able to withstand record-breaking storms, including Storm Desmond;
    - Generally only reacted under extreme hydrological conditions;
    - Have attenuated and stored prolonged winter flows under saturated conditions;
    - Have trapped some sediment within the ponds (silt), and upstream and within the first half of the leaky dam structure (gravel);
    - The knickpoint and overland flow exacerbate the situation;
- Communities cannot be relied upon to observe all events/changes occurring within a scheme, particularly as NFM sites are generally located upstream and are less accessible;
- While anybody can take a photograph, local people are better-placed to carry out unexpected site visits and capture rare sightings;
- Community-based monitoring engages the public in the catchment management process.

Image-based outputs have shown to be useful in the context of NFM here. Technology is continually evolving, and thus photographs and videos will become more readily available in the future. This section explores qualitative monitoring methods further below.

1 **14th August 2015 (13:00-13:30 GMT)** *"After a dry few days it rained all night"*.

This was one of the first times the ponds activated and the logs experienced increased flows (following a Met Office warning for rain). Photographs have been captured after 34mm of rainfall fell in 48 hours and show all four ponds starting to back up. At this point the Slaty Sike was still re-establishing its flow paths following the construction phase. Evidence suggests that flows were too low to activate any noticeable sediment transportation and deposition within the log structure.

According to Broomshaw's high resolution (traditional) rainfall data, the majority of rainfall had occurred by 13:00 GMT, which suggests that this member of the community captured the scheme's response very shortly after. The timing of this qualitative data is therefore very useful.

Figure 6.12. Community-based NFM observations: **Batch 1**. See Appendix 6F for more examples.

2 **9th November 2015 (10:40-11:15 GMT)** *"Rain all day"*, *"Rain night and day"*, *"Wet and mild"*.

Following a spell of prolonged wet weather, one member of the RWFG travelled to the Slaty Sike scheme to see how the system was/had performed. According to community-based rainfall data (Townfoot), 41mm of rain was received over the preceding six days (28mm in past two days). These totals were not substantial, but enough to raise stream levels, allow water to collect in the ponds and fine silt, sand and debris to start accumulating within the log structure. Photographs show foam accumulating against the leaky dam; the first set of logs are initially breaking the stream's energy, and hence it is assumed that sediment will then be encouraged to deposit here.

Pond 4

Leaky dam entrance

Leaky dam ~10m along

3 **11th November 2015 (09:50-10:10 GMT)** *"Rain most of the day and heavy overnight"*

Wet weather continued beyond the 9th, and into 11th November 2015, representing a classic autumn/winter scenario when the catchment was saturated. A further 26mm of rain was observed by the community on the 10th and 11th November. On this occasion, photographs show all four ponds to be full and overtopping, and overland flow to bypass the bunds. While this November event was one of the largest experienced over the duration of the monitoring period, the ponds will have lost some storage and attenuation capacity when overtopped and bypassed. The leaky dam has also been pictured during high flow; as the logs are inundated with murky water, it is not possible to see whether material had been captured within the log structure. This dam is therefore better assessed once the flood peak has passed and stream levels return to normal. While these images only provided a snapshot of information, and did not encompass the 15th November (when this event peaked), they confirmed that the features remained in place, the bunds did not breach and water was held back.

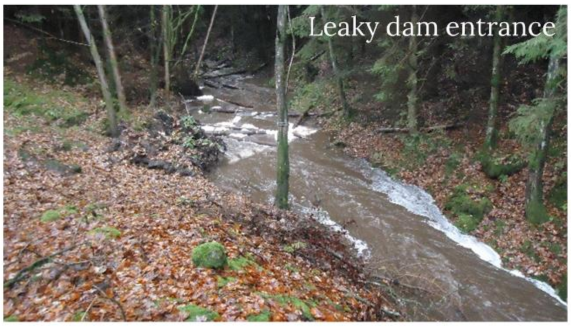


Figure 6.13. Community-based NFM observations: **Batch 2-3**. See Appendix 6F for more examples.

4 **8th December 2015 (10:50-11:30 GMT) – after Storm Desmond had passed.**

"Storm Desmond. The first time my rain gauge in the garden has reached this high!", *"The wind and rain was horrendous. The roads were flooded throughout Tynedale."*, *"Quiet after the storm"*.

After a wet November, December was also extremely wet and saturated. Community-based rainfall totals had already reached 366mm for the period 1st November to 8th December 2015 (135mm was observed between 4th-6th December). A member of the RWFG therefore travelled to inspect the Slaty Sike following these extreme meteorological conditions:

"Wow, gravel, sand and fine sediments all collected up the Slaty!"

"All logs in place with possibly 1/2 slightly raised. Some evidence of erosion around end of some logs. Logs at d/s end with little sedimentation effects. Ponds with lots fine silt in front of pipe outlet."

"Photos taken this morning after the weekend floods."

"Difficult to know whether they [the NFM features] made the difference"

These anecdotes and photographs are valuable data captured by the community only a few days after a significant storm event, and prolonged (weeks of) wet weather. They provide meaningful and visual information about the impacts on the Slaty Sike (e.g. the knickpoint has dramatically changed) and the performance of the NFM features. While it is difficult to determine whether the ponds and logs have 'made a difference' downstream, vast quantities of sediment have been captured and all features remain in place. Some of these photographs provide valuable information required to validate the Slaty Sike diver data. The volunteer observing the scheme confirmed that *"it was the first time the logs had been tested properly"*.

Figure 6.14. Community-based NFM observations: **Batch 4**. See Appendix 6F for more examples.

- ***Cost-effective time-lapse cameras***

The use of low-cost imaged-based tools, such as smartphones and action cameras, have grown significantly in recent years and are readily used by non-specialists. Given that photographs and videos have proved to be a popular monitoring output throughout this project, and can provide visually meaningful catchment information to a broad audience, cost-effective time-lapse cameras have been trialled as an NFM monitoring tool here. Despite the community not being involved in this particular data collection trial, it is argued that this potential citizen science approach offers an alternative to handheld cameras, and is a simple monitoring method which ordinary consumers can implement. As with the Slaty Sike demonstration site, catchment management will (or should) involve monitoring remote sites which are located away from urban areas. Time-lapse cameras permit regular observations to be captured automatically over time, allowing RWFG volunteers to focus their efforts on downstream flooding during an event. Members of the community often preferred to monitor within the town (nearer home) during high flow events, rather than the NFM features upstream. The latter point is therefore an NFM monitoring barrier. It is also argued that traditional monitoring methods, involving in-situ sensors, require specialist skills, software and accompanying hardware in order to use them, and are therefore unattractive, expensive and unrealistic to citizen science.

Time-lapse cameras operate by taking photographs at regular intervals, and the resulting frames are stitched together to generate a video. This form of FPP allows changes to be detected automatically over time, and hence can be applied to flood- and NFM-related monitoring activities. Time-lapse cameras are starting to support catchment monitoring activities, with some researchers extracting quantitative estimates through image analysis and structure-from-motion techniques (e.g. Young *et al.*, 2015; Benacchio *et al.*, 2017; James *et al.*, 2017). However, time-lapse consumers often use micro DIY computer boards (e.g. Raspberry Pi) which require coding skills, powerful computers to process images, and accompanying hardware. Moreover, battery power, night-time vision and overall costs limit their use for citizen science and NFM.

Taking the aforementioned into account, two regular (consumer specification) time-lapse cameras have been used to monitor the Slaty Sike ponds and leaky dam from August-2015 to Janaury-2017. Table 6.3 describes these cameras which were installed by Pond 4, and at the entrance to the leaky dam structure (refer to Figure 6.6 schematic). These cameras were chosen as they are non-obtrusive, waterproof, portable, simple to operate, do not require any extra hardware, are praised for picture quality (day and night), require little power, and resulting images can be ‘downloaded’ by simply swapping a portable memory card over whilst out in the field (i.e. similar memory card to those used in smartphones, laptops and hand-held cameras). These cameras are therefore regarded here as potential community-based monitoring tools.

Camera	Pond camera	Leaky dam camera
Specification	Ltl Acorn 12 MP scouting camera (HD) (LTL 6310).	Bushnell Nature View HD camera
Cost (excludes memory card and batteries)	£159.99 (regarded as cost-effective / low-cost if monitors over many months).	£165.99 (regarded as cost-effective / low-cost if monitors over many months).
Battery power	x12 lithium batteries. Provides at least 3-6 months power using settings below.	x8 lithium batteries. Provides at least 6-9 months power using settings below.
Data download	Requires SD memory card. 32GB used here. Just push into SD slot. Battery runs out before storage. USB and TV output is also possible.	
Image resolution	5 MP (capable of 12 MP but uses more memory space).	
Frame resolution	15-minutes (finer resolution is possible but uses more power and space)	
Time stamp	Automatically included on image.	
Waterproof	Yes. Can also purchase or make protective casing (not used here).	
Camera mount	Used a wooden fence post and cable ties to fasten and secure into place.	Used existing tree positioned in line of sight. Cable ties used to fasten.
Motion sensor	Not available with this model. Not essential.	Motion sensor activated. Set to detect movement every 15-minutes (in case flood wave or debris). Extra images taken if detected.
Night vision	Infrared-LED activated.	
Data availability	18-Aug-2015 to 29-Jan-2017. A few gaps exist (user error related).	18-Aug-2015 to 29-Jan-2017. A few gaps exist (user error related).
Location	Adjacent to Pond 4 only, side view. NGR: 369268 565257	Immediately upstream (2m) of leaky dam structure. NGR: 369622 565188
Notes	Difficult to capture all four ponds using one camera. Have focused on Pond 4 only to appreciate water entering and leaving the pond, as well as overland flow behind.	This camera appeared more reliable, but possibly because it was sheltered within the plantation. Expected to monitor the build-up of sediment at the start of the dam.
Photograph		

Table 6.3. Time-lapse camera specifications and settings used to monitor NFM performance.

The two cameras were checked every few months and blank memory cards were inserted so that outputs could be processed in batches. Cameras were also checked for water ingress, position (line-of-sight), lens cleanliness, and battery power. Each camera automatically stamped date and time into the image which provided a useful QC check. Although each image is stored as a separate file and can be viewed in this way, Windows Movie Maker (software which is free to Window users) was used to stitch them together to create an ongoing time-lapse video:

1. Pond 4 time-lapse: https://youtu.be/aPzlxV_fNMI
2. Leaky dam time-lapse: https://youtu.be/bsVa5vSbTBU

Both time-lapse videos can also be found on the disk submitted with this thesis.
The cameras have provided 17 months of ongoing post-construction data (and are still monitoring as of June-2017) which is rare in catchment management projects. The time-lapse videos and the original images have been useful here to visually extract feature-specific information. Figure 6.15 and Table 6.4 summarise each time-lapse video by presenting (i) semi-quantitative categories which represent performance over time and (ii) images of interest. These outputs illustrate how relevant information can be extracted effortlessly from qualitative time-lapse photography.

Based on the cameras line-of-sight, the following findings have been extracted:

- Both features remained in place and fully operational despite having experienced the winter 2015/16 high flows. Little change has occurred since February-2016;
- Coarse sediment (stones and gravel) deposited within the first 10-20m of the log structure;
- The leaky dam remained inactive for the majority of the time. Large rainfall totals and high flows, such as Storm Desmond, were required to trigger significant sediment and debris accumulation;
- The logs were stationary throughout, including the winter 2015/16 period. However, one log appeared to lift up and down during very high flows, which was later pinned down by deposited sediment. The logs did not wash away downstream;
- Pond 4 was more active than the leaky dam as it responded to rainfall and streamflow accordingly. The pond was tested on many occasions; high rainfall totals, prolonged wet weather and saturated soils filled the pond more rapidly, causing it to overflow;
- The pond filled and emptied quickly (within 12-hours, e.g. 22/12/2015) on most occasions and did not experience capacity issues. However, it was overwhelmed and the bund was bypassed during extreme conditions, which then affected its ability to store and

attenuate flow during the following 12-24 hours (e.g. on 5th-6th and 25th-26th December 2015);

- Significant overland flow generated in the field on a number of occasions and continued downstream without entering the ponds;
- The pond took time to stabilise following the construction phase and first winter. However, it grassed over and blended into the surrounding landscape by summer 2016. The camera struggled to capture the pond's siltation effect, although it is clear that material accumulated upstream of the bund.

Clear correlations are visible between the traditional rainfall and river level data collected, and the NFM activity captured by the cameras (Figure 6.15). Time-lapse cameras can therefore provide an indication of feature performance, and be used to pinpoint days when significant sediment and pond activity occurred. This level of information provides stakeholders with confidence and informs maintenance protocols.

As with any catchment monitoring method, problems were still encountered with the time-lapse cameras whilst out in the field:

- A few gaps exist in the datasets (attributed to user error, not equipment failure);
- The camera lens steamed up and frosted over in severe weather, but this cleared quickly;
- The leaky dam camera was sheltered from cattle, direct sunlight, strong winds and very wet weather, and thus produced better-quality images than the pond camera;
- Camera distance from the feature affects image quality, particularly in the dark.

Time-lapse videos were hosted on the project website and Flickr to allow the public to benefit from these visual outputs. However, this monitoring approach has yet to be tested with the community.

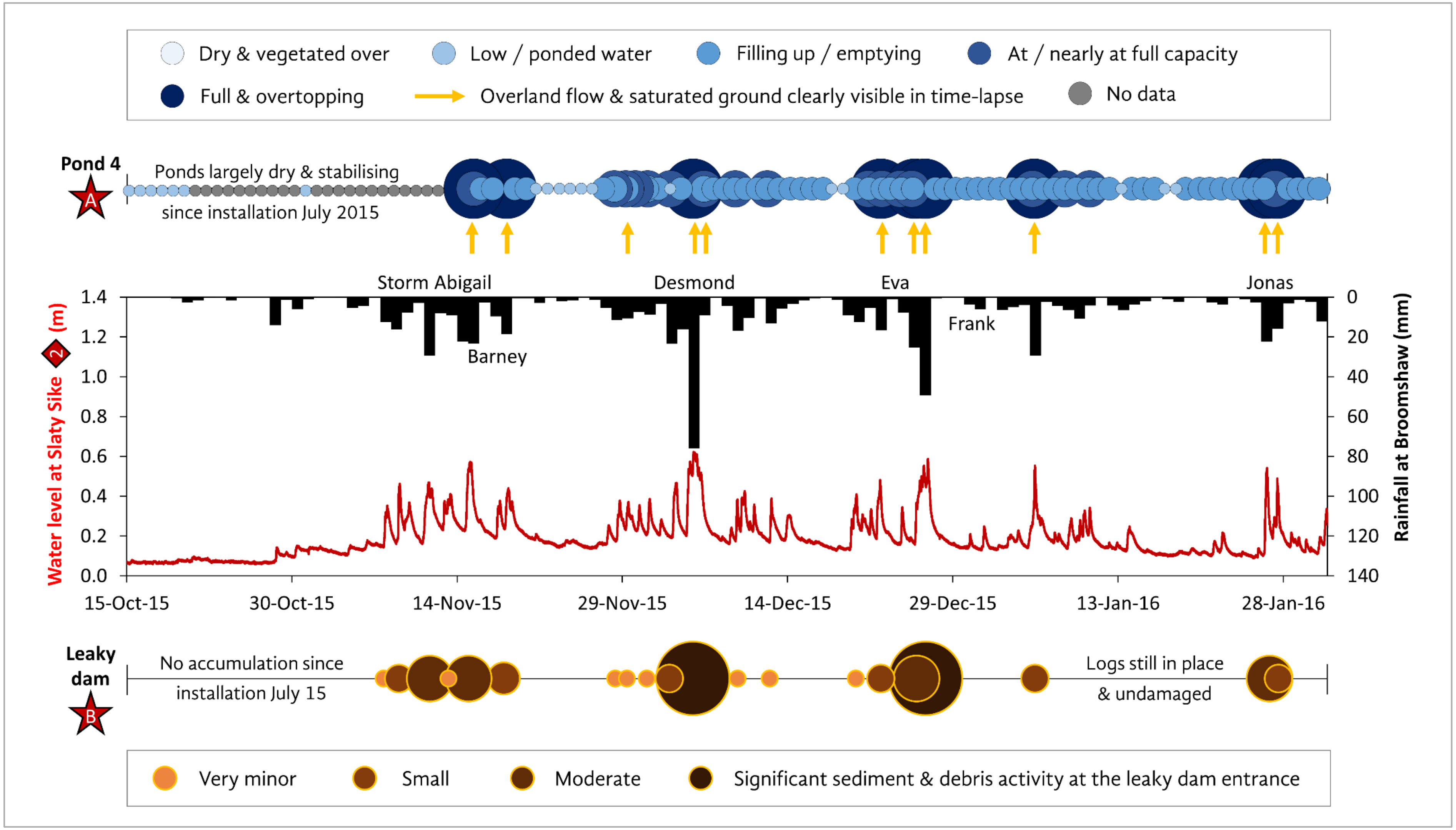


Figure 6.15. A summary of NFM performance based on the time-lapse videos. Data relating to pond (top) and sediment (bottom) accumulation have been visually extracted and placed into meaningful semi-quantitative categories, with focus on winter 2015/16. Traditional data are plotted for reference.

 Pond 4: August-2015	 January-2017	 Leaky dam: August-2015	 January-2017
 Pond 4: 05-Dec-15 08:53	 05-Dec-15 10:01	 06-Dec-15 07:58	 07-Dec-15 08:34
 Leaky dam: 04-Dec-15 12:30	 05-Dec-15 19:00	 06-Dec-15 12:15	 07-Dec-15 11:30

Table 6.4. Selection of time-lapse images which convey pond and leaky dam performance (August-2015 to Janaury-2017).

- ***Inexpensive 'kite-cam'***

Monitoring methods described so far within this chapter contain limited spatial coverage as they generally provide point-based observations, particularly the WLRs and time-lapse cameras. However, catchment management measures are placed within the wider landscape and interact with hydrological and geomorphological processes over time. Aerial and satellite maps are commonly used to provide spatial snapshots, including Google Earth (Large *et al.*, 2017), and more recently, UAVs (Perks *et al.*, 2016; Detert *et al.*, 2017; James *et al.*, 2017). NFM relies on the rural landscape which is often poorly represented by open access imagery (including the Haltwhistle Burn). These free online images are also restricted by poor image resolution and temporal coverage (Breen *et al.*, 2015). The latter point is important for NFM as features are designed to slow, store and filter runoff over short timescales. To date, there are limited remotely sensed images available for NFM, which is surprising given that stakeholders, including land owners, are interested in feature appearance and performance across the landscape.

Citizen science involves monitoring the natural environment using a variety of simple and readily available methods. 'Public Lab' (https://publiclab.org/) for instance is an environmental science community which encourages the use of DIY monitoring methods. Public Lab claims that communities 'lack access to the tools and techniques needed to participate in decisions'. Those involved have created low-cost and attractive methods suitable for monitoring a range of environmental concerns, including 'balloon mapping' (Breen *et al.*, 2015). This grassroots approach has merged citizen science with cartography by capturing the Earth's surface with an ordinary consumer camera whilst attached to a balloon.

Inspired by Public Lab, a 'kite-cam' was devised for use within the Slaty Sike NFM scheme. Similar to the time-lapse cameras, this kite approach was piloted as a potential community-based monitoring method since it is inexpensive, simple to assemble and uses equipment which the public are familiar with. As Figure 6.16 shows, the kite-cam consisted of a £7 kite, an old mobile phone (video mode activated), elastic bands and cable ties for fastening. The kite was flown on a few occasions to capture the extent of the ponds from an aerial perspective. Examples of outputs are presented in Figure 6.16. While there are drawbacks associated with this method, such as it will only work during windy weather and potential invasion of land owner privacy, the kite-cam offers a less technical method than UAVs. It provides a monitoring method which can be used to engage with the public and encourage catchment management involvement. Outputs are unique, visually meaningful to stakeholders, and would otherwise be unavailable to a scheme like this.

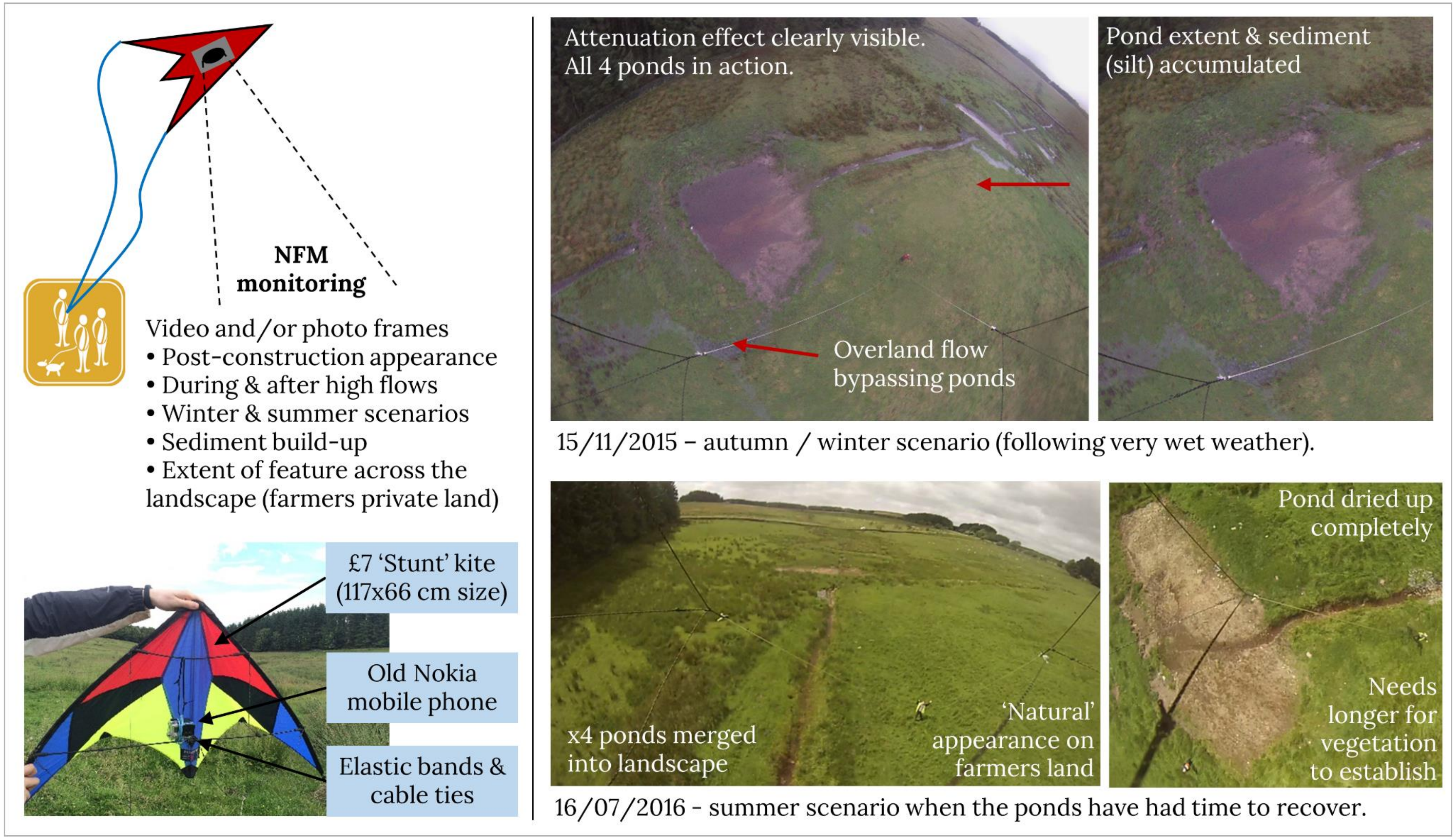


Figure 6.16. Piloting the 'kite-cam' for post-construction NFM monitoring: outputs from the Slaty Sike ponds. Land owner permission was required. This monitoring method has yet to be tested with the community.

6.3.8. Future and impact of the Slaty Sike NFM scheme

Section 6.3.7 has clearly demonstrated how community-based monitoring has supported various stages of the catchment management process. A variety of semi-quantitative and qualitative observations now exist for the Slaty Sike scheme; it is argued that these simple observations are more meaningful and valuable here than those collected by the traditional sensors as they have generated a number of important and reliable conclusions regarding feature performance, which would otherwise be unavailable. Outputs from the RWFG volunteers, the time-lapse videos, and kite-cam tests have shown that the features have worked in line with their design, and are combatting catchment issues first highlighted by the community (Section 6.3.3). As of Janaury-2017, the ponds and leaky dam remained operational and have the capacity to withstand forthcoming high flows. However, these measures will need maintaining over time to ensure that they do not exacerbate sediment, water quality and flood risk issues downstream. They also require the community to monitor the measures beyond the lifetime of this Ph.D. project.

Community-based monitoring has encouraged passionate volunteers to become involved in the scheme; they know how to access the features, they are prepared to travel upstream, they know how they work and acknowledge the concepts and wider benefits of NFM, and because they have physically observed the ponds and logs over time, they are aware of each features 'maintenance status'. While it is not yet clear who is responsible for feature maintenance, or who will pay (Waylen *et al.*, 2017), involving volunteers and documenting change over time can only help to trigger and support a more efficient maintenance programme. It also encourages volunteers to activate their own maintenance programme, and is something which the Haltwhistle Burn RWFG have already shown an interest in (*"Would a session in the ponds clearing some sediment and improving the drainage be of any help? Am more than happy to spend an hour or two with a shovel"* Flood Warden, November 2016). Guidance from TRT or scientists is likely to be required though.

The features themselves, and having the public involved, have resulted in a successful and popular demonstration site which has led to a positive impact within the community, and also on wider regional and national scales. The following examples demonstrate this.

Local impact: the Haltwhistle Burn community have shown signs of enthusiasm, excitement, intrigue and increased levels of NFM knowledge as a result of being involved in the project, or benefitting from the visual outputs:

"It's wonderful that something relatively simple can work so well. Aw, and using a horse as well, I often noticed when works were done up the burn, the big machinery used to leave quite a mess" RWFG volunteer, September 2015.

"They [Slaty Sike features] are great. We just need loads of them to see a difference in the town" Flood Warden, November 2016.

"Love the time lapse, December will be even more interesting!" RWFG volunteer, November 2015.

"Very exciting and absolutely fascinating [kite-cam outputs]" RWFG volunteer, February 2016

"Just wondering whether we can link rainfall and its timing to how quickly they fill up? [...] Have the ponds grassed over yet?" RWFG, 2016.

Despite residents being concerned about blocked culverts, sediment issues and flood risk, the Slaty Sike scheme has created a positive impression on residents directly affected (e.g. *"Wow, gravel, sand and fine sediments all collected up the Slaty!"* RWFG volunteer, December 2015).

Regional impact: the Slaty Sike scheme has appeared in the local/regional newspapers, and thus reached and educated a wider audience[26]. A game of 'Kerplunk' was also included in TRT's end of CRF project event, which allowed different age groups to successfully reflect on the purpose and design of scheme (Figure 6.17). The scheme's outcomes were therefore shared across the wider Tyne catchment.

"I know, I know! It is those logs in the river at Haltwhistle. We have done about it at school"
School pupil, Northumberland. September 2015

Figure 6.17. Project stakeholders, including the public, playing the game 'Kerplunk' during TRT's end of CRF project event in September 2015. The game has been a useful NFM analogy.

National impact: the Slaty Sike NFM scheme has featured several times in the media[27] including BBC News (World, Look North and Science & Environment online), on a BBC documentary, ITV

[26] E.g. http://www.chroniclelive.co.uk/news/north-east-news/haltwhistle-flood-protection-scheme-inspired-9942573.
[27] E.g. http://www.itv.com/news/border/2016-03-17/can-natural-defences-help-prevent-flooding/. A full list of media links can be found on the disk submitted with this thesis.

Tyne Tees and Borders, and was also a runner-up for The Guardian University Awards 2016 under the 'Social and Community Impact' category (Figure 6 *intro*). The Haltwhistle Burn community have therefore contributed to the scheme's success, and the aforementioned coverage used monitoring outputs (community-based, time-lapse and kite-cam) to convey a meaningful narrative to the wider public. Citizen scientists involved in the project also saw their observations being used and fed back to the community in a high profile way.

6.4. Chapter summary – value and integration of community-based data

This chapter has successfully integrated community-based monitoring into the catchment modelling and management process (Objectives 3A-3C). Both the modelling and management (NFM) examples are typical tasks which stakeholders are frequently involved in during the flood risk management process.

Citizen science data has proved valuable in the catchment modelling process with simulation outputs that incorporate this simple and low-cost data source being more reliable than those which use traditional sources alone. Model performance was significantly enhanced after both quantitative and qualitative community-based observations were included at a local level. These findings should alleviate scepticism amongst the professional and academic community towards routinely incorporating this type of new data into their flood risk (and wider catchment) management applications. Beyond modelling, it also gives data users confidence to apply community-based data to a range of other catchment applications. This modelling work was essential to generate such outcomes and should be considered across broader environmental disciplines.

The Slaty Sike NFM demonstration, involving ponds and a 60m long leaky dam, has provided a useful case study where the local community have been involved in multiple phases of the scheme, including post-construction monitoring. The Slaty Sike NFM process has subsequently highlighted the following:

- Community-based data confirmed that the Slaty Sike features performed as expected. Multiple sources and formats of data aligned towards the same conclusions;
- Image-based observations are visually meaningful, simple, relatable, valuable, cost-effective and encourage involvement and ownership on a local level as they can be feasibly collected by members of the public (unlike traditional quantitative methods);

- Community-based monitoring collects NFM data that would otherwise be missed; it offers a monitoring and maintenance tool for long-term catchment management;
- Communities may find it difficult to monitor NFM features regularly if they are installed in remote locations, and may need to rely on automatic methods (e.g. time-lapse cameras). Engagement and involvement rates could also deteriorate or diminish;
- Community-based observations cannot replace robust scientific monitoring methods which quantify catchment management. However, they can provide reliable indications and answer questions raised by concerned locals which are common barriers to wider NFM uptake (e.g. what do the features look like, have they blended in, have they washed away or moved, how long do they take to fill up, when do they need maintaining?).

While citizen science cannot answer all NFM related concerns alone, it adds another important component to the catchment management toolkit. It does however raise concerns over the feasibility and sustainability of long-term citizen science monitoring (see Chapter 7)

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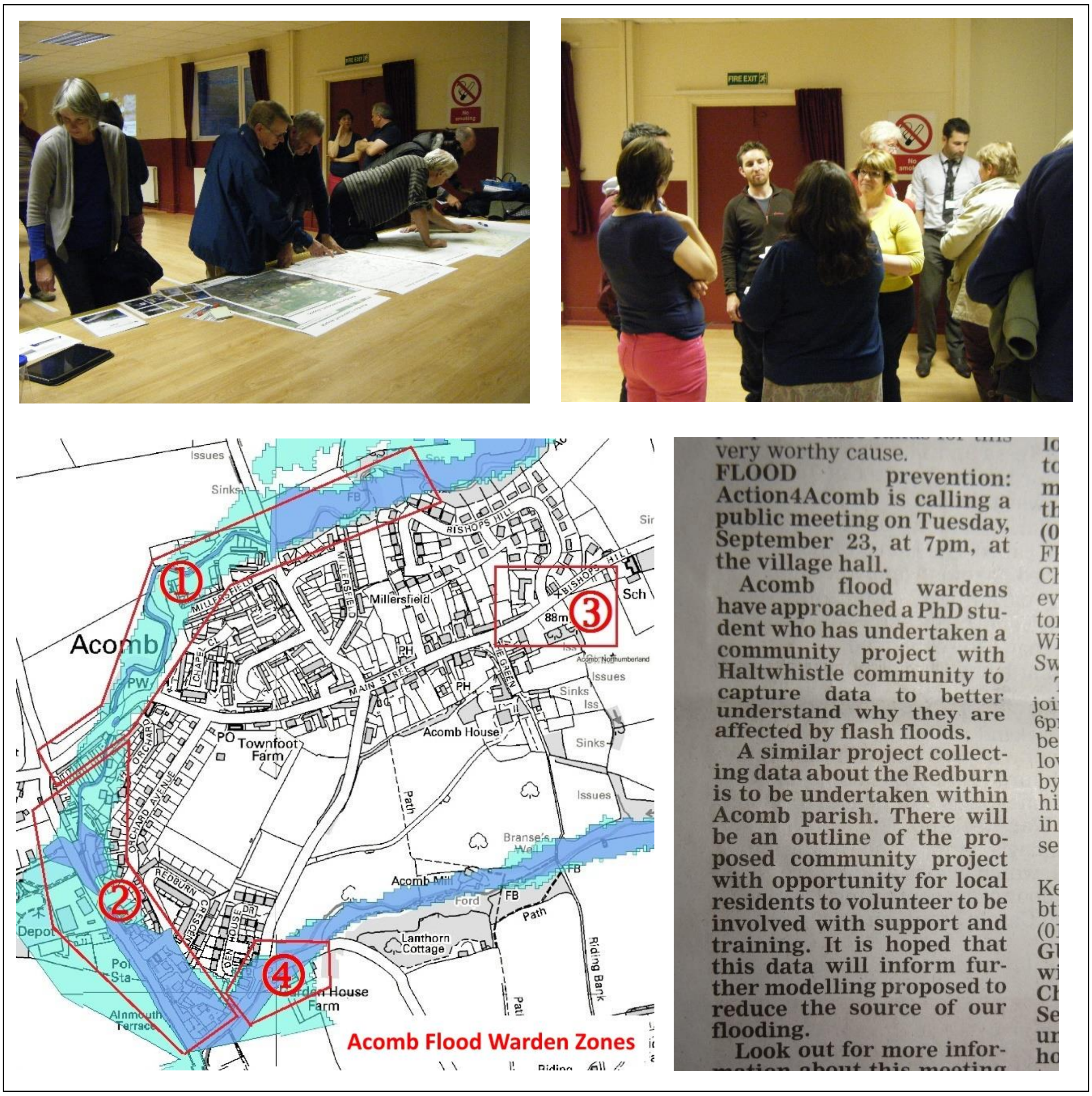
Chapter 7. Sustainability of community-based monitoring in catchment science



very worthy cause.

FLOOD prevention: Action4Acomb is calling a public meeting on Tuesday, September 23, at 7pm, at the village hall.

Acomb flood wardens have approached a PhD student who has undertaken a community project with Haltwhistle community to capture data to better understand why they are affected by flash floods.

A similar project collecting data about the Redburn is to be undertaken within Acomb parish. There will be an outline of the proposed community project with opportunity for local residents to volunteer to be involved with support and training. It is hoped that this data will inform further modelling proposed to reduce the source of our flooding.

Look out for more infor-

Figure 7 (*intro*). Citizen science has been successfully implemented within the Haltwhistle Burn catchment but has raised questions regarding long-term monitoring capabilities, and whether other communities can be sustainably involved.

7.1. Chapter introduction

Despite all of the positive community-based monitoring findings documented throughout this thesis, outcomes have been dictated by the number of volunteers involved, and how long they participated for. Alongside DQ, volunteer retention is one of the main challenges documented within the citizen science literature (Roy *et al.*, 2012; Buytaert *et al.*, 2014; Socientize Consortium, 2013; Pocock *et al.*, 2014a; 2014b; Wentworth, 2014a). The Haltwhistle Burn outcomes have been controlled by the fact that this was a research project which specifically approached the community to participate, test new tools and monitor a range of catchment parameters. TRT also provided funding and facilitation, and had strong connections with the local RWFG as a result of their high-profile CRF project. It is therefore possible that some volunteers participated because they felt that they had a duty to, and because they had guidance from professionals to do so. Without sufficient funding and willingness from volunteers, citizen science cannot occur as a sustainable monitoring method in catchment science. Each community requires dedication, enthusiasm, clear motivations and a long-term vision if monitoring is to be established (Socientize 2013; 2014), and if citizen science is to offer a reliable and ongoing source of catchment information. Chapters 4-6 have therefore raised a number of challenges which affect the sustainability of community-based monitoring for catchment science (Figure 7.1).

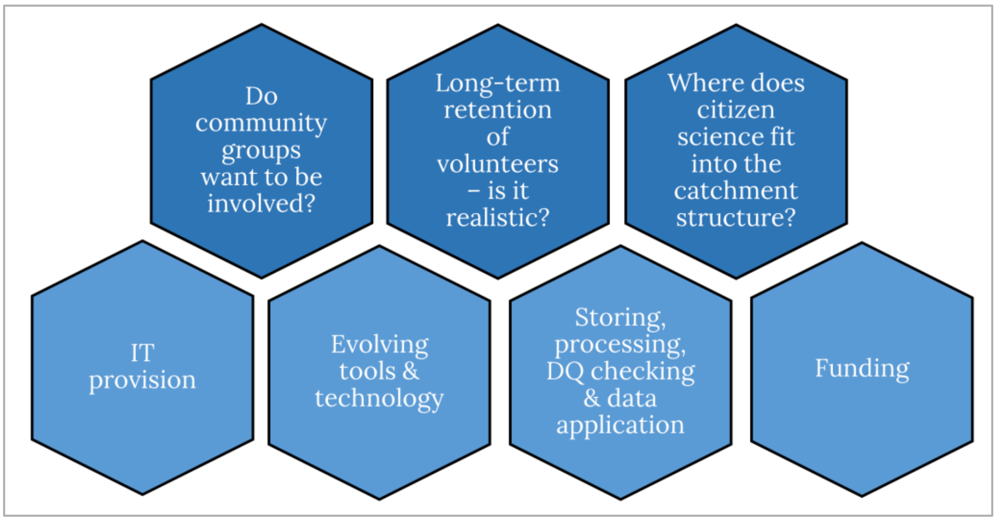


Figure 7.1. Challenges to consider following the Haltwhistle Burn citizen science pilot project.

The challenges listed within Figure 7.1 (with focus on the top row) form the basis of this chapter and are used to address the final **research question (Q4)**; is a community-based monitoring approach sustainable? Case studies, experiences and potential solutions which have surfaced following the implementation of the Haltwhistle Burn citizen science scheme are presented. This includes an appreciation of long-term monitoring efforts within Haltwhistle, and a descriptive summary of the Red Burn citizen science scheme now active in Acomb (Northumberland – see Figure 7 *intro*). Based on face-to-face and email-based enquiries received from professional catchment stakeholders during this Ph.D. project, options for integrating citizen science into the existing catchment structure on a regional or national level are also explored.

7.2. Long-term monitoring (Haltwhistle Burn)

Traditional hydrometric monitoring networks can be installed on a temporary basis, and are particularly useful for demonstrating project-specific outcomes, assuming budgets, time and resources are available to do so (e.g. Nicholson *et al.*, 2012; Owen *et al.*, 2012). However, as Tetzlaff *et al.* (2017) describe, long-term observations provide important foundations for integrated and sustainable catchment management, and are required for detecting and understanding environmental change over much longer time scales. Citizen science has been adopted by professionals inside and outside academia to provide short snapshots of data and/or to engage with the public as a short-term monitoring experience (including Lowry and Fienen, 2012; Breuer *et al.*, 2015). Many of these initiatives also rely on external funding and one-off grants, such as the OPAL Water Survey (Rose *et al.*, 2016), which are likely to terminate. However, from a community-based perspective, flood risk is a long-term issue which requires local data and ongoing surveillance. Long-term data is also required to support catchment and flood risk management plans; community-based monitoring could therefore be formally integrated into the catchment monitoring and management process. However, obtaining such data would require long-term engagement and participation from local communities, an aspect which is yet to be explored given that citizen science is relatively new to catchment science. Sustained participation in academic research has been explored, and is closely related to facilitation, communication and project relevance (Bracken *et al.*, 2014).

Long-term monitoring efforts witnessed during the Haltwhistle Burn monitoring scheme are an important indicator of whether or not citizen science offers a sustainable monitoring approach. The Haltwhistle Burn scheme is one of the only catchment- or flood-related citizen science schemes which has relied upon unpaid volunteers to collect data over a relatively long period of time. While 29-months of data do not represent decadal timescales, it is long enough to acknowledge whether participants are likely to collect regular (e.g. daily and sub-daily) observations, one-off extremes, or nothing at all. Temporal resolutions are important as they control the end application and value of the datasets.

Various results have been presented in earlier chapters, including those within Figure 4.25-4.26 and Table 4.11, which alluded that participation levels initially escalated, peaked and then tailed off over time. It was illustrated that a small number of dedicated and regular volunteers provided most observations during the 'rise' and 'decline' periods, and there were also sudden bursts of observations submitted as a result of high flow events. Given that river level was the most popular parameter to monitor and encouraged a large number of people to participate, RLGB observations have been used here to assess the Haltwhistle Burn's long-term monitoring capabilities in more detail (Figure 7.2) (**Objective 4A**).

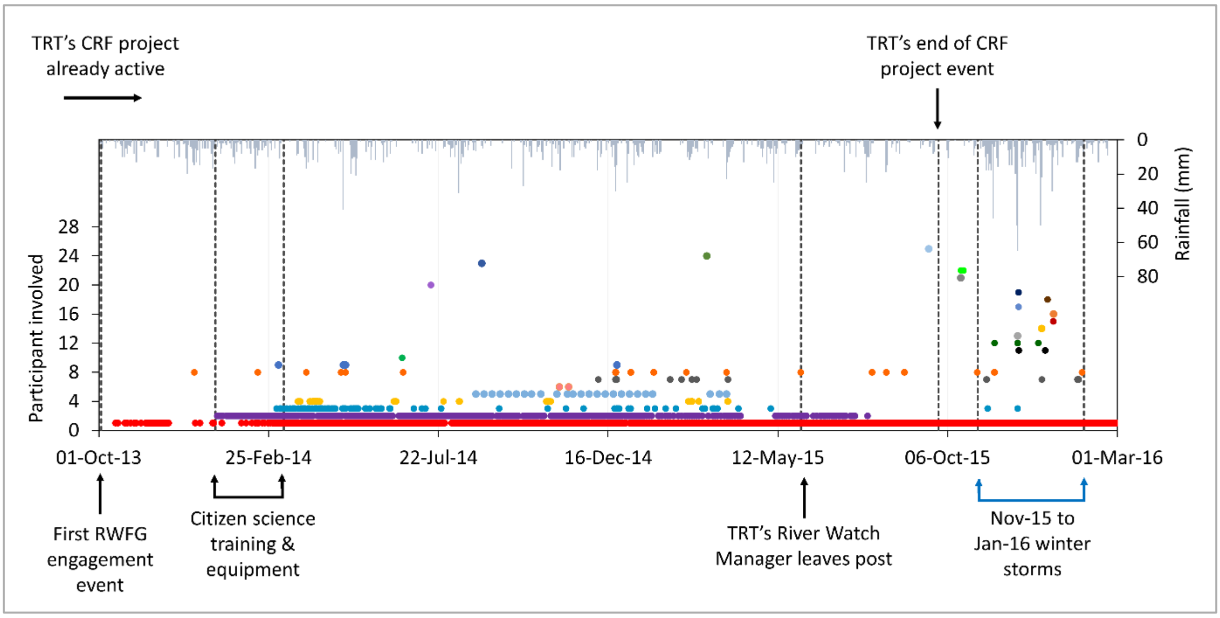


Figure 7.2. Total number of individual RLGB observations collected over the 29-month monitoring period to demonstrate long-term monitoring efforts. Includes community-based rainfall (Townfoot) and key project milestones for reference.

Figure 7.2 presents all river level observations captured during the 29-month monitoring period to illustrate long-term community-based monitoring capabilities within the Haltwhistle Burn catchment. Key project milestones relating to TRT's CRF project and this citizen science monitoring scheme are also included for reference. The plot shows how monitoring generally escalated once participants benefitted from training and had received specialist monitoring equipment (from January/February 2014). Many participants showed initial signs of enthusiasm and a desire to trial different monitoring methods (*"I wouldn't mind trying out new monitoring techniques"* Member of RWFG). Monitoring efforts peaked between March 2014 and April 2015 and then started to decline, which coincided with when TRT's River Watch Manager left the organisation, and when TRT held an end of CRF project event (September 2015). While it is very likely that TRT's project enhanced monitoring efforts and gave the community a clear purpose for participation, it is possible that some members of the public lost interest (i.e. once the initial excitement of participating had diminished). Even though regular monitoring appeared to decline after these important milestones, there was another burst of observations submitted over the record-breaking winter 2015/16 when high rainfall and river flows (*"more interesting events"*) were experienced.

Figure 7.2 and other observational findings have highlighted the following:

- The importance of facilitation and training, the inclusion of a range of monitoring techniques, and the need for clear monitoring objectives if citizen science is to offer a long-term monitoring tool;
- Without links to professional catchment stakeholders, there is a danger that community-based monitoring will quickly deteriorate. However, initial bursts of data are still valuable for catchment characterisation and community engagement activities;
- Even if participants prefer to focus their monitoring efforts on high rainfall and river flow events, their observations still complement other findings as hydrological extremes are rarer, less documented, and have the potential to add most value to existing monitoring, modelling and management activities on a local level;
- It must be acknowledged that participants are unpaid and donate their spare time;
- Evidence suggests that some members of the Haltwhistle Burn community continued monitoring for their own interest, and passers-by still sporadically share one-off river level and early warning observations (even in 2017, see Figure 7.3). While there were a few comments suggesting that people were solely contributing to help scientific studies (*"Are you still wanting the data or have you now finished?"*), others appreciated the importance of the data at a community level. For instance, a RWFG member said that *"The greatest need we have is to get the culvert cleared of silt. We may continue to take the readings for our own interest"* (June 2016). Ongoing observations are closely related to Twitter and River Watch Photo Post users, and can therefore be classified as sustainable monitoring tools. Citizen science is also listed as an ongoing monitoring tool to support the legacy of the CRF project (TRT, 2015);
- It is known that the bulk of observations were provided by a few key volunteers. However, if they terminate their involvement, monitoring efforts are adversely affected. For example, one regular flood and RLGB observer moved away from Haltwhistle during

summer 2015, which then left a significant monitoring gap. However, this individual wanted to continue their monitoring experience within their new community (*"I was wondering if you know of any 'citizen science' projects taking place […]? It would be good to get involved in something again"*).

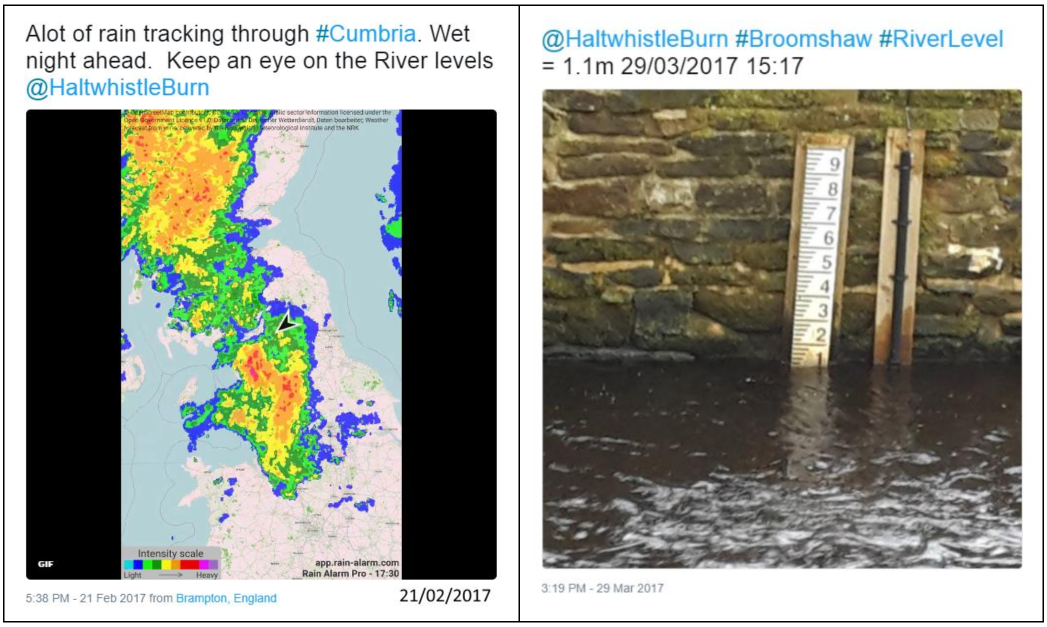


Figure 7.3. Evidence of community-based monitoring continuing into 2017.

In addition to the low-cost community-based monitoring activities, the Haltwhistle Flood Group officially took ownership of the traditional hydrometric monitoring network set up as part of this Ph.D. project (*"It would be a shame for the monitoring to stop after all the effort everyone has put into it so far. It would be a waste of time otherwise",* RWFG, September 2016). Interested volunteers attended a fieldwork training session to allow them to practice equipment maintenance and data downloading (vented pressure transducers and TBR gauges across the catchment). Following this session, feedback included *"It doesn't seem too strenuous to download and sort out the data. We have the capacity and it makes sense to keep it all [automatic equipment network] going"* (Flood Warden, November 2016). It appears that this technical monitoring method may support community-based monitoring methods as long as it is still operational, but would not have occurred if professional stakeholders did not fund and install it at the onset. Later correspondence with the lead Flood Warden confirmed that they had successfully downloaded data from the equipment themselves, but indicated that they may need to *"recruit more people with different skills e.g. those with computer skills who are able to sort out all of this data".* Furthermore, the Flood Group secured their own funding from the Town Council which will pay for ongoing telemetry sim card costs at Broomshaw. This example demonstrates how the

Flood Wardens appreciate the importance of ongoing monitoring for short-term flood risk preparedness and longer term catchment management activities. These positive attitudes and actions all support a sustainable monitoring approach.

7.3. Integration on a local level: additional case study from Northumberland

7.3.1. Red Burn Catchment, Northumberland

The Haltwhistle Burn project has provided a useful citizen science demonstration, which many other community groups across Northumberland and the Tyne Catchment became aware of. TRT held a regional River Watch event at the Hexham Community Centre in May 2014 (approximately 25km east of Haltwhistle) which provided this research project with an opportunity to exhibit the Haltwhistle Burn citizen science scheme. This event enabled Flood Wardens from Acomb (Northumberland - see overview in Section 3.5) to express their interests in community-based monitoring. The village of Acomb is situated close to the outlet of the 12km^2 Red Burn catchment (Figure 3.6), and has experienced flash flooding in recent years. Twelve residents volunteered as Flood Wardens, whom also work alongside the Environment Agency to ensure that they have a working Community Flood Plan in place (Section 2.4.6). Acomb's Flood Action Group (AFAG) expressed their monitoring interests in order to *"know about our catchment, spatial rainfall patterns and the response of the Red Burn"*. AFAG exists alongside Action4Acomb (A4A), a community-led organisation which supports people living and working within the Acomb Parish.

Based on the Haltwhistle Burn project, A4A and AFAG implemented their own citizen science monitoring scheme, and has therefore been observed over time and reported here to demonstrate how communities do want to monitor their local weather and water environment, they can establish and support these monitoring schemes, and can integrate citizen science into an existing community and flood risk management structure. Figure 7.4 and Table 7.1 provide an overview of Acomb's proactive involvement, which together illustrate how community-based monitoring can be realistically and sustainably implemented on the ground (**Objective 4B**).

Figure 7.4 and Table 7.1 demonstrate how A4A and AFAG have successfully embedded citizen science into their existing community structure. A4A have taken ownership of the project and proactively engaged with the wider community using newsletters, newspaper articles, website material, social media, and face-to-face events. They also have a Dropbox file sharing system in place which allows other participants to view observations collected. Volunteers support the project in different ways depending on their skills and interests (e.g. equipment installation or adding website content). Acomb acknowledged that the Red Burn catchment was originally unmonitored, and that local data did not exist. This community also value the importance of working alongside professional stakeholders, such as the Environment Agency, to attain local flood risk management solutions. Furthermore, the community have detailed within Acomb's 2015-2020 Community-led Plan that they recognise the importance of nominating a 'Citizen Science Project Leader', volunteer recruitment, and securing future funding to safeguard a sustainable monitoring programme. The group have established clear objectives, and while this does include carrying out data collection activities, they understand that the end goal involves informing future flood risk management solutions (e.g. NFM) and supporting flood response.

While the value of citizen science data is not the focus of this chapter, it is important to highlight how this community succeeded in collating all flood observations to generate their own flood timeline following the 5th July 2015 flash flood event (Appendix 7A). This timeline (involving an unexpected 38mm of rainfall in 40 minutes) was sent to the Environment Agency, who then confirmed that they did not receive an alarm (to trigger flood plans) in advance because their forecasts were less severe than what was actually experienced locally on the ground (*"the forecast rainfall was not expected to cause a problem"* Environment Agency Flood Warning Duty Officer). This example demonstrates the relevance and value of local data, similar to Haltwhistle's 30th April 2014 event.

1. May-2014

Members of A4A and AFAG approached this PhD project to find out how they could implement their own monitoring scheme. Flood risk is a principal motivation.

"We need to know what is fully going on"

2. July-2014

A4A requested an inception meeting with NU for monitoring advice. They want to link with the Environment Agency and wider community

"We are one step ahead, we have already shared historical information"

3. July-2014

Environment Agency asked for information on A4A & AFAG's monitoring intentions, implying that data could support their own Acomb modelling project.

"Peak levels and flood information would be very useful to us"

4. Sept-2014

A4A planned & advertised a flood monitoring workshop in the village hall with the wider community. This PhD project presented the Haltwhistle Burn scheme = positive feedback.

"I am interested in learning about weather, floods.."

5. Nov-2014

Using catchment walkovers, local knowledge, best practice from Haltwhistle, and advice from NU, the community agreed on a monitoring plan:

- Community-based gauges;
- Automatic sensors.

6. Dec-2014

A4A submitted a funding application & was successful, based on engagement, education & environmental objectives. 'Local Environmental Action Fund'.

7. Mar-2015

A4A ran a flood partnership meeting at Village Hall to query the Environment Agency over their proposed modelling work: *"What about timescales, will your model include major floods? What if the community collect data, will it help?"*

8. Mar-2015

- A4A launch their own website, includes flooding & citizen science page;
- A4A Treasurer orders monitoring equipment/tools
- Flood Wardens install monitoring equipment (x1 TBR gauge & x3 RLGBs).

9. May-2015

A4A Secretary organises & advertises 'monitoring launch event' at Village Hall. Equipment shared,

"Opportunity to get some really good data [...] provide a case for future works in flood mitigation/prevention"

10. 5th July 2015

Acomb experienced a flash flood event. Monitoring activities were put into practice:

- Community-based rain gauge: 38mm
- Automatic TBR gauge: 38mm

Flood observations were used by the community to generate a timeline (*"we want to work out response times to inform our flood plan"*), & was then shared with the Environment Agency.

11. May-2016

A4A launched their 5-year community-led plan which addresses social, environmental and economic issues identified by residents, such as flooding. Citizen science has been integrated into the plan to support long-term understanding of catchment behaviour and flood risk.

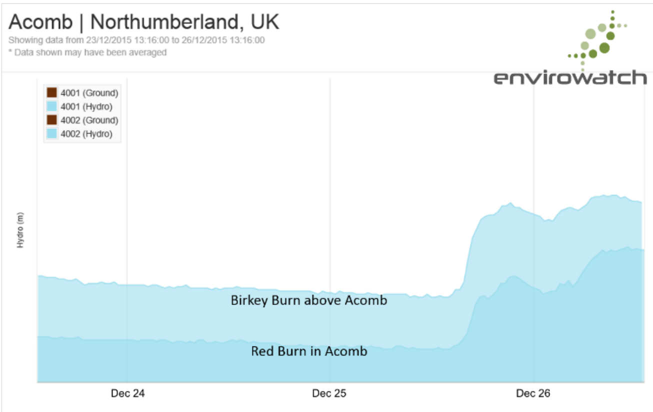
Acomb's Community Led 5 Year Plan – 2015 to 2020

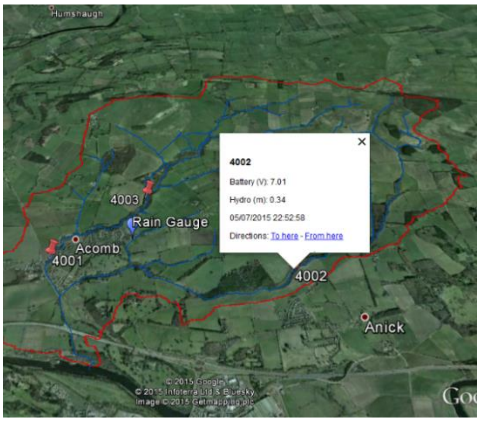
Figure 7.4. Timeline of events as a result of A4A and AFAG implementing their own citizen science monitoring scheme.

Community-led engagement, facilitation, workshops & equipment installation

Community-led monitoring: manual & automatic methods (includes rain gauge at the school)

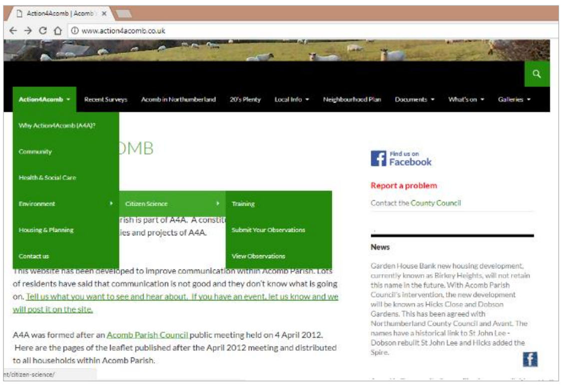
Community-led monitoring: live data streaming from automatic WLRs every 15-min (x3 locations)

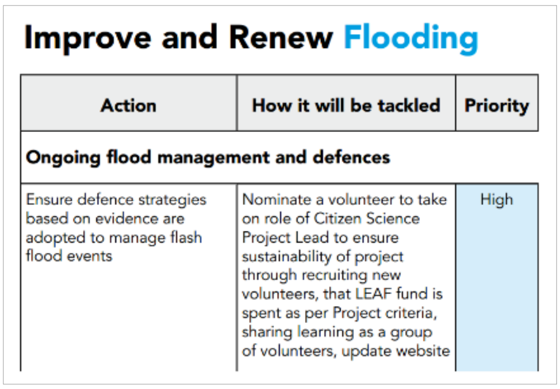




"This early warning system has been invaluable [...] At times of heavy rain, I can see, particularly on the Birkey Burn, what is happening 1 mile upstream [...] and hence take the necessary action" Flood Warden

Citizen science integrated into the community: e.g. website[28] (left) and village plan[29] (right)




Improve and Renew Flooding

Action	How it will be tackled	Priority
Ongoing flood management and defences		
Ensure defence strategies based on evidence are adopted to manage flash flood events	Nominate a volunteer to take on role of Citizen Science Project Lead to ensure sustainability of project through recruiting new volunteers, that LEAF fund is spent as per Project criteria, sharing learning as a group of volunteers, update website	High

Table 7.1. Evidence that citizen science is now integrated within the Acomb community.

[28] A4A website: http://www.action4acomb.co.uk/action4acomb/environment/
[29] Acomb's Community-led 5 Year Plan: http://www.action4acomb.co.uk/documents/the-community-led-plan/

This case study illustrates how strong leadership and enthusiasm can help to drive volunteer-led facilitation, engagement, ownership, data collection and data application. This community demonstrates how citizen science is closely linked to the Environment Agency's Community Flood Plan initiative and how Flood Wardens are naturally engaged in catchment monitoring activities. These arrangements offer many viable solutions to the challenges outlined within Figure 7.1, however, even with strong leadership and foundations (such as A4A), professional stakeholders are still required to provide some level of support. Acomb required some support and advice at times when setting up their monitoring programme for instance. They also showed signs of being overwhelmed by data and tools one year after the monitoring programme had commenced, and may seek further support in the future.

7.3.2. A comparison – Haltwhistle and Acomb

The Haltwhistle Burn and Red Burn communities have both shown great enthusiasm for participating in monitoring activities, and have been able to feasibly monitor a range of relevant catchment parameters. Both communities understand the need for, and value of, long-term datasets for managing catchment-specific issues, which is an important factor affecting the sustainability of community-based monitoring schemes. They are also heavily motivated by flood risk (existing Flood Action Groups are therefore engaged), and are using their monitoring knowledge to improve community flood plans. Both case studies have experienced a decline in participation (or lower than expected initial uptake) and are likely to be restricted by data processing, analysis and visualisation tasks in the future. However, A4A are interested in sharing observations with university student projects. These two communities have also demonstrated how they are capable of carrying out manual monitoring methods, and have been involved with some automatic sensors. Acomb relies more on automatic WLRs, and can be attributed to the fact that the equipment supplier has designed a cost-effective, low-power and less demanding system than others on the market, which streams live data (in the final format) continuously to Google Earth and a designated website. While A4A have a desire to continue automatic WLRs, they are not as viable long-term (for non-professionals) as manual methods, including RLGBs.

The key difference between Haltwhistle and Acomb is that Acomb (A4A and AFAG) initiated and took complete ownership and leadership of their community–based monitoring scheme. Haltwhistle participants on the other hand were affected by the research and CRF projects. Acomb appears to have a more resilient and sustainable monitoring programme as they have officially embedded this grassroots approach into their long-term community-led plan, and used it to empower decisions. O'Connell and O'Donnell (2014) describe these social groups (like A4A) as 'influential agents' that can help to shape relationships, views and flood risk management action.

A further enquiry was received from a resident in March 2015 who lives in Wark (Northumberland), as they are also interested in having *"some indication of the delay time of the burn because we believe it is very short and the burn is very flashy".* As with Haltwhistle and Acomb, Wark is classified as a rapid response catchment ('very high' status - see location map in Appendix 3A) and *"it seems past floods have not been documented well"*. Monitoring activities did not materialise within the Wark community after this; the interested resident confirmed that they do not have a local community-led group set up like A4A (*"nothing similar looks even remotely likely in Wark"*).

7.4. Integration on a regional or national level: exploring options

The Haltwhistle and Acomb case studies have demonstrated that citizen science is feasible and valuable, therefore it is important to consider regional and national options for wider uptake. This will allow citizen science to be integrated into the flood risk and catchment management process, rather than informally on a local level. Support from professional stakeholders will ultimately encourage long-term monitoring activities, assist with overcoming barriers listed in Figure 7.1, and thus maximise sustainability. There are examples of citizen science being integrated into national initiatives and organisations already. A pertinent example includes long-term wildlife surveys, which have contributed to the Biological Records Centre (and CEH) for decades (Tweddle *et al.*, 2012; Pocock *et al.*, 2015).

Several options for integrating citizen science are presented within this sub-chapter, and are primarily based on face-to-face and email-based enquiries received, and impact generated, as a result of this Haltwhistle Burn Ph.D. project (**Objective 4C**). PAR projects are known for creating pathways to impact (Bracken *et al.*, 2014).

Exploring options and interests based on specific enquiries and project impact:

- **Northumberland County Council:** A Flood & Coastal Erosion Risk Management Engineer said that *"local data on these smaller watercourses is rare. So it is very useful information to us"* when questioned about the value if citizen science;
- **Environment Agency (regional/national):** A Flood & Coastal Risk Management Officer expressed their interest in community-based datasets. *"We would find peak river levels*

and flood information collected by the community very useful [...] we can update the models at a later date when more data becomes available". Additional Environment Agency staff have since requested access to community-based data to support their Haltwhistle Burn modelling projects. The Haltwhistle Burn citizen science project also features in the Environment Agency's national NFM toolbox (Environment Agency and Cbec, 2017). Furthermore, the Slaty Sike scheme (including the community involvement and monitoring, kite-cams and time-lapse photography) is one of the 65 case studies listed within the Environment Agency's national WwNP Evidence Directory[30] (Defra, 2018);

- **TRT[31]:** following the CRF project, a successful River Watch initiative, and the Haltwhistle Burn citizen science project, TRT has launched an 'Adopt a Stream' scheme which allows communities to monitor and manage their local watercourse. Monitoring packs are available to purchase or sponsor (see Figure 7.5), including the same RLGBs, water quality test kits and time-lapse cameras used within the Haltwhistle Burn catchment (*"this community engagement will create data that can be used to identify issues and activities to improve rivers across the Tyne catchment"*). This forms part of the wider 'My Tyne' project;

- **Yorkshire Dales Rivers Trust**: a Catchment Co-ordinator requested best practice information from the Haltwhistle Burn study, with hope that techniques would help them during an NFM scoping study. *"They want to measure the quantity of water [...] The project has a modest budget and a short timescale, and as a small trust we would like to make use of our volunteers to undertake this monitoring"*;

- **Wear Rivers Trust:** A Project Officer expressed their interest in collecting flow data using volunteers. This information was required to design a wetland scheme. *"Our flow gauging stations will effectively be a fence post with depth markings on which volunteers will record whenever they are in the area [...] not massively high tech, but I'm hoping that by collecting as much data as possible..."*;

- **Trent Rivers Trust:** A Senior Project Officer requested information about citizen science techniques (*"I remember you saying you had sourced good cheap equipment to enable people to test for P etc. Are you able to share?"*);

[30] Environment Agency's WwNP Evidence Directory https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk
[31] TRT http://www.tyneriverstrust.org/support-us/adopt-a-stream/

- **CaBA and The Rivers Trust:** the Haltwhistle Burn citizen science work is listed as a monitoring case study on the CaBA website and appears as a case study within the 'Citizen Science and Volunteer Monitoring Resource Pack'[32]. Catchment stakeholders refer to this resource across the UK;

- **Schools:** two primary schools and an 'Outdoor and Sustainability Education Specialist' enquired about school children carrying out weather and river related monitoring activities. They highlighted that citizen science covers multiple themes within the curriculum (*"The rain gauge ticks many boxes for us, like maths, metrics. We want them to learn about the weather and the different seasons"*);

- **Met Office WOW:** The WOW portal (summarised in Table 2.4) has been used by the public on an international scale to submit weather observations. In 2015 the Haltwhistle Burn project was asked to provide a case study (Appendix 7B) containing requirements from a citizen scientist's perspective, which the Met Office incorporated into their WOW redevelopment project. These requirements, such as needing open access and online tools to store, visualise and download community-based data, were based on experiences gained within the Haltwhistle Burn catchment. WOW has since been relaunched and includes greater capabilities to harness a wide range of data, including flooding impacts, weather diaries and river levels;

- **Defra (national):** A Strategic Advisor has expressed Defra's interest in involving the public in NFM monitoring to fill data gaps. Defra has confirmed that community involvement is a key issue and that they are interested in scaling it up by learning from the Haltwhistle Burn project outcomes. Defra has therefore written an impact paper containing the Haltwhistle Burn project as an important case study.

- **EU Environmental Policy (international):** A team from the EU requested project-specific information as they identified the Haltwhistle Burn case study as being of high relevance. The EU are currently identifying how citizen science can benefit environmental policy so that it can be recommended for use by member states.

[32] CaBA: http://www.catchmentbasedapproach.org/resources/volunteer-monitoring

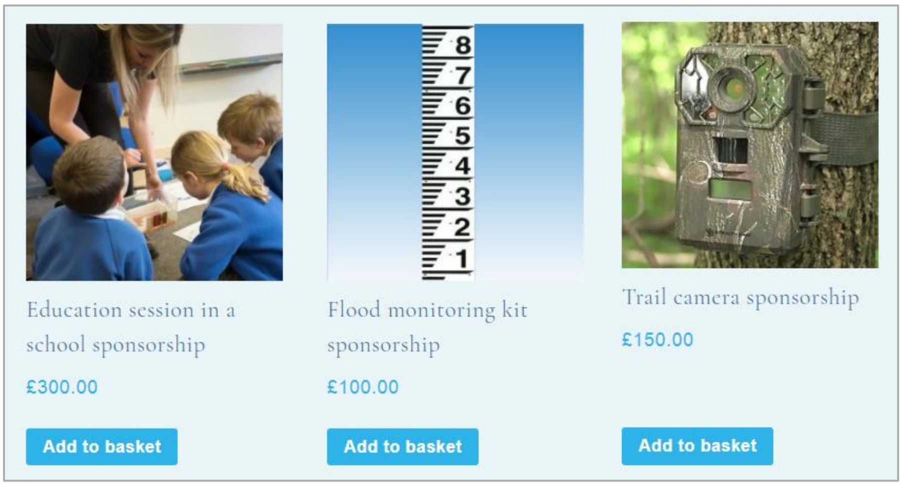


Figure 7.5. Examples of monitoring equipment that can be purchased to support TRT's forthcoming 'Adopt a Stream' initiative (TRT, 2017b).

Further options which may support (maximise) a sustainable citizen science approach include:

- **CEH:** current citizen science activities could be extended to include water quantity and support CEH's existing hydrological services;
- **Environment Agency (community flood plans):** similar to Acomb's approach, relevant data collection activities could be encouraged and included within flood plans, and adopted by Flood Wardens;
- **SEPA:** they launched a 'report a flood' service[33] in 2015, which the public can use to record flooding incidents on a web-map. SEPA encourages the use of crowd-sourced data;
- **BBC Weather Watchers:** The BBC are currently promoting the Weather Watchers service by encouraging the public to submit local weather observations (generally photographs and temperature information, see Table 2.4). This national organisation provides a useful tool that already exists, which could be extended to include new parameters. This would connect communities across the UK, similar to the Met Office WOW platform;
- **Community flooding partnerships:** partnerships which encourage stakeholders to work together to provide a better response to flooding, for instance, the Northumberland Community Flooding Partnership. They have established links with community groups;

[33] SEPA www.floodlinescotland.org.uk/report-a-flood

- **National Flood Forum**: this is a national body that engages, supports and empowers local communities to reduce flood risk. They share similar objectives to those arising from citizen science monitoring.

These options demonstrate that organisations are starting to consider citizen science as a viable engagement and data collection method, and have tools and IT infrastructure already in place to support community-based monitoring. Many organisations, such as River Trusts, also have a remit to engage, educate and collect data within the same project. The Haltwhistle Burn community, and to a lesser extent, the Red Burn community, have also demonstrated that the public do require some assistance and guidance from professionals at times in order to run a successful monitoring scheme.

7.5. Chapter summary – sustainability of community-based monitoring

The long-term retention of volunteers and the overall sustainability of citizen science is regarded as a key challenge across all environmental disciplines, and therefore applies to catchment science. This chapter has evaluated sustainability in the context of long-term monitoring capabilities, whether local communities want to monitor their own local weather and water environment, and has also explored options for wider uptake (local to national, and beyond). These three aspects are regarded as important factors if community-based monitoring is to be relied upon as an ongoing source of catchment information. Long-term monitoring capabilities have been explored within the Haltwhistle Burn catchment, and an additional case study site (Acomb, Northumberland) has been described. Both case studies offer wider benefits too, which contribute to maximising a sustainable citizen science approach. Examples presented within this chapter demonstrate how community-based monitoring has the potential to offer a sustainable catchment monitoring and participation tool.

The following conclusions can be drawn from this chapter:

- Data collection activities started to rise once participants received training, equipment and facilitation within the Haltwhistle Burn catchment, which then peaked and started to decline. However, participation re-activated during the winter 2015/16 storms, which complements findings in Chapters 5 and 6 (that this is the most valuable data anyway). It is likely that the Haltwhistle Burn community were relying on professionals (e.g. TRT and this project) to drive monitoring activities forward. However, evidence suggests that participants do value the importance of long-term monitoring;

- The Acomb case study demonstrates how a community can monitor, want to monitor, are capable of initiating and funding their own monitoring scheme, and take full ownership. The presence of a community-led group which provides strong leadership is essential;
- Facilitators and training are essential for long-term citizen science. Data processing, quality checking, and analysis are still problematic though;
- Examples provide evidence that community-based monitoring is required by professionals and can be sustainably integrated into the existing flood risk and catchment management process.

Working with various stakeholders outside academia has surfaced a number interests from professional stakeholders and organisations, which together suggest that there is a place for citizen science in the current flood risk and catchment management process. The latter should be explored further as communities should not work in isolation; there are mutual benefits for all. Working in isolation is unsustainable, it encourages monitoring fatigue, and fails to achieve key objectives set out by relevant policies and frameworks in the UK and across wider Europe. In particular, the Acomb case study demonstrates how citizen science can be used as a tool to ensure other social, economic and environmental issues are managed sustainably. Effective data visualisation and feedback will encourage activities like this further

Chapter 8. Research summary, wider discussion and conclusions

8.1. Chapter introduction

This final chapter provides a summary of the thesis with respect to the original research hypothesis and research questions (RQ). While specific results have already been discussed throughout this thesis, broader findings and importance are interpreted here with respect to the wider catchment management process. Based on experience, a figure is also presented summarising the key elements involved in setting up a successful, good quality and sustainable community-based monitoring scheme. Conclusions are then presented in relation to the feasibility, reliability, value and sustainability of community-based monitoring when using observations to support catchment characterisation, modelling and management activities. Limitations and recommendations for further work are also summarised.

A reminder of the research hypothesis is useful at this stage:

Community-based ('citizen science') monitoring activities can support the catchment characterisation, modelling and management process because they provide valuable spatial and temporal knowledge about the behaviour and state of individual rural catchments on a local level. The active involvement of the public subsequently triggers various social benefits which are crucial for generating more resilient communities and thus meeting policy targets today.

8.2. Research summary and wider discussion

8.2.1. Research summary

Hydrological catchments are spatially and temporally complex, and even with the most advanced scientific knowledge, monitoring tools and modelling techniques, which exist and 'follow the rules of good science' (WMO, 2008), they are still poorly characterised on an individual scale (Beven, 2007; Beven and Westerberg, 2011). High quality empirical data are required to support all hydrological applications, including characterisation, modelling, forecasting and management activities. Direct and recent observations are also required to better-understand extremes and changes to our climate (Thompson *et al.*, 2017).

Citizen science involves members of the public collecting and sharing new knowledge about the natural environment, alongside professionals (Tweddle *et al.*, 2012). This phenomenon is not new but has grown in recent years, in line with readily available communication tools and data collection technology. This simple monitoring approach has the potential to connect people locally and globally, and contribute to the 'big data' phenomenon (Wentworth, 2014a). However, there is uncertainty, reluctance, and scepticism amongst the hydrological community, and hence citizen science is underused despite its low-cost, low-maintenance, and public engagement and involvement potential (Buytaert *et al.*, 2014; 2016).

This interdisciplinary research project is one of the first studies to successfully combine citizen science with catchment science, by demonstrating its potential using real communities and catchments suffering from multiple pressures within the UK. Whilst every catchment and community is unique, an investigation into the feasibility, reliability, value and sustainability of community-based monitoring provides direct practical evidence which can be applied elsewhere.

The Haltwhistle Burn catchment in Northumberland has provided the main case study site and focus community, where a new community-based monitoring programme was implemented to support Tyne Rivers Trust's (TRT's) restoration project. An additional community (Acomb, Northumberland) has also provided important findings relating to the sustainability of citizen science (Chapter 7). Both case studies experienced widespread and/or flash floods during the project, which generated interesting datasets and tested monitoring capabilities.

Running in parallel, this project has also relied upon a wide range of monitoring, modelling, GIS and catchment management techniques, which 'traditional' or professional catchment scientists use, and are regarded as reliable and well-established methods (Shaw *et al.*, 2011). Substantial efforts were devoted to setting up and maintaining a traditional hydrometric monitoring network across the Haltwhistle Burn catchment. After carrying out quality assurance (QA) and quality control (QC) activities, high quality rainfall, river level and flow data were available for comparison and application.

Designing, implementing and facilitating a novel citizen science monitoring scheme, with supporting training, data collection and data submission tools, enabled a detailed assessment into the **feasibility** of community-based monitoring for catchment science (**Chapter 4, RQ1**). The Haltwhistle Burn community successfully collected a heterogeneous patchwork of quantitative and qualitative observations over a 29-month period. Water quality, weather, early warnings and natural flood management (NFM) related data were feasibly collected and shared by the public. However, rainfall, river levels and flood-related parameters were observed more frequently, and by a greater number of people, as they are directly linked to flooding pressures which the Haltwhistle community experience on an almost-annual basis. Chapter 4 has presented a range of monitoring tools, including river watch photo posts, which can be employed elsewhere, and at a fraction of the cost of formal monitoring equipment. The importance of gatekeepers, engagement, facilitation, effective visualisation, ongoing feedback, simplicity and flexibility are crucial for successful monitoring programmes. Many of these requirements are new to catchment scientists.

Using data generated during the feasibility assessment, the **quality** and **reliability** of community-based observations were then investigated (**Chapter 5, RQ2**). Community-based datasets were compared graphically and statistically against each other, and against data extracted from the traditional hydrometric monitoring network. Outputs have demonstrated that citizen scientists can manually collect high quality, reliable, and sometimes rare observations which would otherwise be missed. Even though community-based observations are heterogeneous, irregular and unpredictable, individual rainfall and river level observations were of a similar scientific standard to those collected using automatic sensors, with correlation coefficients being >0.95. However, a robust QA/QC framework must be applied to community-based observations before datasets can be used. Anecdotes and photographs were popular data formats, and even though they are qualitative, they were invaluable during the QC process.

Once QC checked, community-based datasets were integrated into real catchment applications (**Chapter 6, RQ3**). A robust hydrological modelling study was carried out to determine whether community-based observations add **value** to the modelling process. The well-researched SHETRAN model (Ewen *et al.*, 2000) was used to achieve this as it is physically-based and spatially-distributed, and hence different sources of local data could be incorporated. It was found that quantitative and qualitative community-based information can significantly reduce modelling uncertainty, particularly during and immediately after local flash flood events. Flood peaks were underestimated by as much as 60% when using traditional ground-based gauges or rainfall radar data alone. Whilst results are catchment-specific, modelling is an important application, and thus generalised outcomes are applicable to many stakeholders.

The **value** of community-based monitoring was demonstrated further by integrating this activity into the catchment management process (**Chapter 6, RQ3**). The Slaty Sike NFM scheme (Haltwhistle) was targeted as it involved designing, constructing and monitoring the performance of experimental mitigation measures. NFM schemes are growing in popularity across the UK, yet they still face many evidence-related barriers in practice, and in research. It was found that the new Slaty Sike features, entailing four ponds and a novel 60m long leaky dam installed as part of

TRT's Catchment Restoration Funds (CRF) project, performed as expected. While simple, image-based community-based activities cannot replace robust scientific monitoring methods and automatic sensors (which more precisely quantify NFM performance), they can provide visual and meaningful indications of performance, and be used to answer important questions which are currently restricting wider NFM uptake.

Chapters 4-6 have each answered important questions which provide catchment stakeholders (including communities themselves) with confidence to interact with and use citizen science as an important data collection and participation tool. However, this study has also acknowledged that, without long-term monitoring (therefore volunteer participation) and the willingness of the public to become involved, this community-based approach cannot flourish. It is also unsustainable for data to be extracted from a community if they do not benefit from their own observations, whether this is in the form of feedback from professionals who are using the data, or whether community-led groups are empowered by new knowledge they have generated. As a result, **Chapter 7 (RQ4)** used the Haltwhistle Burn and Red Burn (Acomb) communities to investigate the **sustainability** of community-based monitoring. It was found that monitoring and participation levels declined towards the end of the Haltwhistle Burn project, but reactivated during the extreme winter 2015/16 storms, and could therefore restart during hydrologically important events in the future. However, the Acomb case study demonstrated how community-led groups, such as Action4Acomb and the local Flood Action Group, are capable of initiating, facilitating, funding and taking full ownership of their own citizen science scheme. This powerful example demonstrates how members of the community value the importance of capturing and using local data over time. It is also clear, through impact generated as a result of this participatory project, that community-based monitoring is required and can be integrated into the existing flood risk and catchment management process. Potential solutions for scaling up citizen science have therefore been provided.

It has also been emphasised how this community-based project has had a direct impact on the focus communities involved, in the media (local to national, e.g. Figure 8.1), in practical guidance documents, and in the literature (Starkey and Parkin, 2015; Large *et al.*, 2017; Starkey *et al.*, 2017). The NFM and citizen science aspects are also listed as a case study within the national Working with Natural Processes (WwNP) Evidence Directory (Defra, 2018). This highlights the relevance and transferability of this research, and how this study provides a blueprint for future projects.

News ▸ North East News ▸ Newcastle University

How families living in flood-risk parts of the North East could play key role in future prevention

A research team from Newcastle University carried out a project in Northumberland involving locals and volunteers

Figure 8.1. An example of a media headline as a result of this project (Henderson, 2017). A full list of media and wider project impact links can be found on the disk submitted with this thesis.

8.2.2. Key elements involved in setting up a successful, good quality and sustainable community-based monitoring scheme

After creating and implementing a discipline-specific citizen science framework (Figure 4.2), and subsequently exploring the feasibility, reliability, value and sustainability of community-based monitoring, this study provides a complete 'recipe' for future projects. Good practice, key considerations and various frameworks and templates are provided throughout (e.g. Figures 4.8, 4.13 and 5.25 and Tables 4.2 and 5.6). Haltwhistle, Acomb and wider project experiences have therefore surfaced a number of social, economic and environmental factors which affect the overall success of such schemes (as discussed throughout). The key elements involved in setting up and running a successful, good quality and sustainable community-based monitoring scheme are therefore summarised in Figure 8.2. These guidelines should be appreciated when embedding citizen science into the catchment management process. However, it is important to remember that every catchment, community therefore project are different; the citizen science process should be further refined where possible.

Figure 8.2. Key elements involved in setting up and running a successful, good quality and sustainable community-based monitoring scheme.

8.2.3. *Wider discussion and significance of work*

Outcomes relating to the feasibility, reliability, value and sustainability of community-based monitoring are immediately applicable to anyone working or researching in this sector at a catchment or local scale. This statement is valid as all catchment applications require (or should require) cost-effective and empirical evidence. Examples have specifically demonstrated the potential of citizen science in catchment science, and addressed generic concerns and challenges documented (Socientize Consortium, 2013; 2014; Wentworth, 2014a), and more importantly, sector-specific barriers documented by Buytaert *et al.* (2014; 2016) and Blaney *et al.* (2016). This study has actively demonstrated that community-based monitoring is feasible, reliable and valuable, rather than speculating its potential (Buytaert *et al.*, 2014; Mazzoleni *et al.*, 2015). It has also proactively engaged and trained participants in advance to maximise the collection of valuable catchment information, rather than harvesting data retrospectively (Kutija *et al.*, 2014; Smith *et al.*, 2015). Data quality case studies have been presented throughout, and have profoundly increased the trustworthiness of this new catchment data collection tool as a result. Limitations and how this heterogeneous source of catchment data differs from traditional methods and sources have also been documented. For instance, unpaid volunteers cannot manually observe parameters 24-hours a day, but they can provide different (qualitative) data formats.

Designing and implementing a new citizen science monitoring programme within catchment science has shown that the overarching framework required to do this imitates those applied within other environmental disciplines (Shirk *et al.*, 2012; Tweddle *et al.*, 2012; Pocock *et al.*, 2014a; 2014b). While many traditional hydro-meteorological monitoring and QA/QC guidelines can be applied to citizen science data (WMO, 2008; Shaw *et al.*, 2011), there are additional considerations to appreciate, including engagement and ethics. The importance of effective engagement, leadership and simple monitoring protocols also complement conclusions highlighted in other citizen science projects (Roy *et al.*, 2012; Tweddle *et al.*, 2012). Participation works best when the public have a strong and vested interest in the project, which some community-based schemes have thrived on (e.g. Stone *et al.*, 2014; Walker *et al.*, 2016), whilst others have not (e.g. Breuer *et al.*, 2015; Rose *et al.*, 2016). The Haltwhistle and Acomb examples were driven by flood risk motivations at a personal or community level, and it can be argued that flood risk is one of the UK's most important environmental disciplines for the public to be involved with.

Community-based methods can be used to complement traditional monitoring schemes (such as Owen *et al.* 2012; Bren, 2015), or be used to fill monitoring gaps where budgets are insufficient or non-existent. Assuming good quality observations have been attained, citizen science could be used to characterise and better-understand the impact of land use on the quality and quantity of the river environment (O'Connell *et al.*, 2007). Given the motivations, monitoring capabilities, and the value of the data exhibited by the Haltwhistle and Acomb case studies, citizen science has the potential to provide a better-understanding and management of flash floods, and our changing climate. Communities are best placed (on the ground) to capture and communicate evidence during localised and rapid onset floods, which are still poorly documented, characterised and forecast (Archer and Fowler, 2015; Perks *et al.*, 2016). The importance of flash flood monitoring also increases as a result of climate change projections; citizen science observations have the scope to provide more information on local storm dynamics, river response and resulting impacts, which Kendon *et al.* (2014), and many others, struggle to investigate using gridded datasets. Barlow *et al.* (2014) and SEPA (2015) specifically highlight the importance of evidence-based science for better-understanding and reporting NFM success, although this statement applies across the broader catchment characterisation and management spectrum. Reducing modelling uncertainty is another obvious application for community-based data, particularly at a catchment- or reach-scale. There are a substantial number of studies which do not have access to real, high quality, and ground-based catchment information which is required to model, extrapolate or estimate with confidence (Beven, 2009; Vidon, 2015). However, it will never be feasible to monitor every parameter at all scales (Beven, 2012).

So far, this discussion has related to the increased availability of catchment data. However, community-based monitoring offers a number of wider benefits to both professionals and the public. Unlike traditional monitoring methods, which provided data only, community-based methods encourage various social benefits to emerge as a result of public participation in the catchment monitoring and management process. The Arts Council England (2017) has developed a set of 'Generic Learning Outcomes', which provide a useful checklist for identifying and measuring the benefits and impact of 'participation'. This participatory action research project has captured some of these learning outcomes through observational work during the Haltwhistle and Acomb schemes, as a way of demonstrating that social benefits are attained from community-based monitoring (Appendix 8A). These wider benefits are common to other disciplines where citizen science has been implemented (Tweddle *et al.*, 2012; Socientize Consortium, 2013; 2014). However, these wider benefits are particularly significant to flood risk and catchment management because the community-based monitoring process encourages a bottom-up or grassroots approach, which leads to enhanced engagement, participation, education, awareness, ownership, collaboration and overall empowerment. These outcomes support many governmental objectives and independent studies recommending community involvement (Pitt, 2008; Defra, 2013; 2016; Bracken *et al.*, 2014; 2016), but are traditionally difficult to achieve. Community-based monitoring therefore offers a combined data and participatory tool. Based on experiences, it is also reasonable to say that the stakeholder structure and flow of information is evolving (Figure 8.3).

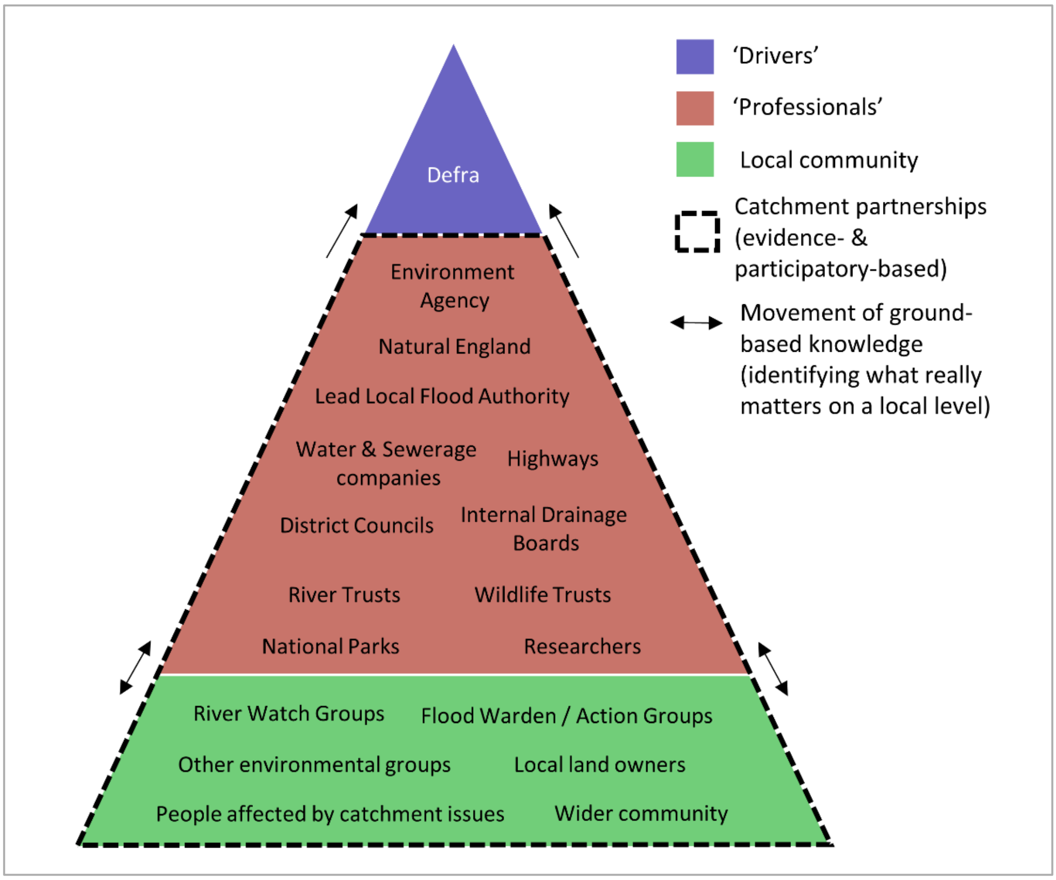


Figure 8.3. Modern day catchment management stakeholders and the movement of knowledge.

8.3. Conclusions

This project has successfully merged citizen science with catchment science, and based on the conclusions below, the research hypothesis can be confidently accepted:

1. **Feasibility:** Can communities feasibly monitor their local catchment using a simple and low-cost citizen science approach?

- Community-based monitoring for catchment science is feasible; the Haltwhistle Burn scheme has produced snapshots of heterogeneous data in a range of formats, for a variety of parameters over a 29-month monitoring period. The majority of observations were collected by a small number of regular volunteers. However, monitoring efforts are unpredictable and sporadic;

- Rainfall, river levels and flood-related observations were favoured by volunteers, and are directly linked to issues affecting the community on the ground. Web-based tools allow these observations to be shared in real-time with the wider community. However, spatial and temporal monitoring efforts are biased towards individual capabilities and interests, hence they cannot replicate or replace traditional monitoring schemes;

- 'One size' does not fit all; participants have their own motivations, preferences and skills. The design phase is therefore crucial;

- Despite being regarded as simple and low-cost, community-based monitoring schemes are not free and they require well-connected gatekeepers and strong leadership in order to drive the scheme forward and maintain participation levels.

2. **Reliability:** Are community-based data reliable and meaningful to catchment stakeholders, including the 'professionals'?

- Citizen scientists can manually collect high quality and reliable observations which would otherwise be missed. Examples presented here illustrate how rainfall and river level observations can be of a similar scientific standard to those collected using automatic sensors. Datasets have also been used to characterise the catchment successfully, including key flood events of interest;

- High quality datasets can only be attained if they are subject to a robust QA/QC process, including a carefully designed monitoring scheme which contains training and facilitation. This provides data users with confidence;

- Well-established traditional QA/QC guidelines have been successfully applied to the community-based datasets. Efforts must also extend beyond this to take into account that citizen science data hold multiple qualities. Expectations, cross-checks and data triangulation are particularly useful;

- Multiple observations collected during hydrological events of interest are required to capture rapid changes or verify unusual sightings;

- Evidence suggests that citizen scientists are conscious of collecting good quality data.

3. **Value:** Can community-based data be used to model, characterise catchment response and be integrated into the management process as a new and valuable source of catchment information?

Catchment (SHETRAN) modelling results highlighted two fundamental findings:

- A patchwork of quantitative and qualitative community-based observations are required alongside traditional sources of hydro-information to fill spatial and temporal data gaps, and characterise local catchment response more accurately than when using traditional data alone. This includes the behaviour, timing and magnitude of river response during and after floods;
- Evidence presented here confirms that community-based rainfall observations are most valuable during and immediately after local flash flood events. This information would otherwise often be missed, be unrecorded by existing ground-based gauges, or else be significantly underestimated by rainfall radar. Community-based observations are less valuable during prolonged and widespread floods, or over longer hydrological periods.

The Slaty Sike NFM case study also highlighted the following:

- Community-based data confirmed that the Slaty Sike features performed as expected. Multiple sources and formats of data aligned and pointed towards the same conclusions;
- Image-based observations are visually meaningful, simple, relatable, valuable, cost-effective and encourage involvement and ownership on a local level as they can be feasibly collected by members of the public (unlike traditional quantitative methods);
- Community-based monitoring collects NFM data that would otherwise be missed; it offers a monitoring and maintenance tool for long-term catchment management;
- Communities may find it difficult to monitor NFM features regularly if they are installed in remote locations, and may need to rely on automatic methods (e.g. readily available time-lapse cameras);
- Community-based observations cannot replace robust scientific monitoring methods which quantify catchment management. However, they can provide reliable indications

and answer questions raised by concerned locals which are common barriers to wider NFM uptake.

4. **Sustainability:** Is a community-based monitoring approach sustainable?

- Data collection activities started to rise once participants received training, equipment and facilitation within the Haltwhistle Burn catchment, which then peaked and began to decline. However, participation re-activated during the winter 2015/16 storms. It is likely that the Haltwhistle Burn community were relying on professionals (e.g. TRT and this project) to drive monitoring activities forward. Nevertheless, evidence suggests that participants do value the importance of long-term monitoring;
- The Acomb case study demonstrates how this community can monitor, want to monitor, are capable of initiating and funding their own monitoring scheme, and take full ownership. The presence of a community-led group which provides strong leadership is essential;
- Facilitators and training are essential for long-term citizen science. Data processing, quality checking and analysis are still problematic though;
- Examples provide evidence that community-based monitoring is required by professionals and can be sustainably integrated into the existing flood risk and catchment management process.

Although the co-production of environmental knowledge is not a new phenomenon, evolving technology and communications provides a timely and cost-effective solution to mass data collection. Without this data, very little information would be available to spatially and temporally characterise catchments, model and implement management measures with confidence on a local level. Results suggests that communities are more likely to focus their monitoring efforts on flood events, which complements findings relating to the value of data. Research activities have focussed on demonstrating the feasibility, reliability, value and sustainability of community-based monitoring, and when combined, they confidently promote citizen science as a vital component of the catchment management toolkit. It is recommended that this participatory monitoring method is used to fill local data gaps, with focus on extreme events, and encourage a bottom-up approach to catchment management. Community-based monitoring can also be used to engage, educate, connect and actively involve the public in the catchment management process. Increased evidence and participation then transpires into confident, well-informed and appropriate decisions, and enhances community resilience. However, citizen science should not undermine the value of traditional monitoring methods, which are well-established in this field.

A full citizen science framework, involving engagement, facilitation, tools and technology, has been developed and put into practice here. This study presents the first 'recipe' for combining citizen science with catchment science. This thesis, combined with the ROCK booklet (Starkey and Parkin, 2015), journal paper (Starkey *et al.*, 2017), media outputs, open access website material, and national case study contributions, provide evidence that citizen science and the wider community-based monitoring toolkit should now be seen as a new and fundamental component of any catchment characterisation, modelling and management study. Outcomes generated as a result of this Ph.D. have made a significant and confident contribution to research in this area, they have generated widespread impact, and thus lay the foundations for future community-based projects.

8.4. Limitations and recommendations for further work

As with any study, research outcomes have been influenced or limited by a number of factors:

- ***Study in general***: it has been stressed throughout that findings have been location-, community-, event- and equipment-specific. Unlike controlled laboratory experiments which isolate and analyse individual components, real communities and catchments are complex. It is widely known that catchments behave in unique ways, but this study has also revealed how the Haltwhistle Burn and Acomb communities were exposed to unique circumstances (personal through to project-specific). While these two case studies represent typical rural, unmonitored and rapid response sites in the UK, there cannot be a 'model' catchment or community to focus research upon. However, findings add confidence to this field of work, and broader findings have been highlighted throughout;

- ***Funding and timescales***: monitoring programmes (community-based and traditional) have been restricted by timescales and available funding. For instance, community-based monitoring methods were extremely low-cost and manual, despite cheaper sensors being available on the market. Also, due to research timescales, it has not been possible to leave the Haltwhistle Burn scheme in a fully independent position, unlike Acomb, which may affect long-term monitoring capabilities. As a researcher, it has also been difficult to balance facilitation and research priorities; providing constant feedback and support to the communities involved has been challenging at times;

- ***Traditional fieldwork:*** even though this has been regarded as the 'accurate' source of data, it can never truly represent the natural world. Monitoring locations, specific equipment used, the number of flow gauging points, rating curve methods (especially when extrapolating high flows), and data aggregation and interpolation techniques all influence and/or increase uncertainty. It was not possible to maintain field equipment on a daily or weekly basis, therefore equipment failure and gauge damage led to gaps in datasets, or having to completely discard them. Funding has also limited the number of co-located monitoring sites available for data quality (DQ) analyses;
- ***Modelling:*** as with any hydrological modelling study, there are a number of stages where error, therefore uncertainty, can be induced. Models, including SHETRAN, are a simplification of the real world and are restricted by the assumptions and equations used to build them. Outputs are limited by the input data and grid resolutions used to drive simulations. SHETRAN can also be difficult to calibrate due to the high number of physical parameters involved, therefore it's performance will have been affected;
- ***Management techniques:*** these were dictated by TRT's CRF objectives, and hence affected where, when and how the Haltwhistle Burn community monitored NFM measures.

This project has provided a starting point for community-based monitoring in catchment science. Given the importance of data tools and participatory methods, there is scope for a wide range of further work/research within this field, including:

- ***Scaling up and integration:*** implementing and testing a community-based monitoring approach within new case study sites (including urban settings), whilst making use of evolving and readily available technology. Options discussed within Chapter 7 also provide initial solutions for scaling up citizen science, including community-groups and organisations that would naturally be interested and involved;
- ***Real-time citizen science:*** given that extreme weather events and associated impacts are still poorly forecast, real-time citizen science should be encouraged and explored further. This will expand on flood forecasting and mapping work carried out by (for instance) Smith *et al.* (2015), and allow communities and responding organisations to benefit from more detailed and meaningful information;
- ***Flash (extreme) floods:*** use community-based data to better-understand the science and impacts associated with flash floods. Long-term datasets will also support studies

exploring and quantifying impacts experienced as a result of climate change, and provide more recent and relevant information;

- ***Tools ('big data' and DQ):*** new tools are required to apply DQ frameworks to observations in an automatic and standardised way. Collaboration with computer scientists from other environmental disciplines may be required (as some tools already exist), or with the Met Office WOW. Communities will also need a platform to store and host data;
- ***Tools (extract relevant hydrological data):*** given that qualitative data are abundantly collected by the public, image-analysis techniques should be extended further to include community-based datasets (e.g. extract river level gauge board observations automatically), rather than in just controlled and experimental studies. Video footage is also likely to grow in popularity in the coming years (e.g. through Twitter Live), and hence quantitative information will need to be extracted with greater confidence (e.g. discharge estimates during peak flows);
- ***Flexible models (and wider catchment applications):*** adapt or create catchment models so that they can consume or assimilate heterogeneous and qualitative information collected by communities in a more efficient or automated way. This will avoid retrospectively fitting empirical data to their existing (and sometimes inappropriate) structures, and allow a smoother transition of hydro-information, from the landscape to the model. Simple models may be required for communities to use. Professionals must also trust and accommodate citizen science observations, and use this type of data in new and creative ways;
- ***Continued innovation:*** this applies across all areas of the citizen science framework (especially visualisation and feedback methods) to increase participation levels, encourage wider community involvement (all age groups), and reduce monitoring fatigue over time.

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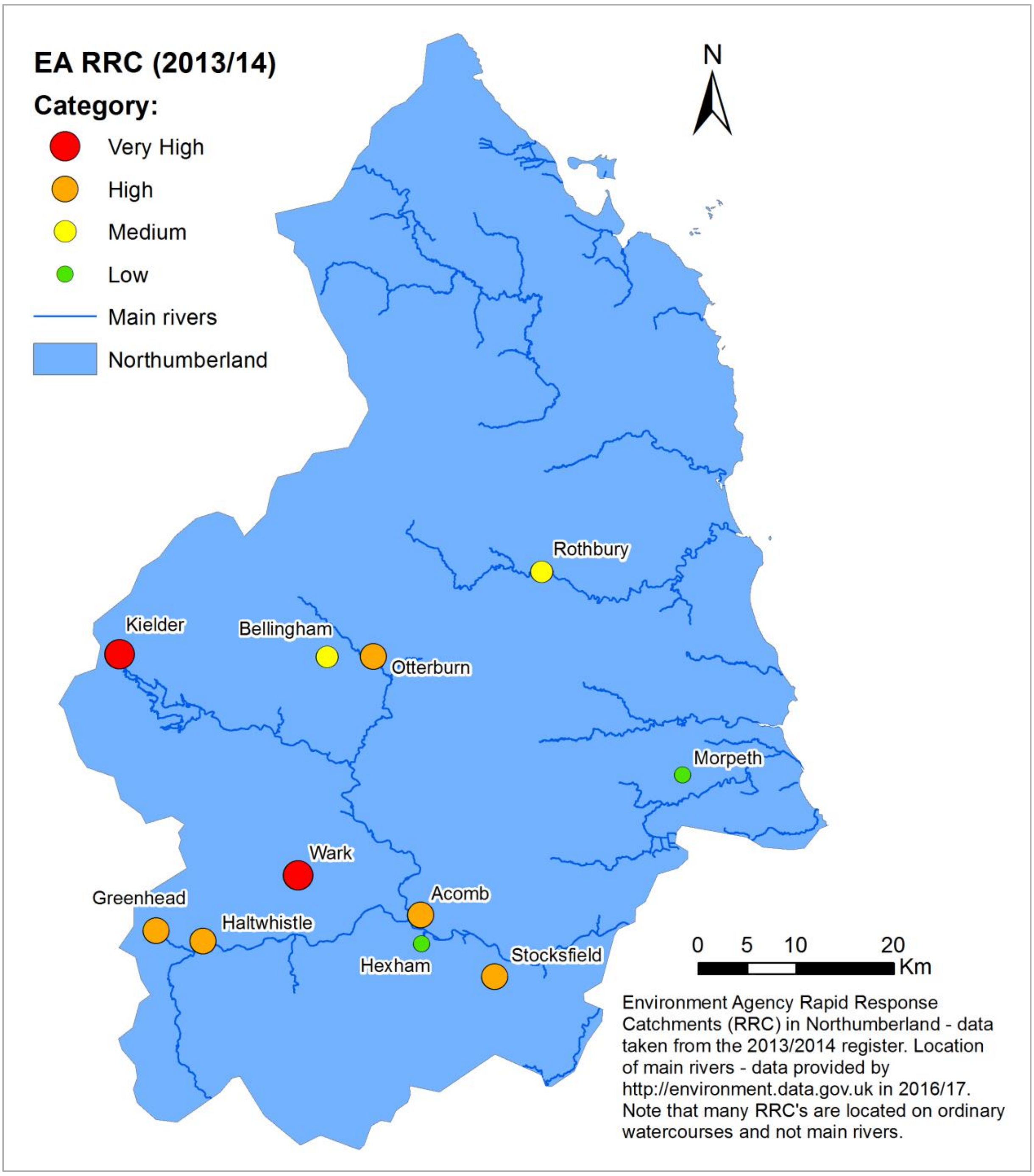
Appendices

Appendix 3A – Location of Environment Agency RRC (Northumberland only)



Location of Environment Agency Rapid Response Catchments (RRC) and the relevant communities affected within Northumberland. Risk categories are also defined. Note that the Haltwhistle's RRC status is associated with the Haltwhistle Burn, and not the South Tyne.

Appendix 3B – TRT'S CRF project briefing

TYNE RIVERS TRUST

Environment Agency

Catchment Restoration Fund (CRF) Project Briefing Note

Haltwhistle Burn

Haltwhistle Burn: 'a total catchment' approach is a partnership project which will use CRF funds to improve the whole catchment which has suffered the pressures of quarrying, farming, industry and an increasing population. Although the 'official' reasons for failure concern pressures on fish according to the criteria provided by the Water Framework Directive (WFD) this project addresses total waterbody issues deriving from a multitude of pressures, each creating 'sub-lethal' but chronic stresses.

Haltwhistle's 'Centre of Britain' identity, together with attraction of Hadrian's Wall makes it a potentially significant tourism centre, with a focus on both heritage and natural features. There are however significant economic difficulties and youth behaviour issues. Haltwhistle Burn is a central focus and has already attracted works of improvement and interpretation by the Haltwhistle Partnership.

Since the 2007 floods in the town, Tyne Rivers Trust has nurtured excellent relationships with agencies and extremely enthusiastic individuals directly connected to their catchment. Whilst the project is not a flood defence project this CRF funding now gives us a clear focus for agency action and direct spending on mitigating excess runoff and pollution.

Key facts	
River Basin District	Northumbria
Catchments	Haltwhistle
Outcomes	A total catchment approach targeted at improving fish populations, chemical water quality and hydromorphology.
Start Date	September 2012
End Date	March 2014
Budget	£363,433
Project Partners	Haltwhistle Town Council, Northumberland National Park, Northumberland County Council, Forestry Commission, Natural England, Environment Agency, Newcastle University (NiRES), Hadrian's Wall Heritage Ltd

Tyne Rivers Trust have already carried out geomorphological and habitat assessment of the entire burn, concluding that the 'catchment approach' would, by combining the small issues, create a significant benefit for the South Tyne and address the WFD 'poor status' classification.

Description of Works

To tackle the sub-lethal yet chronic stresses, the Haltwhistle Burn project will manage the following activities:

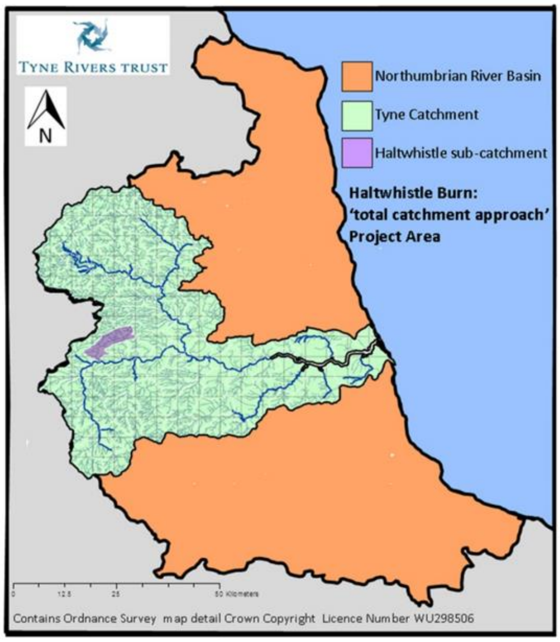
Alleviate water quality stresses on Greenlee Lough – applying forest management techniques listed in the 'Forest and Water Guidelines' to private and Forestry Commission plantations in the headwaters of the catchment.

Members of Haltwhistle River Watch group tackle a landslide problem by planting trees.

Control diffuse nutrient pollution from livestock farming – using established techniques of treating 'hot-spots' for silt sources / nutrients / farm runoff and simultaneously promoting 'Natural Flood Control' by runoff management.

Promote woodland habitat management – using management of fallen / damaged trees, careful replanting in relation to landslides and rebuilding / strengthening of existing stone pitching.

Removal of obstruction to fish passage – simple easements of bedrock or coarse woody debris (CWD) barriers.



Increase awareness of flood issues – working with Northumberland Community Flood Partnership and Northumberland County Council to help the local community prepare and protect from flooding whilst simultaneously improving channel capacity and removing principle causes.

Promotion of better urban runoff management – identification of blocked drains, and also identification of Combined Sewerage Overflows which are not discharging in the correct conditions. This activity will include working with Northumbria Water Ltd to review and improve the discharges from the local Sewage Treatment Works.

Improved understanding and management of the accretion of sediments in the South Tyne – these have progressively interrupted drainage from the burn, stagnating water if poor quality.

Community engagement with, and responsibility for, the delivery within every strand of this project will be encouraged. A Tyne Rivers Trust River Watch group has already been set up collating existing local knowledge, carrying out some improvement tasks such as tree planting and to achieve monitoring via fixed point photography, invertebrate analysis, electro-fishing, and rainfall and flow measurements. The local school has also experiences a 'Living Rivers' day with Tyne Rivers Trust exploring their local burn and issues of the wider catchment. They will be further engaged as the project develops.

What will success look like?

As a small charity, the Tyne Rivers Trust will only achieve the outcomes for this project with the active involvement and support of its project board - partners and stakeholders representing 20 different organisations and local residents. Through regular communication and engagement/educational events we hope that awareness and understanding of the pressures on Haltwhistle Burn will be improved within the local residents and agencies that have a stake in the catchment. A continued willingness for stakeholders to work together after the duration of this project to maintain and protect the improvements achieved will be an important legacy.

About the team
Project Manager: Dr Ceri Gibson
Admin/Finance/PR: Mrs Mairi Hextall
Director: Professor Malcolm Newson
Other contacts
Environment Agency: Eva Diran

Department for Environment Food & Rural Affairs

NATURAL ENGLAND

THE RIVER RESTORATION CENTRE

TYNE RIVERS TRUST

Contact the Tyne Rivers Trust on 01434 636900 or email info@tyneriverstrust.org

Appendix 4A – Project information and participant consent sheets (ethical)

Newcastle University

School of Civil Engineering & Geosciences

<date>

Haltwhistle Burn River Watch Programme
Project Information and Participant Consent

An innovative 'citizen science' project is being carried out by a PhD research student from Newcastle University. You can take part - share your local knowledge, attend workshops and/or monitor the local water environment.

Principal researcher: Eleanor Starkey BSc. MSc. (eleanor.starkey@ncl.ac.uk)

Project title: Community-based monitoring and modelling for catchment management and restoration within the UK

What is the research about? The research project is about engaging with the local community and encouraging them to share their local knowledge, attend River Watch workshops and/or monitor the local water environment that they live in (the Haltwhistle Burn catchment). This research project will determine whether this approach is feasible, how useful this type of data is and whether it can help professionals understand how the Haltwhistle Burn catchment behaves, how the rivers respond to rainfall and support any future management strategies. Various social benefits are also anticipated, including increased awareness and understanding catchment processes, awareness of floods and empowerment.

Why is the research being conducted and who for? Research findings will support Eleanor's PhD project at Newcastle University and also the wider 'Haltwhistle Burn Total Catchment Approach' project managed by the Tyne Rivers Trust. Both projects are encouraging members of the local community to become involved and share information so that together locals and professionals can improve the health of the Haltwhistle Burn catchment.

The PhD project is part funded by Tyne Rivers Trust through Defra's Catchment Restoration Funds (CRF) project and also the Natural Environmental Research Council (NERC).

What are the participants required to do? The PhD project is looking for members of the Haltwhistle Burn community to take part in workshops, discussions, (if applicable) questionnaires, share local knowledge and/or monitor parameters out in the field. Monitoring activities may include observing rainfall in back gardens, various water quality parameters (pH, temperature, water clarity, dissolved oxygen etc), river levels and taking photographs or videos during flood events. Date, time and location of each observation is required so that it can be added to a database of results. A range of monitoring equipment will be provided as well as different data submission tools.

What will happen to the results? Observations collected by participants will be sent to the leading researcher who will then i) store them within a secure electronic folder which only the research team has accessed to ii) anonymise the data so that personal or sensitive data is not used within the research itself iii) summarise the anonymised data iv) use the anonymised data to run computer models to find out new information about the Haltwhistle Burn catchment and v) present research findings back to the community. The quality of the data observed will also be compared to that collected by catchment scientists and engineers. Participant's details will not be shared or used as part of the research project –

Newcastle University
Find out more about the project:
http://research.ncl.ac.uk/haltwhistleburn/

Tyne Rivers Trust
A project part funded by Defra's Catchment Restoration Fund (CRF) Project

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Newcastle University

School of Civil Engineering & Geosciences

<date>

observations about the water environment themselves will only be used. Data will be kept for the duration of the research project (until the end of 2016).

Where will the results appear? This project is encouraging participants to share their local knowledge and observations about the water environment with the rest of the community and the research team. As a result, any data submitted or information shared will be stored electronically and anonymised by the university, then shared on the research webpage (internet), shared with the community during workshop events and could also potentially published within future research reports. The researcher will ensure all data is anonymous before it is shared beyond the research team at Newcastle University.

Who will have access to the results? Only the research team at Newcastle University will have access to raw data submitted by participants and in some cases, Tyne Rivers Trust. The researcher will ensure all data is anonymised before sharing on the internet with the public and used within research reports.

Research Project Participation – Provide Informed Consent

If you would like to take part in this research project then please take the time to fill out the data consent form below by providing the relevant information and **ticking the boxes to confirm that you agree**.

Name:	Reason for participation:
Email:	
I agree to take part in this research project and acknowledge that my participation is voluntary.	☐
I am aware that I can withdraw my participation from the research project at any time and for any reason.	☐
I understand that any information that I provide, including local knowledge and observations about the water environment, as well as surveys about my monitoring experience, will be used to support the research project findings.	☐
I understand that I may be observed and sometimes photographed during workshops, meetings and fieldwork activities.	☐
I agree for my data or information about the water environment to be used to support the research project findings, displayed on the web and used within future research reports, articles and presentations.	☐
I understand that when observations are made about the water environment and are accompanied by a date, time and location, it is the responsibility of the researcher to ensure that my observations are anonymous, they are assigned a generic name and grid reference for locational purposes and that they do not contain names of specific buildings before being used or disseminated.	☐
I agree to review and comply with relevant risk assessment and health and safety guidance documents if I decide to take part in field-based activities and monitor the weather / water environment.	☐
I acknowledge that any data or information that I provide (including on this form) will be used fairly, stored securely, treated with full confidentiality and that, if published or shared outside the research team, will not be identifiable as mine (thus will be anonymised).	☐
Signature:	Date:

Newcastle University

Find out more about the project:
http://research.ncl.ac.uk/haltwhistleburn/

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Haltwhistle Burn PhD Project – River Watch Event (dd/mm/yyyy)
List of Attendees, Contact Details and Data Consent

Name	Role / Organisation / Group	Address (if Haltwhistle)	Tel. No	Email	Please sign to provide data consent*

***By signing this sheet you are providing consent for your data/information/photographs to be shared during the workshop/meeting to be used as part of the CRF / PhD research project, and in some cases, published in material or made available on the web. The researcher (Eleanor Starkey) will ensure that your personal information is anonymised before being used for research purposes.**

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Appendix 4B – River Watch Photo Post text (Broomshaw example)

River Watch Photo Post

The Haltwhistle Burn catchment suffers from multiple pressures, including flooding & poor water quality.

Help us monitor the Haltwhistle Burn over time by taking a photograph of the river level gauge board (giant ruler) each time you pass. Here's what to do:

1. Whilst standing in a safe place on the footpath, rest your phone / camera on top of the fence post above this sign and face it towards the gauge board;
2. Take a clear picture of the gauge board and observe how high the water is (each black or white line = 1cm)
3. Share your observations with the rest of the community:
   - ➲ Online submission form: http://bit.do/sendmydata
   - Or
   - ➲ Twitter example: @HaltwhistleBurn #Broomshaw #RiverLevel = 0.32m 01/09/2014 14:32 (& your pic!)
4. Explore all river watch data here: http://bit.do/mydata

Data = knowledge = greater understanding:

✓ Photos before, during & after rainfall

✓ Daily variation: low, normal & high river levels

Submit data

Find out more about the project:

@HaltwhistleBurn http://bit.do/riverwatch

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Appendix 4C – Training cards (monitoring and data submission techniques)

- **Health and safety:**

Stay Safe: A Guide for River Watchers

Haltwhistle Burn river watch

Your safety is the No.1 priority whilst monitoring the water (river and flood) environment

Who is this guide for and what does it cover? Anyone taking part in community-based monitoring activities. It provides generic advice on how to stay safe when working in and around the water environment, (especially when there is a flood event).

SAFETY FIRST

****PLEASE READ BEFORE CARRYING OUT ANY MONITORING ACTIVITIES****

- **Be prepared:** check local weather forecast before heading out http://www.metoffice.gov.uk/ and read the Environment Agency's '*How To Stay Safe*' during a flood document http://bit.do/staysafe.
- **Stay safe:** if possible, carry out monitoring activities in pairs. If you are alone, let a family member or friend know if (and where) you plan to be out in the catchment. Take a mobile with you and stick to footpaths or routes which you are familiar with.
- **Flood water is dangerous, deep and fast flowing** - never walk or drive through it. The Environment Agency stress that it only takes six inches of fast flowing water to knock over an adult.
- **River banks can be steep and slippery.** Take care if you are taking a water sample. If in doubt, find a safer location or monitor when conditions improve.
- **If you are under the age of 16**, ensure you are accompanied by an adult.
- Avoid any monitoring activities as soon as **daylight begins to fade.**
- If you intend to make observations during and immediately after heavy rainfall, be aware that **river levels may rise rapidly**. Keep away from the river bank, move to high ground and take photos or videos from where you are. Be aware of the situation around you.
- If you are taking water samples to monitor the quality of the water, ensure that you wash your hands as soon as you return home / before eating. Where possible, wear gloves and use a sampling pole. Store monitoring equipment away from children and animals.
- **Wear** suitable footwear, warm clothing and a waterproof coat.
- **Do not share your home address on social media.** 'Haltwhistle' is sufficient.

Remember... you are responsible for your own health and safety. Think before you act.

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- **River level:**

Training Card: River Level

Haltwhistle Burn river watch

A participatory approach to river level monitoring
Measuring river level using the river level gauge boards

Why measure river level?

River level (also known as 'stage') provides us with information on how deep the water is at key locations and an indication of water quantity. Rivers and streams are extremely variable and we need to capture this. Regular river level monitoring can also help notify the community when the water levels are rising fast.

What equipment do I need?

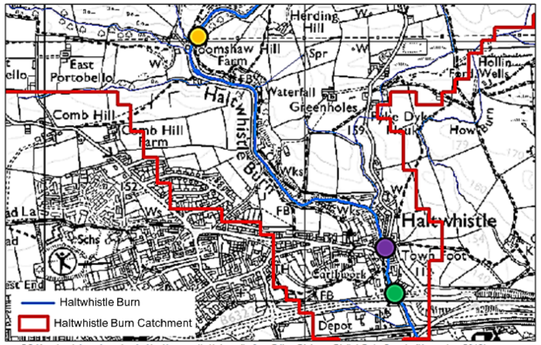
You do not need any equipment – this monitoring activity is based on a **visual inspection of the river level gauge boards** at key locations. You might need some paper to record your readings and a watch to note the time of your observation.

How often should I take river level readings?

As often as you can! **At least once a day is desirable** and if not, once a week. If it is forecast to rain, it is raining now or it was raining in the last 24 hours, you could also take extra readings as the river and stream levels will begin to rise. It is important to take note of the location, date and time of your observation. Each time you are passing.. why not take a quick look?!

Where are the river level gauge boards in the Haltwhistle Burn Catchment?

Tyne Rivers Trust has installed 3 river level gauge boards within the Haltwhistle Burn Catchment. Locations are highlighted on the map below. It is important to obtain river level readings from fixed locations so we can build up a picture over time.



Location of river level gauge boards

- (yellow) Just off Willia Road, by the footbridge, opposite Broomshaw Hill Farm
- (purple) Under the road bridge in the Townfoot area, on Castle Hill Terrace, at the bottom of Shield Hill.
- (green) Under the road bridge (B6322 road) in the Townfoot area of Haltwhistle

OS Map backdrop downloaded by Newcastle University from Edina Digimap Digital Data Supply (November 2013)

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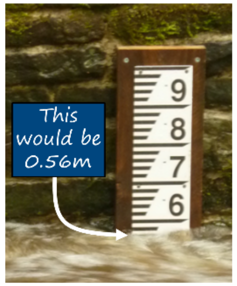
What do the river level gauge boards look like and how do I take a reading?



The river level gauge boards are 'giant rulers' fixed onto the wall (at one side of the river). Look out for a white plastic sign with graduated lines and numbers marked in black. From the footpath, visually observe where the water reaches on the gauge board and take a reading. Your reading should be taken to the nearest 0.01 metre (m). If the burn has dried up or is in flood then make a note of this and if possible take a photograph. If the water does not reach the gauge board (at low flow)then make an estimate and make it clear in your monitoring sheet that it was estimated ('E').

How do I submit my results and how often?

#RiverLevel
@HaltwhistleBurn

It is suggested that you record your daily/weekly river levels each time and submit a monitoring sheet at the end of each month. You could use Twitter or an Android app to submit your data as soon as you have taken a reading so the community can benefit from this information. There are many ways in which you can submit your data. Please discuss this during the next River Watch meeting to find out what options are available and what will work best for you.

An example and suggested river level monitoring sheet..

River Level Gauge Board: Broomshaw		Observers Name: E. Starkey	
Location: Broomshaw, Willia Road, Haltwhistle		Grid Reference: (http://gridreferencefinder.com/) 370582 565015	
Month / Year: February 2014			
Observation Date (DD/MM/YYYY)	Time of Observation (24hr clock)	River Level (metres)	Notes (e.g. recent weather conditions, recording issues, estimate, sign of flooding impacts, visual inspection of water speed)
01/02/2014	09:00	0.24	Dry weather. Burn slow flowing
02/02/2014	09:10	0.62	Heavy rain storm over night. Burn fast flowing. No flooding

Important Please take care when observing river levels, especially when the Burn is fast flowing and in flood. You do not need to enter the water to take a reading.

For further support and guidance please discuss during the next River Watch meeting.

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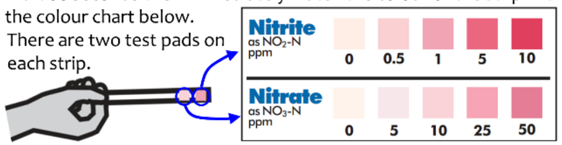
- **Water quality (phosphates and nitrates/nitrites):**

Training Card: Water Quality

Haltwhistle Burn river watch

Nitrates & Nitrites

Nitrates (NO_3-N) & Nitrites (NO_2-N)	
What & why	Nitrates (NO_3) and nitrites (NO_2) are a form of nitrogen - a nutrient which acts as a fertiliser for aquatic plants. Excessive plant and algae growth occurs at high levels (see algae sheet for water quality impacts). Sources include agricultural fertilisers and animal manure which can easily make their way into waterbodies, e.g. when surface water flooding occurs.
Category	Chemical observation
Equipment	Small plastic sample bottle • x1 LaMotte Nitrate & Nitrite Insta-test strip (2996) • Pen • Paper • Watch • Camera (optional)
Method (click on colour chart for larger copy)	1. Find a safe place on the river bank where you can reach the water easily at arms length. 2. Kneel down and fill up the sample bottle – rinse it out a few times. 3. Point the top of the bottle upstream at (if possible) 0.6 of the depth (i.e. just a bit more than half way down) and fill it to the top. 4. Take one nitrate/nitrite test strip out of the packet, hold it at one end and **dip it in the water sample for 2 seconds**, then pull it out. 5. **Wait 60 seconds** then immediately match the colour of the strip with the colour chart below. There are two test pads on each strip.  6. Record your nitrate (0-50ppm) nitrite (0-10ppm) observations and note the date / time. 7. Put your water sample back in the stream and bin your test strip.
Other info	Wash your hands as soon as you return home / before eating. Be consistent with your monitoring approach and use the same location. Keep wet fingers out of the test strip bottle & store in a cool / dry place.

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Training Card: Water Quality

Haltwhistle Burn river watch

Phosphates

Phosphates (PO_4)	
What & why	Phosphorus is a nutrient which acts as a fertiliser for aquatic plants. Excessive plant and algae growth occurs at high levels (see algae sheet for impacts). Phosphorus occurs in natural waters in the form of phosphates (PO_4) and excess levels found in rural UK streams, rivers and lakes is often attributed to agricultural practices (use of fertiliser). Phosphate levels higher than 0.03ppm support plant growth.
Category	Chemical observation
Equipment	Small plastic sample bottle • LaMotte Phosphate test kit (test tube and x1 Phosphate 'TesTab' tablet (5422)) • Pen • Paper • Watch
Method (click on colour chart for larger copy)	1. Find a safe place on the river bank where you can reach the water easily at arms length. 2. Kneel down and fill up the sample bottle – rinse it out a few times. 3. Point the top of the bottle upstream at (if possible) 0.6 of the depth (i.e. just a bit more than half way down) and fill it to the top. 4. Fill the small test tube to the 5 ml line, add **one LaMotte Phosphate TesTab tablet** and **put the lid on.** 5. **Mix the test** tube by inverting until the tablet has dissolved and **wait 5 minutes.** 6. Match the colour of the test tube water with the colour chart below: 0 ppm • 1 ppm • 2 ppm • 4 ppm (tip: rest your sample over the top of the colour chart) 7. Record your observation (ppm) and note the date / time. 8. Once complete, put your water sample back in the stream.
Other info	Wash your hands as soon as you return home / before eating. Store the LaMotte TesTab tablets in a safe place at home. Be consistent with your monitoring approach and use the same location.

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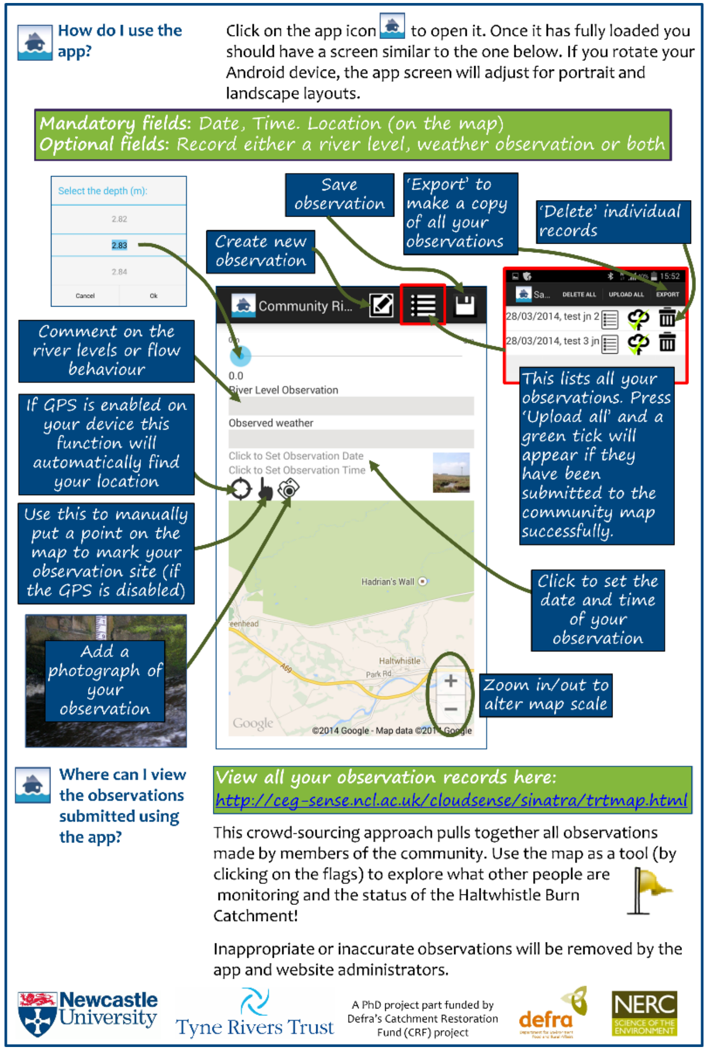
- **Twitter and Android App example:**



All remaining training cards can be found on the disk submitted with this thesis or on project website (http://research.ncl.ac.uk/haltwhistleburn/communityhub/communitytrainingresources/).

Appendix 4D – Blank 'monitoring preferences and capabilities' questionnaire

Haltwhistle Burn PhD Project
Understanding Your Monitoring Preferences and Capabilities

- Do you want to be part of an innovative and pioneering research project that is directly related to contemporary issues and could change the way we monitor and manage our catchments across the UK?
- Do you want to understand and care for your local water environment?
- Are you interested in becoming a citizen scientist*?

**A citizen scientist can be someone (in this case a member of a local community) who helps scientists and engineers to carry out research by collecting and sharing data about a natural phenomenon*

This project is encouraging the local community to connect with their local catchment by carrying out simple yet low-cost and innovative monitoring techniques. If you would like to take part in monitoring the water environment within the Haltwhistle Burn catchment then it would be extremely useful to understand what you might like to monitor, where you are able to monitor and when / how often you are willing to do this. By providing this information we can tailor monitoring plans around you and your preferences. A few questions are provided below in order to understand your monitoring preferences and capabilities. If you are **interested at this stage** in taking part in any monitoring activity then please fill out the form below. Contact details are simply required to keep track of preferences. By filling in this form you are not committed to anything – it will only be used to get an idea of what you might like to do.

Please return any completed forms or direct queries to: **Eleanor Starkey**
By email: eleanor.starkey@ncl.ac.uk
By Post: **School of Civil Engineering and Geosciences, PGR Centre (Room G.03), Cassie Building, Newcastle University, Newcastle upon Tyne, NE1 7RU**
River Watch Meeting: **Bring to the next River Watch meeting (printed forms will be available if you need one during this event)**
Thank you!

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Website: http://research.ncl.ac.uk/haltwhistleburn/
Twitter: @HaltwhistleBurn
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Understanding your monitoring preferences and capabilities

Name: **Address:** **Email:**	**Telephone / Mobile number:** **Role / Organisation / Group:** **Reason(s) for wanting to take part:**

1. What catchment issue(s) or parameter(s) would you be interested in monitoring?		Please tick
➢ This might be something that you are interested in, directly affected by or perhaps you would like to learn more about it; ➢ Remember that all monitoring techniques will be simple to perform, you will be provided with the relevant equipment and supported with training material (e.g. quick guides).	**A) Daily rainfall** ➢ Using a manual rain gauge in your backyard, in your garden or on your land within the catchment to capture microclimates.	☐
	B) Description of the weather and impacts ➢ Using a 'weather story' book, Twitter, or choose from a pre-define list of answers	☐
	C) River level (depth) ➢ By reading river level gauge boards, measuring using a ruler or by taking a photograph	☐
	D) River flow (speed) ➢ By taking a video or using a simple float over a specified distance	☐
	E) Flood events and catchment issues ➢ Take photographs and provide descriptions **(e.g. build-up of rubble)**	☐
	F) Morphological (landform) change ➢ For example take note of river bank erosion, collapse or sediment build-up by taking photographs and providing descriptions.	☐
	G) South Tyne gravel bars ➢ Provide an indication of change using a reference point or photograph	☐
	H) Blockages under bridges ➢ Take photographs at fixed points e.g. in the Townfoot area	☐
	I) Turbidity (water clarity / cloudiness) ➢ By filling a plastic bottle with stream water, carrying out a visual	☐

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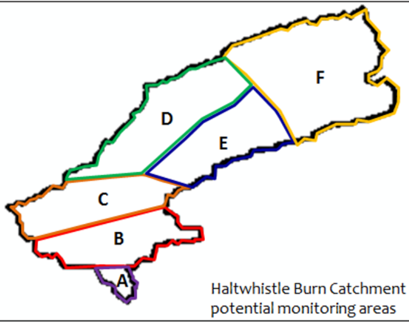
	inspection and compare against a chart	
	J) Water colour ➢ Visual inspection and compare against a colour chart for an indication of water quality (e.g. green for excessive algal growth)	☐
	K) Water temperature ➢ Using a thermometer or temperature strips	☐
	L) Water chemistry (pH, nitrate, phosphorus and/or dissolved oxygen levels) ➢ Take a water sample and dip in a test strip e.g. pH strip	☐
	M) Fish species count ➢ Electrofishing activities led by Tyne Rivers Trust	☐
	N) Invertebrate (bug) and river habitat surveys ➢ Activities led by Tyne Rivers Trust	☐
	O) Look out for native and invasive species ➢ Visual inspection (e.g. Japanese knotweed)	☐
	P) Monitor the performance of natural runoff management features ➢ Take photographs at fixed points and provide descriptions.	☐

2. Where in the catchment would you be willing to walk / travel to for monitoring purposes?

- ➢ Think about where you live and whether you could tie any monitoring activities in with any regular journeys or walks you would normally take? For example do you take a specific and regular route to work, a school run or walk with your dog? Does your property overlook a watercourse within the catchment?
- ➢ Most monitoring locations are likely to be along the watercourses (except for example, rainfall and weather monitoring which can fall outside the Haltwhistle Burn Catchment boundary);



Haltwhistle Burn Catchment potential monitoring areas

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➢ Take a look at the Haltwhistle Burn catchment (to the right). Which area(s) would you be willing to monitor? A more detailed map of the catchment can be found at the end of this document.	Any Area ☐ Area A ☐ Area B ☐	Area C ☐ Area D ☐	Area E ☐ Area F ☐

3. Would you be willing to go out in the catchment when for example, it is raining to collect data during 'extreme events'? ➢ We can point you towards weather forecasts and warnings to keep you informed; ➢ You could join up with other members of the community to do this; ➢ Remember that extreme events do not usually occur as often and because of this any data collected helps us to understand how the catchment behaves during these events (for example during potential flood events).	Yes ☐	No ☐
4. When would you prefer to monitor? ➢ Again you could tie this in with regular journeys or walks which you take.	Morning ☐ Afternoon ☐	Evening ☐ Any / all ☐
5. Typically how often would you be able to monitor? ➢ Some parameters are extremely variable such as rainfall, river level and river flow. These parameters are usually monitored on a more frequent basis to capture any changes.	More than once a day ☐ Once a day ☐ Weekly ☐ Monthly ☐	Seasonal ☐ Annual ☐ As a one-off activity ☐ Other (please state) ☐
6. How would you prefer to submit your data? ➢ If you do not have a computer, smart phone, tablet or internet connection, you could arrange for another member of the group to submit your data;	Daily / weekly using the Haltwhistle Burn website ☐ Daily or real-time using Twitter ☐ Real time using an Android app ☐ Email your data ☐	

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Website: http://research.ncl.ac.uk/haltwhistleburn/
Twitter: @HaltwhistleBurn
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➢ If you have never used a particular method then please remember that full guidance will be provided to help you get started should you wish to try something new; ➢ An Android smartphone or tablet is required to use the app. If you do not have one of these devices then we may be able to purchase a few tablets for use across the catchment for monitoring purposes.	On paper and then post ☐ On paper and share during River Watch / community meetings ☐	
7. Do you have any children, relatives or friends who may be interested in monitoring the catchment? ➢ All age groups are welcome to take part and monitor as often or as little as they want. ➢ The success of the project is dependent on public awareness. Please spread the word to family, friends and neighbours!	Yes ☐ If 'yes', please provide details:	No ☐
Do you have any comments / suggestions?		

Please return any completed forms or direct queries to: Eleanor Starkey
By Post: School of Civil Engineering and Geosciences, PGR Centre (Room G.03), Cassie Building, Newcastle University, Newcastle upon Tyne, NE1 7RU
By email: eleanor.starkey@ncl.ac.uk

v1.0

Website: http://research.ncl.ac.uk/haltwhistleburn/
Twitter: @HaltwhistleBurn
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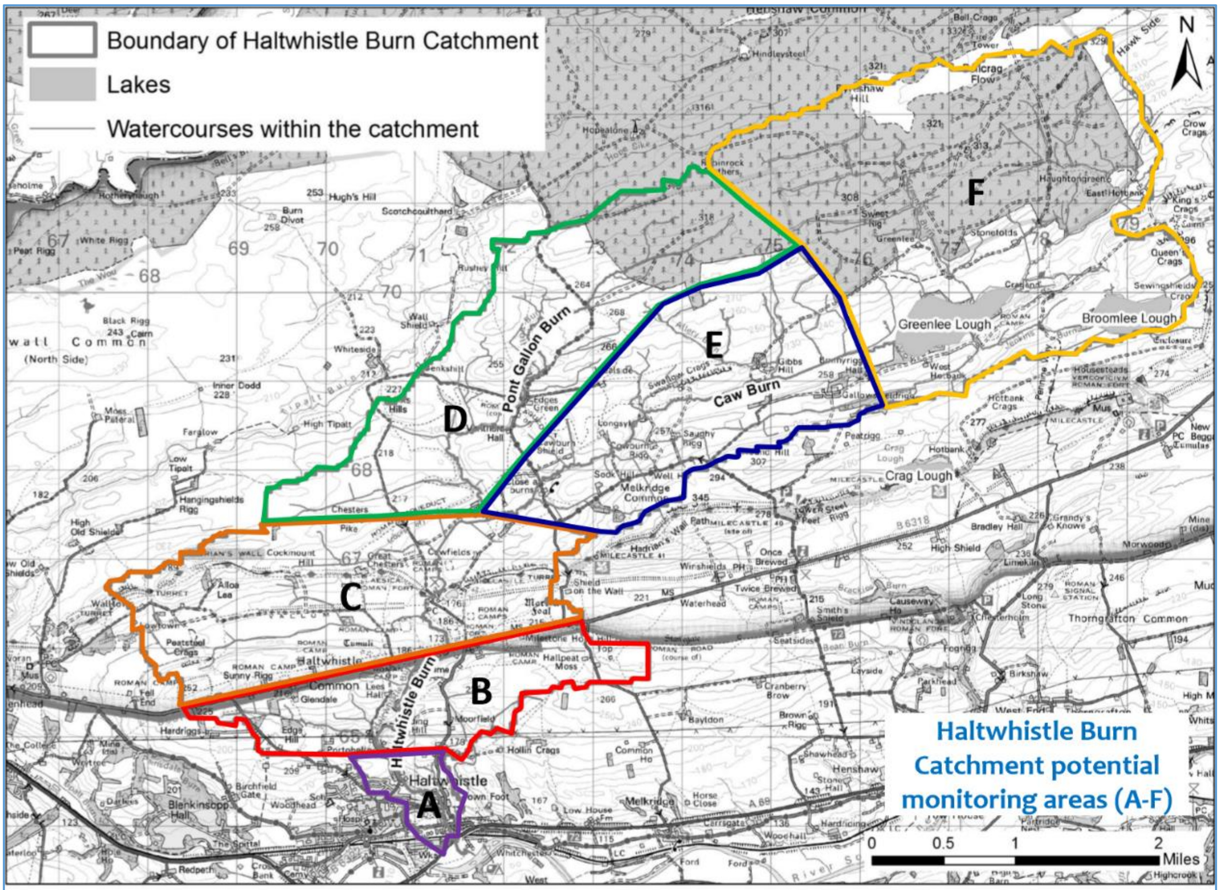


Mapping backdrop has been reproduced with permission of Ordnance Survey (GB) and downloaded using: EDINA Digimap Ordnance Survey Service. This map has been produced in February 2014 to support the Catchment Restoration Funds (CRF) project funded by Defra.

Appendix 4E – Evidence of community-based training and piloting events

Demonstrating monitoring equipment during a River Watch meeting (February 2014).

'Citizen Science speciality walk' officially scheduled by the Haltwhistle Walking Festival (2014). See walk No.17.

Special Interest Walks

For all our special interest walks an expert is on hand to provide fascinating facts about the land we walk over. Numbers are strictly limited so that walkers can hear what is said and be able to ask questions. There will be frequent stops.

Walk 8 Archaeology Walk
Join Phil Bowyer and see the signs of previous civilisations under your feet. We will visit wild lands north of Hadrian's Wall and see a well-known but rare stone circle, an ancient standing stone ridge and a newly discovered burial ground.

Walk 12 "Skywalking"
Richard Holmes will keep our eyes looking upwards to see what we can learn about weather forecasting from the skies. Be prepared to be amazed (and hope for a good mixture of clouds on the day).

Walk 17 Citizen Science
We are working with the Tyne Rivers' Trust and Newcastle University for this fascinating event. There are a number of important water management projects around Greenlee Lough. Local landowners have given permission for our walkers to go on private land to visit these. There will be an opportunity to test water samples

Walk 20 Know your Fungi
This year Gordon Beakes of Newcastle University will lead us in an exploration of both sides of the river Allen, starting at Plankey Mill above Allen Banks. He will concentrate on the identification of the species found by the participants. This walk is an annual event and is very popular.

17.Citizen Science Walk – water management around Greenlee Lough	7m	1030 Permissive CP near Gibbs Hill Farm,	£10

Walking festival participants testing the water quality monitoring kit and training material around Greenlee Lough inlets.

'River Day' with local school children testing RLGBs, rain gauges, weather descriptions, water quality kits and the community Android app.

One-to-one training with a member of the River Watch Group (data submission techniques).

Appendix 5A – Gauge summary sheets (NU hydrometric network)

Rain gauge: Gibbs Hill

Coordinates: 374963 569143

Elevation: 233m AOD

Model: TBR (ARG100) rain gauge

Supplier specification sheet:
http://bit.do/TBR_ARG100 (CEH approved)

Bucket calibration: 0.202mm

Installation date: 24/01/2014

Logger resolution: 2-minute

Notes:

1) No gaps in the data found;

2) No site interferences;

3) After initial discussions with the local farmer during the gauge installation phase, it was apparent that a family member was once a Met Office voluntary rainfall observer at Gibbs Hill (~1975-1990). Datasets were unavailable when requested, but our TBR rain gauge was installed in the exact same place. Site selection was therefore Met Office approved.

Rain gauge: Broomshaw Hill

Coordinates: 370550 565056

Elevation: 149m AOD

Model: TBR (ARG100) rain gauge

Supplier specification sheet:
http://bit.do/TBR_ARG100 (CEH approved)

Bucket calibration: 0.201mm (1st gauge) & 0.201mm (2nd gauge)

Installation date: 13/11/2014 (1st gauge) 14/02/2015 (2nd gauge)

Logger resolution: 2-minute

Notes:

1) Telemetry (2nd gauge) was expected to be installed at this site from the onset. However, due to signal, power and cattle damage issues, it was not operational until February 2015. A temporary TBR gauge (manual download – 1st gauge) was therefore installed whilst waiting for the supplier. A lengthy cross-over period (Feb-2015 to July-2015) was used to provide a smooth transition and avoid gaps. Other than data transmission methods, the TBR gauges functioned identically and were co-located.

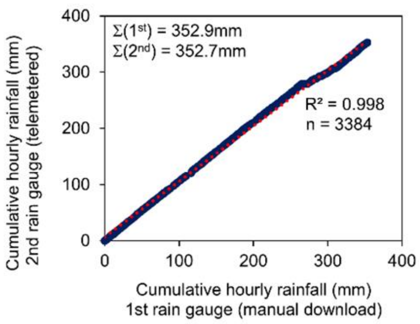
2) Gaps were present in the data (2nd gauge) as cattle disturbed the enclosure. However, this was before the gauge was fully operating.

TBR gauge used

Inside the TBR gauge

Downloading data manually

Telemetry – logger box and solar panel power supply.



QC check during the Broomshaw cross-over period:

- 15/02/15 to 05/07/16
- Hourly rainfall totals
- Double-mass (cumulative regression) plots
- Datasets accepted.

Water level recorder: Caw Burn (CB) at Gibbs Hill

Coordinates: 374853 568980

Upstream catchment area: 17.97km^2

Model: Impress Pressure Transducer (IPT)

Software: TinyTag Explorer

Supplier specification sheet: http://bit.do/IPT

Installation date: 24/01/2014

Logger resolution: 5-minute

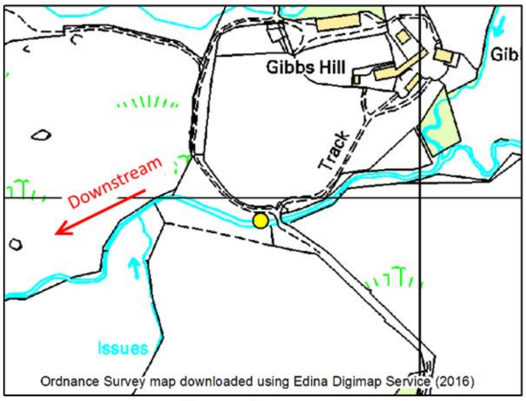
Notes:

1) Located immediately downstream of Gibbs Hill bridge, right-bank;

2) Located downstream of Greenlee Lough;

3) Gibbs Hill rain gauge located in close proximity;

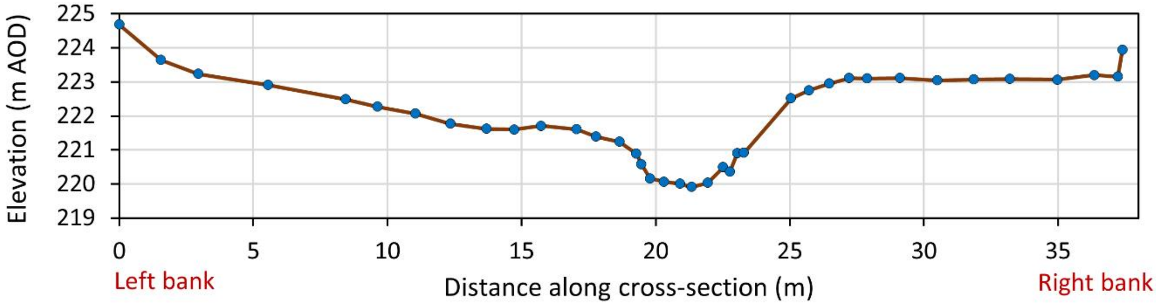
4) No gaps in the dataset.



Location map

Photograph: equipment & cross-section

Cross-section - surveyed with Leica Geosystems RTK smart rover GPS, at least 20mm accuracy.

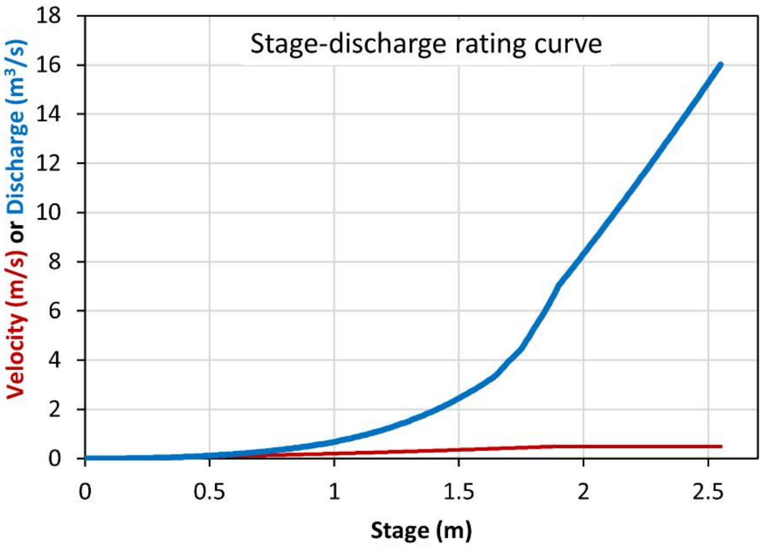


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 9 (8 used), covers 95% of the observed flows

Mass balance checks: Uses Jan-14 to May-15 data. R^2 value of 0.97 obtained during paired checks (Q flow gauging & Q rating curve).



Water level recorder: Pont Gallon Burn (PGB) at Sheep Dip

Coordinates: 372956 569903

Upstream catchment area: 1.55km^2

Model: Diver

Software: Diver Office

Supplier specification sheet: http://bit.do/divers

Installation date: 07/03/2014

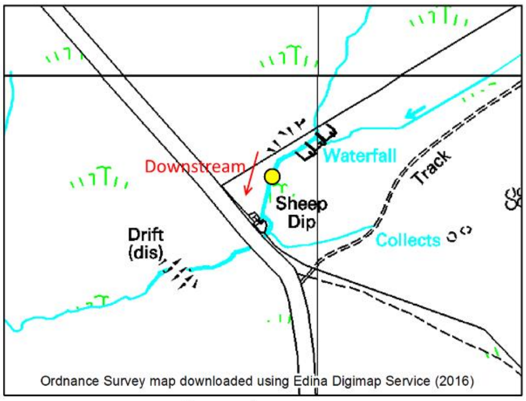
Logger resolution: 5-minute

Notes:

1) Installed left bank;

2) Very low flow experienced during prolonged warm and dry weather. This left the pressure transducer above the water column (offset in dataset has been corrected). Also difficult to flow gauge at low flow;

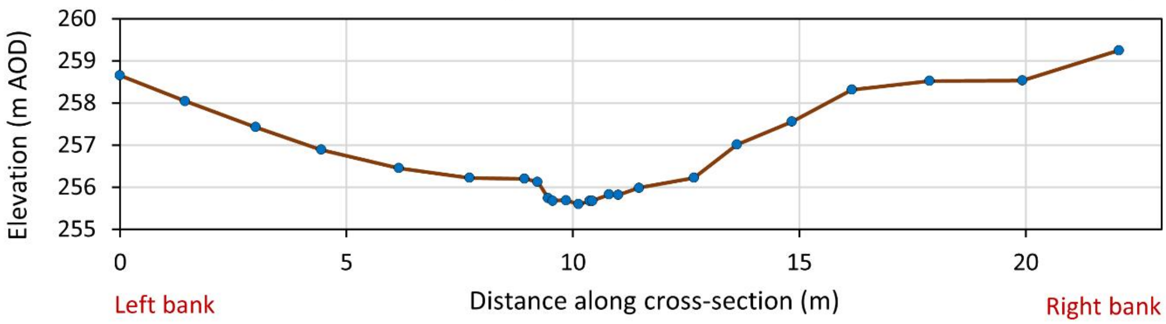
3) No gaps in the dataset.



Location map

Photograph: equipment & cross-section

Cross-section - surveyed with Leica Geosystems RTK smart rover GPS, at least 20mm accuracy.

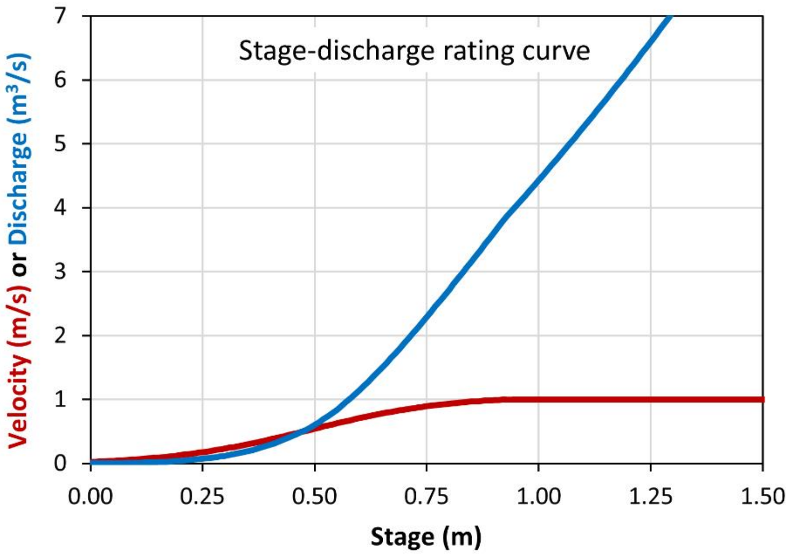


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 9 (8 used), covers 95% of the observed flows

Mass balance checks: Uses Mar-14 to May-15 data. R^2 value of 0.98 obtained during paired checks (Q flow gauging & Q rating curve).



Water level recorder: Pont Gallon Burn (PGB) at Cleughfoot

Coordinates: 371804 567553

Upstream catchment area: 6.19km^2

Model: Diver

Software: Diver Office

Supplier specification sheet: http://bit.do/divers

Installation date: 28/01/2014

Logger resolution: 5-minute

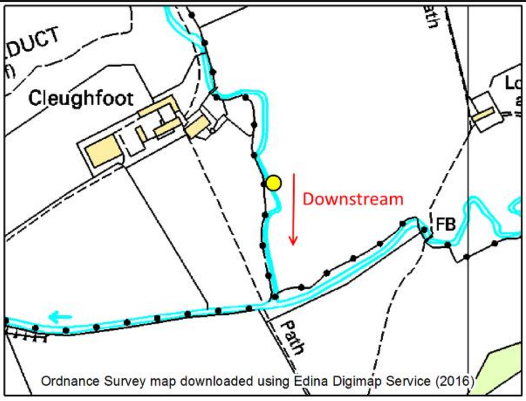
Notes:

1) Located approximately 125m upstream from the Pont Gallon Burn and Caw Burn confluence;

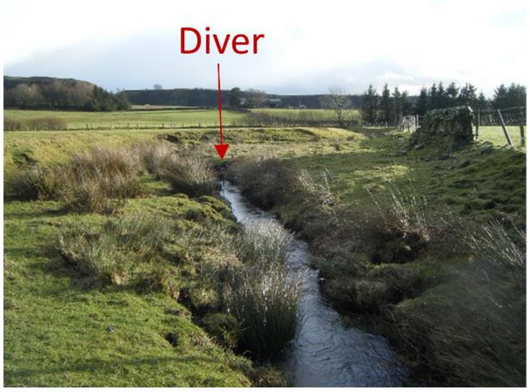
2) Gauge located near the 'Caw Burn at Cleughfoot' gauge;

3) Installed middle of channel;

4) No gaps in the dataset.

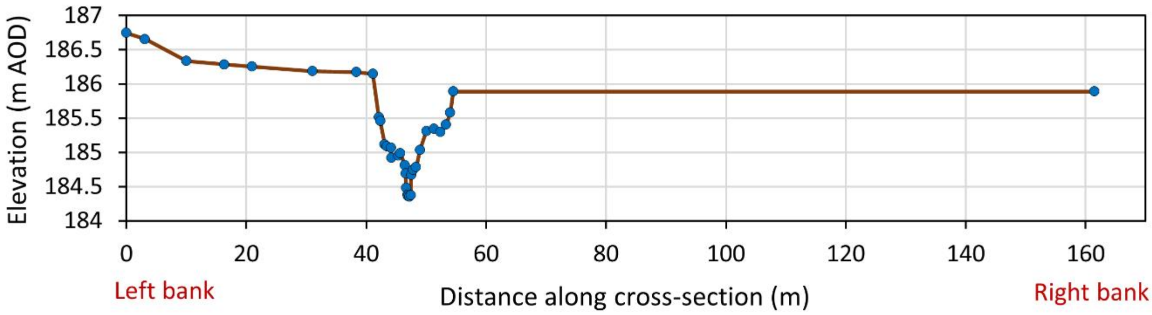


Location map



Photograph: equipment & cross-section

Cross-section - surveyed with Leica Geosystems RTK smart rover GPS, at least 20mm accuracy.

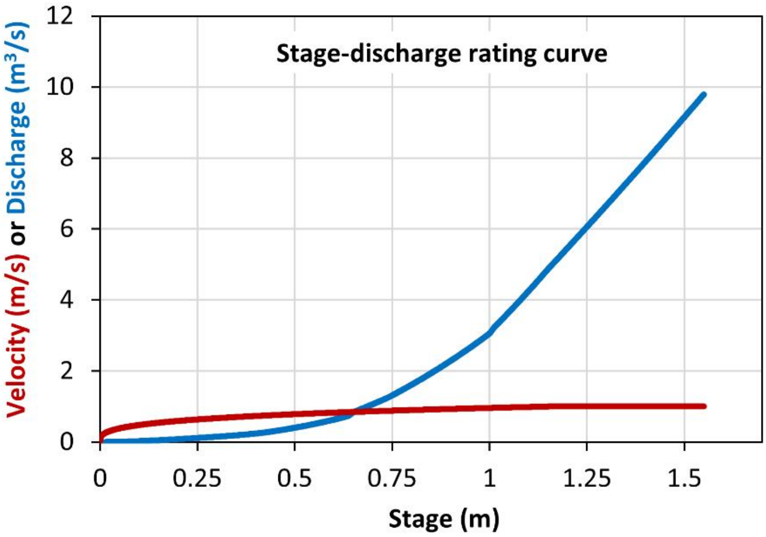


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 6, covers 95% of the observed flows

Mass balance checks: Uses Jan-14 to May-15 data. R^2 value of 0.94 obtained during paired checks (Q flow gauging & Q rating curve).



Water level recorder: Caw Burn (CB) Cleughfoot

Coordinates: 371765 567428

Upstream catchment area: 29.19km^2

Model: Impress Pressure Transducer (IPT)

Software: TinyTag Explorer

Supplier specification sheet: http://bit.do/IPT

Installation date: 28/01/2014

Logger resolution: 5-minute

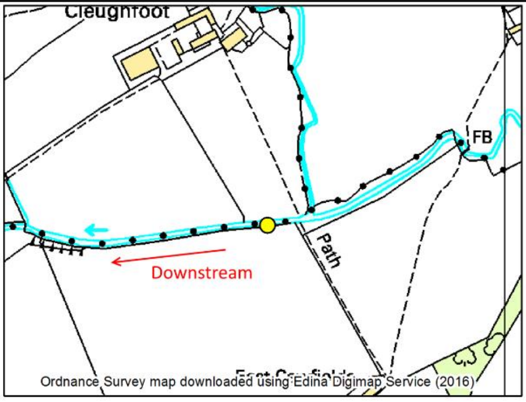
Notes:

1) Located approximately 45m downstream from the Pont Gallon Burn and Caw Burn confluence;

2) IPT installed left-bank;

3) Gauge located near the 'Pont Gallon Burn at Cleughfoot' gauge;

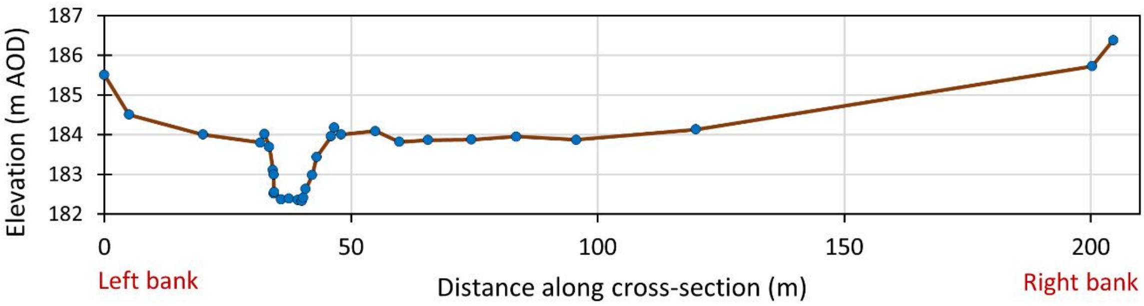
4) No gaps in the dataset.



Location map

Photograph: equipment & cross-section

Cross-section - surveyed with Leica Geosystems RTK smart rover GPS, at least 20mm accuracy.

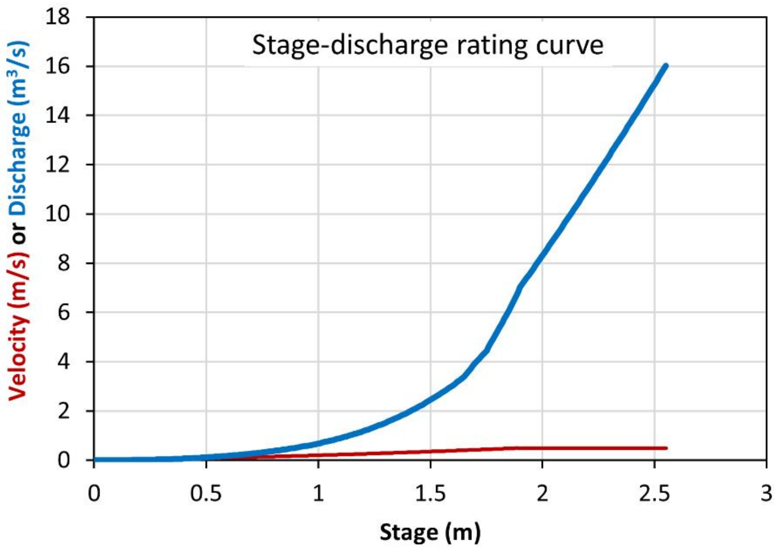


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 6, covers 95% of the observed flows

Mass balance checks: Uses Jan-14 to May-15 data. R^2 value of 0.94 obtained during paired checks (Q flow gauging & Q rating curve).



Water level recorder: Caw Burn (CB) at Cawfields

Coordinates: 371117 566466

Upstream catchment area: 31.49km^2

Model: Impress Pressure Transducer (IPT)

Software: TinyTag Explorer

Supplier specification sheet: http://bit.do/IPT

Installation date: 28/01/2014

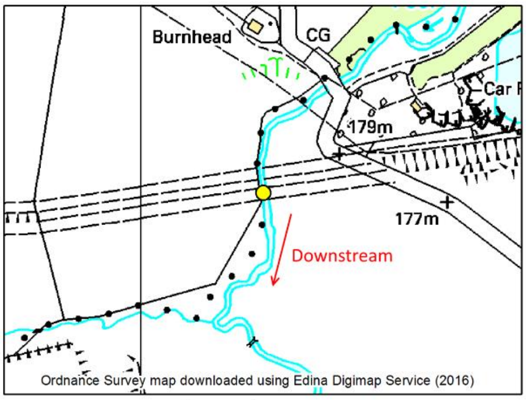
Logger resolution: 5-minute

Notes:

1) Located downstream of Cawfields Quarry;

2) IPT installed right-bank;

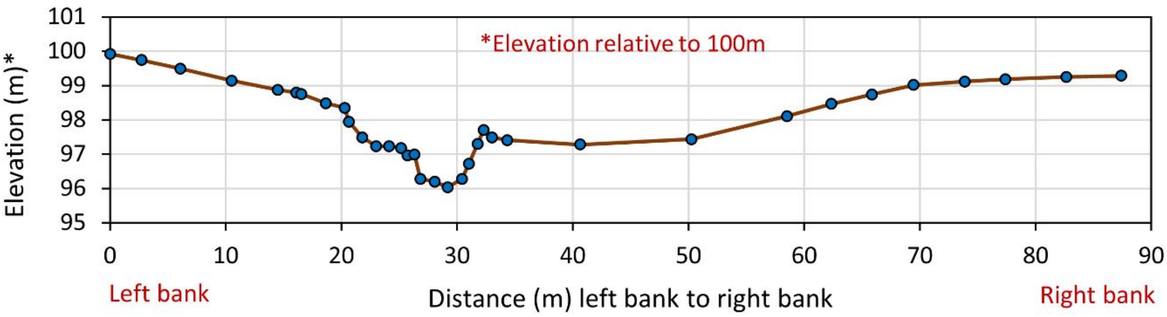
3) Gap in the dataset 22/12/2014 to 21/02/2015 following winter 2014/15 high flows. Re-installed February 2015 using the same datum.



Location map

Photograph: equipment & cross-section

Cross-section - surveyed with high precision Leica Geosystems digital level (Sprinter 250 model).

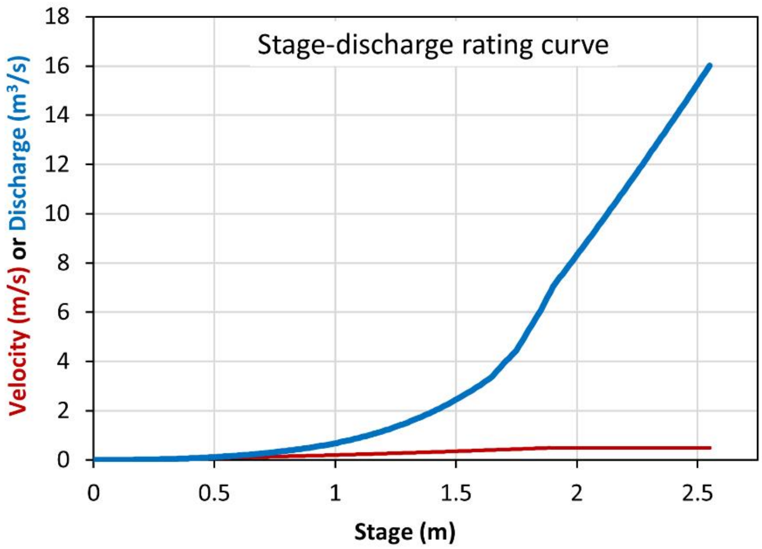


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 10 (9 used), covers 95% of the observed flows

Mass balance checks: Uses Jan-14 to May-15 data. R^2 value of 0.91 obtained during paired checks (Q flow gauging & Q rating curve).



Water level recorder: Haltwhistle Burn (HB) at Broomshaw (Page 1)

Coordinates: 370687 565050

Upstream catchment area: 37.78km^2

Model: Diver & IPT

Software: Diver Office & Telemetry (off site)

Supplier specification sheet: http://bit.do/IPT & http://bit.do/divers

Installation date: 21/05/14 (diver) 14/02/15 (IPT)

Logger resolution: 5-minute

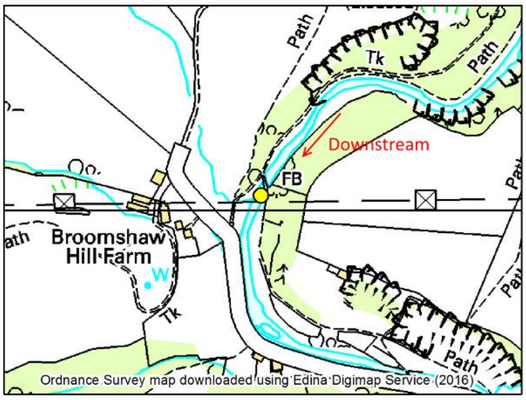
Notes:

1) Co-located next to community-based RLGB;

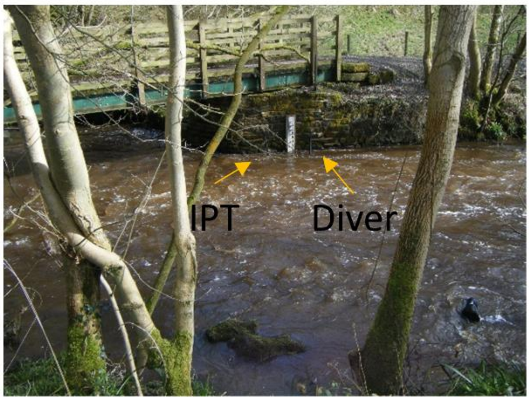
2) Diver and IPT installed left-bank, downstream of the Broomshaw footbridge;

3) Located upstream of Slaty Sike confluence;

4) Gap in the dataset 15/11/15 to 28/11/15 following winter high flows. Re-installed 28/11/2015 and corrected for datum offset.

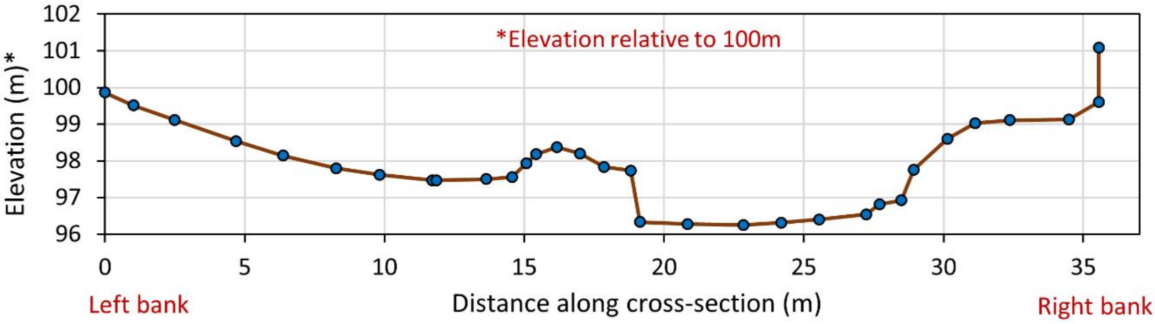


Location map



Photograph: equipment & cross-section

Cross-section - surveyed with high precision Leica Geosystems digital level (Sprinter 250 model).

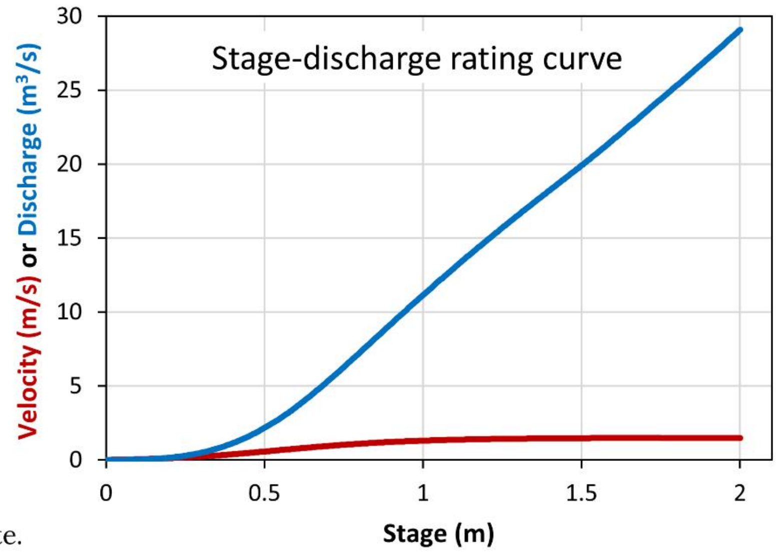


Rating curve

Method: stage-velocity-area method modified to include a calibration phase and mass balance checks (see Ewen *et al.*, 2010).

No. flow gauging points: 11 (10 used), covers 95% of the observed flows

Mass balance checks: Uses May-14 to May-15 data. R^2 value of 0.97 obtained during paired checks (Q flow gauging & Q rating curve). Flow remained in bank at this site.



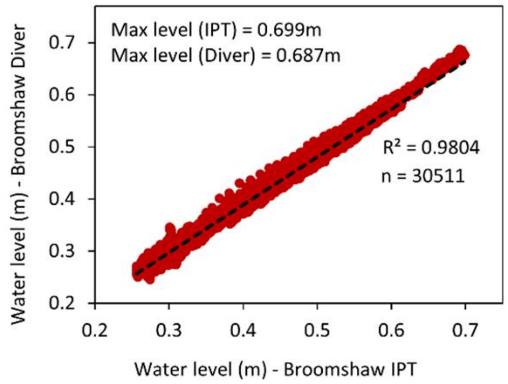
Water level recorder: Haltwhistle Burn (HB) at Broomshaw (Page 2)

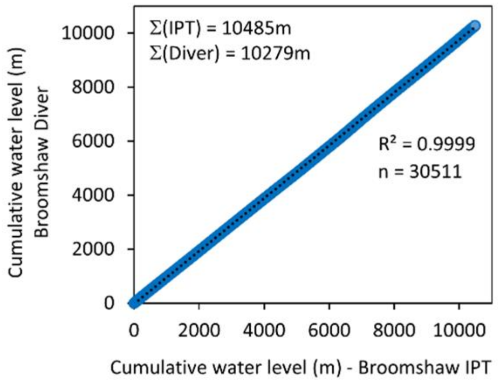
Telemetry notes (diver-IPT cross-over period):

1) A telemetered IPT was expected to be installed at this site from the onset. However, due to signal, power and cattle damage issues, it was not operational until Feb-2015. A diver (manual download) was therefore installed whilst waiting for the supplier. A lengthy cross-over period (Feb-2015 to May-2015) was used to provide a smooth transition and avoid gaps;

2) QC checks during the Broomshaw cross-over period from 15/02/2015 to 31/05/2015:

- 5-minute water level observations provided a direct comparison;
- Linear regression plot (red) containing IPT and diver data generated an R^2 value of 0.98;
- Double-mass (cumulative regression) plot (blue) also illustrates a very close/perfect match;
- Datasets accepted, datum offsets corrected & combined to create one final dataset for this site





IPT, diver and RLGB located at Broomshaw, downstream of the main public footbridge

Appendix 5B – Modified stage-velocity-area (SVA) rating curve method

This appendix provides details on the SVA approach adopted (previously introduce within Section 5.3.3.4) by using the 'Haltwhistle Burn at Broomshaw' gauging station as an example.

Flow gauging and surveying:

Once the WLR's had been QC checked and accepted, they were then converted to discharge (Q). In order to do this, repeat flow gauging measurements were required over time and cross-sections were surveyed (Figure App-5B-1). Flow gauging measurements were undertaken throughout March 2014 to March 2015 at each gauging station to ensure seasonal variations (i.e. varying river levels, thus velocities and discharge) were captured at all gauging stations. Discharge was obtained using an impellor flow meter and calculated using the velocity-area method described by Davie (2008), Herschy (2009) and Shaw *et al*. (2011). Due to time constraints, and the difficulty of being out on site during a range of observable stages and budgets for travelling, only 6 to 11 (average of 8) sets of rating data were available for each gauging station. However, these data points fell within 95% of the observed stage time series data (see example in Figure App-5B-2).

Figure App-5B-1. Flow gauging (left) and surveying using the RTK GPS rover station (right).

The following quality assurance (QA) measures were implemented whilst flow gauging and surveying:

- Water level recorders (WLR) were installed with flow gauging in mind: easy access, flow behaviour (e.g. avoiding backwater effects), away from other water outlets, well-defined cross sections etc;
- Cross sections were checked for erosional and depositional changes following flood events;
- Cross sections were carefully surveyed using accurate surveying equipment;

- Cross sections were checked upstream and downstream on a regular basis;
- The same impellor flow meter was used throughout and at all sites.

It was assumed that cross sections remained the same over the monitoring and flow gauging period, and did not altered rapidly during flood events.

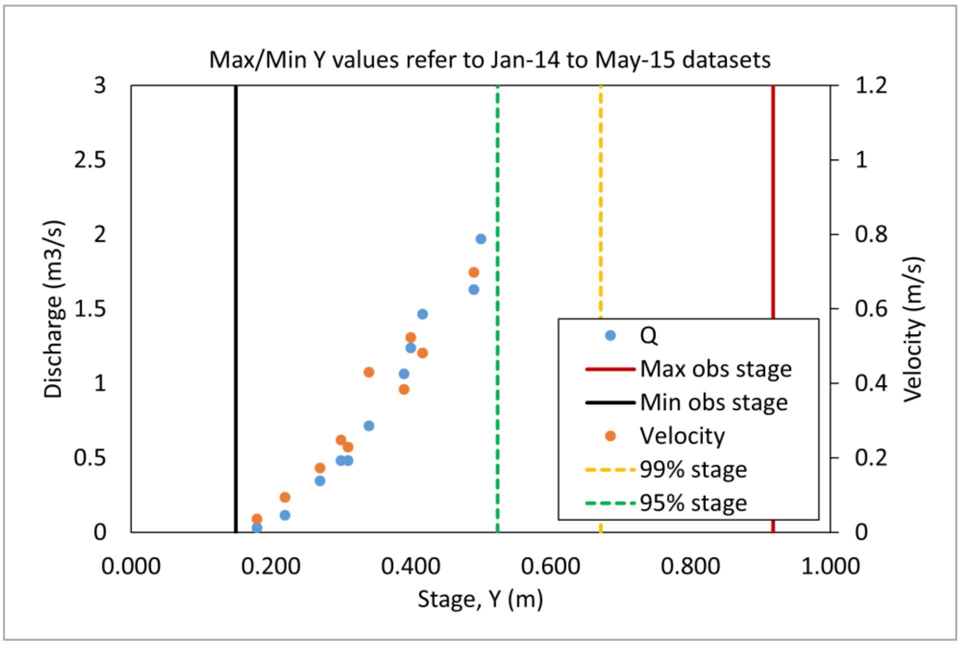


Figure App-5B-2. Availability of observed stage, velocity and discharge data for Haltwhistle Burn at Broomshaw.

Selecting an appropriate rating method:

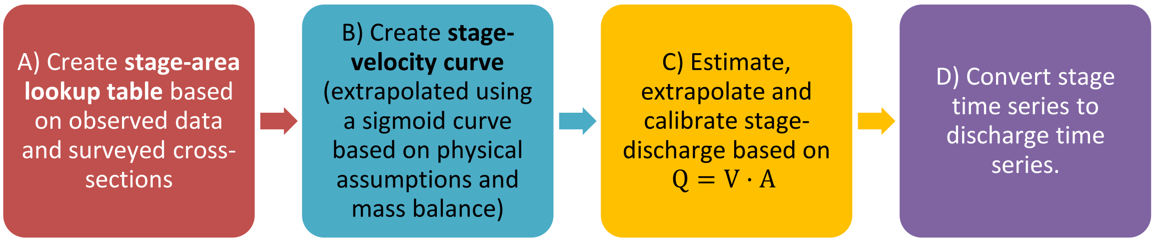


Figure App-5B-3. A summary of the modified SVA method (Ewen *et al.*, 2010) used to produce, extrapolate and calibrate the six rating curves. Note that final Q time series were only calibrated for January-2014 to May-2015 datasets (making use of the available data at the time).

The stage-velocity-area (SVA) method described by many (including Ramsbottom and Whitlow, 2003; Shaw *et al.*, 2011, Herschy, 2009) was used to generate a rating curve for each monitoring site within the Haltwhistle Burn catchment, which was then extrapolated to account for out-of-bank flow. The SVA method is popular as it makes use of observed, therefore catchment-specific, data. However, a more sophisticated SVA approach, described and successfully used by Ewen *et al.* (2010), was adopted here to provide additional confidence when extrapolating each rating curve. The flow chart in Figure App-5B-3 outlines the steps taken to produce the Haltwhistle Burn rating curves. These steps were carried out independently for each gauging station as each stretch of the river system is unique.

A) Create a stage-area lookup table based on observed data:

Using surveyed cross-sections (Figure App-5B-4), cross sectional area was calculated for a number of stage intervals. This produced an accurate stage-area look-up table and curve, which covered all possible stage, thus discharge measurements later required during modelling activities (Figure App-5B-5).

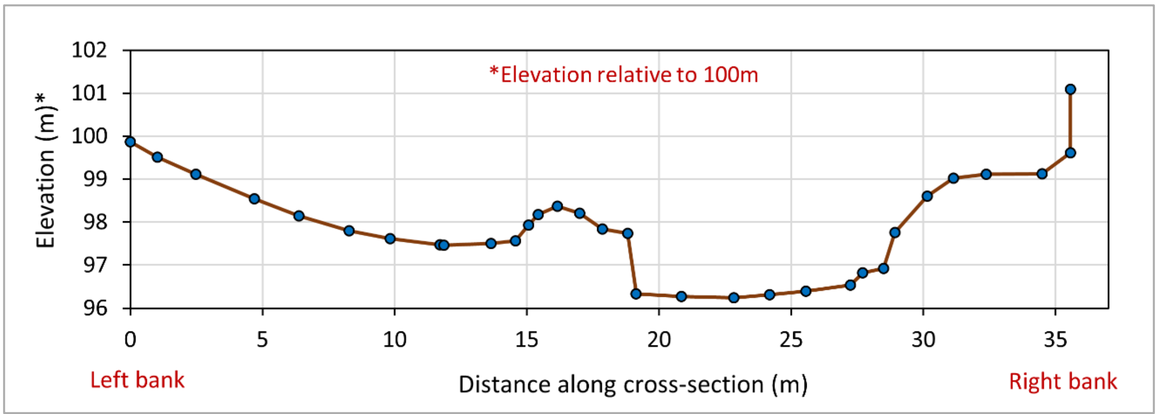


Figure App-5B-4. Haltwhistle Burn at Broomshaw Hill cross-section (LB = left bank looking downstream RB = right bank looking downstream)

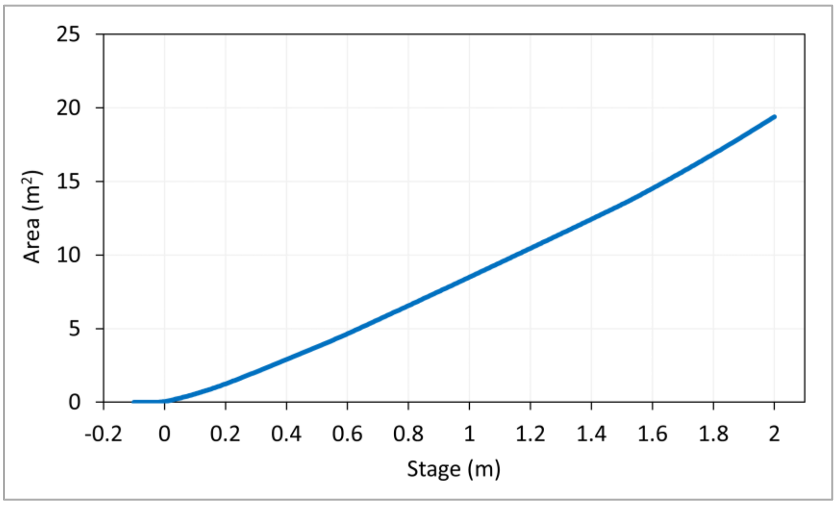


Figure App-5B-5. Stage-area look up graph for the Haltwhistle Burn at Broomshaw Hill.

B) Create a stage-velocity curve:

As stage increases, the velocity increases within streams and rivers. However, the velocity aspect of the stage-velocity-area method applied here bears in mind that, for UK upland streams, the maximum velocity that is typically attained is 1.5m/s (Bathurst, 1988; Ewen *et al.*, 2010). This assumption is particularly important when extrapolating velocity (thus discharge) when flood water is out of bank.

A stage-velocity curve was therefore created (App-5B-6) using Equations App-5B-1 to App-5B-3 which, when calculated, presented a custom designed sigmoid (G) curve for mean velocities. This approach assumes that y_{min} is 0, v_{min} is 0 and v_{max} is 1.5. This leaves parameters α, β and y_{max} to be used during the calibration phase below (c), which then dictated the shape of the site-specific sigmoid curves.

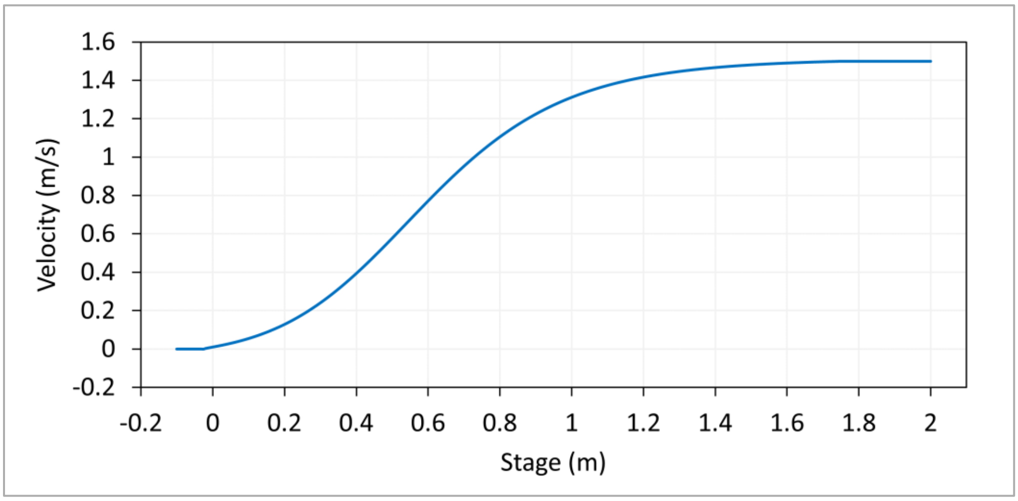


Figure App-5B-6. Stage-velocity sigmoid curve for the Haltwhistle Burn at Broomshaw Hill.

Generating a stage-velocity curve and look-up table

$$X = MIN\left(1, \frac{y - y_{min}}{y_{min} - y_{max}}\right)$$

Equation App-5B-1. (Ewen *et al.*, 2010)

$$G = \frac{1}{2}\left[1 + \frac{\tanh(2\alpha X^{\beta} - \alpha)}{\tanh(\alpha)}\right]$$

Equation App-5B-2. (Ewen *et al.*, 2010)

$$v = v_{\min} + (v_{max} - v_{min})G$$

Equation App-5B-3. (Ewen *et al.*, 2010)

Where Y = stage (water level), Y*min* = zero stage, Y*max* = bankfull stage, V*min* = zero velocity, V*max* = 1.5 (UK upland streams – note that this was set lower for some upstream gauging stations), α = alpha and β = beta which are calibrated. Equations 1 & 2 are required for 3.

Although this method is based on physical assumptions, they are well established and assist with reducing error during the calibration phase because they utilise observed stage-discharge pairs and mass balance information. Ewen *et al* (2010) describes this approach as a ‘robust’ way of extrapolating rating data out of bank to obtain a reliable rating curve.

C) Estimate, extrapolate and calibrate stage-discharge:

Using the velocity-area formula ($Q = V \cdot A$), paired velocity-area data can be used to determine discharge for each of the stage intervals of interest. This creates a stage-discharge lookup table and curve which can be used to convert all observed stage values into discharge.

In order to ensure the rating curve fit the observed stage-discharge pairs obtained from flow gauging, values for α, β and y_{max} were adjusted through a trial and error approach until the error between observe and predicted discharge was as low as possible. Figure App-5B-7 shows an extract from the Broomshaw Hill data following the calibration stage.

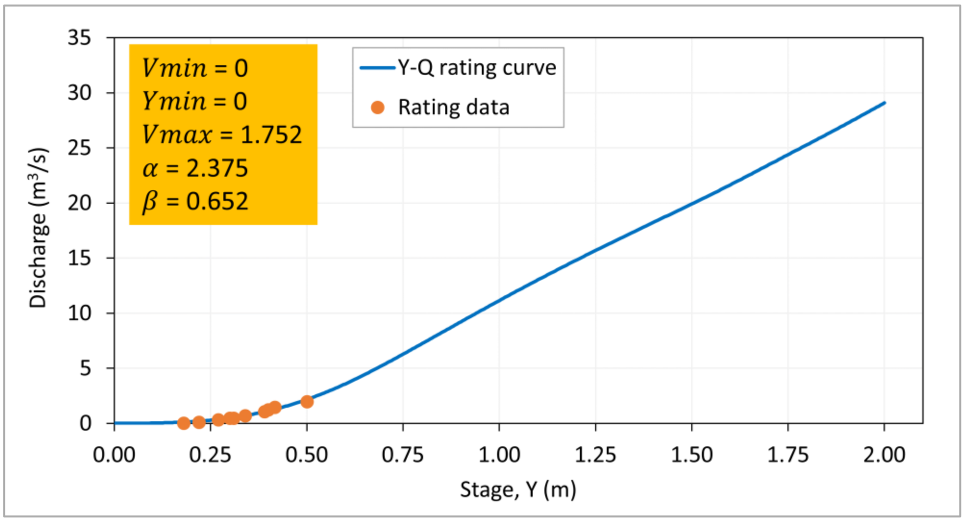


Figure App-5B-7. Stage-discharge rating curve for the Haltwhistle Burn at Broomshaw Hill. Includes stage-discharge rating points collected during flow gauging fieldwork.

Since observed discharge values are not available for out of bank situations, there are still uncertainties as to whether the 'out of bank' range of the rating curve has been extrapolated correctly. To overcome this, the water mass balance equation (Equations App-5B-4 and App-5B-5) was used to provide a further calibration and validation stage on the rating curve procedure.

Water (mass) balance equation – validating the rating curve

$$Q = P - E \pm \Delta S$$

Equation App-5B-4. (Shaw *et al.*, 2011)

Or

$$P - Q - E \pm \Delta S = 0$$

Equation App-5B-5. (Shaw *et al.*, 2011)

Where P = total precipitation (mm/hr), E = total evapotranspiration (mm/hr), ±ΔS (mm/hr) = change is storage in the soil or bedrock and Q = total discharge (mm/hr).

Q and P data was used to calculate the mass balance equation for each sub-catchment area. Since actual evaporation (AE or AET) is required to close the mass balance equation (rather than potential evaporation which is calculated using the Penman-Monteith equation), an average annual value (derived from 1961 to 1990 datasets) was used from the Met Office's MORECS system (Kay *et al.*, 2013). As Jain *et al.* (2007) explains, applying the mass balance equation to an annual timeframe means that storage can be assumed to remain as 0mm. All rating curves were adjusted to ensure mass balance was as close to zero as possible. It is unlikely that a catchment's water balance will ever mirror an exact value of 0mm/year due to other errors encountered during the fieldwork and rating curve process. However, the mass balance equation still served as a useful quantitative check.

D) Convert stage time series to discharge time series:

The stage-discharge lookup table and curve were then used to convert all observed stage values in the time series into discharge, as shown in Figure App-5B-8 for Broomshaw Hill.

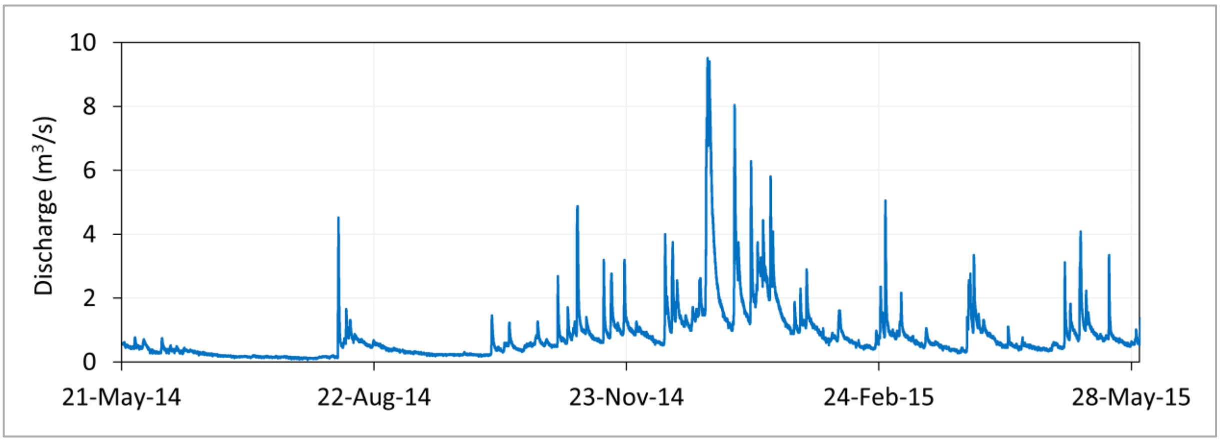
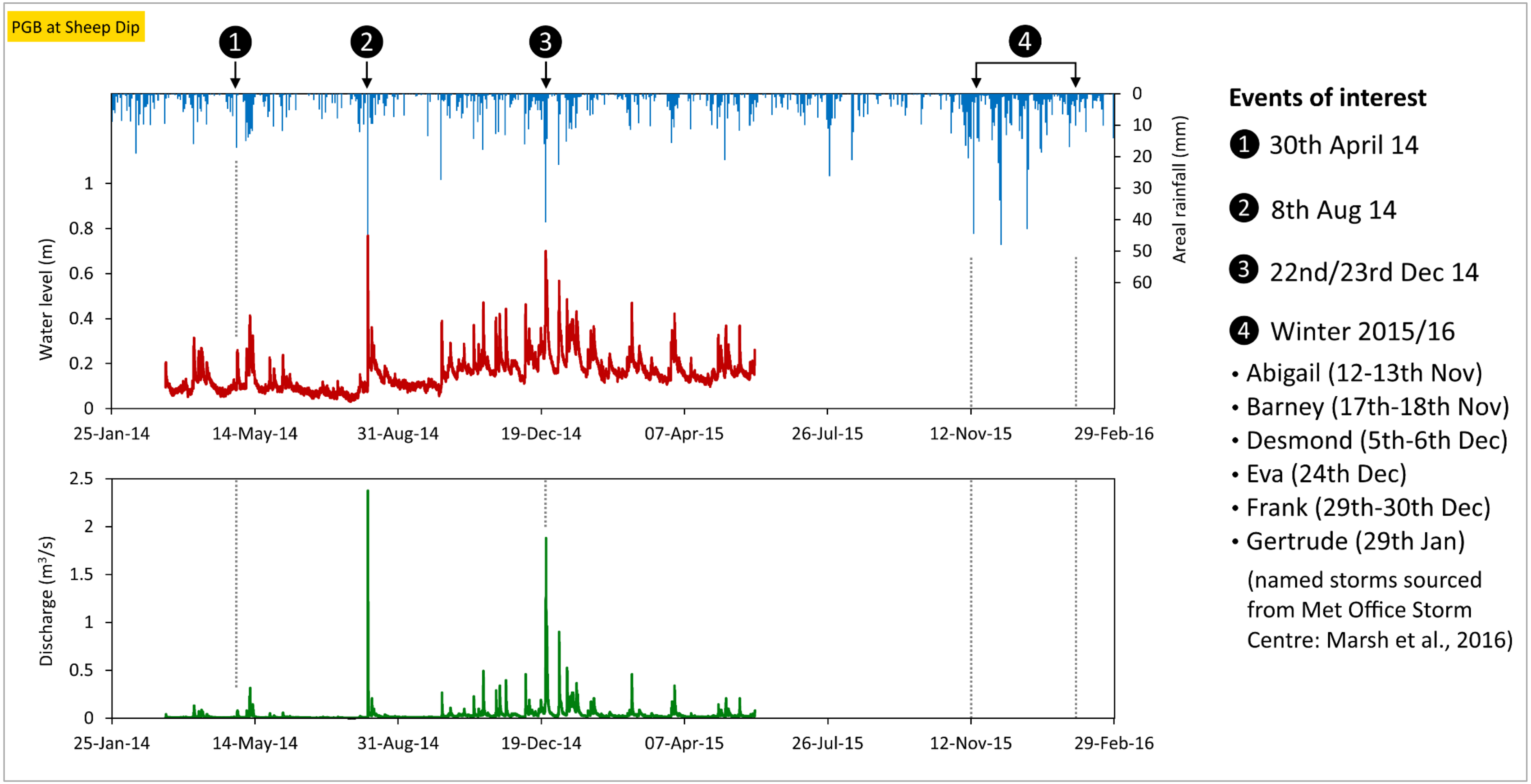


Figure App-5B-8. Resulting discharge time series for the Haltwhistle Burn at Broomshaw

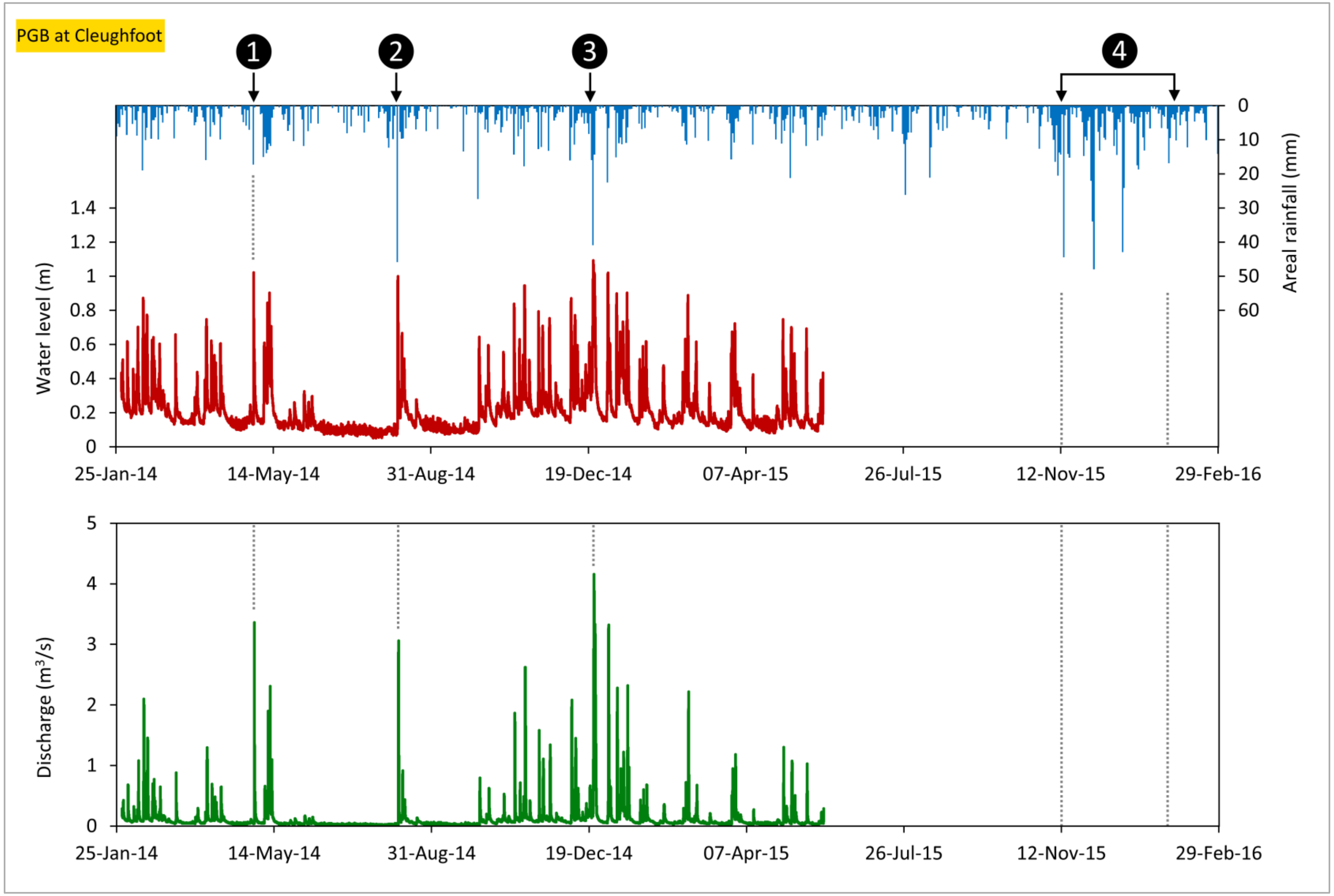
Final validation checks have already been presented within the main text (Section 5.3.3.4). All stages outlined within this Appendix have been applied to each of the six gauging stations. Resulting cross-sections and rating curves are available within Appendix 5A.

Appendix 5C – Overview of catchment response (traditional data plots)

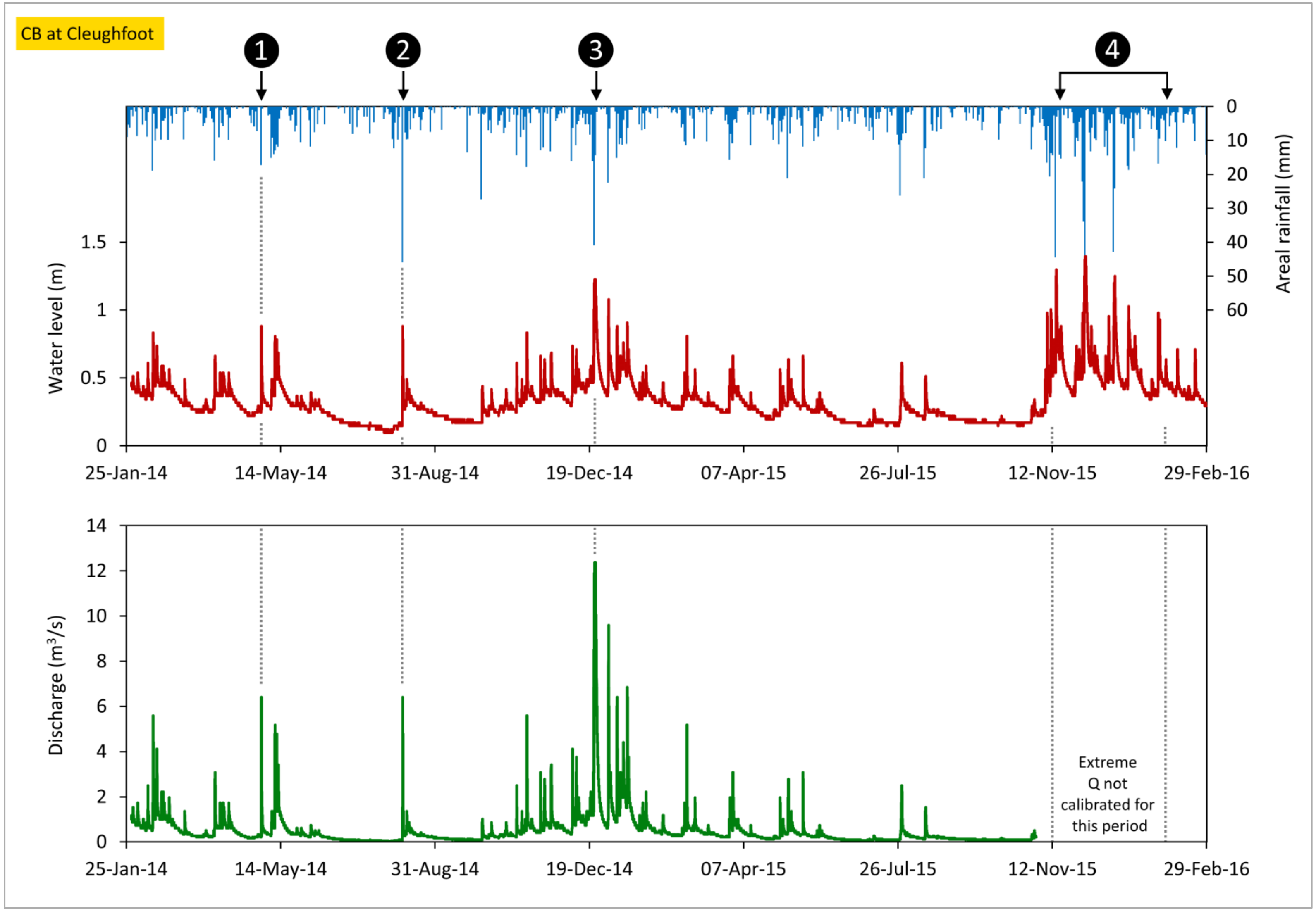
PGB at Sheep Dip:



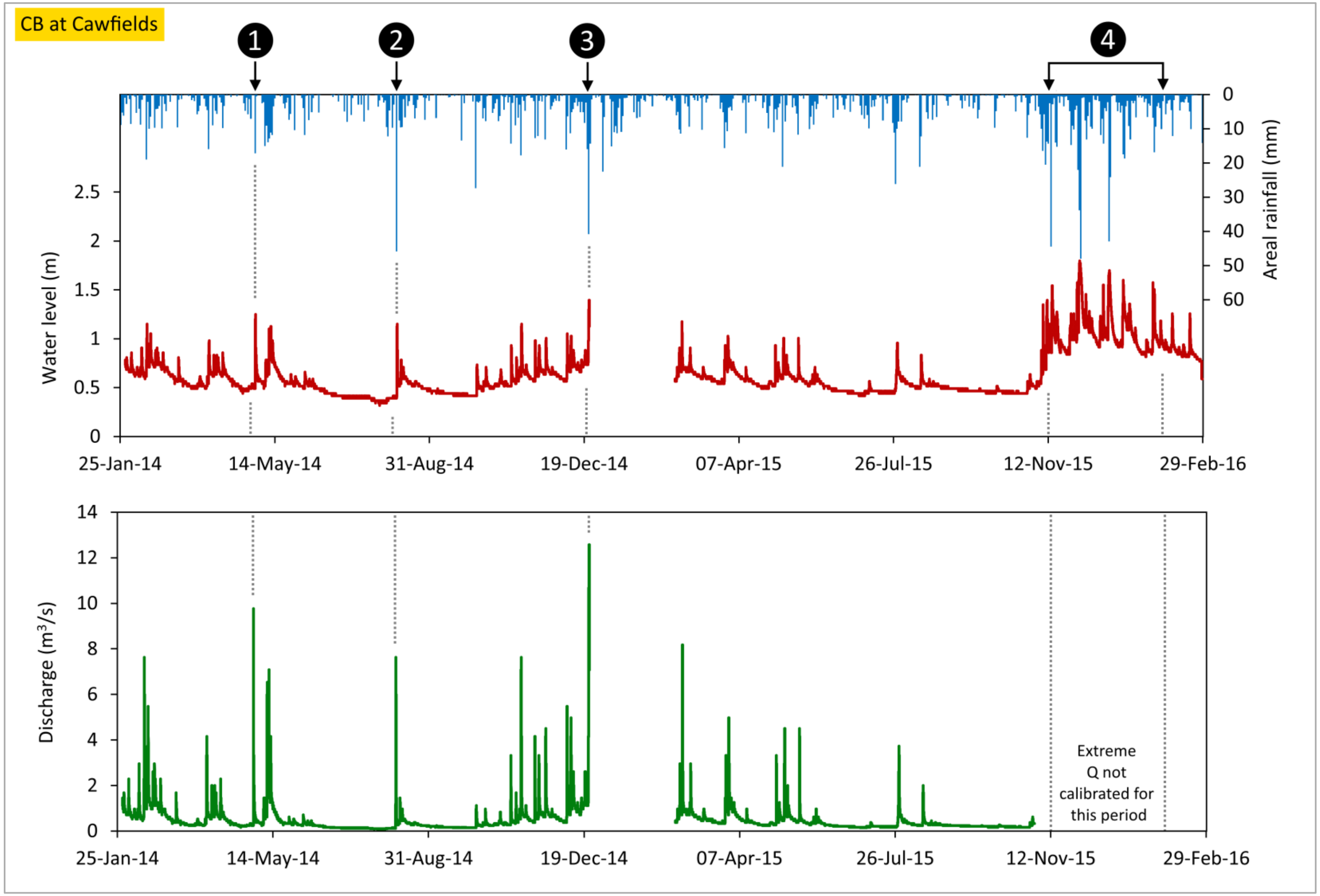
PGB at Cleughfoot:



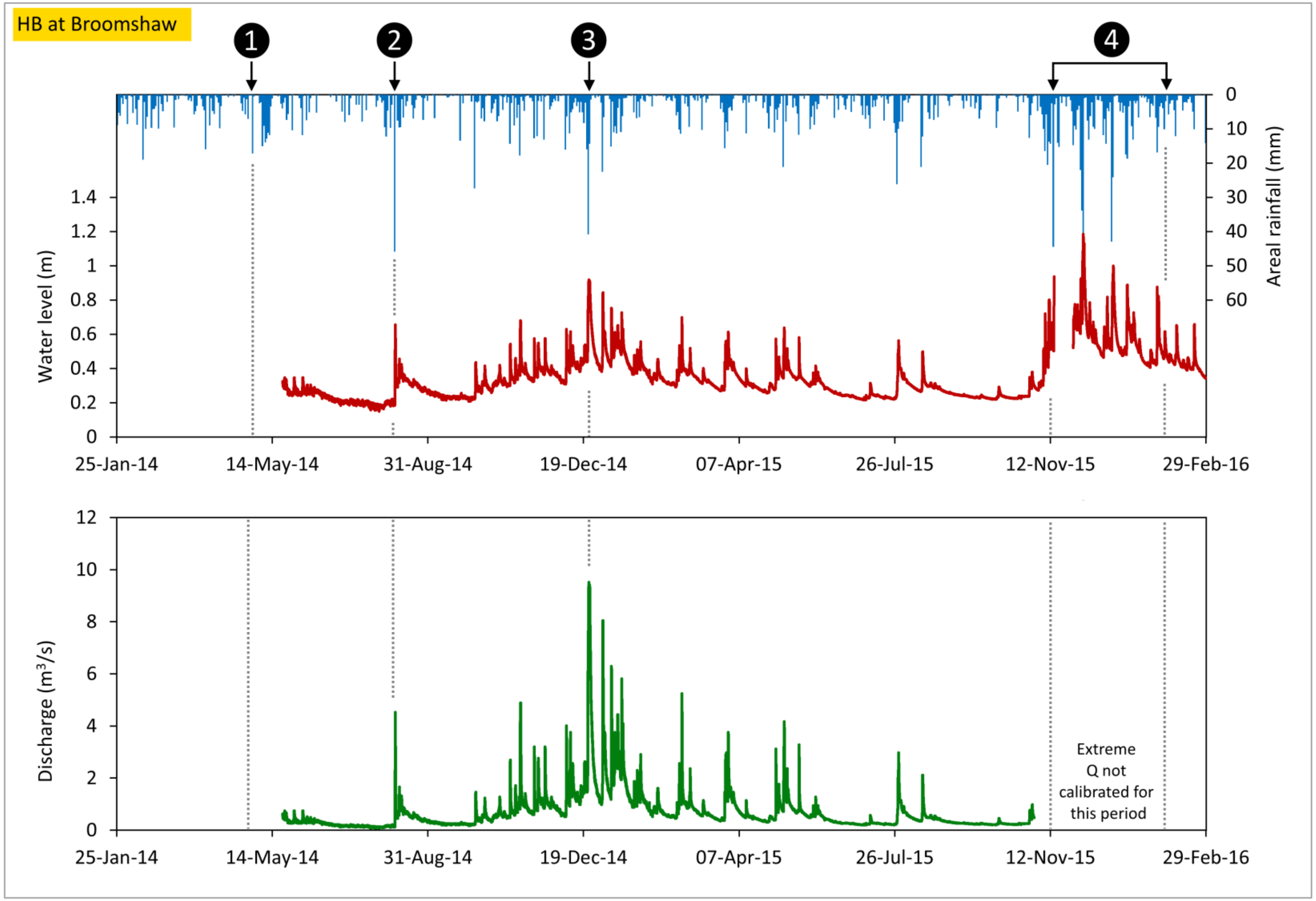
CB at Cleughfoot:



CB at Cawfields:



HB at Broomshaw:



Appendix 5D – Parameter-specific QC checks applied to the community-based observations

Water quality (all seven tests – quantitative, semi-quantitative and categorical)

- *Tolerance and format* – strict equipment and monitoring protocols meant that the water quality variables had a finite scale or set of categories to fall within:
    - Water clarity: 13 categories (0-12 opals);
    - -10°C ≤ Temperature ≤ 110°C;
    - Algae: 3 categories (none, some, abundant);
    - Dissolved oxygen (DO): 3 categories/colours (0, 4, 8ppm);
    - Nitrates/Nitrites (NO_3/NO_2): 5 categories/colours (0, 5, 10, 25 50/0, 0.5, 1, 5, 10ppm);
    - Phosphates (PO_4): 4 categories/colours (0, 1, 2, 4ppm);
    - pH: 14 categories/colours (1-14)

  Some observers also estimated water quality observations if it fell in between two categories or colours on their chart;

- *Tolerance, expectations and expert judgement* – sensible tolerance judgements required e.g. pH 5-8 (Rose *et al.*, 2016) and temperature 0-30°C. Seasonal variations also expected, and trends should correlate with rainfall and river levels;

- *Temporal and completeness* – water quality was observed using spot samples at fixed locations over time, hence gaps were expected within datasets. All seven tests were required on each occasion, along with supporting anecdotal descriptions;

- *Trust, reliability and consistency* – added confidence that only regular and committed volunteers could observe water quality, which increased consistency. Identical equipment and strict monitoring protocols were used by all observers;

- *Sources of error* – spot sampling by the river bank restricts the ability to fully characterise the quality of the reach over time. Test kits also provide very simple outputs, and are spatially and temporally restricted by health and safety protocols (e.g. during dangerous flows);

- *Cross-checks, triangulation, expert judgement and precision* – check data against other water quality datasets (should expect spatial and temporal variability though) and timing/trends during a multi-triangulation approach (see Figure 5.31).

Other weather data (quantitative)

In this case study, 'other weather' relates to an electronic weather station located in the Cawburn area. Alongside rainfall (already covered), maximum temperature, minimum temperature and maximum wind data were recorded by the observer:

- *Tolerance, format and expectations* – temperature and wind should fall within realistic limits expected for a northern England catchment, and exhibit seasonal trends;

  (-10°C ≤ Temperature ≤ 35°C; (0 ≤ Wind Speed ≤ 70mph);

- *Completeness* – check for gaps and ensure regular temporal monitoring pattern (in this case, weekly);
- *Cross-checks, triangulation, expert judgement and precision* – check data against other community-based datasets (should expect spatial and temporal variability though) and timing/trends during a multi-triangulation approach (see Figure 5.31).

Appendix 5E – Extended list of community-based anecdotes collected

Date	Time (local)	Parameter	Location / gauge	Anecdote
07/04/2014	08:17	Level	Townfoot	*"Storm before the calm"*
07/04/2014	17:28	Level	Townfoot	*"Levels rising"*
22/04/2014	16:49	Level	Townfoot	*"Rainy and horrible. But burn has not yet responded. Low levels"*
30/04/2014		Flood	Townfoot	*"A pallet and tree came floating by"*
30/04/2014		Flood	Haltwhistle	*"Firefighters frantically pumped water away from the Mart Yesterday, after a 30-minute downpour"*
30/04/2014	15:05	Flood	Haltwhistle	*"Some heavy rain nearby. #Haltwhistle looks to be getting a hammering"*
30/04/2014	15:20	Flood	Townfoot	*"Heavy rain started about 3.20pm. The rain was so heavy. The Burn peaked around 4pm."*
30/04/2014	15:40	Flood	Townfoot	*"Monsoon Alert! Heaviest rain I've seen in ages! #Haltwhistle #Floods"*
30/04/2014	16:00	Flood	Townfoot	*"We noticed the colour of the water – silt and sand during the floods"*
30/04/2014	16:52	Flood	Haltwhistle	*"Flooding on Castle Hill"*
30/04/2014	17:21	Flood	Haltwhistle	*"Home to closed roads and fire trucks!"*
30/04/2014	17:47	Flood	Haltwhistle	*"Had 4 fire engines going past my front window in the last half hour. Must be really bad somewhere #Haltwhistle #flashfloods"*
07/05/2014	17:17	Level	Townfoot	*"Rain rain go away"*
09/05/2014	18:02	Level	Broomshaw	*"rain woke me up through the night"*
10/05/2014	10:55	Level	Townfoot	*"Video to follow. Didn't realise it had been raining that much"*
10/05/2014	17:37	Level	Broomshaw	*"38 mins later gone up quick"*
11/05/2014		Flood	Haltwhistle	*"Thunder storm Haltwhistle 1420 to 1450hrs approx. Terrifying driving home"*
11/05/2014		Flood	Haltwhistle	*"I would not consider the even to be classified as '1 in 100 year'"*
11/05/2014		Flood	Haltwhistle	*"Water has emerged along tarmac footpaths and flooded several gardens"*
11/05/2014		Flood	Townfoot	*"Crickey look at that! I was surprised it wasn't higher.. But then it was!"*
11/05/2014	14:52	Flood	Townfoot	*"Lots of surface run off on Shield Hill!"*
11/05/2014	15:15	Flood	Haltwhistle	*"Here we go again"*
11/05/2014	15:15	Flood	Haltwhistle	*"Think the worst of the horrific thunder storm we've just had is over. Hope the flooding isn't too bad, that was frightening"*
11/05/2014	15:26	Level	Townfoot	*"Murky water"*
11/05/2014	15:26	Flood	Townfoot	*"Nice & murky ;)"*
11/05/2014	19:23	Level	Broomshaw	*"serious footpath damage"*
12/05/2014		Flood	Haltwhistle	*"Im not sure we can take any more #prayforhalty"*
13/05/2014	13:11	Level	Broomshaw	*"seems to be going down"*
20/05/2014	13:36	Level	Townfoot	*"Wow! Heavens just opened. Gone from calm to monsoon like in a second!"*
24/05/2014		Rainfall	Townfoot	*"Heavy rain"*
02/06/2014	17:03	Level	Townfoot	*"#tut-tut looks like rain"*
07/06/2014	09:10	Level	Townfoot	*"Did I miss a deluge during the night?!"*
08/06/2014	09:43	Level	Townfoot	*"Quite heavy in early pm but when I went out around 3 or 4pm the level had scarcely changed. Ground not that wet today so.."*
24/06/2014		Rainfall	West Haltwhistle	*"Cloudy but dry"*
24/06/2014	08:32	Level	Townfoot	*"It's grey & much cooler today but no rain as yet"*
11/07/2014		Rainfall	West Haltwhistle	*"Lovely day"*
22/07/2014		Low flow	Broomshaw	*"Providing a much needed relief for Billy and Widget [the dogs]!"*
24/07/2014		Level	Broomshaw	*"I've seen it [Haltwhistle Burn] lower than this before... not for a while though"*
28/07/2014	09:59	Level	Townfoot	*"Think that gauge is stuck :p"*
29/07/2014		Rainfall	West Haltwhistle	*"Dry with Sunny Periods"*

Date	Time (local)	Parameter	Location / gauge	Anecdote
30/07/2014		Low flow	Broomshaw	*"Seems more rocks than water!"*
05/08/2014		Rainfall	Central Haltwhistle	*"heavy overnight"*
08/08/2014		Rainfall	Central Haltwhistle	*"heavy between 4pm [...] and 12am"*
08/08/2014		Rainfall	West Haltwhistle	*"Sun am, torrential rain pm"*
08/08/2014		Rainfall	PGB Headwaters	*"very wet"*
08/08/2014		Level	Townfoot	*"Rain started about 3.30pm. 9.15pm max level"*
08/08/2014	16:39	Early warning	Haltwhistle	*"HaltwhistleBurn will be taking a hammering - really throwing it down here"*
12/08/2014		Rainfall	Central Haltwhistle	*"blustery showers"*
14/08/2014		Low flow	Haltwhistle	*"The Burn has been lower than this before but I've never seen it dry up"*
14/08/2014		Low flow	Haltwhistle	*"Last week I saw the Haltwhistle Burn reduce [approximately 50cm wide]"*
26/08/2014		Rainfall	West Haltwhistle	*"Dry and Cloudy with wind"*
27/09/2014		Rainfall	West Haltwhistle	*"nice dry breezy day"*
03/10/2014		Rainfall	Townfoot	*"Rain came overnight 3rd to 4th"*
09/10/2014		Rainfall	Central Haltwhistle	*"very heavy"*
20/10/2014		Rainfall	West Haltwhistle	*"Wet and Windy all day"*
03/11/2014		Rainfall	Central Haltwhistle	*"Torrential rain from 1430hrs"*
04/11/2014		Rainfall	West Haltwhistle	*"Horrible wet day"*
05/11/2014		Flood	Broomshaw	*"Fair bit off erosion caused by Slaty Sike (?) blockage"*
05/11/2014	09:13	Level	Townfoot	*"On the up" - heavy rain over night?"*
09/11/2014		Rainfall	Central Haltwhistle	*"A quiet day"*
14/11/2014		Rainfall	Townfoot	*"Rain started 10.30am"*
19/11/2014		Rainfall	West Haltwhistle	*"damp and dull day"*
05/12/2014		Rainfall	Central Haltwhistle	*"heavy rain and hail/sleet overnight and early morning"*
07/12/2014	10:45	Level	Broomshaw	*"the Burn was well up this morning, on level 3 on the gauge board at 1045am"*
08/12/2014		Rainfall	Central Haltwhistle	*"Heavy rain and sleet showers"*
09/12/2014		Rainfall	West Haltwhistle	*"Cold wet and windy"*
22/12/2014		Rainfall	West Haltwhistle	*"Wet overnight, Windy"*
22/12/2014	12:09	Flood	Haltwhistle	*"Building a boat and collecting animals in pairs... @HaltwhistleBurn #rain #RainInDecember"*
22/12/2014	14:00	Flood	Haltwhistle	*"There was major erosion downstream by the playing fields"*
22/12/2014	18:30	Level	Broomshaw	*"Flow has a bit of a wave on it! And it is still raining!"*
23/12/2014	08:47	Level	Townfoot	*"Both photos taken in the same second! Fast Flow!"*
23/12/2014	08:47	Flood	Haltwhistle	*"Wheee! Definitely highest since I've been monitoring - best get me waterproofs on and go out..."*
24/12/2014		Level	Broomshaw	*"Lots of water in the @HaltwhistleBurn today! Lovely afternoon for a walk"*
25/12/2014	10:35	Flood	Haltwhistle	*"Big erosion on meander"*
28/12/2014		Flood	Townfoot	*"Waterway filling up quick [with sediment]"*
30/12/2014		Flood	Haltwhistle	*"Throwing up some Victorian treasures following erosion of riverbank!"*
01/01/2015		Rainfall	West Haltwhistle	*"Horrid day, rained continually"*

Date	Time (local)	Parameter	Location / gauge	Anecdote
01/01/2015	14:17	Level	Broomshaw	*"Double drenching today, yuk"*
09/01/2015		Rainfall	West Haltwhistle	*"Wet, windy and cold"*
31/01/2015		Rainfall	Central Haltwhistle	*"Very cold and dry"*
03/02/2015	16:01	Snow	Broomshaw	*"#Snow and #icicles today!"*
07/02/2015		Rainfall	West Haltwhistle	*"Cold but dry"*
22/02/2015	14:18	Level	Broomshaw	*"Glad the walk is over :)"*
24/02/2015	18:00	Level	Haltwhistle	*"Looking quite full on this evening's walk"*
26/02/2015		Rainfall	Townfoot	*"Heavy Over Night Rain"*
26/02/2015	09:30	Flood	Slaty Sike	*"You can see some of the surface field flow. All taken this am just before 10am"*
27/02/2015		Level	Townfoot	*"11.15 am Burn Still Brown"*
03/03/2015		Rainfall	Central Haltwhistle	*"Sunshine all day!"*
27/03/2015		Rainfall	Central Haltwhistle	*"Heavy rain and wind overnight into Sunday"*
29/03/2015		Flood	Slaty Sike	*"Slaty was overtopping"*
06/04/2015		Rainfall	Central Haltwhistle	*"Warm and sunny"*
30/04/2015		Level	Townfoot	*"No water running past [Mill Bridge]"*
07/05/2015		Rainfall	Central Haltwhistle	*"started raining at tea time and rained all night until about 11 am"*
11/05/2015	23:11	Rainfall	Haltwhistle	*"Line of heavy showers developing [..]. Looks like #Haltwhistle is very wet @HaltwhistleBurn"*
19/05/2015	14:45	Early warning	Haltwhistle	*"Heavy weather on the way? Lots of thunder & Ben [the dog] in hiding…"*
01/06/2015	20:59	Early warning	Haltwhistle	*"Very intense rainfall 45mm pr/hr/ #Brampton #Cumbria @HaltwhistleBurn it's on its way to you"*
03/06/2015		Rainfall	Central Haltwhistle	*"Dry and warm"*
07/06/2015		Level	Townfoot	*"[RLGB] out of water"*
28/06/2015		Rainfall	Central Haltwhistle	*"Hot and sunny"*
30/06/2015		Rainfall	Central Haltwhistle	*"Thunder and lightning overnight but not much rain"*
04/07/2015		Rainfall	Central Haltwhistle	*"Hot and sunny"*
28/07/2015		Level	Townfoot	*"Rose to 0.30, 0.25, 0.19 at noon. Highest ?"*
06/08/2015		Level	Townfoot	*"Board [Mill Bridge] out of water"*
13/08/2015		Rainfall	Central Haltwhistle	*"After a dry few days it rained all night"*
16/08/2015		Rainfall	Central Haltwhistle	*"Dry"*
29/09/2015		Rainfall	Central Haltwhistle	*"Very dry and mostly sunny"*
06/10/2015		Rainfall	Central Haltwhistle	*"Very heavy rain overnight. It woke me up!"*
06/10/2015		Rainfall	Townfoot	*"Overnight rain"*
08/11/2015		Rainfall	Haltwhistle	*"It's definitely indoors weather now – tipping it down out there!"*
10/11/2015		Rainfall	Central Haltwhistle	*"rain most of the day and heavy overnight"*
14/11/2015		Rainfall	Central Haltwhistle	*"Mainly overnight. The most I have ever recorded!"*
29/11/2015		Rainfall	Central Haltwhistle	*"Still raining"*
03/12/2015		Rainfall	Central Haltwhistle	*"Heavy rain showers all day"*
05/12/2015		Rainfall	Central Haltwhistle	*"Storm Desmond. The first time my rain gauge in the garden has reached this high! The wind and rain was horrendous. The roads were flooded throughout Tynedale."*

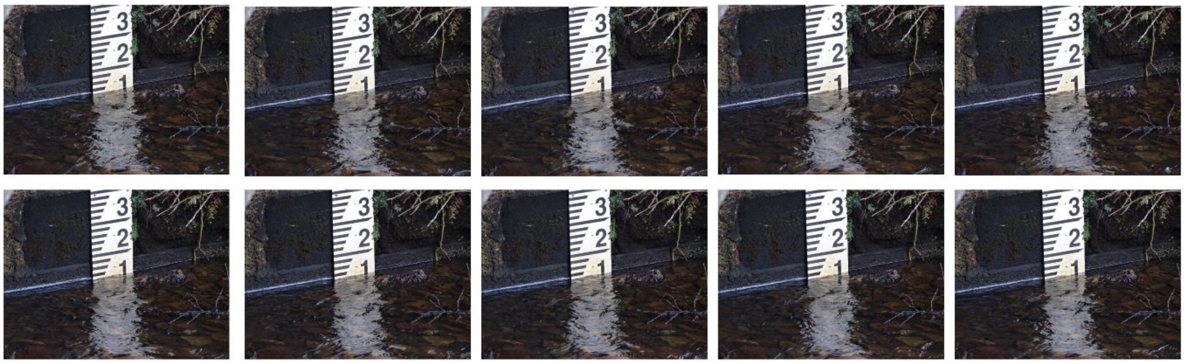
Date	Time (local)	Parameter	Location / gauge	Anecdote
05/12/2015		Level	Townfoot	*"Neither board at the culvert visible"*
05/12/2015		Flood	Haltwhistle	*"HaltwhistleBurn already higher than 15 Nov and rising steadily"*
05/12/2015	11:48	Flood	Haltwhistle	*"A69 horrendous. Only just passable [...] #Haltwhistle #floods"*
05/12/2015	13:46	Flood	Haltwhistle	*"Waterfall @HaltwhistleBurn(not usually a waterfall)"*
05/12/2015	14:55	Flood	Mill Bridge	*"Just a bit soggy on @HaltwhistleBurn today - this as 2.55pm #flood"*
05/12/2015	14:58	Flood	Townfoot	*"#StormDesmond is reaching it's peak. Lots of flooded homes in [...] #Haltwhistle"*
05/12/2015	14:58	Flood	Townfoot	*"These are the highest I've ever seen river levels around here"*
06/12/2015		Rainfall	Central Haltwhistle	*"Quiet after the storm"*
25/12/2015		Rainfall	Central Haltwhistle	*"Rain all day and night"*
26/12/2015		Flood	Slaty Sike	*"Boxing day rain was not as bad as expected so Slaty again able to cope . Water was again overtopping the culvert [...] onto the road"*
30/12/2015		Flood	Haltwhistle	*"Awake all night thanks to Frank! How our roof hasn't been ripped off I'll neve know #StormFrank #Haltwhistle"*
04/01/2016		Rainfall	Central Haltwhistle	*"Rained all day and all night"*
05/01/2016		Level	Townfoot	*"Good news we were not flooded out"*
05/01/2016		Flood	Broomshaw	*"[The Slaty Sike] was overtopping and running down the road"*
05/01/2016		Level	Broomshaw	*"Gauge board at Broomshaw currently [15:00] reads 5, higher than when I went out at 10am"*
05/01/2016	15:30	Level	Broomshaw	*"HaltwhistleBurn yesterday it was on number 1, today it on 5"*
26/01/2016	10:10	Flood	Haltwhistle	*"I think it's safe to say it [the storm] has been here for a few hours - howling and lashing it down out there"*
26/01/2016	10:25	Flood	Haltwhistle	*"Batten down the hatches people. It's really not good out there! House feels like it's going to take off! #StormJonas #Haltwhistle"*
08/02/2016		Level	Townfoot	*"Burn [at Townfoot] is now in a narrower channel due to build up of rocks etc on eastbank brought down by heavy rain over a month or more."*

Appendix 5F – RLGB observations (low flow) obtained using a multi-burst camera setting

21/02/2015 14:09hrs (GMT) Haltwhistle Burn at Broomshaw Hill. Max = 0.06m | Min = 0.06m | Average = 0.06m. (Broomshaw traditional WLR sensor recorded 0.06m at 14:10).

21/02/2015 14:47hrs (GMT) Haltwhistle Burn at Townfoot. Max = 0.09m | Min = 0.07m | Average = 0.08.

21/02/2015 14:59hrs (GMT) Haltwhistle Burn at Mill Bridge. Max = 0.12m | Min = 0.12m | Average = 0.12m .



Appendix 6A – Introducing SHETRAN, the research gaps and the modelling framework implemented

What is SHETRAN?

First developed in the 1970s (Abbott *et al.*, 1986), Système Hydrologique Europeén TRANsport (SHETRAN) is a physically-based spatially-distributed (PBSD) hydrological model which is capable of simulating, therefore predicting, fundamental hydrological processes at a catchment-scale (Newcastle University, 2016). Catchments are represented by a three-dimensional discretised grid and a simplified river network known as 'channel links', which run along the grid squares. The model consists of three key modules including water flow, sediment transport and contaminant (solute) transport (Ewen *et al.*, 2000; Birkinshaw *et al.*, 2010a; 2010b; Shaw *et al.*, 2011). The schematic in Figure App-6A-1 illustrates SHETRAN's hydrological components.

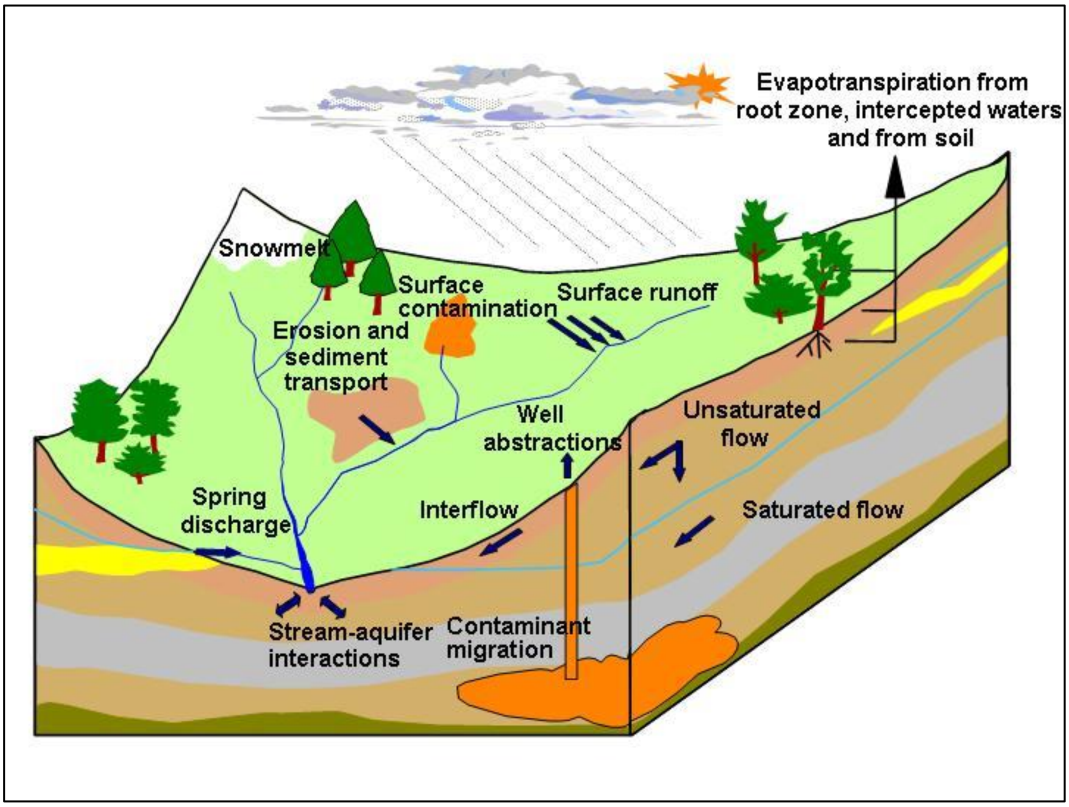


Figure App-6A-1. A schematic of SHETRAN's hydrological components (image source: Newcastle University, 2016).

SHETRAN is readily regarded as a 'powerful' and 'robust' tool (Ewen *et al.*, 2000) and is capable of being used to obtain surface water information. It is argued by Abbott *et al.* (1986) that simple rainfall-runoff models are unable to simulate complex spatial hydrological problems and that the SHE model (which later developed into SHETRAN) is able to do this by providing realistic results across space and through time. Mourato *et al.* (2015) claim that SHETRAN's PBSD element has the ability to represent a catchment's internal variability which is essential for local planning and management activities. SHETRAN is also unique because it accounts for sub-surface processes using columns and layers which define soil and hydrogeological properties. These aspects are ignored by many models despite playing an important role in the hydrological cycle, and hence the overall water balance. The main output from SHETRAN is river flow (surface runoff as discharge, Q) which can be extracted spatially and temporally. SHETRAN can then assist various catchment management applications, including characterising the response of individual sub-catchments, as well as calculating runoff and storage quantities involved. Initial conditions can also be extracted from SHETRAN outputs and used to set up other models more realistically.

SHETRAN is known for demanding large quantities of input data (Abbott *et al.*, 1986), and can take weeks or even months to set up and obtain relevant input datasets (Ewen *et al.*, 2000; Birkinshaw *et al.*, 2010b; Lewis *et al.*, 2014; 2018). Although having multiple parameters included within the model is beneficial for realistically representing processes and properties, it can also be a challenge to calibrate. Furthermore, as SHETRAN can simulate lengthy periods of time (years and decades) using many sources of input data, it is also computationally intensive to run and analyse all the output data. However, SHETRAN can simulate a full catchment, at a desired resolution, using a computer which has a general consumer specification. Bathurst and Cooley (1996) conclude that a high level of hydrological expertise is necessary in order to use this model successfully. Consequently, it is likely that professionals would be modelling using community-based data, rather than the communities modelling with their own data.

Applications and research to date:

What has SHETRAN been used for previously?

SHETRAN is a well-established and researched model in the academic literature. Table App-6A-1 provides a list of studies to demonstrate the diversity of SHETRAN and its capabilities in terms of being applied to solve real catchment-related applications. More recently, a tool has been developed by Lewis *et al.* (2014; 2018) to facilitate setting up SHETRAN automatically using national datasets. The advantage of this approach is that SHETRAN can be set up quickly and easily for any catchment in Great Britain, potentially by a non-expert. As a result, this tool has been tested here for the Haltwhistle Burn catchment for the period of January 1960 to December 2006. However, as Figure App-6A-2 illustrates, the resolution of the model and its outputs are not detailed enough for the application of interest. Nevertheless, it still provides a worthwhile output because the Haltwhistle Burn catchment was ungauged until this project commenced.

Reference	Model application	Catchment area, grid resolution & output resolution	Location / Notes
Bathurst and Cooley (1996)	Snowmelt.	Area: 0.4km^2 Grid resolution: 50m	Reynolds Creek in Idaho (US).
Parkin *et al.* (2007)	Groundwater abstraction; river-aquifer interaction.	n/a	Estimating the impact of groundwater abstractions on river flow in England and Wales.
Birkinshaw and Ewen (2000a; 2000b)	Nitrate leaching and transport (pollution from fertilisers); surface and sub-surface.	Area: 0.94km^2 Grid resolution: 50m Output resolution: 1-hour	Slapton Wood catchment in Devon (UK).
Birkinshaw *et al.* (2010a)	Deforestation; forest cover; flood peaks; sediment discharge.	Area: 0.35km^2 Grid resolution: 50m Output resolution: hourly / daily	A field and modelling study in central-southern Chile.
Zhang *et al.* (2013)	Land use; soil; storms; desertification; climate change impacts.	Area: 705km^2 Grid resolution: 2km Output resolution: 1-hour	Focusses on automatic calibration procedures in the Cobres basin (Portugal).
Janes (2013); Janes *et al.* (2015)	Channel bank erosion; bank vegetation and channel sinuosity; high magnitude events.	Grid resolution: 100m Output resolution: 1-2 hours	Calibrates and validates the model (Eden catchment in North West England) with NRFA data.
Mourato *et al.* (2015)	Climate change scenarios and runoff impacts to address water management.	Area: 1044-4605km^2	River basins in the Mediterranean region (southern Portugal).

Table App-6A-1. Review of previous SHETRAN studies and their applications.

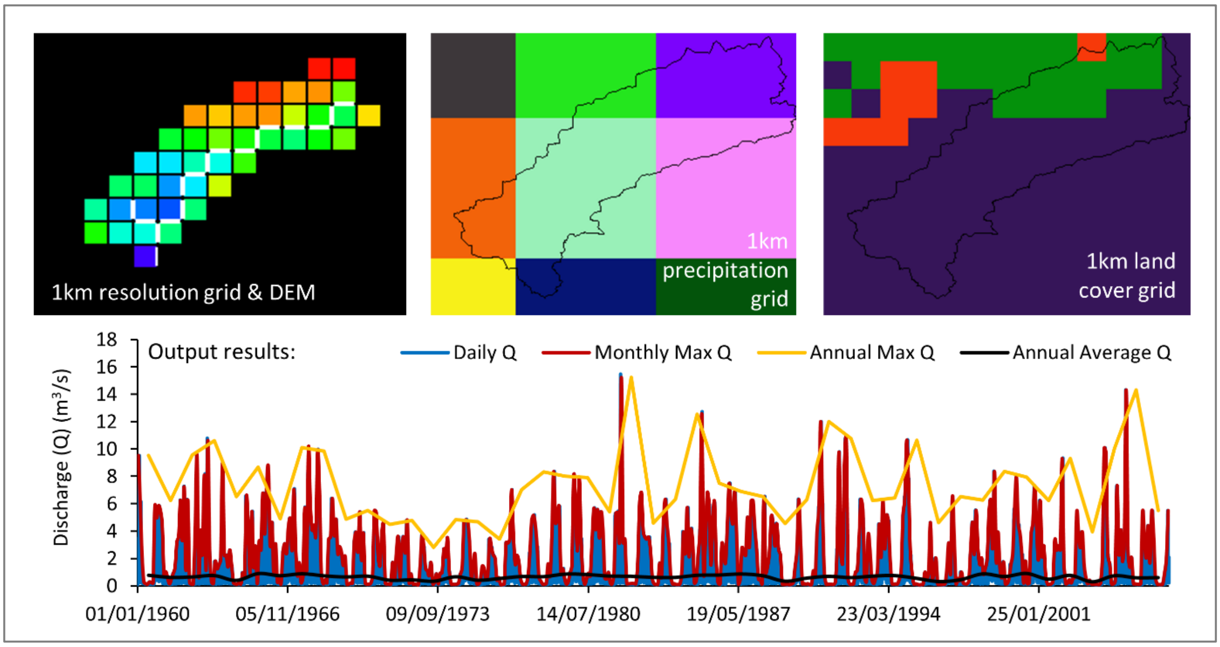


Figure App-6A-2. SHETRAN results over 1960-2006 for the Haltwhistle Burn catchment outlet obtained using the 'automatic setup tool' developed by Lewis *et al.* (2014; 2018). Extract includes examples of input data layers and the detail (resolution) which they provide.

The SHETRAN-specific research gap:

Based on the literature and SHETRAN applications discussed so far, the following aspects are not well documented and should be investigated further:

- SHETRAN has not yet been used to test the performance of community-based (or citizen science) catchment data within the modelling process;
- There are very limited citizen science projects on a local level which focus on the collection and use of hydrological data. Observations are usually just mapped or summarised back to the community, rather than being used to support applications;
- It is unusual to use SHETRAN for a catchment similar in size to the Haltwhistle Burn catchment, and at such fine resolutions (the model grid itself and input/output timesteps). Many studies also rely on just the catchment outlet when analysing output results;
- It is rare for SHETRAN modellers to make use of rainfall radar data and thus have been compared here alongside other sources;
- Catchment response during flash flood events is still poorly understood on a local level.

Why use SHETRAN for the Haltwhistle Burn catchment?

Detailed observations collected out in the catchment, using traditional and community-based monitoring techniques (Chapter 5), have delineated how spatially variable the Haltwhistle Burn catchment is. This finding is particularly valid during heavy rainfall events when:

- Rainfall is spatially and temporarily variable across the catchment;
- River response varies significantly depending on the location, amount and intensity of a 'cloud burst' event. The headwater catchments (1st and 2nd order streams) respond differently to the Haltwhistle Burn itself;
- The catchment is either saturated or dry (due to antecedent conditions).

SHETRAN was therefore a suitable model for many reasons:

1. SHETRAN can simulate a 42km^2 catchment grid at reasonable and realistic resolutions;
2. Data required to set up, run, calibrate and validate SHETRAN were available;
3. As it is a catchment-scale model, catchment connectivity is taken into account;
4. Being physically-based, SHETRAN represents surface and sub-surface processes well;
5. The model has spatial and temporal capabilities, especially rainfall, and the ability to incorporate multiple sources of data;
6. SHETRAN can carry out longer simulations i.e. over hydrological years rather than 'event-based' simulations, and provide initial conditions for later scenarios;
7. SHETRAN produces discharge (therefore hydrographs) as an output for locations of interest, offering an alternative approach when demonstrating the value of citizen science observations;
8. SHETRAN is an open access model.

The aforementioned list emphasises how SHETRAN greatly contributes to the modelling strategy.

SHETRAN-specific modelling methodology

The flow diagram presented within Figure App-6A-3 details the stages that were adopted to set up SHETRAN and produce a fully working and reliable model (known here as the 'initial simulations'). An **initial model** of the Haltwhistle Burn catchment was therefore created for the purpose of carrying out the initial sensitivity tests. Results from these tests have informed decisions such as appropriate grid resolution, model timesteps and resolutions of input and output data used to build the **main** SHETRAN models.

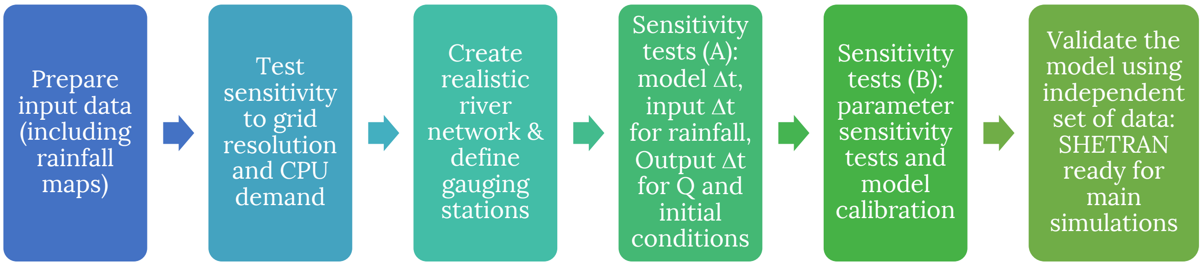


Figure App-6A-3. Steps taken to set up SHETRAN and produce a fully working model (initial simulations). Δt refers to timestep.

Once the initial model had been built, a useable model (**Model 1A**) was created and used to carry out the calibration and validation procedures, and then the main modelling activities. Two additional sets of models were then created (**Model 2A+** and **Model 3A+**), both of which sourced the initial conditions from Model 1A. The number of models used (three) was governed by the spatial and temporal availability of traditional and community-based precipitation data. Figure App-6A-4 illustrates the stages implemented to determine whether community-based data improved or sustained SHETRAN's performance (known here as the 'main simulations').

Figure App-6A-4. Stages required to determine whether community-based data improved or sustained model performance (main simulations). A 'leave-one-out' approach has been adopted.

Given the quantity of observed data within individual sub-catchments, this modelling study adopted a multi-basin and multi-response approach during the calibration process. This meant that several observed gauging stations were used to check SHETRAN's performance. Other than Mourato *et al.* (2015), previous SHETRAN studies have not achieved this level of detail, and have only relied upon the catchment outlet due to the absence of sub-catchment data.

Appendix 6B – Calibrating and validating SHETRAN

How will SHETRAN be calibrated?

Sensitivity tests previously outlined within App-6A-3 were run using an uncalibrated model. Before simulating any of the final scenarios, SHETRAN had to be manually calibrated using an iterative (trial and error) approach. Calibration was achieved by systematically changing the values of specific input parameters which have been reported as being hydrologically sensitive in the literature, and here during the forthcoming parameter sensitivity tests. Simulated Q (Q*sim*) was validated against observed Q (Q*obs*) which, due to this project, were readily available. Model calibration involved altering the chosen model parameters so that the error between Q*obs* and Q*sim* was minimised as much as possible (Beven, 2012). Ewen (2011) described this process as being a 'typical task' in hydrological modelling. The validation phase entailed running the model for an independent set of data to check that the same parameter values, obtained during the calibration phase, still produced a realistic simulation. Figure App-6B-1 details the main stages adopted during the calibration and validation process. Calibrating and validating the model also provided a modelling log, which Ewen and Parkin (1996) describe as being useful when endeavouring to understand how the catchment responds.

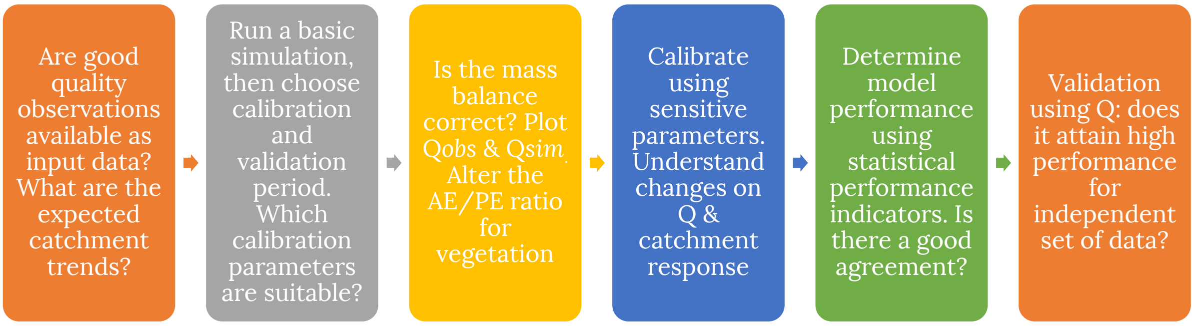


Figure App-6B-1. Steps taken to attain a calibrated and validated SHETRAN model.

The problem with SHETRAN is that there are many physical parameters it is sensitive to, each of which also vary spatially. This meant that the calibration procedure was very time consuming. To overcome this, the following guidelines were followed:

- Calibrate by altering one parameter at a time, whilst remembering that each parameter also affects how others behave;
- Concentrate efforts on the most sensitive parameters;
- Concentrate on the dominate soil (layer 1) and vegetation (land cover - grass) classes;

- Choose separate calibration and validation periods, both of which include low and high flows;
- Assesses SHETRAN's performance at multiple locations, rather than just at the outlet.

Madsen's (2000) and Beven's (2012) calibration objectives have also been considered, including:

- Average discharge values;
- Shape of the hydrograph;
- Timing, rate and volume of peak flows;
- Low flows.

Automatic calibration and validation procedures have been developed over recent years to streamline the process (Madsen, 2000; Zhang *et al.*, 2013; Lewis *et al.*, 2014). However, Ewen (2011) argues that automatic procedures cannot outperform the human eye and its ability to detect and interpret patterns. A manual approach also allows the modeller to fully understand their study.

Availability of observed discharge data (Q*obs*) for the calibration process:

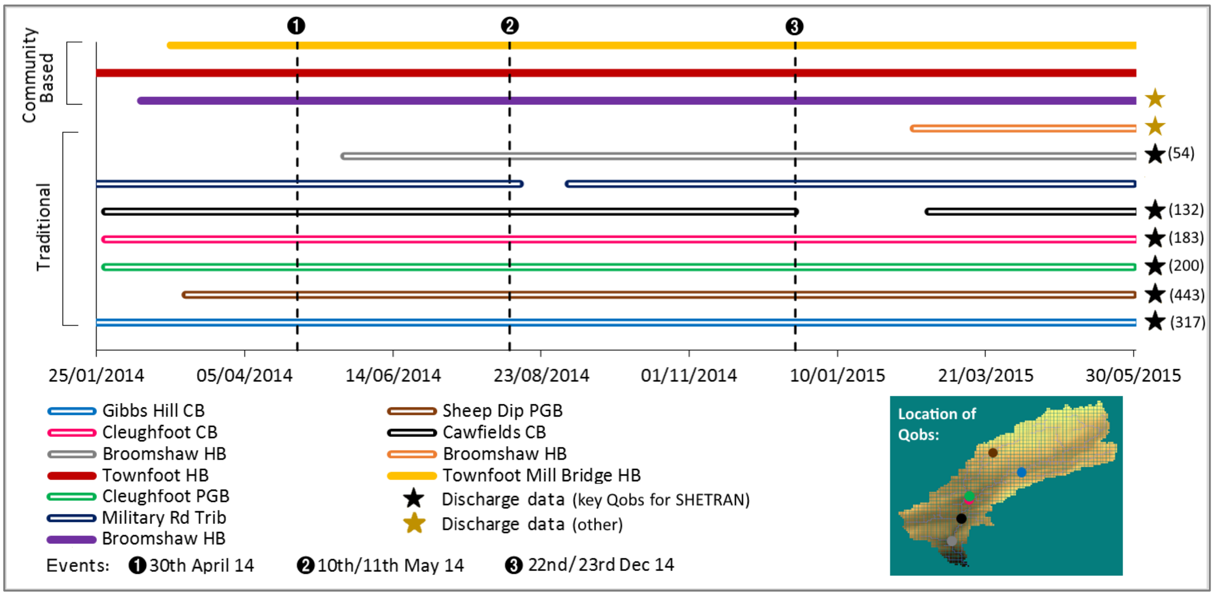


Figure App-6B-2. Observed water level data and where available, discharge data (Q*obs* - black star symbols) used to calibrate SHETRAN. Datasets were QA/QC checked in Chapter 5.

Figure App-6B-2 illustrates the spatial and temporal availability of Q*obs* data which was used during the calibration and validation process to determine SHETRAN's predictive power. Six gauging stations were available for this activity, and together they covered the main sub-catchments and events of interest. Figure App-6B-2 also highlights how other sources of information were available, including community-based river levels. These observations were used, for example, where gaps existed in the traditional datasets, and provided additional local knowledge during the events of interest.

Which parameters will SHETRAN be calibrated against?

Table App-6B-1 presents a set of modelling studies and associated calibration parameters which have been reported as being sensitive in SHETRAN.

Reference	Calibration parameters (used or suggested)	Notes
Zhang *et al.* (2013)	• Vegetation parameters (AE/PE ratio; Strickler overland flow) • Soil parameters (top soil depth; saturated hydraulic conductivity; soil water retention).	Described as being the most important parameters. Strickler overland flow is most sensitive. Authors have based these findings on a literature review.
Birkinshaw *et al.* (2010a)	• Vegetation parameters (Strickler overland flow coefficient; aerodynamic resistance; canopy resistance • Soil parameters (saturated hydraulic conductivity.)	Undertook further fieldwork to obtain values for other parameters which are often calibrated e.g. soil depth and infiltration rate.
Birkinshaw (2013)	• Vegetation parameters (AE/PE ratio; Strickler overland flow) • Soil parameters (soil depth; saturated hydraulic conductivity).	Main guidance document for SHETRAN simulations produced by Newcastle University. These are regarded as the most important parameters.
Birkinshaw *et al.* (2014)	• Vegetation parameters (canopy storage and resistance; Strickler overland flow coefficient) • Soil parameters (soil depth; saturated hydraulic conductivity)	Research focussed on forest hydrology so the vegetation parameters were important. Mass balance results, daily maximum discharges and peak events have also been assessed.
Mourato *et al.* (2015)	• Vegetation parameters (AE/PE ratio) • Soil parameters (van Genuchten parameters, saturated hydraulic conductivity and residual water content)	A 'multi-basin' and 'multi-location' (therefore multi-response) calibration procedure was carried out to capture internal dynamics.

Table App-6C-1. Review of key calibration parameters used in other SHETRAN studies.

Table App-6C-1 confirms that both vegetation and soil parameters are readily used to determine SHETRAN's predictive power. The AE/PE ratio, soil depth, saturated hydraulic conductivity and the Strickler overland flow roughness coefficient appear to be the most common parameters, with the latter reported as being the most sensitive. Although there are other parameters adopted to calibrate SHETRAN, many are used because they support specific applications. For example, Birkinshaw *et al.* (2014) used more vegetation parameters given that their study was related to forest hydrology. The dominant calibration parameters are described in detail here:

- ***AE/PE ratio at field capacity***:

SHETRAN accounts for evapotranspiration by inferring AE from PE. PE is used because it is difficult to observe evapotranspiration out in the field. PE represents the loss of water from a vegetated surface when there is an unlimited supply of water, hence ‘potential’. In reality, an unlimited supply of water is unlikely, especially during the summer months, therefore SHETRAN uses the AE/PE ratio and multiplies this by PE to estimate AE. This parameter can vary spatially, assuming the catchment of interest has a non-uniform land cover map (which the Haltwhistle Burn catchment has). A ratio of 1 would suggest that water is freely available in the catchment, whereas a ratio of zero indicates that soils have reached wilting point (Fredlund *et al.*, 2001; Agnew and Woodhouse, 2010). The AE/PE ratio exhibits information closely related to soil moisture content. As the ratio is unobserved, it was used here to calibrate the model, whilst remembering that realistic values for this part of Northumberland are 0.95-1, according to the Met Office MORECS system (Kay *et al.*, 2013).

- ***Strickler overland flow* (SOF) *roughness coefficient:***

This parameter (measured in $m^{1/3}$ s^{1}) controls the roughness of the surface and subsequently controls how quickly water moves across the catchment’s surface. Although it is common for hydrological models to use the Manning’s *n* roughness coefficient (e.g. Ali *et al.*, 2015; Crispino *et al.*, 2015; Skinner *et al.*, 2015), SHETRAN uses the Strickler overland flow coefficient (SOF) (Equation App-6B-1). Working in reverse to Manning’s n (Chow, 1959), this coefficient represents a rougher surface at low values. This parameter is found within SHETRAN’s land cover (vegetation) layer and can be changed for any grid square, therefore it is spatially variable. Typical values for the SOF coefficient are usually in the range of 0.1 to 1 for the floodplain, 3 for the lakes, with higher values of 20 used for the channel itself to encourage flow. However, there are limited guidelines to confirm this in the literature.

Strickler overland flow (SOF): **Equation App-6B-1.**

$$SOF = \frac{1}{n}$$

- ***Soil depth* (SD):**

Thicker soils have a greater storage capacity and ability to reduce runoff generation. Soil depth also affects a catchment’s response during different storm intensities. Soil depth usually reduces at higher elevations and varies with land use type, and therefore exhibits high spatial variability. Soil depth (thickness, measured in meters) was examined here as it was the only spatially varying parameter within the soil layer covering the Haltwhistle Burn catchment. All other soil parameters remained constant, spatially, before any calibration activities took place. Detail was also restricted by the overall resolution of the model (100m).

- ***Saturated hydraulic conductivity (Ks):***

Embedded within the soil layer, this parameter controls how freely water flows (in m/s) through a porous medium. Ks therefore varies depending on the type of soil, land cover and geology. There can be up to three separate values for each soil type in SHETRAN, with each also varying across the catchment. Hydraulic conductivity (K) is a major component of Darcy's Law (Darcy, 1856), whereby saturated subsurface flow is directly proportional to the gradient of the hydraulic head (Shaw *et al.*, 2011). Ks can be measured directly out in the field by, for example, taking cores and analysing these samples back in the laboratory (Shaw *et al.*, 2011). Archer *et al.* (2013) observed Ks in the field to understand the relationship between land cover and soil permeability and found that it varies significantly. However, this level of detail was not necessary here.

Despite there being many possible parameters to calibrate SHETRAN with, Abbot *et al.* (1986) describe how SHE (now SHETRAN) shouldn't actually require a calibration process because it is based on physical and observable parameters. However, due to the difficulties of accurately observing all hydrological parameters, SHETRAN was still calibrated. The Haltwhistle Burn model subsequently relied on the aforementioned four parameters selected for use during the calibration phase. It was also acknowledged that calibration results were not expected to yield a perfect match between Q_{obs} and Q_{sim} given the errors associated with various data collection activities, obtaining discharge whilst flow gauging out in the field, extrapolating rating curves, as well as parameter and geometry estimations (Birkinshaw and Ewen, 2000a; Mukolwe *et al.*, 2014; Beven *et al.*, 2015). Bathurst and Cooley (1996) also point out that calibration parameters should still lie within realistic physical limits.

SHETRAN was set up to run between 25/01/2014 00:00 and 01/06/2015 00:00 GMT, a period of 492 days which made use of the most available and favourable data when both community-based and traditional datasets overlapped (491 days once the model run-in period was excluded from model analyses). Table App-6B-2 shows how a split sample test was used to divide the calibration and validation periods; both periods contained an adequate range of hydrological conditions.

Simulation period	Time period (from – to) (GMT)	Notes
Model run-in	25/01/2014 00:00 to 25/01/2014 23:55	Initial sensitivity tests confirmed that 24-hours was sufficient for SHETRAN to 'run in'. This period was excluded from any model analyses.
Calibration	28/09/2014 00:00 to 01/06/2015 00:00	The calibration period falls under the second half of the simulation (rather than the validation period) because more *Qobs* were available.
Validation	26/01/2014 00:00 to 27/09/2014 23:55	Less gauged data was available for the validation period (compared with the calibration period) because some gauging stations were installed at a later date. Nevertheless, the validation period still used *Qobs* data which characterised the Haltwhistle Burn well.

Table App-6B-2. Defining the model run-in, calibration and validation periods.

The Haltwhistle Burn model was only calibrated on one occasion (Model 1A) as this covered the full simulation period of interest.

How will SHETRAN's performance be evaluated?

Some studies complete the calibration and validation phases using expert judgement to confirm whether the model has performed well or not. The problem with this approach is that it is subjective (Madsen, 2000) and modellers are unlikely to interpret, accept or reject a model with confidence. It is also common for modellers to have limited knowledge about how their catchment of interest behaves (Hall, 2001) which is often due to the absence of fieldwork involvement (Vidon, 2015). To safeguard a successful calibration and validation process, it is important to carry out model performance tests to determine its predictive power. As Moriasi *et al.* (2007) rightly point out, a model should be scientifically robust and performance should be quantitatively assessed as part of the QA/QC process.

There are many statistical tests performed by hydraulic and catchment modellers in order to quantify the quality of their modelled simulations using one numerical value. Examples are presented below, including the Nash-Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970), coefficient of determination (R^2) and Root Mean Square Error (RMSE). Although there are many established performance indicators, there is limited published guidance on which is most beneficial, primarily because there isn't a 'universal' indicator. It is advised that a combination of indicators should be adopted to assess the full range of dynamics associated with hydrographs (Madsen, 2000; Krause *et al.*, 2005; Hall, 2001; Moriasi *et al.*, 2007; Ewen, 2011; Chai and Draxler, 2014). A large number of performance indicators have been used over recent years to assess the performance of catchment models and other environmental datasets, but there are no clear guidelines as to what the acceptance or rejection limits should be.

Hall (2001) describes how some modellers split up and assessed different parts of their output hydrographs to validate important hydrological features independently. Some also use, for example, RMSE to assess errors relating to the timing and magnitude of each peak. Krause *et al.* (2005) have carried out a comparison on a number of statistical performance measures when observing hydrographs at catchment outlets, including R^2 and the NSE coefficient. This study concluded that different statistical performance indicators are sensitive to different aspects of the hydrograph, thus have their own advantages and disadvantages. Krause *et al.* (2005) also regard the NSE coefficient and R^2 as being the most frequently employed parameters, although neither of them should be used alone. Moriasi *et al.* (2007) have also reviewed suitable model evaluation techniques, and concluded that modellers should consume a combination of statistical indicators to fully quantify model performance. They also advise that the combination should include a technique from each of the following categories:

- **Standard regression –** linear relationship between observed and simulated data;
- **Dimensionless –** provides a relative assessment between observed and simulated data;
- **Error index –** provides an error assessment between observed and simulated data;
- **Graphical –** visually detect and interpret obvious patterns of interest.

It is clear that there are many different statistical performance indicators available for use. To ensure the most effective techniques were chosen for the Haltwhistle Burn work, the following criteria was applied:

- The technique must be widely used and appraised in the literature;
- The technique has been reported to evaluate hydrological data well and the catchment's characteristics of interest, i.e. peaks and troughs in the hydrograph;
- Acceptable performance values (limits) are documented.

As a result, R^2, RMSE, Percentage Bias (PBIAS) and the NSE coefficient were used to assess the overall performance of SHETRAN (Equations App-6B-2 to 5). The NSE coefficient was particularly important because it is one of the most widely used statistical parameters in hydrology (McCuen *et al.*, 2006; Ewen, 2011). NSE is known for being sensitive to the magnitude and timing of flashy peaks (Nash and Sutcliffe, 1970), which R^2, for example, is not. R^2 and RMSE are however well-known thus understood parameters, and PBIAS provides a clear indication on the overall direction of the models performance, hence total discharge or mass balance errors. The parameters also have acceptable limits detailed within the literature. All of these performance techniques were applied to each of the six gauging stations where *Qobs* were available, and then catchment averages were obtained. This provided information relating to SHETRAN's performance on a sub-catchment and catchment scale. Where necessary, specific elements of the hydrograph were also assessed separately to provide further detailed analyses and assist with meeting the modelling objectives. To compliment these analyses, graphical and visual inspections were also carried out to aid model understanding and interpretation.

Coefficient of determination (R^2): **Equation App-6B-2.**

$$R^2 = \left[\frac{\left[\sum_{i=1}^{n}\left(Qobs_i - \overline{Qobs}\right)\left(Qsim_i - \overline{Qsim}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(Qobs_i - \overline{Qobs}\right)^2 \sum_{i=1}^{n}\left(Qsim_i - \overline{Qsim}\right)^2}}\right]^2$$

Root mean square error (RMSE): **Equation App-6B-3.**

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Qerror_i - \widehat{Qerror_i}\right)^2}$$

Percentage bias (PBIAS)*: **Equation App-6B-4.**

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Qobs_i - Qsim_i) \cdot 100}{\sum_{i=1}^{n}(Qobs_i)}\right]$$

*can also represent overall discharge errors and mass/water balance issues.

Nash-Sutcliffe efficiency (NSE) coefficient: **Equation App-6B-5.**

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Qobs_i - Qsim_i)^2}{\sum_{i=1}^{n}(Qobs_i - \overline{Qobs})^2}\right]$$

Calibration and validation results can be found within Appendix 6C (Starkey *et al.*, 2017) which demonstrate how SHETRAN was accepted for use prior to modelling the final scenarios.

Appendix 6C – SHETRAN Models 1A-1H (Starkey *et al.*, 2017 publication)

This Appendix provides a summary of the SHETRAN modelling methodology and an analysis of the results using techniques (including performance indicators) described in Appendix 6B. These results focus on Models 1A-1H which were each simulated from 26/01/2014 00:00 to 01/06/2015 00:00 (i.e. known as the 'full model'). Results have also focussed on Event 1 only which involved simulations from 29/04/2014 00:00 to 03/05/2014 00:00.

Work presented within Chapter 6 has led to a publication in the Journal of Hydrology (Starkey *et al.*, 2017). The reviewers specifically highlighted this work to be *"interesting and potentially useful, and very timely"* and *"a useful and worthy contribution [to hydrology and water resources]"*. The research paper is open access, allowing communities and catchment stakeholders to access it with ease. This publication subsequently triggered regional media coverage (e.g. Henderson, 2017), and has been cited within peer-reviewed academic material since. A copy of the published journal paper is included below. It demonstrates how SHETRAN's performance was significantly enhanced after quantitative and qualitative community-based observations were included.

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Research papers

Demonstrating the value of community-based ('citizen science') observations for catchment modelling and characterisation

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ABSTRACT

Despite there being well-established meteorological and hydrometric monitoring networks in the UK, many smaller catchments remain ungauged. This leaves a challenge for characterisation, modelling, forecasting and management activities. Here we demonstrate the value of community-based ('citizen science') observations for modelling and understanding catchment response as a contribution to catchment science. The scheme implemented within the 42 km^2 Haltwhistle Burn catchment, a tributary of the River Tyne in northeast England, has harvested and used quantitative and qualitative observations from the public in a novel way to effectively capture spatial and temporal river response. Community-based rainfall, river level and flood observations have been successfully collected and quality-checked, and used to build and run a physically-based, spatially-distributed catchment model, SHETRAN. Model performance using different combinations of observations is tested against traditionally-derived hydrographs. Our results show how the local network of community-based observations alongside traditional sources of hydro-information supports characterisation of catchment response more accurately than using traditional observations alone over both spatial and temporal scales. We demonstrate that these community-derived datasets are most valuable during local flash flood events, particularly towards peak discharge. This information is often missed or poorly represented by ground-based gauges, or significantly underestimated by rainfall radar, as this study clearly demonstrates. While community-based observations are less valuable during prolonged and widespread floods, or over longer hydrological periods of interest, they can still ground-truth existing traditional sources of catchment data to increase confidence during characterisation and management activities. Involvement of the public in data collection activities also encourages wider community engagement, and provides important information for catchment management.

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1. Introduction

Under future climate change scenarios, wetter winters and more intense summer storms are expected to exacerbate already complex catchment management issues throughout the UK and western Europe (Chan et al., 2015; Forzieri et al., 2016; Kendon et al., 2014). Empirical data is therefore required to characterise catchment behaviour over time, model floods, improve forecasts and subsequently enhance community resilience as part of the wider catchment management process. The importance of meaningful data is further emphasised when considering the performance of new flood management interventions such as 'natural flood management' (Nicholson et al., 2012; SEPA, 2015). The potential benefits of engaging, collaborating and actively involving local communities within affected catchments is also rapidly being

Abbreviations: AE, Actual Evaporation; AWS, Automatic Weather Station; BADC, British Atmospheric Data Centre; CB, Caw Burn; HB, Haltwhistle Burn; Ks, Saturated Hydraulic Conductivity; NSE, Nash-Sutcliffe Efficiency; PGB, Pont Gallon Burn; P, Precipitation; PBIAS, Percentage Bias; PBSD, Physically-based spatially-distributed; PE, Potential Evapotranspiration; Q, Discharge; Q*obs*, Observed Discharge; Q*sim*, Simulated Discharge; RLGB, River Level Gauge Board; RMSE, Root Mean Square Error; R^2, Coefficient of Determination; SD, Soil Depth; SOF, Strickler Overland Flow; TRT, Tyne Rivers Trust.

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recognised as a vital component of an integrated catchment management toolkit (Bracken et al., 2014; Large et al., 2017).

Despite the UK having some of the world's most reliable and dense hydrometric and meteorological monitoring networks, data remains scarce for many rural catchments (Buytaert et al., 2016; Illingworth et al., 2014; UK Met Office, 2010). A variety of methods are used for observing and/or estimating spatial rainfall patterns (Bárdossy and Pegram, 2013; Durkee, 2010; Lanza et al., 2001; Shaw et al., 2011) but data availability and accuracy issues still persist on a local level. There are a number of issues; catchments are spatially and temporally complex, and flash floods, while of particular interest and importance to both hydrologists and communities, are hard to characterise given that they are rare, spatially localised, short lived and often occur in locations without formal monitoring (Archer and Fowler, 2015; Archer et al., 2016; Perks et al., 2016).

The absence of whole-catchment data can complicate the catchment modelling process (Seibert and McDonnell, 2015), especially when attempting to replicate or predict extreme events in unique locations. While workers like Zhu et al. (2013, 2014) describe how rainfall radar observations are becoming more readily available, providing improved spatial and temporal coverage in hydrological models, errors relating to timing and magnitude can propagate through the modelling process (Harrison et al., 2000). Good quality and detailed ground-based observations are therefore required to create robust models (Beven, 2009; Beven and Westerberg, 2011; Vidon, 2015). Through incorporation of such observations, the improved predictive power of the model will then play a significant role in influencing choices made by stakeholders in the catchment characterisation and management process.

The co-production of 'indigenous' knowledge and the activity of community-based monitoring (and related activities described in the literature using a range of terminology including citizen science, volunteered geographical information (VGI), crowdsourcing, citizen observatory and participatory monitoring) is rapidly expanding (Follett and Strezov, 2015; Pocock et al., 2014; Wentworth, 2014). The term used depends on the degree of 'volunteer' involvement and the specific techniques adopted, but in general they all refer to the participation of the public (i.e. non-professionals) in the generation of new knowledge about the natural environment (Buytaert et al., 2014; Pocock et al., 2014; Starkey and Parkin, 2015). Regardless of which term is used, encouraging general engagement, participation and empowerment on a local level means that the public have the potential to offer timely and low-cost solutions to the data collection phase in catchment science. Social benefits to the community are also valuable, supporting policies and management frameworks which increasingly request an integrated and bottom-up approach to catchment management. A relevant example includes the emerging 'Catchment Based Approach' (CaBA, 2016) which has surfaced from the EU Water Framework Directive and is managed in the UK by Defra, the Department of Environment, Food and Rural Affairs.

The growth in more readily available and low-cost technologies, such as smartphones, social media and the internet itself, is allowing community-based initiatives to grow rapidly. Areas include biodiversity (Sutherland et al., 2015), weather and climate (Burakowski et al., 2013; Muller et al., 2015) and disaster management (Aulov and Halem, 2012). Across North America the public are collecting regular rain, hail and snow observations and sharing them with the national CoCoRaHS network (http://www.cocorahs.org/), and a similar scheme is also active primarily across Europe, North America and Australia through the UK Met Office 'Weather Observations Website' (http://wow.metoffice.gov.uk/).

It is only recently that this type of data collection activity has started to flourish in hydrology and hydrogeology, for example, in Ethiopia (Walker et al., 2016). Only a few examples exist in the UK which specifically collect river and flood observations with some form of public involvement, for instance the Wesenseit (http://wesenseit.eu/) and Oxford Flood Network (http://flood.network/). Even fewer studies have explored the potential value of this data to support real hydrological applications, including catchment modelling, primarily due to data quality concerns or general lack of recognition (Buytaert et al., 2014, 2016; Muller et al., 2015). Only a small number of studies have made use of crowd-sourced data to validate their models, but they frequently discarded multiple observations as location, date and time stamps were absent (Fohringer et al., 2015; Kutija et al., 2014; Mazzoleni et al., 2015; Smith et al., 2015). In addition, these studies either involved 'reactive' data collection methodologies following large floods or used synthetic data to imitate citizen science, thus did not actually involve or even engage with the public. Full engagement is essential if ongoing community-based monitoring schemes are to be relied upon by professionals and regularly harnessed as an additional source of catchment information. Nevertheless, scientists and engineers are still generally reluctant to integrate this type of data into their work, which Barthel et al. (2016) attributes to professionals not being experienced enough to actually carry out the full range of participatory activities required. This includes engagement, facilitation, training and dissemination activities which are all prerequisites of successful community-based monitoring schemes.

This paper presents results from a catchment study which demonstrates the value of community-based observations for understanding and modelling spatial and temporal catchment response, including the ability to capture the shape, timing and magnitude of flood peaks for a sequence of flash flood events. Data quality issues are a particular concern with 'citizen science' studies and we take this into account by applying appropriate data quality checks before allowing further use of the data in the modelling process. The modelling results presented also infer additional information about the quality of the observations used. Walker et al. (2016) concluded that data quality from community-based observations can be of high quality if they are properly managed. Our study takes this approach a step further as it is one of the first assessments which embeds real community-based observations into a detailed catchment modelling study. To achieve this, work has been carried out on the Haltwhistle Burn catchment, a tributary of the River Tyne in northeast England, where a physically-based, spatially-distributed hydrological catchment model, SHETRAN (Ewen et al., 2000), has been used. The findings will be of interest to catchment managers, hydrologists, as well as community and environmental groups who have a common interest in holistic catchment management and who wish to expand their management toolkits.

2. Study area & focus community

Known for being located in the 'Centre of Britain', the 42 km^2 steep and low stream order Haltwhistle Burn catchment responds rapidly to heavy rainfall. This predominantly rural catchment suffers from multiple pressures (Fig. 1) and in recent years it has experienced a number of floods, including 2007, 2012, 2014 and winter 2015/2016. Flood risk is exacerbated as the main impact zone (the town of Haltwhistle) is located at a 'pinch-point' close to the outlet, and just downstream of an incised gorge section. The elongated shape of the catchment and resulting river network have also been influenced by the igneous Whin Sill outcrop which intersects this area.

Rivers Trusts exist across the UK and aim to enhance their local river basin with the help of volunteers and communities through their charitable objectives. Tyne Rivers Trust (TRT) led an

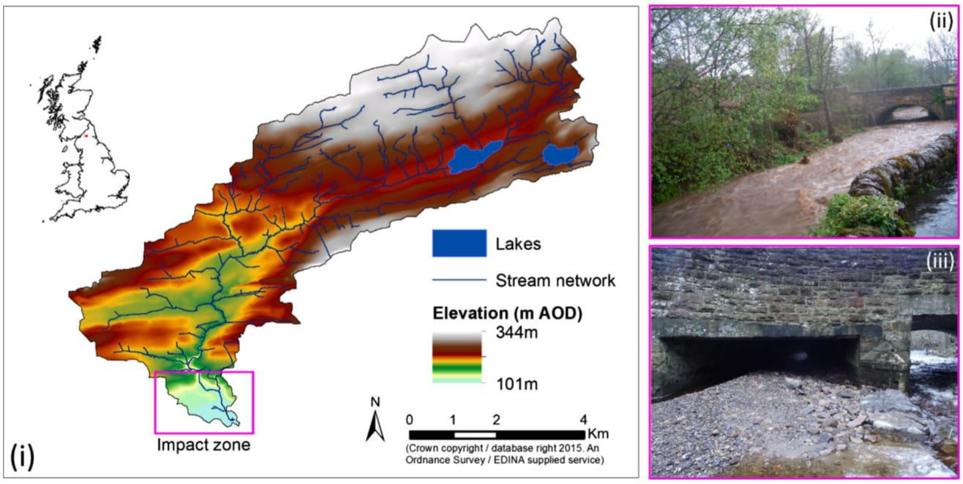


Fig. 1. (i) Location and elevation map of the Haltwhistle Burn catchment, (ii) Haltwhistle Burn at high flow and (iii) Sediment deposited under a culvert in the town following high intensity rainfall. Photographs have been provided by members of the community.

ambitious multi-partnership restoration project from 2012 to 2015 with the aim of improving the health of the Haltwhistle Burn and its tributaries, using community engagement from the onset (Tyne Rivers Trust, 2015). Although the project focused around headwater runoff and pollution, flooding was also included as an objective given that these issues are closely aligned. While TRT required evidence to characterise the catchment and assist with designing and implementing a suite of catchment management measures, no monitoring stations operated within the catchment before the project started.

The Haltwhistle Burn catchment and the already engaged 'Haltwhistle Burn River Watch Group' offered a good case study site and focus community to trial a community-based monitoring and modelling approach. Although findings are location- and community-specific, this case study site has numerous characteristics and issues which are common to many rural UK catchments. We therefore designed, implemented and facilitated a low-cost community-based monitoring programme within the catchment to support TRT's existing restoration project (Large et al., 2017 in press), to further understand flash flooding and to allow appropriate alleviation measures to be designed and implemented.

3. Methodology

3.1. Overview

The value of quantitative and qualitative observations collected by the local community have been demonstrated here by using the data alongside a traditional monitoring network to build and run a physically-based, spatially-distributed (PBSD) catchment model, SHETRAN. The community-based data includes rainfall, river level and flood observations, all of which have been used to extract timing and magnitude information for the April 2014 high intensity rainfall event which occurred in the catchment. The modelling framework involved calibrating, validating and accepting a 'baseline' model which consists of rainfall data integrated from the best available gauge combination (in this case, both community-based and traditional ground-based gauges). While keeping all other model settings and datasets the same, a 'leave-one-out' methodology allowed the effect of different combinations of these rainfall observations to be tested. All modelled outputs were statistically and visually compared with traditionally-derived hydrographs, as well as to each other. These community-based observations were also compared with the same SHETRAN model using UK Met Office rainfall radar observations over the same period.

3.2. Community-based monitoring

Participatory projects involving members of the public contain a number of stages, from initial engagement activities through to feedback and ongoing facilitation. Fig. 2 summarises the stages involved in initiating the community-based monitoring network in Haltwhistle. Key guidance documents such as those produced by Pocock et al. (2014), Science Communication Unit (2013) and Tweddle et al. (2012) were consulted for best practice during this process.

Using TRT as a 'gatekeeper', an initial workshop was held by the research team, inviting the already established River Watch Group, as well as key partners in the wider community (land owners and residents). Other engagement techniques were adopted, including social media (@HaltwhistleBurn), local newspaper articles, the project website (http://research.ncl.ac.uk/haltwhistleburn/) and leafleting. Many authors, including Tweddle et al. (2012) have argued that ongoing feedback is essential. The project website therefore acted as an ongoing community-hub and toolkit, where information and observations could be hosted.

Following these initial (but vital) engagement activities, a variety of simple low-cost citizen science style monitoring and data submission tools were sourced or developed for use. Maximising participation levels and ensuring relevant and meaningful parameters were recorded was at the forefront of the design process. Unlike many projects which strap micro-sensors to volunteers or their belongings (e.g. Castell et al., 2015; Hut et al., 2014), activities were designed here to encourage long-term monitoring beyond the lifetime of the project and for citizen scientists to physically observe and learn about their weather and water environment themselves, rather than simply distributing automatic sensors. In order to maximise the usefulness of observations and improve

Fig. 2. Key stages involved during the community-based monitoring process to capture observations ready for the modelling activities.

their quality, a 'pro-active' monitoring approach was adopted. This involved training participants in advance so that they were confident to participate and collect good quality observations relevant to the management process. It also meant that they knew what to look out for both during and immediately after flash floods. Laminated training cards were created to ensure this awareness, and also to standardise monitoring methods (see examples in the Supplementary Material).

Although a wide range of monitoring activities were trialled, efforts ultimately focussed on rainfall, river levels and flood-related evidence (Table 1). These were the most popular and frequently observed parameters across the full monitoring period of October 2013 to February 2016. Depending on user preference, web forms, Excel spreadsheets and email, paper and face-to-face meetings, Twitter and an Android '*River and Weather*' app developed in-house were all used by volunteers to submit observations.

Once observations had been submitted and shared, datasets were anonymised and databases created. In many cases, the observations were either photographs or videos (river levels and flood information) which were named and ordered by date and time. A large quantity of flood observations obtained from multiple members of the community during the events of interest were analysed; they were generally found to be self-consistent, confirming their validity as evidence of the intense rainfall and high flow impacts experienced on the ground. Quantitative observations were manually extracted from river level photographs by the lead author in order to minimise error. Quality control checks were also manually carried out on the rainfall datasets to ensure valid observations were available for use. This involved comparing daily totals against each other, checking for gaps and outliers in the datasets, only authenticating extreme rainfall values when photographs/videos of impacts aligned, and comparing observations against average annual rainfall totals.

After establishing a network of manual rain gauges for ongoing 24-hour community observations, data from both 'Townfoot' (data quality accepted, representing the town and lower catchment) and 'Cawburn' (poor quality data sourced from the mid-catchment region) were then used within this modelling study. These two gauges offer a good comparison between datasets to emphasise the importance of good quality citizen science observations. They also contain data for the full modelling period of interest (January 2014 to May 2015). The spatial and temporal availability of community-based observations used in the SHETRAN modelling study are presented in Fig. 3, along with statistics which were used to rule out the Cawburn gauge during the quality control process. The Cawburn gauge was rejected for valid use because rainfall totals were considerably underestimated, particularly with respect to extreme events; it was, however, used in this modelling study to demonstrate the effect of a poor quality community dataset on model performance. The Cawburn observer originally highlighted that their gauge may be invalid due to lack of regular maintenance.

Flood observations provided by the community highlight three interesting high flow (flash flood) events. This paper explores all three events, focussing mainly on Event 1 (further outputs for Events 2 and 3 are in the Supplementary Material):

1. 30th April 2014: an intense convective storm (described as a 'cloud burst') which was localised over the town of Haltwhistle;
2. 8th August 2014: a convective summer storm falling on dry ground and mainly in the upper catchment;
3. 22nd/23rd December 2014: an intense and prolonged period of winter rainfall over a saturated catchment, causing widespread flooding, and morphological response comprising mass transportation and deposition of sediment.

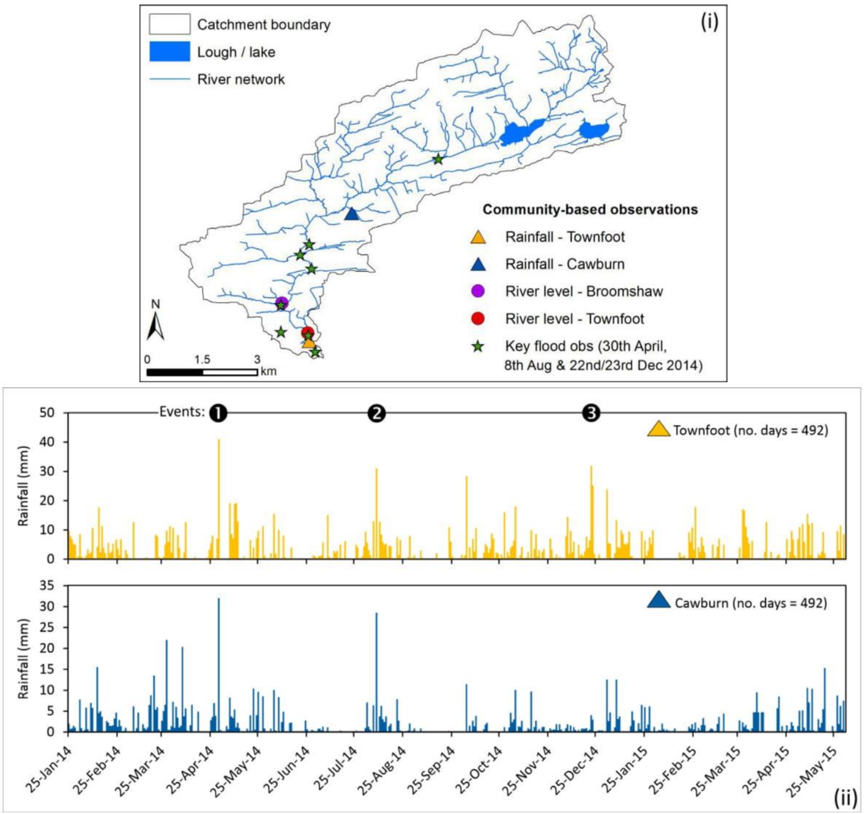
3.3. Traditional hydrometric monitoring network

Prior to the project, there were no traditional ground-based hydrometric monitoring networks in operation within the catchment boundary. A traditional hydrometric monitoring network was therefore set up alongside the community-based scheme to fill the data gaps, capture local response and offer scientifically robust

Table 1
Examples of community-based monitoring techniques used in Haltwhistle which are relevant to this modelling study.

Parameter	24-hour rainfall totals	River (water) levels (sporadic/daily)	Flood-related information
Method	Plastic manual rain gauge in back gardens, placed at ground level. Graduated scale in millimetres for quantitative observations taken at the same time, usually every day in the same location.	Manual river level gauge boards at key (fixed) locations. 'River Watch Photo Posts' erected to provide instructions and consistency. Photographs or direct quantitative measurements taken.	• Anecdotes/eye-witness descriptions; • Photographs; • Videos; • Extra river levels. All provided with date, time and locational information.
Example			

E. Starkey et al./Journal of Hydrology 548 (2017) 801–817 805



(iii) Quality control checks (*note that the 1961-1990 average annual rainfall is 1000-1500mm, Kay et al., 2013)

Gauge	No. gaps in data	Σrainfall (mm) 492 days	Σrainfall (mm) annual*		Extremes valid?	Dataset accepted?
			01/03/14 – 01/03/15	01/05/14 – 01/05/15		
▲ Townfoot	0	1530	1107	1087	✓	✓
▲ Cawburn	0	857	587	472	x	x

Fig. 3. Spatial (i) and temporal (ii) availability of community-based observations used to model, along with a summary of the quality control checks used to accept or reject individual rain gauges (iii). The Townfoot rain gauge has also been compared with traditional gauges (see Supplementary Material). Note that Cawburn rainfall totals are significantly lower than expected, hence it was rejected. (See above-mentioned references for further information.)

hydrological data. Rainfall and discharge datasets were necessary to calibrate and validate SHETRAN, but also to demonstrate the value of community-based input data (as rainfall influences runoff).

An aerodynamic tipping bucket rain gauge and six pressure transducers for water level recording were installed between January and May 2014. Flow gauging was required to convert water level into discharge (Q) using stage-velocity-area derived rating curves (see Supplementary Material for detail). Data from a nearby UK Met Office daily rain gauge at Blenkinsopp Hall (west of the catchment boundary) was also sourced from the British Atmospheric Data Centre (BADC). The spatial and temporal availability of traditional data used in SHETRAN are shown in Fig. 4. A few gaps exist in the time series because of equipment failure, including battery failure, network issues, data storage capacities and damage caused by cattle.

Met Office 1 km NIMROD rainfall radar data was also sourced from the BADC and represents an alternate source of traditional data. It was only feasible to study the three flood events listed above due to the large the amount of processing required to extract and prepare the data, as well as run SHETRAN.

3.4. Hydrological modelling using SHETRAN

SHETRAN (Système Hydrologique Européen TRANsport) is a PBSD hydrological model which is capable of simulating spatially-distributed hydrological processes at a catchment scale (Newcastle University, 2016). Catchments are represented by a three-dimensional discretised grid and a simplified river network (known in this model as 'channel links'), thus the model can represent both surface and subsurface processes. SHETRAN is well-established and researched in the literature, with modellers utilis-

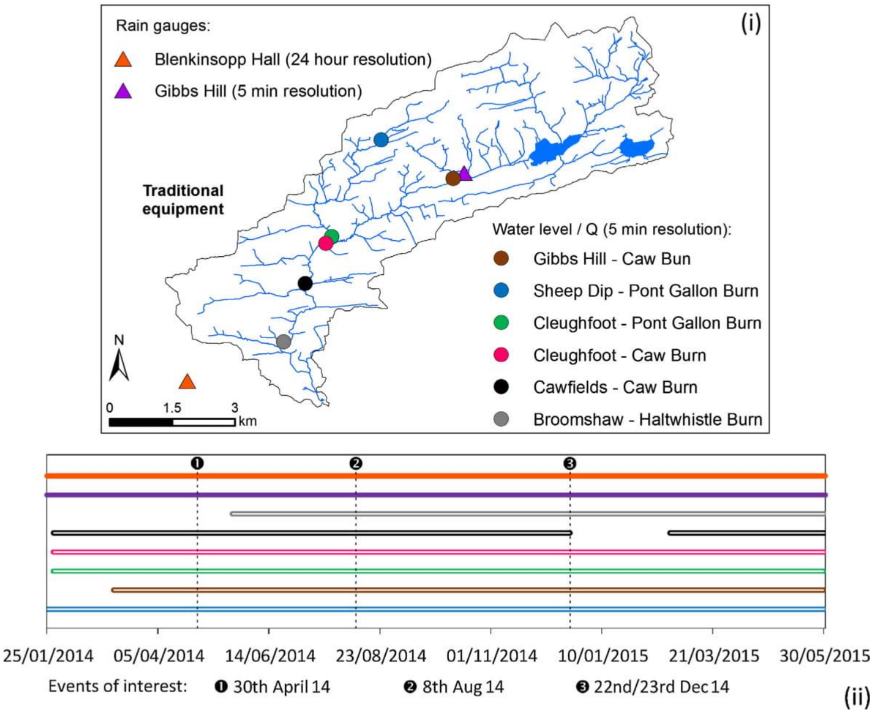


Fig. 4. Spatial (i) and temporal (ii) availability of traditional datasets used in this study. Colours correspond to each individual gauge on the map.

ing it to obtain discharge information for a variety of applications (Birkinshaw et al., 2011, 2014; Mourato et al., 2015; Parkin et al., 2007). However, SHETRAN has not yet been used to demonstrate the value of community-based observations. Being a PBSD model, it provides an opportunity to use observed data from various sources and locations, and integrate them into the hydrological cycle.

The most recent version of SHETRAN was sourced from Newcastle University (2016). Table 2 summarises the input data sourced and prepared for the Haltwhistle Burn catchment, along with other relevant model settings required. SHETRAN was set up to run between 26/01/2014 00:00 and 01/06/2015 00:00 GMT, a period of 491 days which makes use of the best available data when both community-based and traditional datasets overlap.

Based on the input layers, SHETRAN represents the Haltwhistle Burn catchment using the river network and catchment grid presented in Fig. 5. Output locations (Q*sim*) corresponding to each gauging station (Q*obs*) are also highlighted. The model described in this section is referred to as 'Model A'. Where changes have been made to input rainfall, a new model name is used.

SHETRAN has been manually calibrated using an iterative approach by systematically changing the values of input parameters. The parameters are those which are reported to be hydrologically sensitive in the literature and in SHETRAN (Birkinshaw et al., 2011, 2014; Đukić and Radić, 2016; Mourato et al., 2015), including the Strickler overland flow (SOF) roughness coefficient, soil depth (SD), saturated hydraulic conductivity (Ks) and the ratio of actual to potential evapotranspiration (AE/PE). These parameters can be adjusted within the soil and land cover layers and therefore allow the model to account for local variability in surface and subsurface properties. The aim of the calibration phase is to alter the model parameters in order to minimise the error between Q*obs* (the benchmark) and Q*sim*, whilst still being physically acceptable (Beven, 2009). The validation phase involved running the model for an independent set of data to check that the model settings still produced an acceptable simulation. A split sample test was used to divide the calibration and validation periods (see Table 3); both periods contain an adequate range of hydrological conditions.

Alongside graphical and visual inspection, it is good practice to use a combination of statistical performance indicators to assess model performance (e.g. Hall, 2001; Krause et al., 2005; Moriasi et al., 2007). The following tests, which are frequently used to assess hydrographs, were used. The acceptable performance values listed for each were chosen based on limits reported in the literature as providing reliable modelled outputs (Moriasi et al., 2007; Mourato et al., 2015):

- Coefficient of determination (R^2), with 0.7 being used as the minimum acceptable value;
- Root mean square error (RMSE), to provide an indication of performance in the same units as Q;
- Percentage bias (PBIAS), with ±25% being reported as the maximum acceptable error;
- Nash-Sutcliffe Efficiency (NSE) coefficient, with anything above +0.5 reported to provide at least a 'good' fit.

In order to demonstrate the value of community-based observations, a 'leave-one-out' methodology was adopted. The leave-one-

Table 2
Input data sourced and prepared ready for the Haltwhistle Burn SHETRAN model. Additional information is given in the text.

Item/setting required	Data source	Preparation for SHETRAN
Model resolution	100 m chosen – maximum resolution feasible (when considering model stability and simulation time).	
Mask	Outline derived using EDINA Digimap 5 m Panorama elevation data.	Aggregated to 100 m (4110 active cells in plan view available for simulation).
Minimum & mean filled DEM	50 m panorama elevation data supplied by EDINA Digimap. Elevation ranges from 101 m to 344 m AOD.	Resampled to 100 m resolution grid using minimum and mean aggregation techniques.
Precipitation (P)	Combination of data from Figs. 3 and 4 and rainfall radar used in the main modelling framework. Refer to the Thiessen polygons in Fig. 6 for spatial interpolation and distribution. Gibbs Hill, Blenkinsopp Hall and Townfoot gauges were initially used to set up the model.	
Potential evaporation (PE)	No automatic weather stations (AWS) available within catchment boundary. Met Office Spadeadam AWS used from the BADC (located 10 km north west from the catchment): • Maximum and minimum temperature; • Wind speed; • Relative humidity. Spadeadam did not contain any sunshine data. Brampton manual weather station run by a Met Office volunteer (located 21 km west from the catchment) used instead for 'total sunshine hours'. No gaps found in datasets used.	PE calculated using five weather parameters and the UN Food and Agriculture Organization recommended Penman-Monteith approach (Raes, 2012). This approach represents evaporation from a vegetated surface with an unlimited supply of water, which was considered sufficient for this study site and land cover. An open access tool described by Raes (2012) was used to calculate PE automatically. Final PE dataset was aggregated to a 24-hour resolution and used uniformly across the catchment.
Soil & geology	Peaty (upper catchment) and loamy (mid/lower catchment) soils with a moderately productive aquifer dominate. The EU soils database and British Geological Survey hydrogeology layers (1 km resolution) initially used to obtain realistic properties and set up the model.	Resampled to 100 m resolution grid. Calibration activities later refined the soil and geology datasets to allow for local variations in runoff.
Land cover	25 m Land Cover Map 2007 supplied by EDINA Digimap. Catchment is dominated by grassland (64%), evergreen forest (18%) and Shrub (11%).	Land cover codes reclassified to fit SHETRAN (arable, bare ground, grass, deciduous forest, evergreen forest, shrub and urban). Aggregated to 100 m grid. Calibration activities later refined land cover properties to allow for local variations in runoff.
Lakes	Ordnance Survey 1:10,000 Master Map shapefiles. Includes Greenlee (0.51 km^2) and Broomlee (0.30 km^2) Loughs in the upper catchment.	Converted to 100 m raster grid.
Max & min temperature	Temperatures are used directly in SHETRAN only for simulating snowpack development and snowmelt; there were no snow events during the simulation period.	
Output resolution & locations	SHETRAN was set to produce simulated discharge ($Qsim$) every 5 min for the six gauging stations which contain observed discharge ($Qobs$).	

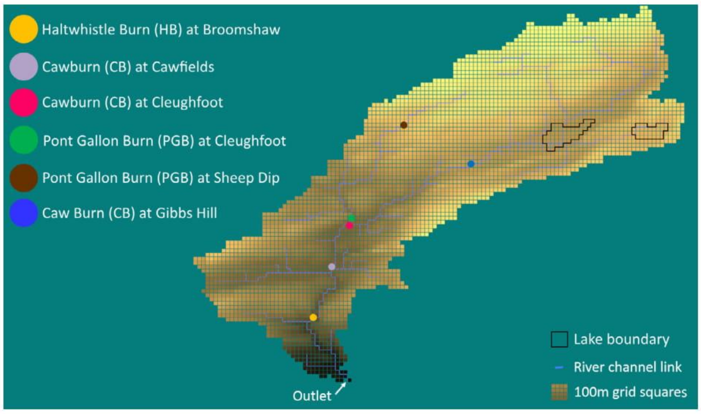


Fig. 5. SHETRAN 100 m grid and river network used to represent the Haltwhistle Burn catchment. Coloured dots represent locations where modelled discharge (Q*sim*) have been extracted. Watercourse abbreviations are referred to in later sections.

Table 3
Defining the calibration and validation periods within the full simulation period of interest.

Simulation period	Time period (from – to) (GMT)	Number of days
Calibration	28/09/2014 00:00 to 01/06/2015 00:00	246
Validation	26/01/2014 00:00 to 27/09/2014 23:55	245

out procedure involved re-running the already calibrated, therefore accepted, SHETRAN model multiple times. On each occasion different elements of information were excluded from the simulation to test how well the model performs without it. Beven (2009) and Otieno et al. (2014) advocate leaving observations out of the rainfall interpolation and modelling process as a way of demonstrating their value. Such an approach has allowed different sources (therefore combinations) of rainfall data to be used and assessed against the 'baseline' (Model A). This approach was feasible as precipitation is SHETRAN's main temporal and spatial driving variable. Making use of a 'patchwork' of heterogeneous information, combinations used were dictated by the spatial and temporal availability of input precipitation data previously described. SHETRAN was not recalibrated before each combination; other than the rainfall data, all parameters and datasets remained constant throughout. The performance of Model A was expected to degrade with diminished rainfall information, offering an opportunity to test model performance in relation to each other.

Point rainfall measurements were spatially interpolated across the catchment to create a 100 m resolution grid using conventional Thiessen polygons (Fig. 6). Although there are many other interpolation techniques available (e.g. Shaw et al., 2011), Thiessen polygons, which assign areas of the catchment to the nearest point measurement, are able to represent localised storms well if enough rain gauges are present (therefore providing a good test here). Interpolation methods, such as arithmetic mean, cannot achieve this and more advanced geostatistical techniques were not expected to yield better results. Alongside catchment-wide rainfall radar data, traditional, community-based and a combination of both data sources were used to create these spatial maps. It should be noted that the Cawburn gauge data was also incorporated into some scenarios to demonstrate potential implications when 'rejected' observations are used. Since community-based rainfall observations and the UK Met Office Blenkinsopp Hall gauge have coarser temporal resolutions, these data have been disaggregated into 5-min timesteps by imposing the same rainfall pattern from a traditional 5-min resolution rain gauge (Gibbs Hill), in model scenarios where this detail is available (Models A, B and E). Where this detail is not available (Models C, D, F and G), they have kept their original resolution to allow model performance to be evaluated whilst using these temporally coarser observations. The statistical performance indicators were then utilised to quantitatively assess the effects of each rainfall combination.

4. Results & discussion

4.1. Enhancing SHETRAN's inputs using quantitative and qualitative observations

Analysis of different sources of rainfall has highlighted the importance of spatial and temporal observations, particularly during the period of intense localised rainfall experienced on the 30th April 2014 (Event 1). Fig. 7 displays a set of 48-hour cumulative rainfall plots which represent Event 1 for each of the three gauges used to initially build Model A. It is clear that the traditional gauges observed much lower rainfall totals (17.6 mm and 17.9 mm) compared with community-based (41 mm), despite being only a few kilometres apart. If the community-based observations had not been available, the traditional gauges would have completely missed these larger totals observed over the lower catchment and the impact zone. However, Fig. 7 also confirms that while rainfall radar totals were significantly lower than those observed by the community, the radar observations did show the spatial location and extent of the storm and provided detailed temporal resolution, thus have captured steeper cumulative trends, hence implying a more intense, short-lived storm.

One obvious drawback with community-based rainfall observations is that they are usually reported on a 24-hour basis. If used in isolation at this resolution, only rainfall totals can be extracted. However, the full range of qualitative and quantitative community-based observations displayed in Fig. 8 (photographs, videos, tweets and anecdotes) illustrate how the wider community can contribute to the generation of an 'event timeline' which

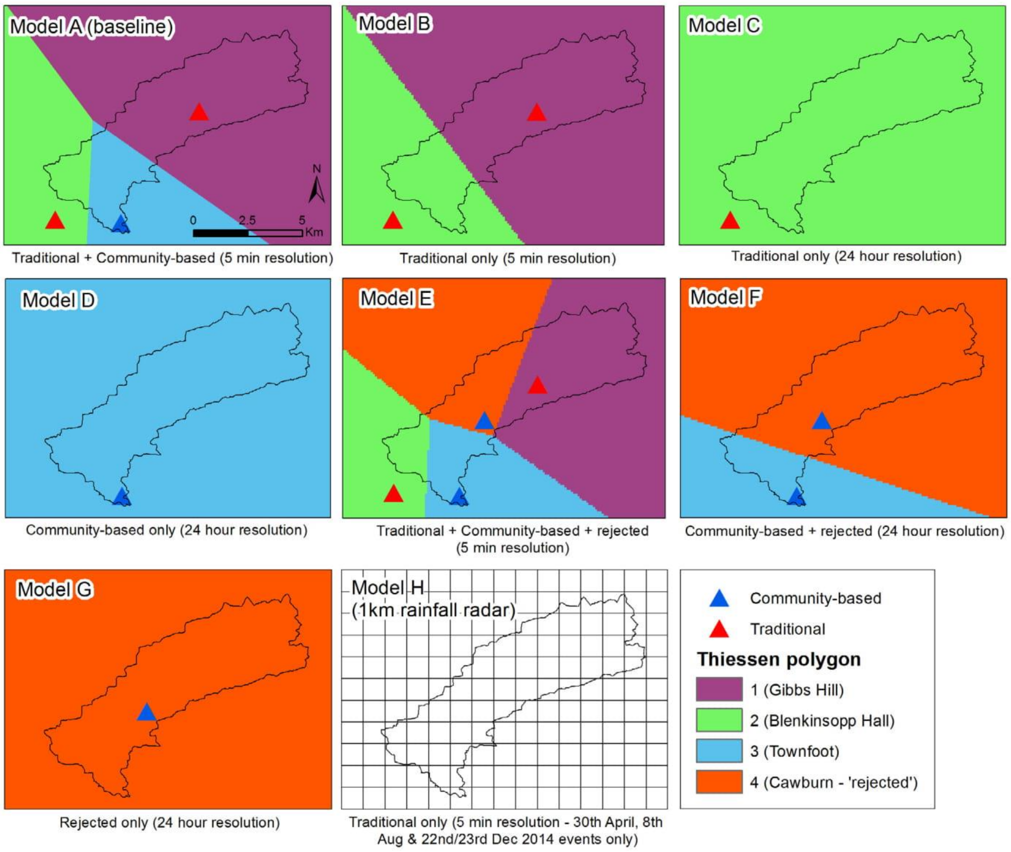


Fig. 6. Combination of rain gauges and resulting Thiessen polygons used to spatially estimate precipitation across the catchment in Models B-G (includes original Model A), as well as a 1 km resolution grid which utilises Met Office rainfall radar data (Model H). Original rainfall datasets have been directly fed into these models, rather than calculating areal rainfall, in order to capture spatial variability.

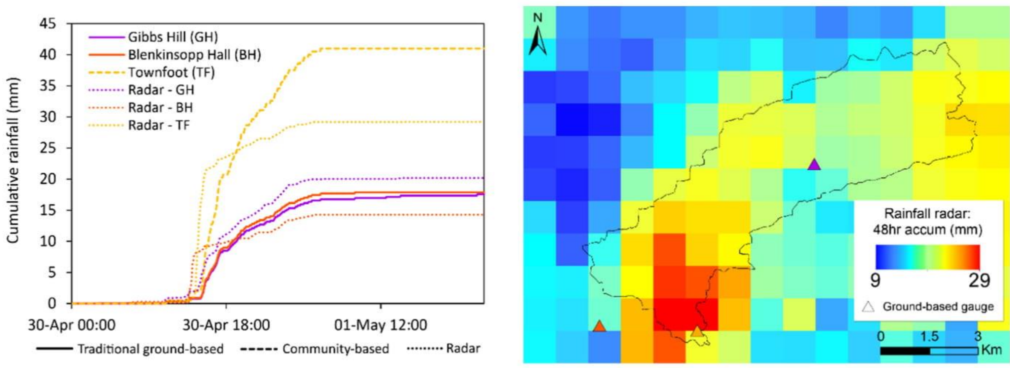


Fig. 7. Left: 48-hour cumulative rainfall plots for Event 1 (30/04/2014 00:00 to 02/05/2014 00:00 GMT) for each gauge initially used in Model A, and rainfall radar where each gauge overlaps. Right: Rainfall radar accumulations for the same period across the catchment. Ground-based gauges are overlaid onto the radar grid. Plots relating to Events 2 and 3 can be found in the Supplementary Material.

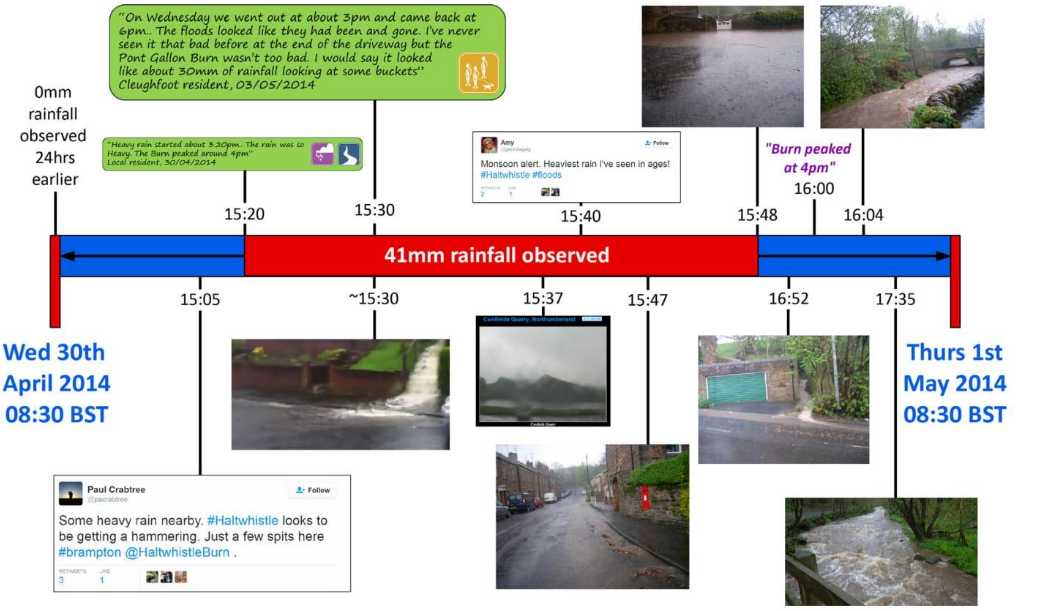


Fig. 8. A timeline of Event 1 (30th April 2014) created by harnessing a range of community-based quantitative and qualitative observations collected on the ground. Note quotes such as "*Monsoon alert. Heaviest rain I've seen in ages*!", and early warnings submitted and then crowd-sourced using Twitter.

specifically highlights when the storm started and finished. Together with the quantitative rainfall totals, this simple source of ground-based evidence allows duration, magnitude and intensity information to be inferred on a local scale. For Event 1, after observations were captured and shared by the public, it was clear that the event was extremely intense with 41 mm falling in just 30 min in the lower Haltwhistle Burn catchment. This was derived by assessing the timeline of observations presented in Fig. 8, which visually and anecdotally confirms that heavy rain was experienced locally on the ground between 15:20 and 15:50 (BST). An event as intense as this would also be required to generate the flood and debris-related impacts witnessed on the ground by the community. Rainfall totals can thus be disaggregated across the specific time period when it was physically observed (in this case, 41 mm of rain disaggregated evenly across 30 min), rather than 24 hours, to realistically replicate a high intensity storm. SHETRAN's precipitation time series were therefore updated to reflect the nature of Event 1 before Model A was calibrated.

This heterogeneous data integration process has only been possible due to the number of community-based observations being available and because the rainfall event hit the town where people live and walk past the Haltwhistle Burn. Event 2 (8th August 2014) provides an example where the storm was centred higher up in the catchment, meaning the downstream community were unable to provide information to help interpret quantitative rainfall totals. Event 3 (in December 2014) was more widespread with saturated antecedent conditions, so observations captured by the community were useful for highlighting downstream impacts. The value of the community-based rainfall observations for Event 1 have therefore been enriched as it was possible to extract important hydro-information from the patchwork of informal and heterogenic community-based observations, and utilise them within SHETRAN to characterise the high intensity storm. These sub-hourly and highly localised hydrological events, which are still poorly monitored and understood by professionals, require this level of detail in order to better characterise them and their impacts (Archer and Fowler, 2015; Archer et al., 2016; Perks et al., 2016).

4.2. Final calibration and validation results (Model A)

Initial calibration simulations for Model A reproduced the overall shape and timing of each hydrograph reasonably well. In order to improve SHETRAN's ability to reproduce Q*obs* at Gibbs Hill, the SOF values of the actual channel links of the loughs (links which overlapped the lake layer) needed to be reduced from 3.0 to 0.1. These results have subsequently highlighted the importance of the two lakes (Greenlee and Broomlee Lough – shallow water and wetland nature reserves) in the upper catchment and their ability to naturally attenuate high flows during and after rainfall. Final model settings adopted are listed in the Supplementary Material.

Final calibration and validation results are presented in Table 4. Fig. 9 also contains graphical comparisons of Q*obs* and Q*sim* (using Gibbs Hill, Sheep Dip and Broomshaw as examples) as well as Q*sim* for each gauging station. All of the statistics fall within acceptable limits, except for the Pont Gallon Burn at Sheep Dip during the validation period. This has been attributed to the Pont Gallon Burn sub-catchment not containing its own rain gauge, which would have been necessary to fully capture the localised rainfall experienced during Event 2. Despite this, the model's overall average (catchment-wide) performance is still well above the acceptance levels across the multiple indicators, so this SHETRAN model was accepted for its intended use. The multi-location and multi-response approach has highlighted the importance of sub-catchment information and catchment connectivity to the

Table 4
Final statistical results for the calibration and validation periods. Results relate to Model A using best available data, including quantitative and qualitative community-based observations (watercourse acronyms: Caw Burn, CB; Haltwhistle Burn, HB; Pont Gallon Burn, PGB).

Gauge/Output Location	R^2	RMSE (m^3/s)	PBIAS (%)	NSE
Calibration period: 28/09/2014 00:00 to 01/06/2015 00:00 (where observed data is available)				
CB at Gibbs Hill	0.92	0.26	−5.56	0.85
PGB at Sheep Dip	0.83	0.04	3.33	0.78
PGB at Cleughfoot	0.89	0.11	−13.29	0.88
CB at Cleughfoot	0.92	0.35	−9.31	0.90
CB at Cawfields	0.84	0.36	−6.71	0.86
HB at Broomshaw	0.88	0.47	0.48	0.77
Average	**0.88**	**0.27**	**−5.18**	**0.84**
Validation period: 26/01/2014 00:00 to 27/09/2014 23:55 (where observed data is available)				
CB at Gibbs Hill	0.90	0.10	10.47	0.88
PGB at Sheep Dip	0.52	0.04	−47.63	0.21
PGB at Cleughfoot	0.77	0.09	−12.20	0.76
CB at Cleughfoot	0.89	0.19	−8.34	0.86
CB at Cawfields	0.86	0.24	−4.77	0.85
HB at Broomshaw	0.87	0.14	14.86	0.72
Average	**0.80**	**0.13**	**−7.94**	**0.71**

calibration process as the Haltwhistle Burn catchment does not respond in a uniform way.

4.3. Performance of SHETRAN using different combinations of rainfall data

Models B-G have been assessed across the full modelling period to determine the change in SHETRAN's performance in relation to the calibrated and validated (therefore accepted) baseline model, A.

Table 5 (i) presents the statistical results (averaged across all six gauging stations) for each model simulated i.e. rain gauge combination tested. The most notable trends exposed are that model performance progressively deteriorates from Model A to G and, as expected, A continues to be the most acceptable model for use. These trends are strengthened by the fact that multiple statistical performance indicators express the same trends, as well as overall discharge error (as PBIAS results, which relate to mass balance, illustrate). A more pronounced case for these trends is exemplified in Table 5 (ii) which present the same set of statistics, but only for the Haltwhistle Burn at Broomshaw, where the bulk of community-based observations exist. For instance, the NSE coefficient falls by 1.30 when comparing Model G against A, whereas the difference between the same two models is only 1.09 when assessing all six gauging stations at the same time. Note that this trend is still apparent despite the Broomshaw gauge analysis excluding Event 1 (i.e. missing Q*obs*).

The following points can also be noted when assessing the full modelling period (rather than individual peaks):

- The performance of Model A is only marginally better than B, implying both should be acceptable for wider use. The use of community-based observations has not therefore degraded SHETRAN's predictive power, but similar results would have been obtained for the full modelling period if only two traditional gauges (Model B) were available. Nevertheless, this comparison emphasises that it is feasible to create an acceptable model containing community-based observations and achieve statistical results similar to those obtained in other SHETRAN studies (Birkinshaw et al., 2011, 2014);
- 'Rejected' community-based rainfall observations have significantly affected (degraded) model performance, particularly the mass balance aspect. Comparisons between Model A and E show this most clearly;
- Use of community-based observations alone significantly degrades model performance. However, the use of one good quality community-based rain gauge (Model D) produces statistical results which are similar to the outputs obtained when using one traditional rain gauge (Model C). However, this is not the case for the 'rejected' community-based data when used in isolation (Model G);
- Models containing two or three rain gauges, for which it has been possible to disaggregate time series into 5 min intervals, have produced reliable outputs. This is also true for models containing input data which had not been rejected during the quality control process. Models using only one rain gauge at a 24-hour resolution (Models C and D) would be rejected here. Nevertheless, some modelling studies regularly use these coarser resolutions.

Overall, these findings confirm that the resolution of the input data, the data quality and the total number of rain gauges used override the importance of whether or not community-based observations are used alongside traditional sources. These are obvious and important factors which modellers traditionally consider (Beven, 2009; Beven and Westerberg, 2011; Montanari and Di Baldassarre, 2013). This suggests that there is potential for integrating community-based observations with traditional sources to fill monitoring gaps, to support the modelling process and to characterise catchments on a local scale meaningful to resident communities. Findings here also complement results obtained by Mazzoleni et al. (2015) who found that synthetic intermittent observations improved model performance for streamflow. It is also important to remember that traditional observations are not free from error and can still provide incorrect information (Beven and Westerberg, 2011).

4.4. Importance of community-based observations during flood events

Event 1 (30th April 2014) has been isolated here for analysis to determine how SHETRAN performs during a localised flash flood

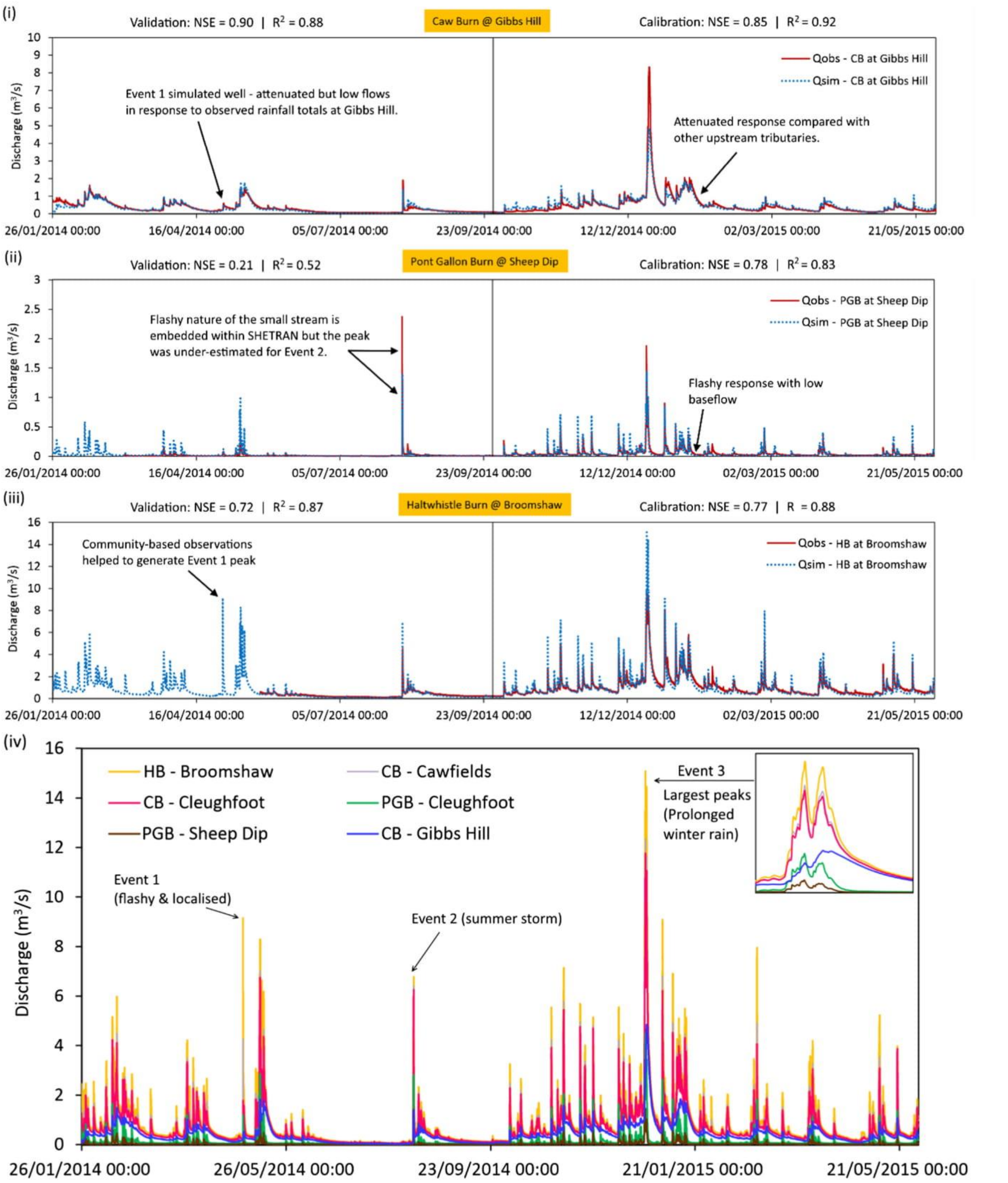


Fig. 9. *Qobs* and *Qsim* results for the Caw Burn at Gibbs Hill, the Pont Gallon Burn at Sheep Dip and the Haltwhistle Burn at Broomshaw, plotted (i-iii) for Model A over the calibration and validation periods. *Qsim* for all gauging stations are also presented together, which emphasises variation in sub-catchment response (iv).

event when a patchwork of community-based observations are most abundant, as well as rainfall radar.

Table 6 (i) contains the statistical results relating to Event 1, comprising an analysis covering four days to capture the rise and recession of a single event-based hydrograph. The dominant pattern generally involves a degradation in model performance when rain gauges are removed or rainfall radar is used. Performance diminishes when community-based observations are completely absent or when the Thiessen polygon over-exaggerates the spatial scale of the convective storm (in this case the 41 mm captured by

Table 5
Average (i) and Broomshaw only (ii) SHETRAN results for Models A-G across the full modelling period (rain gauge combinations: • traditional and community-based, * traditional only, ◆ community-based only and ◇ rejected).

Model, rain gauge combination & total number of rain gauges used (brackets)	R^2	RMSE (m^3/s)	PBIAS (%)	NSE
Full modelling period: 26/01/2014 00:00 to 01/06/2015 00:00 (where observed data is available) *(i) Average results across all six gauging stations:*				
A • (3)	0.86	0.22	−5.17	0.83
B * (2)	0.85	0.23	−4.90	0.82
C * (1)	0.61	0.33	2.98	0.61
D ◆ (1)	0.55	0.36	−5.10	0.48
E •◇ (4)	0.58	0.30	25.09	0.53
F ◆◇ (2)	0.11	0.63	59.98	−0.23
G ◇ (1)	0.05	0.64	61.08	−0.26
Full modelling period: 26/01/2014 00:00 to 01/06/2015 00:00 (where observed data is available) *(ii) Results for the Haltwhistle Burn at Broomshaw only:*				
A • (3)	0.90	0.39	2.42	0.81
B * (2)	0.89	0.40	2.71	0.80
C * (1)	0.80	0.42	12.01	0.77
D ◆ (1)	0.79	0.41	6.56	0.78
E •◇ (4)	0.93	0.32	23.48	0.86
F ◆◇ (2)	0.46	0.99	74.21	−0.26
G ◇ (1)	0.09	1.07	80.34	−0.49

Table 6
Average (i) and Cawfields only (ii) SHETRAN results for Models A-H across Event 1 (rain gauge combinations: • traditional and community-based, * traditional only, ◆ community-based only and ◇ rejected). ° Assessment excludes any Broomshaw observations.

Model, rain gauge combination & total number of rain gauges used (brackets)	R^2	RMSE (m^3/s)	PBIAS (%)	NSE
Event 1 (30th April): 29/04/2014 00:00 to 03/05/2014 00:00 (° where observed data is available) *(i) Average results across five gauging stations:*				
A • (3)	0.76	0.44	13.94	0.49
B * (2)	0.43	0.60	21.55	0.22
C * (1)	0.32	0.64	36.01	0.03
D ◆ (1)	0.53	1.55	−189.92	−134.82
E •◇ (4)	0.80	0.24	−19.10	−4.72
F ◆◇ (2)	0.65	0.82	−148.71	−50.24
G ◇ (1)	0.58	0.74	−122.50	−47.17
H Rainfall radar •	0.52	0.56	13.55	0.09
Event 1 (30th April): 29/04/2014 00:00 to 03/05/2014 00:00 *(ii) Results for the Caw Burn at Cawfields only:*				
A • (3)	0.75	1.03	28.67	0.54
B * (2)	0.09	1.50	42.53	0.02
C * (1)	0.03	1.57	52.64	−0.08
D ◆ (1)	0.92	2.46	−82.72	−1.65
E •◇ (4)	0.96	0.55	18.78	0.87
F ◆◇ (2)	0.96	1.09	−69.08	0.48
G ◇ (1)	0.95	0.99	−43.65	0.57
H Rainfall radar •	0.23	1.40	38.68	0.14

the community). Analysis confirms that the community-based observations have helped to capture river response following the storm but the spatial extent of the event is not accurately represented, even by Model A. Table 6 (ii) contains SHETRAN's response for the Caw Burn at Cawfields. This gauging station is used to represent river response upstream of the town because observed water level (therefore discharge) was not recorded at Broomshaw for this period (see data gap in Fig. 4). Compared to the catchment's average response, model performance at the Cawfields gauge is significantly enhanced when community-based observations are incorporated.

Fig. 10 presents discharge plots for each model at each gauging station, along with observed data for comparison. Manual river levels observed by the community (subsequently converted to

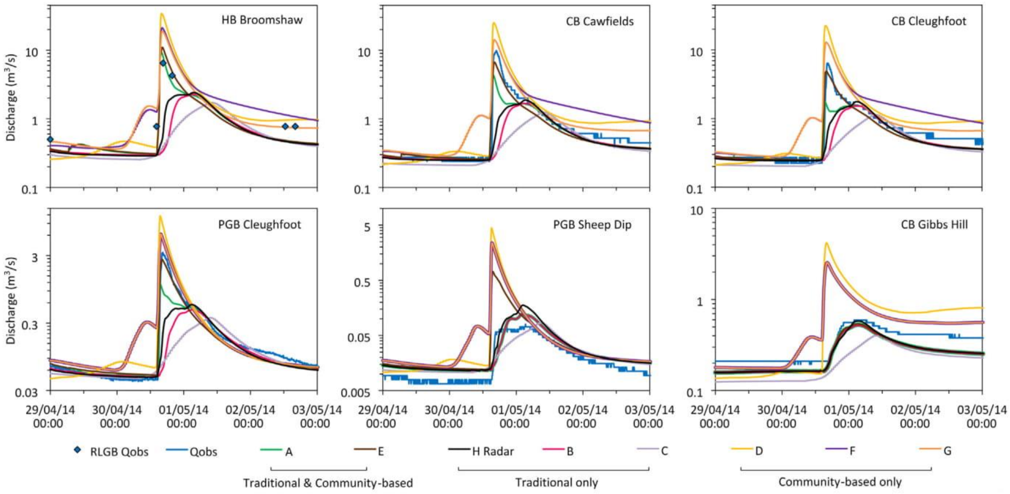


Fig. 10. Hydrograph shape: final simulated discharge obtained from SHETRAN Models A-H for all relevant gauging stations during the April 2014 event. Includes manual river level gauge board (RLGB) observations collected by the community which have been converted into discharge. Note that discharge has been plotted using a logarithmic scale.

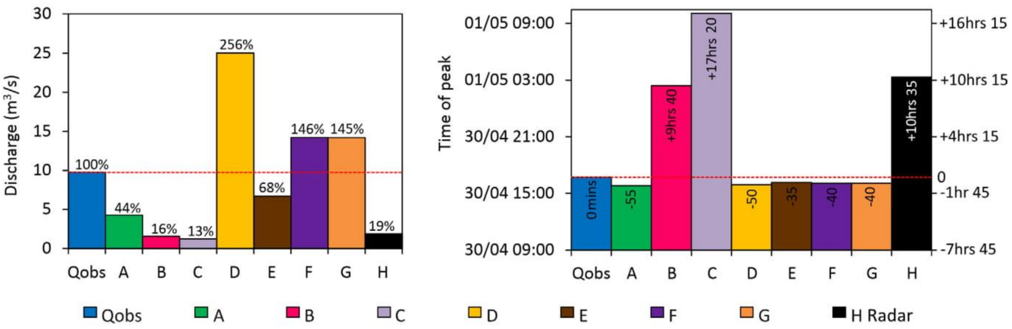


Fig. 11. A comparison between observed Q (*Qobs*) and modelled discharge (*Qsim*) for Models A-H at Cawfields Caw Burn during the 30th April 2014 event: peak discharge (left) and timing of the peak discharge (right).

discharge using the site's rating curve) have also been added to the Broomshaw comparison. Graphs help to interpret model performance relating to the shape of the hydrographs, and more specifically, the rapid rise which is only reproduced when community-based observations are integrated. Use of rainfall radar appears to improve the response of the model compared with use of only the two traditional rain gauges, but a flashy response is still absent. Although the community failed to record a river level (therefore river level gauge board (RLGB) *Qobs*, once converted to discharge) as the burn peaked at Broomshaw, the modelled hydrographs did correlate well with the six spot readings that they did manage to observe. This is true for all but the 'traditional only' models. A variety of quantitative and qualitative community-based observations have therefore been beneficially incorporated into SHETRAN and used to validate the model. However, the value of these observations are governed by a number of factors, for instance, when the peak exactly occurs (time of day, week and season) and proximity of monitoring sites to residents' homes.

Fig. 11 quantifies the impacts of each rain gauge combination on timing and magnitude of the flood peak for the Caw Burn at Cawfields. For this particular case, the following findings are highlighted when compared with observed peak discharge:

- Models B and C (traditional only combination) underestimate the flood peak by 84% and 87% respectively. Rainfall radar closely follows with 81%;
- Model D, which used a uniform grid of community-based observations, overestimates the flood peak by 156%;
- The best representation of magnitude comes from Model E, a combination of four gauges which underestimates the flood peak by 32%. This is better than Model A, and despite containing the rejected rain gauge, Model E is likely to have created a better representation of the rainfall extent;

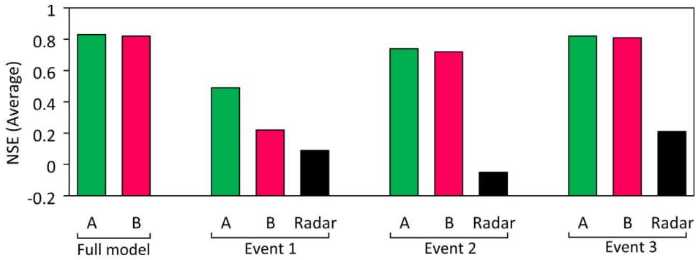


Fig. 12. NSE coefficients obtained from three key models of interest (Model A, B and Rainfall radar), each shown for the full modelling period (Jan 2014 – May 2015) and Events 1, 2 and 3. Graphs display average NSE results across all six gauging stations.

- All models containing community-based observations produce peaks which arrive within 55 min of the observed, with Model E being the closest at 35 min. Extra rain gauges above the town would have captured the extent of this intense storm more precisely, which in turn would generate a more accurate time lag;
- The timing of the traditional only combinations were considerably delayed because the hydrographs were too attenuated. The peak of the flood was over 9 h (Model B), 10 h (rainfall radar) and even as delayed as 17 h (Model C).

Event 1 has also been compared here against Event 2 (August) and 3 (December) to determine how far the value of community-based observations varies depending on the nature and length of the hydrological event (the same set of statistics and plots as those in this section are available in the Supplementary Material for these two additional events). Fig. 12 highlights the key differences between Events 1, 2, and 3, and the full 491 days modelled. The comparison uses NSE coefficients obtained, on average across the six gauging stations, from Model A and also B and H (radar) as these models alone present practical combinations which stakeholders would typically use (i.e. the best combination of traditional ground-based gauges (B) or rainfall radar (H) data which would normally be available) if the community-based observations did not exist to create Model A. Based on these plots, it is clear that the inclusion of community-based observations alongside traditional data (Model A) adds most value (higher NSE) to the localised flash flood event in April. Very little value is added during the longer modelling period and the prolonged winter storm, meaning that the traditional gauges alone were sufficient. Little value is also added to Event 2, a short-lived storm which was concentrated over the upper catchment. Nevertheless, the outcome obtained from Event 2 was significantly governed by the location of this particular storm and the fact that there were no community-based rain observations to represent it. Models containing rainfall radar observations consistently reduced model performance, thus has not been affected by the nature or length of the storm.

The patchwork of quantitative and qualitative community-based observations used here were required to help capture the intense rainfall and flash flood response during Event 1. Smith et al. (2015) and Kutija et al. (2014) also emphasise the value of community-based observations during these hydrologically important events given that they are short-lived. Accurate coverage of the rainfall extent is also required, however, as it can cause significant over- or under-estimation if incorrect. Timing and magnitude are important factors which affect public response on the ground, response by organisations responsible for flood forecasting and warning, as well as catchment managers designing intervention measures to withstand or relieve short-lived floods. Community-based observations can therefore make a difference; they have the potential to increase the spatial resolution of ground-based gauges, as well as ground-truth rainfall radar observations which are routinely adjusted using gauge-based factors (Wang et al., 2015). Our findings also compliment Seibert and McDonnell (2015), who found that a small number of 'soft' and 'fuzzy' qualitative (knowledge-based) observations are extremely useful for understanding and modelling how catchments work, particularly under high flow conditions. Seibert and McDonnell (2015) also suggest combining these informal observations with the often limited network of traditional gauges. However, such an approach relies on unpaid members of the public to be physically present, actively monitoring and collecting good quality observations, which cannot always be guaranteed.

In this case study, seven manual rain gauges were originally distributed within the Haltwhistle Burn catchment ready for community-based monitoring, but only two of these (Townfoot and Cawburn) returned data covering the full modelling period. Due to the nature of citizen science and the practicality of getting volunteers to observe parameters manually over time, it is to be expected that datasets may be missing or incomplete from some monitoring sites. If the community were to be informed that their observations are most useful during localised flash flood events, then they can prioritise their monitoring efforts and pinpoint these specific occasions. In turn, the most valuable observations are more likely to be captured for a greater number of monitoring sites, and with an increased temporal resolution. There are obvious health and safety implications for members of the general public with this regard and the engagement, training and facilitation activities required to activate community-based monitoring schemes should be prioritised.

5. Conclusions

The Haltwhistle Burn catchment and focus community have been used to demonstrate the value of real community-based observations using a PBSD catchment model (SHETRAN) under a range of scenarios. It is clear that the wider public can provide valuable inputs via citizen science style data collection activities pertinent to catchment characterisation, modelling and management. Community-based activities are less complicated, significantly cheaper and less demanding (e.g. for power and processing) than their traditional counterparts, yet results here highlight how effective and valuable they can be. Examples presented here emphasise the importance of spatial and temporal information at a sub-catchment scale. Two key conclusions can be drawn from this work:

1. Our modelling results illustrate how a patchwork of quantitative and qualitative community-based observations (which together yield information relating to rainfall totals, timing, duration, and therefore intensity) are required alongside tradi-

tional sources of hydro-information in order to fill spatial and temporal data gaps, and to characterise local catchment response more accurately than using traditional data alone. This includes the behaviour, timing and magnitude of river response during and after floods;
2. Evidence presented here confirms that community-based rainfall observations are most valuable during local flash flood events. This information would otherwise often be missed, be under-unrecorded by existing ground-based gauges, or else be significantly underestimated by rainfall radar. Community-based observations are less valuable during prolonged and widespread floods, or over longer hydrological periods of interest.

Community-based observations have the potential to add spatial detail and to ground-truth existing traditional sources of catchment data, providing accurate information to support monitoring applications nationally, including weather and flood forecasting, modelling and longer-term catchment management initiatives. If community-based monitoring efforts are to be prioritised or streamlined, then, as with any hydrological monitoring, this potential can only be realised if appropriate procedures for quality control checking are established and followed. If the public recognise which of their observations are most valuable, and they are properly trained, then they are more likely to continue monitoring and providing good quality datasets which can contribute to the catchment management toolkit in the longer term.

It is acknowledged that the results presented here are location-, community-, event- and equipment-specific. However, this case study provides an early insight into what can be achieved and the value that is added when public participation is integrated into the catchment characterisation and management process. Data outcomes will evolve and improve over time given that citizen science is flourishing in line with technological advances, but will be naturally limited by participation levels. Overall, we conclude that a citizen science approach offers local communities an exciting way to learn about their local water environment, engage with professional stakeholders, and be actively part of the catchment management process.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.03.019. These data include Google maps of the most important areas described in this article.

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Appendix 6D – SHETRAN Models 2A-2I and 3A-3H

The calibrated and validated SHETRAN Model 1A (described in Appendix 6C) was edited by simply altering the input rainfall grids in order to simulate scenarios 2A+ and 3A+. To ensure that the same conditions (groundwater, soil and surface water) were passed through to these additional models, Model 1A was incorporated into the beginning of each simulation (i.e. provided initial conditions) and then run until it reached the starting point for Models 2A+ and 3A+. This methodology ensured seasonal variations in infiltration capacities were accounted for.

Rain gauge combinations for Models 2A-2I (with focus on the 8th August 2014 event)

Figure App-6D-1 illustrates the combination of rain gauges and subsequent Thiessen polygon maps used to drive each model. Each of these models were run from 05/08/2014 to 24/10/2014 (full model) and also analysed from 07/08/2014 to 11/08/2014 (Event 2).

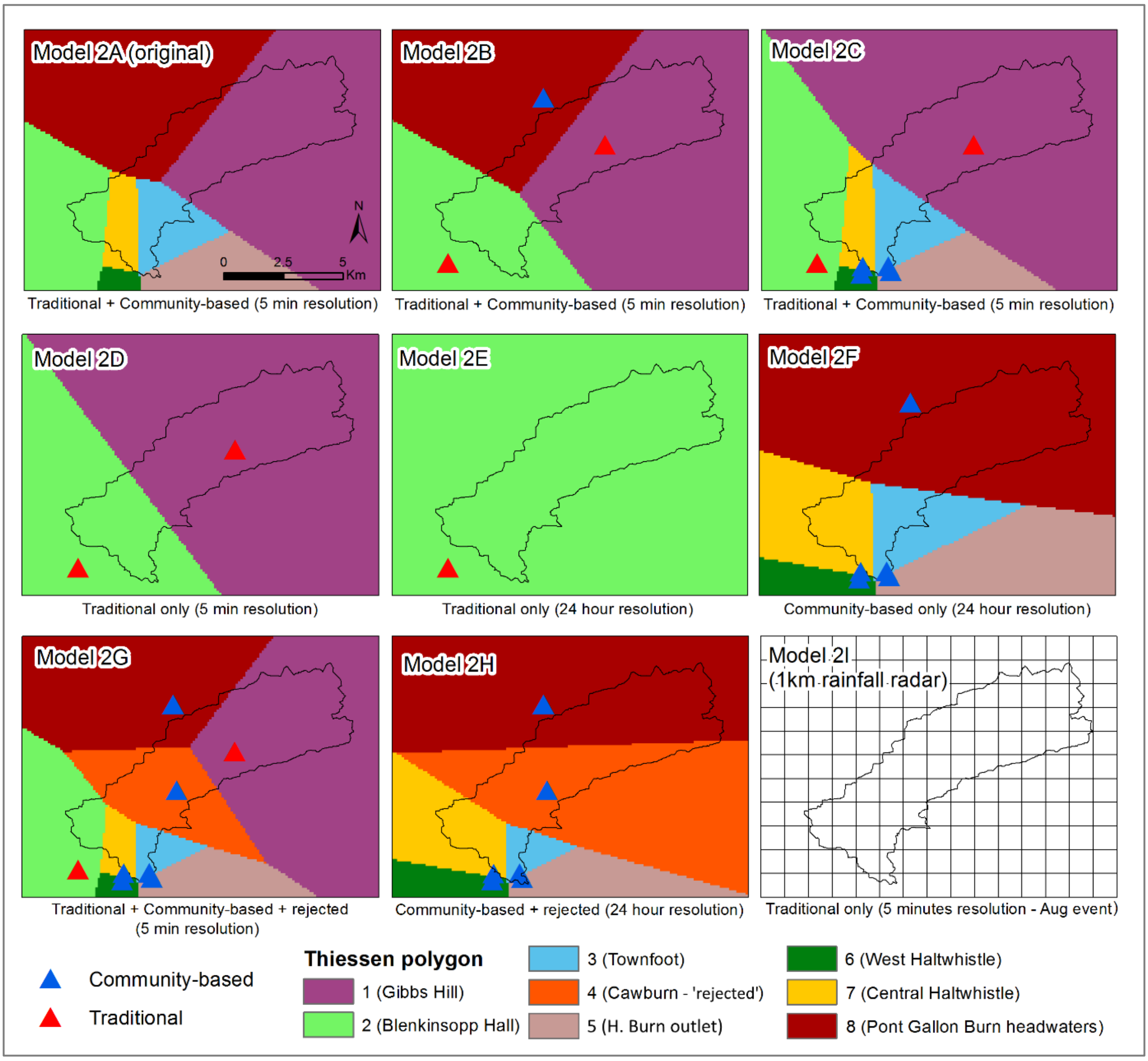


Figure App-6D-1 Combination of rain gauges and resulting Thiessen polygons used to estimate rainfall across the catchment in Models 2B-2I. These scenarios were tested using SHETRAN.

Rain gauge combinations for Models 3A-3H (with focus on the 22nd-23rd December event)

Figure App-6D-2 illustrates the combination of rain gauges and subsequent Thiessen polygon maps used to drive each model in this series of scenarios. Each of these models were run from 13/11/2014 to 01/01/2015 (full model) and also analysed from 21/12/2014 to 29/12/2014 (Event 3).

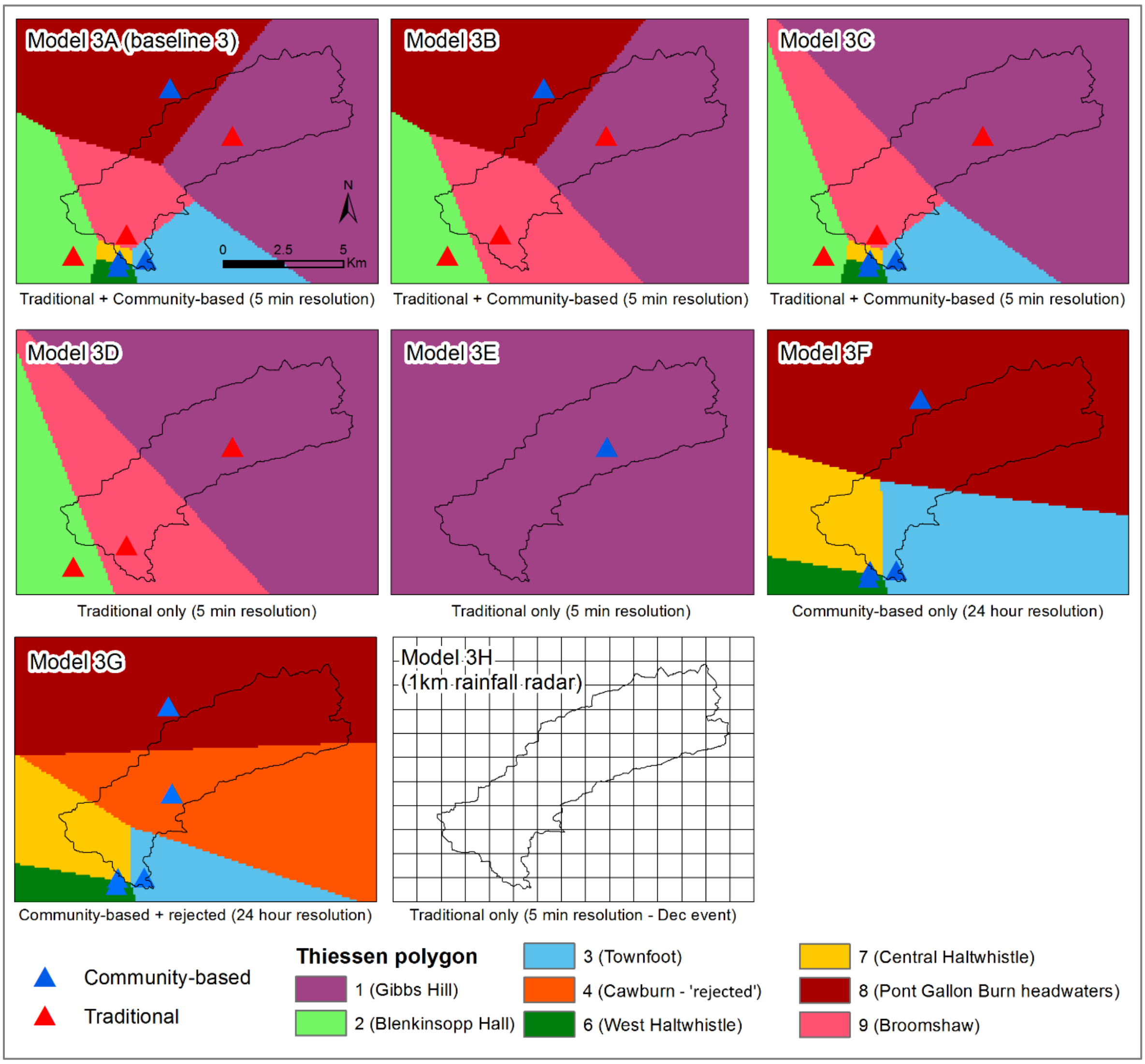


Figure App-6I-2. Combination of rain gauges and resulting Thiessen polygons used to estimate rainfall across the catchment in Models 3B-3H. These scenarios were tested using SHETRAN.

Appendix 6E – Slaty Sike NFM gauge summary sheet & QC checks (traditional)

Water level recorder (WLR): Slaty Sike 1

Coordinates: 369077 565365

Upstream catchment area: 0.25km^2

Model: Diver (DI: 241)

Software: Diver Office

Supplier specification sheet: http://bit.do/divers

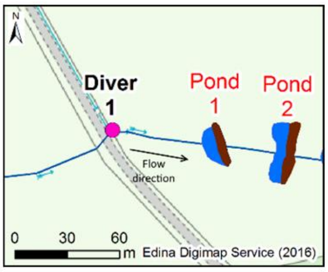
Installation date: 31/05/2015

Logger resolution: 5-minute

Siting: upstream of all NFM features.

Notes: located downstream of road culvert which controls the flow. Installed in white tube to reduce diurnal temperature effect. No gaps in data after 01/10/2015. Gauge installed left bank of channel.

Location map & photograph of gauge



Water level recorder (WLR): Slaty Sike 2

Coordinates: 369323 565343

Upstream catchment area: 0.48km^2

Model: Diver (DI: 240)

Software: Diver Office

Supplier specification sheet: http://bit.do/divers

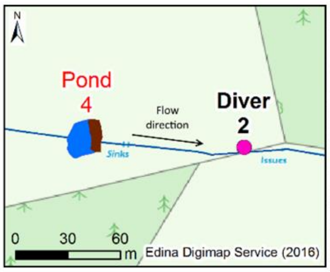
Installation date: 31/05/2015

Logger resolution: 5-minute

Siting: downstream of all four ponds.

Notes: Installed in white tube to reduce diurnal temperature effect. No gaps in data after 01/10/2015. Gauge installed left bank of channel.

Location map and photograph of gauge



Water level recorder (WLR): Slaty Sike 3

Coordinates: 369605 565189

Upstream catchment area: 0.66km^2

Model: Diver (DI: 241)

Software: Diver Office

Supplier specification sheet: http://bit.do/divers

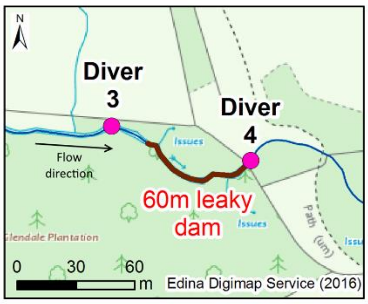
Installation date: 31/05/2015

Logger resolution: 5-minute

Siting: downstream of knickpoint, but upstream of the 60m leaky dam.

Notes: Installed in white tube to reduce diurnal temperature effect. No gaps in data after 01/10/2015. Gauge installed left bank of channel.

Location map & photograph of gauge



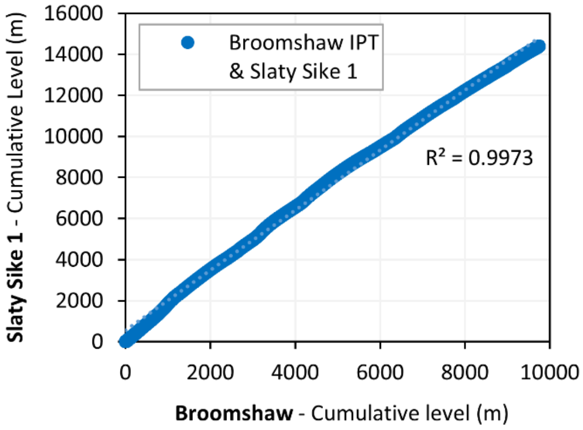
Slaty Sike 4

Slaty Sike 4 did not yield any data due to equipment failure (which created gaps). The gauge was also left permanently damaged by cattle.

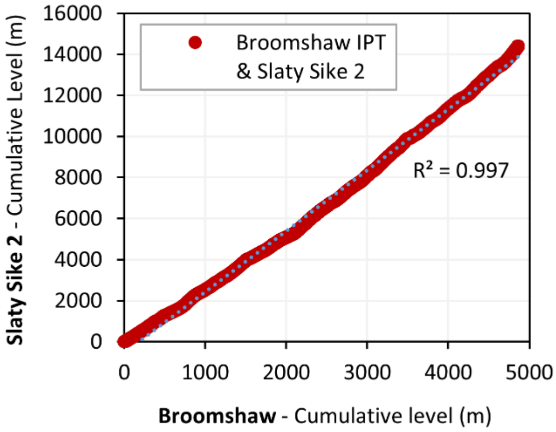
Quality control (QC) – applies to all Slaty Sike gauges 1-3:

WLRs were installed appropriately following relevant guidance documents (WMO, 2008). Sensors were located along clear, representative, safe and accessible stretches of the river network, away from obstructions, backwater effects, and morphological activity, and were secured to the river bed at well-defined cross-sections. The sensors themselves were submerged into white plastic pipes to protect them from debris-, flood- and ice-related damage, which also helped to maintain a constant datum over time. It was important that the sensor's position remained unchanged over time. Checks were carried out during each site visit using a tape measure to ascertain this. While divers are known to be sensitive to diurnal temperature changes, they have not been corrected here for this as the effect is negligible in the context of this case study (especially as high flow events are of interest). White tubes have also been used which minimised this effect. Raw data were processed using Diver Office, and checked for outliers and erroneous points. All datasets have been compared against the high precision data obtained by the impress pressure transducer (IPT) at the Broomshaw gauge, which is located on the main Haltwhistle Burn - see double-mass plots below.

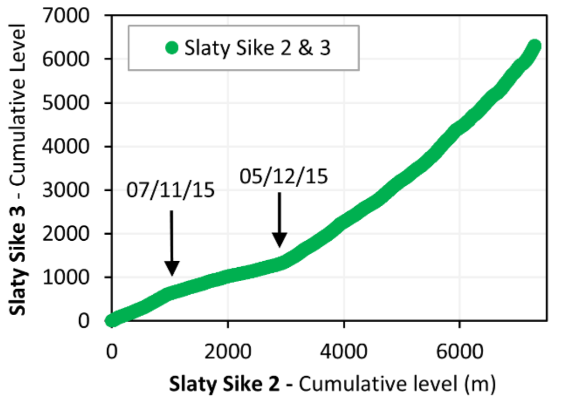
Slaty Sike diver 1:



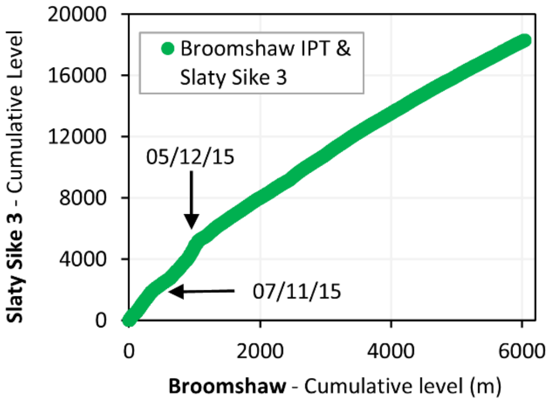
Slaty Sike diver 2:



Slaty Sike Diver 3:



Slaty Sike diver 3:



Double-mass curves use paired data where available for Oct-2015 to Feb-2016. Slaty Sike 3 has been affected by sediment movement and deposition as it is located upstream of the leaky dam.

Appendix 6F – Slaty Sike NFM observations (community-based)

1) 14th August 2015 (13:00-13:30 GMT)


Pond 2


Pond 3


Leaky dam (half way along)

2) 9th November 2015 (10:40-11:15 GMT)


Pond 1


Pond 2


Pond 3


Knickpoint


Leaky dam (entrance)


Leak dam (towards exit)

3) 11th November 2015 (09:50-10:10 GMT)


Pond 1

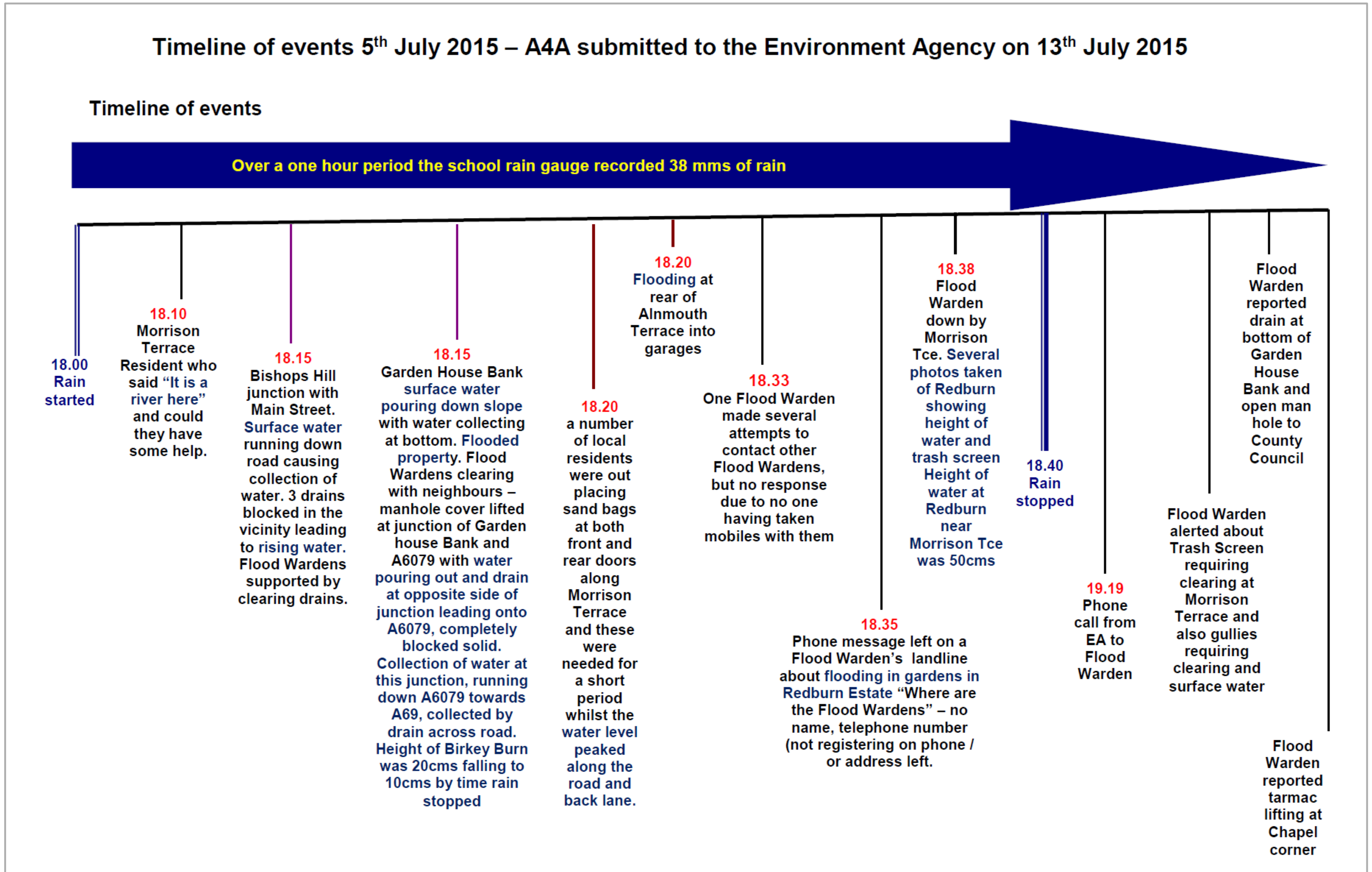

Pond 1 bund


Leaky dam (half way along looking upstream)


Leaky dam (half way along looking downstream)

4) 8th December 2015 (10:50-11:30 GMT) – after Storm Desmond had passed.	
 Example of pond siltation *"The bottom of the ponds are very very silty"*	 Knickpoint – mass erosion *"I am pretty sure the point of erosion is moving back u/s leading to the collapse of the bank d/s"*
 Leaky dam entrance - gravel & stones trapped *"The gravel, sand and mud in the gravel amongst the logs is very firm"*	 Leaky dam entrance - gravel & stones trapped *"There a few areas of deeper water too where the logs have held back the water"*
 Leaky dam entrance - gravel & stones trapped	 Leaky dam (half way along) – no deposition.

Appendix 7A – Acomb's flood timeline generated using community-based observations



Flood timeline reproduced with permission from Acomb Flood Action Group (edited to ensure content is anonymised.). Blue text relates to community-based rainfall, river level or flood-related observations collected during the event. This timeline was used by the community and Environment Agency to improve Acomb's Community Flood Plan.

Appendix 7B – Case study used by the Met Office to redevelop WOW

river watch

River Watcher

Community Group

A 'River Watcher' is a member of the local community who voluntarily carries out citizen science style monitoring activities and shares their observations with the wider community. Their primary goal is to understand and manage their own weather and water environment.

Summary

We live in a typical UK rural setting where there is limited historical records about our weather and water environment. In order to characterise river response, raise awareness across our community and plan for mitigation measures, we need data, therefore evidence on a local level.

As a River Watcher, I would like access to Met Office WOW to primarily

- Submit my own river, weather and flood observations
- View other people's observations (within my own community and others nationally)
- Visualise observations through space and time in an effective way
- Download current and historical data relating to a location or boundary of interest

As a community group, we need somewhere to store and share our data using a service which is free, familiar, accessible, reliable and will be available long term.

We have access to desktop computers, tablets and smartphones so we would like Met Office WOW to work easily using any of these devices. Some of us also use Twitter.

As we are often out observing our local watercourses, we would also make use of a Met Office WOW app to submit real-time observations on the go. The app would need to be simple, quick and easy to use and freely available for download via the Apple and Android app stores. Ability to store records whilst offline and upload later would also be advantageous.

The types of observations we are currently collecting include historical anecdotal weather and flood information, manual river levels, 24 hour rainfall totals, evidence before, during and after heavy rain and flood events, as well as various water quality parameters. We would ideally like to submit as many of these observations as possible using WOW. Some of our observations are manually collected, others are via automatic equipment. Date, time and location (georeferenced where possible) are mandatory information for each data record.

Even though we collect quantitative information, videos and photographs are the most common form of observation. The system would need to cope with large file sizes.

Visualisation and feedback is essential, therefore we would like observations to be summarised using effective graphics (e.g. graphs) and key statistics and for this information to be extracted through a simple and customisable widget which we can easily add to our own website.

The more communities who use Met Office WOW the better, therefore successful advertisement and engagement with all age groups is essential.

Appendix 8A – Evidence of wider benefits as a result of community-based monitoring

Quotes extracted from observational work carried out in the Haltwhistle and Acomb communities over the duration of the project.