Resilience of shallow groundwater resources and their potential for use in small-scale irrigation: a study in Ethiopia

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Abstract

Groundwater use for small-scale irrigation in sub-Saharan Africa is low, though is expected to increase in the near future. There is currently limited understanding of shallow groundwater resources, which are most likely to be exploited by poor rural communities due to their accessibility. This PhD study aimed to determine the potential for use of shallow groundwater for small-scale irrigation and the resilience of the resources to increased abstraction, land-use change and climate variability.

Research was conducted principally at a study site in northwest Ethiopia with seasonal rainfall and a predominance of rainfed agriculture. The shallow aquifer comprises a thin weathered regolith above largely impermeable basalt. Hydrochemistry analyses suggested little connection between the shallow aquifer and a deep fractured aquifer.

To fill gaps in formal hydrometeorological monitoring, a community-based monitoring programme was initiated. Statistical comparisons confirmed that the datasets were of as high or higher quality as those from formal networks, remote sensing and reanalyses.

A recharge assessment estimated annual recharge of 280-430 mm, confirming that a sufficient renewable shallow groundwater resource is available for small-scale irrigation. Four nested catchments were modelled using SHETRAN, a physically-based spatially-distributed modelling program. The modelling identified the foot of hillslopes and narrow valleys as showing the greatest potential for irrigated agriculture as groundwater in those locations remained available and accessible for the longest periods. Potential future scenarios were run in the SHETRAN models considering likely climate variability, land use change and increasing abstraction. Around 35% of arable land in the modelled catchments had shallow groundwater available throughout the dry season. During simulated multi-year droughts, a significant percentage of arable land still had sufficient groundwater available for irrigation of a second growing season. Conversion of pasture and scrubland to cultivated land did not have a significant impact on water resources while degradation of highlands to bareground had a positive impact. The severest impact on water resources resulted from increased coverage of Eucalyptus. Notably, simulation of increased abstraction and irrigation at smallholder levels had little impact on surface and groundwater availability.

This study demonstrates the potential for greater exploitation of shallow groundwater for small-scale irrigation by rural communities and the resilience of the resource to climate variability, land use change and increasing abstraction.

For Robert and Kate, Jack and Mavis

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Related publications

The following publications contain work related to or derived from this thesis:

Walker, D., Jovanovic, N., Lebea, T., Bugan, R.D.H., Abiye, T.A., du Preez, D., Parkin, G. and Gowing, J. (2018) 'Alluvial aquifer characterisation and resource assessment of the Molototsi sand river, Limpopo, South Africa'. *Under review*.

Walker, D., Smigaj, M. and Jovanovic, N. (2018) 'Ephemeral sand river flow detection from satellite optical remote sensing'. *Under review*.

Walker, D., Parkin, G., Schmitter, P., Gowing, J., Tilahun, S.A., Haile, A.T. and Yimam, A.Y. (2017) 'Insights from a multi-method recharge estimation comparison study', *Groundwater*. *In-press*.

Walker, D. (2016) 'Properties of shallow thin regolith aquifers in sub-Saharan Africa: a case study from northwest Ethiopia', *7th RWSN Forum "Water for Everyone"*. Abidjan, Côte d'Ivoire, Nov-Dec 2016. Available at: https://rwsnforum7.files.wordpress.com/2016/12/full_paper_0061_submitter_0166_walker_david-rev1.pdf

Walker, D., Forsythe, N., Parkin, G. and Gowing, J. (2016) 'Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme', *Journal of Hydrology*, 538, pp. 713-725.

Gowing, J., Parkin, G., Forsythe, N., Walker, D., Haile, A.T. and Alamirew, D. (2016) 'Shallow groundwater in sub-Saharan Africa: neglected opportunity for sustainable intensification of small-scale agriculture?', *Hydrol. Earth Syst. Sci. Discuss.*, 2016, pp. 1-33.

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List of abbreviations and acronyms

ADSWE	Amhara Design & Supervision Works Enterprise (consultancy and laboratory in Bahir Dar, Ethiopia)
AET	Actual evapotranspiration
ARBA	Abay River Basin Authority
AMGRAF	Adaptive management of shallow groundwater for small-scale irrigation and poverty alleviation in sub-Saharan Africa (Newcastle University research project)
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
BFI	Baseflow index
BP	Before present
CMB	Chloride mass balance
DEM	Digital elevation model
DFID	Department for International Development (UK)
DHI	Danish Hydrological Institute
EC	Electrical conductivity
ENSO	El Niño – Southern Oscillation
ERT	Electrical resistivity tomography
ESRC	Economic and Social Research Council (UK)
ET	Evapotranspiration
Ethiopian ATA	Ethiopian Agricultural Transformation Agency
FAO	Food and Agriculture Organization of the United Nations
GCM	General circulation model
GDP	Gross domestic product
GPS	Global positioning system
GSE	Geological Survey of Ethiopia
GWI	Groundwater irrigation
HDW	Hand-dug well
IPCC	Intergovernmental panel on climate change
ITCZ	Inter tropical convergence zone
IUC	Irrigation user community
IWMI	International Water Management Institute

K	Hydraulic conductivity
LST	Land surface temperatures
LULC	Land use land cover
Ma	Million years
MAP	Median annual precipitation
m asl	Metres above sea level
mbgl	Metres below ground level
MC	Soil moisture retention (root zone storage)
MDG	Millennium Development Goal
MER	Main Ethiopian Rift
METI	Ministry of Economy, Trade, and Industry of Japan
MPI	Multi-dimensional poverty index
MoWIE	Ethiopian Ministry of Water, Irrigation and Electricity
MoWR	Ethiopian Ministry of Water Resources
MoANR	Ethiopian Ministry of Agriculture and Natural Resources
NASA	United States National Aeronautics and Space Administration
NDVI	Normalized difference vegetation index
NERC	Natural Environment Research Council (UK)
NGO	Non-Governmental Organisation
NMA	Ethiopian National Meteorology Agency
NSE	Nash and Sutcliffe efficiency
PET	Potential Evapotranspiration
PCC	Pearson correlation coefficient
QGIS	An open source geographic information systems (GIS) application
RCM	Regional climate model
RIB	Rainfall infiltration breakthrough model
RMSE	Root mean square error
R-S	Remote sensing
RWSN	Rural Water Supply Network
SDGs	Sustainable Development Goals
SMB	Soil moisture balance
SPEI	Standardised precipitation-evapotranspiration index
SPI	Standardised precipitation index
SRA	Standardised rainfall anomaly
SRTM	Shuttle Radar Topography Mission

SSA	Sub-Saharan Africa
S_y	Specific yield
T	Transmissivity
T-M	Thornthwaite-Mather method
TEJ	Upper-level tropical easterly jet
TRMM	Tropical Rainfall Measuring Mission
UNSA	Unconsolidated sedimentary aquifer
UPGro	Unlocking the Potential of Groundwater for the Poor (NERC/ESRC/DFID funded research programme)
USAID	United States Agency for International Development (USA)
VSMOW	Vienna Standard Mean Ocean Water
WETSPRO	Water Engineering Time Series Processing Tool
WHAT	Web GIS based Hydrograph Analysis Tool
WHO	World Health Organisation
WHYMAP	Worldwide hydrogeological mapping and assessment programme
WMO	World Meteorological Organisation
WTF	Water table fluctuation
WUA	Water users association
WUC	Water user committee

Chapter 1. Introduction

1.0 Chapter summary

This chapter provides the context of the PhD research, which will be explored in greater detail in Chapter 2. The overall aims are presented along with the research questions that this study attempts to answer. A general methodology states how the research was conducted and how the chapters link together. Finally, an outline of the thesis explains what can be found in each chapter.

1.1 Context

The availability of groundwater in Africa and its potential for agricultural use has been increasingly reported in recent years with many authors predicting that a rapid expansion in groundwater exploitation may be about to happen in sub-Saharan Africa (SSA) (MacDonald *et al.*, 2012a; Namara *et al.*, 2013; Pavelic *et al.*, 2013a; Villholth, 2013; Baguma *et al.*, 2017). Such a growth in the exploitation of groundwater resources in South and East Asia since the 1970s promoted improved living standards and fostered economic development (Calow et al., 2009a; Narayanamoorthy, 2010). MacDonald *et al.* (2012a) estimate the total groundwater storage in Africa to be 0.66 million km^3. Despite this seemingly extremely high groundwater availability, over 90% of agriculture in Africa is rainfed (Wani *et al.*, 2009; McClain, 2013) and Siebert et al. (2010) report that only 3.3% of arable land in SSA is irrigated, compared to 37% in Asia (Figure 1-1). Such figures suggest there is ample water and space to expand areas under irrigation. Indeed, the renewable groundwater resources per capita in some of the Asian countries that experienced the "Green Revolution" stand at ~600 m^3/a in China and ~400 m^3/a in India, while in SSA the available quantity is ~2400 m^3/a (FAO (2003) cited in Giordano (2006)). Considering the sustainability of the available resource, Frenken (2005) using FAO AQUASTAT data, showed that the Sudano-Sahel region uses only 35% of its total internally renewable water resource while coastal West Africa uses just 1.3%. The maps in Figure 1-1 show a remarkable contrast between Asia and Africa; however, fifty years ago, prior to the Green Revolution, the Asia map would have looked similar to how the Africa map looks today.

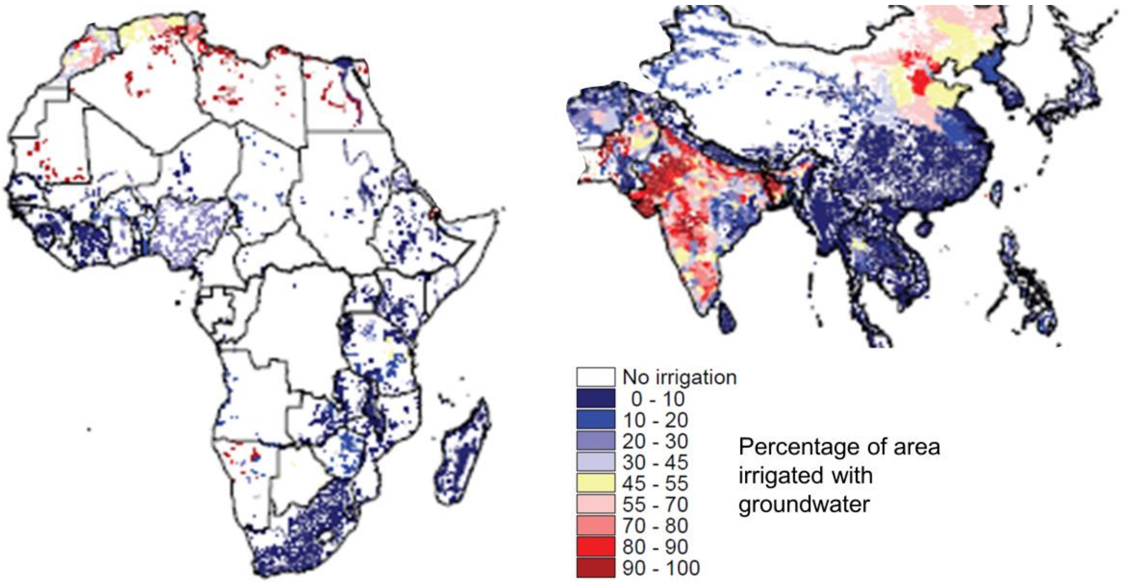


Figure 1-1. Comparison between South and East Asia, and Africa of percentage area irrigated by groundwater (adapted from Siebert et al. (2010)).

Small-scale irrigation, in particular from groundwater, is increasingly promoted by governments, donors and NGOs as an important tool to alleviate poverty, improve food security, boost rural employment and economic development, promote gender equality, and mitigate against increasing climate variability (Kay, 2001; Ngigi and Denning, 2009; Abric et al., 2011; Villholth, 2013). In the latter case, groundwater behaviour is significant in that it responds slowly to drought, unlike the "flashy" response of surface water (Figure 1-2). Therefore, groundwater is considered able to buffer short-term climate impacts (Calow *et al.*, 1997; MacDonald *et al.*, 2009).

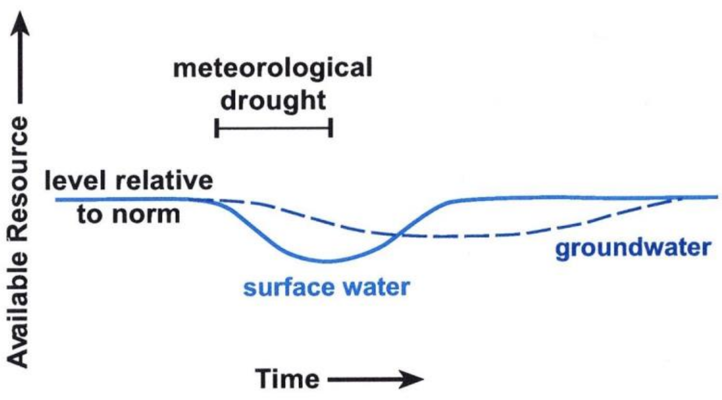


Figure 1-2. Contrasting response and recovery behaviour of groundwater and surface water to drought (from Robins and Fergusson (2014)).

Smallholders themselves, where they can find the necessary means and finances, prefer groundwater irrigation in comparison to large-scale irrigation schemes, due to the autonomy it provides and the enhanced livelihoods created by moving from subsistence to market-oriented agriculture (Giordano et al., 2012; Dittoh et al., 2013). Groundwater is further preferred because it is generally available at the point of use, can often be developed quickly with low capital cost by individuals, and is available on-demand (Foster and Shah, 2012). It is well documented that abundant groundwater abstracted via deep formal systems can provide secure and perennial water availability. However, deeper systems require large initial investment, high maintenance, and strict farmer organisation to deal with water-sharing. Shallow informal systems, which tend to be farmer-driven rather than in the control of the public sector, are spontaneous and autonomous (Kay, 2001; Villholth, 2013). For example: in Tanzania, surveys by Sokile and van Koppen (2004) revealed that more than 70% of water users prefer to settle water disputes via informal channels, such as local water users associations (WUAs), rather than relying on formal state-based institutions; and in Ghana, private smallholder irrigation already employs 45 times more people and covers 25 times more area than public irrigation schemes (Giordano *et al.*, 2012).

The focus of this study concerns the utilisation of shallow groundwater resources for small-scale irrigation. Notably, Figure 1-3 shows that low to moderate-yielding shallow aquifers predominate in the more densely populated areas. There is little agreement in the literature over how shallow is "shallow" when it comes to groundwater. For this research, shallow groundwater is defined as <25 m. Although there are exceptions around the world, 25 m depth is considered the maximum feasible limit of excavation of "hand-dug" wells (Watt and Wood, 1977; Abbott, 2013). In addition, much of the existing small-scale groundwater irrigation depends on a water table depth less than 5 m because of power limits on water-lifting and because of available technology. Motorised pumps are much less common than manual lifting methods in SSA – used in less than 20% of water-lifting cases in various surveys conducted by Namara et al. (2013) – due to smallholder farmers' lack of capital and ability to obtain credit. This means that groundwater irrigation is restricted to shallow hand-dug wells for poorer farmers; depths of 50 m – the definition of shallow by some authors – cannot be regarded as easily accessible for small-scale irrigation. Because poor rural communities manually excavate wells, the predominance of consolidated and crystalline bedrock restricts the potential locations for manual well excavation. However, unconsolidated sediments cover approximately 25% of Africa (Guiraud, 1988). What's more, when river valley sediments and regolith above crystalline basement or more recent volcanics are considered, the extent of the shallow geology with potential for manually-excavated or manually-drilled wells becomes pervasive (a conclusion supported by the work of Fussi (2011); Fussi *et al.* (2016)).

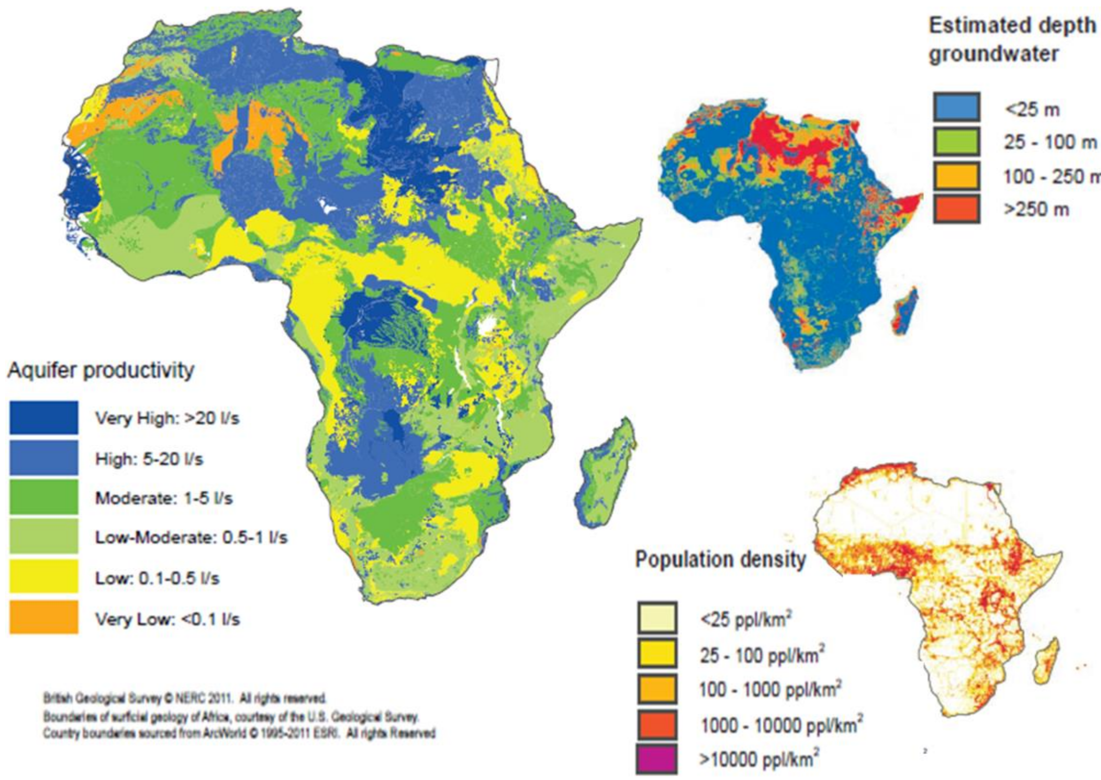


Figure 1-3. The aquifer productivity map across Africa, estimated depth to groundwater, and population density map (adapted from MacDonald *et al.* (2011)).

The importance of these shallow materials as locally important aquifers is well reported. Typically simultaneously reported is the dearth of observations of such groundwater systems, in particular sustained time-series data (Martin and Van De Giesen, 2005; Robins *et al.*, 2006; Calow *et al.*, 2009b; MacDonald *et al.*, 2009; Taylor *et al.*, 2009; Ethiopian ATA, 2013). This scarcity of data leads to poor understanding of the resource. What's more, any attempts to model the hydrogeological system to improve understanding would be problematic without monitoring data. Community-based monitoring data was utilised for this research to circumvent the issue of the lack of formal hydrometeorological time-series data. In addition to providing data in locations where there are sparse formal alternatives, benefits to the local community include an increased understanding of their resource and a sense of ownership and empowerment (Garduño and Foster, 2010; Conrad and Hilchey, 2011; Buytaert *et al.*, 2014).

It is not straightforward to define what is meant by "small-scale", or "smallholder", irrigation. The World Bank (2003) defines smallholders as those having a low asset base and less than 2 ha of cropped land. The FAO defines smallholders as farmers with “limited resource endowments, relative to other farmers in the sector” (Dixon *et al.*, 2003). Essentially, “small-scale irrigation” is used to describe irrigation activities of small spatial extent and/or involving a low number of irrigating farmers, although it is also applied to irrigation schemes that have a high degree of local involvement at planning and development stage, use locally available resources and technology, and have a local impact (Adams and Carter, 1987). The latter such situation is frequently described as “informal” to draw a distinction from centrally planned and bureaucratically controlled schemes. While for many authors “informal” irrigation is synonymous with “smallholder”, it is noted that many others draw a distinction between “smallholder” and “small-scale” citing examples such as the large-scale irrigation projects in Egypt and Sudan of 50+ ha that are farmed by hundreds of smallholders each occupying <1 ha (Kay, 2001). The only consensus on small farms seems to be the lack of a clear definition (Nagayets, 2005). The working definition used here is from Adams and Carter (1987), though in this study smallholder and small-scale irrigation are used interchangeably: “…the management of the supply of water to crops or other economically useful plants, which is organised and controlled by the landholder or groups of landholders; the extent of such activities does not normally exceed 10 ha per farm family, and may be as little as 0.1 ha.” A study by Nagayets (2005) revealed that Ethiopia tops the list of African countries with small farms, having almost 9.5 million small farms (<2 ha), comprising 87% of all farms within the country. Incidentally, the top two countries on the global list are China and India with ~190 million and ~93 million small farms.

1.2 Aims

The aims of this PhD research were, firstly, to determine the potential for small-scale irrigation and the resilience of shallow groundwater resources used by rural communities at a representative study site in Ethiopia. Secondly, to develop transferable methodologies for assessment of shallow groundwater resources throughout SSA. The following questions were researched:

1. Do shallow aquifers have the requisite properties, in terms of hydraulic conductivity, potential well yield, specific yield, aquifer geometry and hydrochemistry, for productive groundwater use?
2. Due to the scarcity of time-series data, are community-based hydrometeorological monitoring programmes able to produce useful, high quality data comparable to formal data sources?

3. Can shallow groundwater be considered a renewable resource, and; which recharge assessment methods provide the highest confidence in the calculated recharge amounts when applied to these types of aquifers?
4. Are there identifiable zones that show the greatest potential for sustainable intensification of agriculture through shallow groundwater irrigation?
5. How will climate variability, land use change and increased abstraction impact shallow groundwater resources and surface water?

1.3 Study site

The principal research, including field investigations, was conducted for a field site in Ethiopia (Figure 1-4). The field site was chosen to be representative of a much wider area. The site is currently reliant on rainfed agriculture though has been identified by the Ethiopian Agricultural Transformation Agency (ATA) as a location for potential future agricultural expansion: Currently 90-95% of farmed land in SSA is rainfed (Wani *et al.*, 2009; McClain, 2013). The field site is at high elevation within highlands and experiences high annual rainfall, which mostly falls during the five-month wet season; the Ethiopian Highlands are laterally extensive comprising 50% of Ethiopia, consequently they are known as the roof of Africa, and highland areas with >1000 mm/a seasonal rainfall exist across Central and West Africa (Frenken, 1997). Cenozoic volcanics underlie the field site: Around 40% of Ethiopia is underlain by Cenozoic volcanic rocks (Prave *et al.*, 2016) and similar geology can be all along the East African Rift. Ethiopia is classified as a "low-income economy" by the World Bank (World Bank, 2017b), which translates on the ground to poor access to agricultural equipment and markets and poor ability to cope with climate or other stresses: 27 of SSA's 48 countries are classified as low-income. The study site is detailed in Chapters 3 and 4 while the transferability of the research is discussed further in Chapter 9.

Figure 1-4. Study site location.

1.4 Methodology

A graphic showing the step-by-step methodology is presented in Figure 1-5. Following desk study analysis of data relating to the study sites, extensive field investigations were conducted during three visits to Ethiopia. Time-series hydrometeorological data were analysed from a community-based monitoring programme and formal sources for use in modelling studies. Recharge assessments were conducted to estimate the renewable shallow groundwater resource. Models were constructed combining data from field investigations and hydrometeorological monitoring. At local scales, community monitored networks allowed direct comparison between modelled hydrological responses and field observations of groundwater levels and river flow. The modelling furthered the development of the conceptual model, increasing understanding of the shallow groundwater system, and enabling production of groundwater potential zone maps that revealed the best locations for groundwater abstraction for productive use. Simulations were run with potential future climate variability, land use and abstraction scenarios. Modelling outputs were processed to assess the impact of these potential future scenarios on the shallow groundwater resource and on surface water resources.

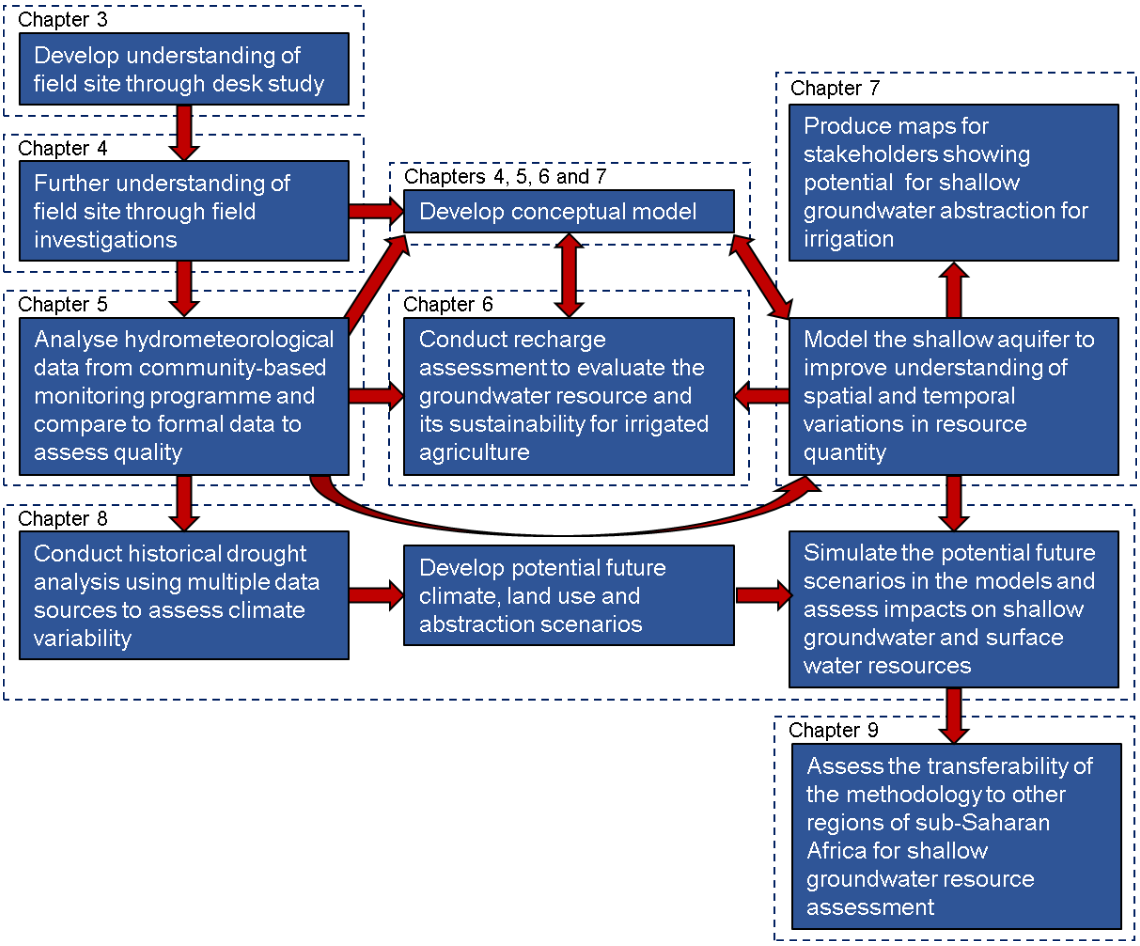


Figure 1-5. Methodology flow chart.

1.5 Thesis outline

Chapter 1 gives the context of the research and defines terms used throughout the thesis, presents the aim and research questions, and introduces the methodology applied to answer those questions.

Chapter 2 is a literature review that presents Asia's "Green Revolution" as justification for the study as well as providing background information on African hydrogeology and the African climate. The chapter then reviews literature identifying the research gap this PhD study aims to fill. It is noted here that this thesis does not have a single all-inclusive literature review as each chapter and some sections within chapters have their own relevant literature reviews.

Chapter 3 provides background information from desk study of the study site for which the research was predominantly conducted.

Chapter 4 details the field investigations conducted at the study site that led to the development of the described conceptual model.

Chapter 5 concerns community-based monitoring, detailing the programme setup in order to gather hydrometeorological time-series data for the project. The chapter presents the statistical comparison study conducted against data from formal sources in order to assess the quality of the community data.

Chapter 6 discusses groundwater recharge assessments. The multiple recharge estimation techniques applied are described and critically analysed.

Chapter 7 presents the modelling of the shallow aquifer. Model selection, construction and calibration are described along with the resulting insights and update on the conceptual model. Maps of shallow groundwater potential for irrigation generated from the modelling are shown and discussed.

Chapter 8 presents the modelling of potential future climate, land use and abstraction scenarios for assessment of impacts on the surface and shallow groundwater resources.

Chapter 9 draws together findings from all chapters and presents conclusions with reference to the project aims. The chapter provides recommendations for stakeholders and discusses the transferability of the results and the methodology, and presents limitations of the study. Finally, suggestions are provided for future work.

Chapter 2. Literature review

2.0 Chapter overview

Firstly, information is provided on the "Green Revolution" that occurred in Asia in the 1960s and 70s explaining the potential for irrigation to have positive impacts on food security, poverty alleviation, and gender equality, amongst other benefits. Justification for this PhD research is then provided with literature concerning how such a green revolution could occur in sub-Saharan Africa (SSA). This is followed by a background on African hydrogeology and the African climate along with projections of future changes to climate and land use. The chapter then details the research gap, namely: insufficient understanding of shallow aquifers in sub-Saharan Africa, their potential for productive use, and their resilience.

2.1 The role of groundwater in Asia's "Green Revolution"

Growth in the exploitation of shallow groundwater resources in South and East Asia since the 1970s has promoted living standards and fostered economic development (Calow *et al.*, 2009a; Narayanamoorthy, 2010). The impact on hunger and poverty from the explosion in use of groundwater irrigation (GWI), combined with the spread of higher yielding crops, fertilizers and modern pest control methods, has been such that it is known as Asia's "Green Revolution" (Evenson and Gollin, 2003; Hazell, 2009).

In Bangladesh, the area irrigated by groundwater increased from zero to 2.8 million ha between 1980 and 2000. From the 1950s to 2000, the number of mechanised wells in India increased from <100,000 to 19 million. In Bangladesh over the same time period the increase in mechanised wells was <1000 to 1 million, while in Hubei Province, China, mechanised wells increased from 730 to 840,000, and in Punjab, Pakistan, the number increased from <1000 to 500,000. In India, agricultural productivity increased by 80% per ha. Conversely, the number of people living below the poverty line from the 1970s to 2000 decreased from 250 million to 29 million in China, from 45% to 28% in Pakistan and from 71% to 44% in Bangladesh. The latter figures are even more remarkable when it is considered that global population doubled from three to six billion between 1960 and 2000, and in South and East Asia, national populations more than doubled (Palmer-Jones, 1992; Shah *et al.*, 2003; Hussain *et al.*, 2006; World Bank, 2017b).

The Green Revolution proved that the positive impacts from expansion of GWI can include, at the local level (list adapted from Bhattarai *et al.* (2001)):

- Greater food security as communities are less reliant on there being consistent rains
- Increased cropping intensity
- Crop diversification
- More wealth to enable purchase of fertilizers, pesticides and insecticides leading to higher crop yield
- Year-round cropping opportunities
- Improved livelihoods
- Increased farm employment
- Less labour-intensive agriculture causing increased school attendance
- Improved gender equality because girls are no longer walking long distances for water so can receive a better education and suffer less drudgery
- Increased wealth has a positive impact on off-farm activities and employment such as house building and shops/markets
- The water can also be used for bathing, providing health benefits, and for livestock.

At national level:

- Causes a decline in food prices that also helps the urban poor who still spend 50% of their income on food
- Increases export revenue, for example coffee from Vietnam and rice from Thailand.

The list above shows that expansion of GWI directly and indirectly targets many of the United Nations Sustainable Development Goals (SDGs) (Figure 2-1). In addition to Goals 1-6, 8, 10, 11 and 15, Goal 13 “Climate Action” is also targeted, as GWI is a means to mitigate against increasing climate uncertainty.

Figure 2-1. The United Nations Sustainable Development Goals (SDGs) (UN, 2015).

The impact of irrigation on farming income has been the focus of numerous studies. Research by Bhatia (1991) in Bihar, India, revealed additional net income due to improved irrigation access of Rs 2,511 (~£30) per ha. This translates to farm income in irrigated areas of Bihar being 77% higher than income in unirrigated areas. The study further states how only 32% of the cropped area of Bihar is irrigated while that value is 60% for the state of Haryana, also in north India. Consequently, the rural population living below the poverty line stands at 51% in Bihar and 15% in Haryana. This shows how improved access to irrigation contributes toward poverty alleviation and the improvement of livelihoods in a region. A similar study by Ut *et al.* (2000) in Vietnam showed a 68% increase in cropping intensity from irrigated over rainfed agriculture and a consequent increase in income of US$188/ha. A broad study by Giordano *et al.* (2012) found that having access to water during the dry season made a large difference to farmers' incomes and nutrition: In Madhya Pradesh, India, farmers' incomes who began irrigating pulses and wheat increased by more than 70%.

Bangladesh is analogous to the potential of SSA where shallow wells have proved easier to manage and more cost-effective than deep wells which has encouraged investment in shallow GWI. The outcome has been an increase in irrigated area and an improvement from monopolistic water and food markets to oligopolistic markets (Akteruzzaman *et al.*, 1998). Hossain and Islam (2000) reported how women in rural areas have benefitted particularly in Bangladesh, because prior to the increased access to safe water, they had to carry water over long distances, with significant impact on their health and productivity.

2.2 The potential for such a green revolution in sub-Saharan Africa

There are several studies available in the literature that suggest the green revolution is both possible for SSA and has already begun (e.g. Inocencio *et al.* (2007); Foster *et al.* (2008)). Giordano *et al.* (2012) provide examples from Tanzania where growing irrigated vegetables contributes half of the dry season cash income of smallholders, and in Zambia, 35% more is earnt by smallholders who cultivate vegetables in the dry season with irrigation than those who do not. A study in Ghana by Dittoh *et al.* (2013) showed the net revenue from groundwater irrigation ($631.51/acre) was significantly greater than from a reliance on rain ($129.46/acre) and that irrigators regard pumps as "saviours", but the major constraint is the financial means to buy them. Giordano *et al.* (2012) further state how investing in motor pumps could benefit 185 million people in SSA and generate net revenues up to US$ 22 billion per year. They estimate that 400,000 pumps were imported into Ethiopia in the last decade, and that there are 20,000 motor pumps in Burkina Faso, 160,000 in Ghana, 70,000 in Tanzania, and 15,000 in Zambia. However, manual water-lifting is still used by 70% of irrigators in Ethiopia, and from 84 to 91% of irrigators in the other aforementioned countries.

A key difference with Asia is the generally lower yield of wells in SSA (low-productivity basement aquifers vs productive alluvial aquifers) that restricts their cooperative use (an important factor in the achievements of Bangladesh) because a single well typically has only sufficient yield, generally less than 1 l/s, to irrigate a single smallholding (MacDonald and Davies, 2000). However, this may not be entirely disadvantageous. The low-yielding nature of typical SSA aquifers may provide, according to MacDonald *et al.* (2012b), "a solution to the intractable problem of sharing common-pool natural resources equitably (Hardin's "Tragedy of the Commons"). In low permeability aquifer environments, overpumping of an individual well is unable to exert much influence beyond the hectare-sized plot on which most farming is conducted in sub-Saharan Africa. As a result, the in situ hydrogeological conditions will restrict localised overexploitation naturally."

As of 2010, only 3.3% of arable land in sub-Saharan Africa was under irrigation, with a groundwater demand of 2.178 km^3/year (Siebert *et al.*, 2010). Increasing the area of land under irrigation will require increasing groundwater abstraction. Carter and Alkali (1996) quote several studies from rural areas of West Africa with groundwater abstraction estimates of 1-4 mm/a, increasing at 0.027 mm/a in line with population growth.

Expansion of agriculture is widely considered to be the only pathway to long-term and pro-poor economic development in SSA, by stimulating growth in the wider economy and absorbing excess labour through advances in the rural non-farm economy (Adelman, 1984; Collier and Dercon, 2014; Dawson *et al.*, 2016).

2.3 African hydrogeology

In this context, an understanding of the hydrogeology is from the point of view of understanding the potential groundwater resource. The availability of groundwater resources is critically dependent on the geology, the degree of weathering and fracturing, and recharge (whether historical or recent). According to MacDonald *et al.* (2008), the SSA region can be divided into four hydrogeological provinces (Figure 2-2):

1. Crystalline basement, which occupies 40% of the land area.
2. Consolidated sedimentary rocks: 32%
3. Volcanic rocks: 6%
4. Unconsolidated sediments: 22%.

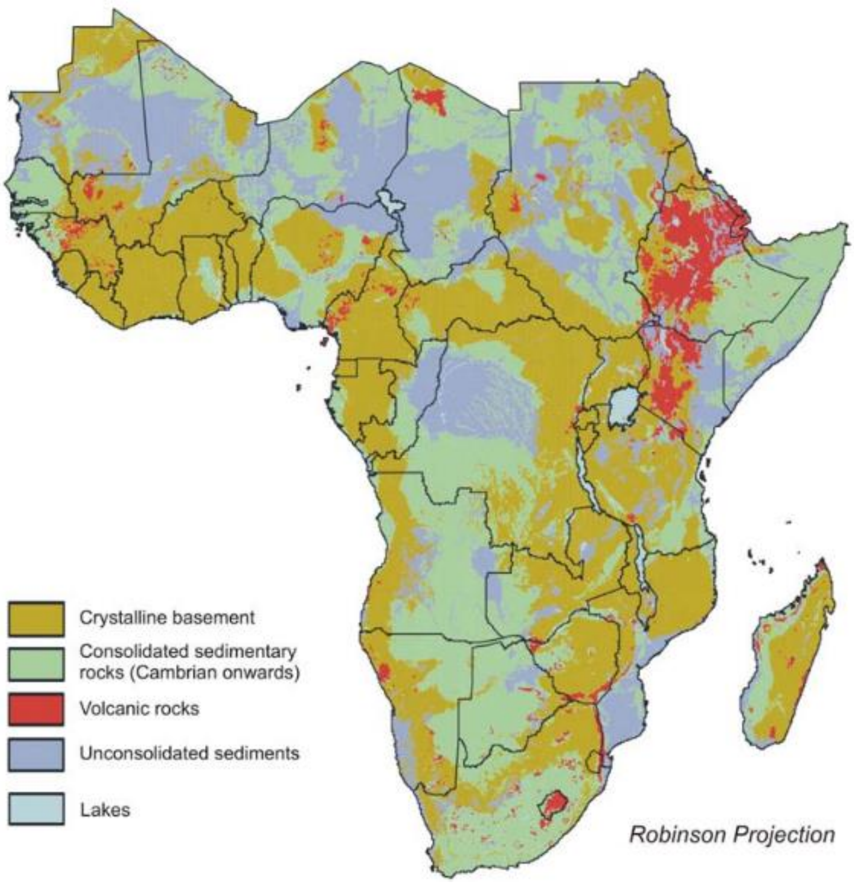


Figure 2-2. The hydrogeological environments of SSA (from MacDonald and Davies (2000)).

As can be seen in Figure 2-2, Precambrian crystalline basement is pervasive across SSA. It comprises igneous and metamorphic rocks greater than 541 million years old. Where unweathered and unfractured, the basement rocks contain negligible groundwater, however, important aquifers can develop within fracture zones and the weathered mantle (Wright and Burgess, 1992). Deep fractures within basement rocks are tectonically controlled and can be important sources of groundwater, especially where sub-vertical and below a thin or absent weathered zone. The weathered mantle, or regolith, consisting of variously gravelly and clayey decomposing parent rock, can be 90 m thick in tropical regions, though is more commonly in the range of 20-30 m (MacDonald *et al.*, 2005). Regolith hydrogeology is discussed more thoroughly in Chapter 3.

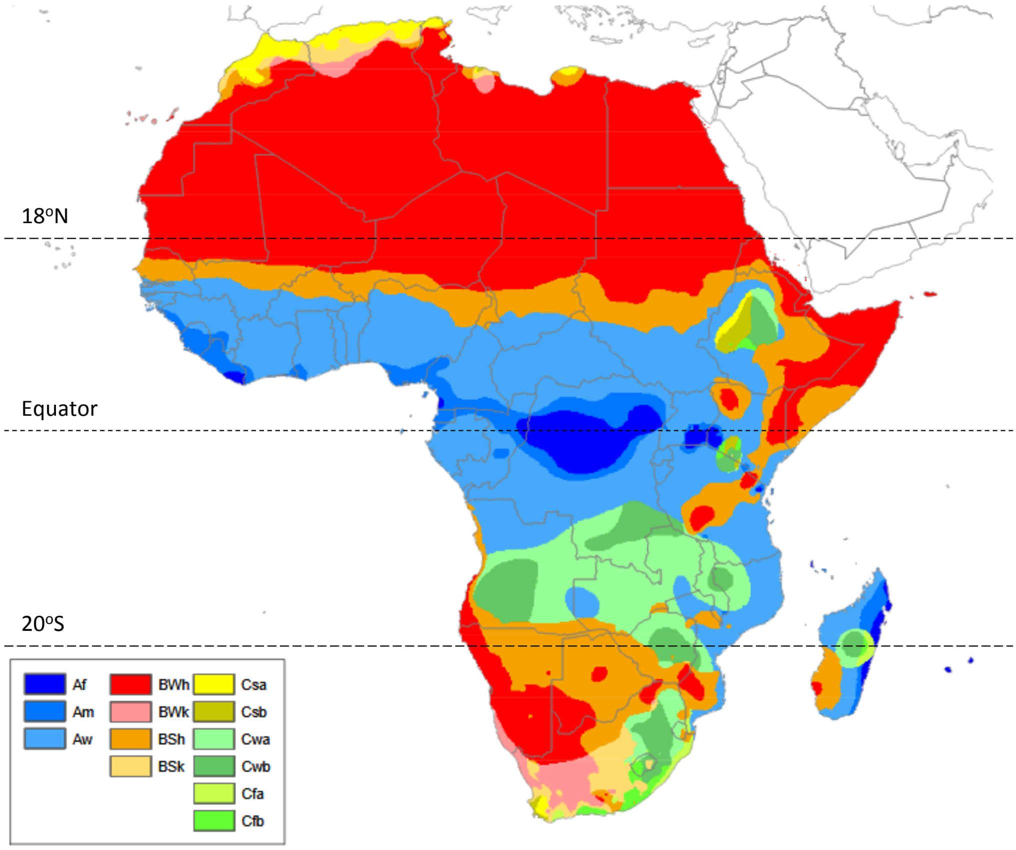
Large sedimentary basins are present within SSA that store vast quantities of groundwater. However, in semi-arid and arid regions the groundwater is largely non-renewable, or fossil, having been recharged in the past when rainfall was much greater; any abstraction is essentially water mining (Döll, 2009). The best aquifers are found within sandstone and limestone units; unfortunately, around 65% of consolidated sedimentary rocks are low-permeability mudstones (Aplin *et al.*, 1999). Where the mudstones are hard, groundwater may be obtained from fracture zones. Similarly, older sandstones may be cemented and it is again secondary (fracture) porosity that is targeted for groundwater abstraction (MacDonald *et al.*, 2005). Limestones generally make good aquifers, though where fractures are enlarged through dissolution, i.e. karsts, giving high groundwater flow and infiltration rates, there can be high vulnerability to contamination and saline intrusion (Robins *et al.*, 2007).

Volcanic rocks of SSA are mostly of Cenozoic age and formed during three major pulses of late Eocene, mid-Miocene, and Plio-Pleistocene age related to the opening of the East African Rift, though some volcanic rocks date from the Jurassic (Baker *et al.*, 1972). The groundwater potential of volcanic terrains is extremely variable, reflecting the complexity of the geology. Volcanic sequences are often 100s m thick, consisting of interbedded lavas and pyroclastic rocks. Massive lava flows can be impermeable, though extensive jointing can allow groundwater infiltration and flow (MacDonald and Davies, 2000). The junctions between lava flows often develop into important conduits as cracks, joints and rubble develop when the base of the more recent lava flow rapidly cooled (Kehinde and Loehnert, 1989). Ash layers are generally of low permeability but have high storage, therefore, useful aquifer systems can form where ash is present in alternating layers with fractured or rubbly lavas (MacDonald *et al.*, 2005).

Relatively young (less than a few million years old) unconsolidated sediments range from coarse gravels and sands to silts and clays, and from regionally extensive (e.g. coastal or deltaic) deposits 100s m thick to thin strips of alluvium beside small rivers (MacDonald *et al.*, 2005). Large unconsolidated sedimentary aquifers (UNSAs) can be highly productive where sand and gravel beds are continuous over 10s-100s km (Guiraud, 1988). However, depending on the depositional environment, complex multi-layered aquifers can form with sands and gravels interbedded with silt and clay aquitards; the sediments varying laterally every few metres (MacDonald and Davies, 2000). Small UNSAs, less than 100 m in width and with sediments less than 10 m in thickness, form locally important aquifers, typically in valleys, deposited by modern rivers; groundwater is usually close to the surface so pumping lifts are small (Owen, 1989; Carter and Alkali, 1996). Proximity to a river gives a reliable source of recharge though in semi-arid areas where surface water is rare, i.e. sand rivers, recharge occurs during infrequent flood events (Hussey, 2007; Love *et al.*, 2007).

2.4 The African climate

The climate of Africa is best portrayed by the updated Köppen-Geiger climate type map presented in Figure 2-3, based on global climate classification studies conducted by Köppen a hundred years previous (Köppen and Geiger, 1930; Peel *et al.*, 2007). The map shows that only three of the main climate types are present in Africa and, of these, the dominant climate type by land area is the arid B (57.2%), followed by tropical A (31.0%) and temperate C (11.8%). The map is ground-truthed against 1436 precipitation and 331 temperature stations.



1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold}\geq 18$
	f		- Rainforest	$P_{dry}\geq 60$
	m		- Monsoon	Not (Af) & $P_{dry}\geq 100\text{–}MAP/25$
	w		- Savannah	Not (Af) & $P_{dry}<100\text{–}MAP/25$
B			Arid	$MAP<10\times P_{threshold}$
	W		- Desert	$MAP<5\times P_{threshold}$
	S		- Steppe	$MAP\geq 5\times P_{threshold}$
		h	- Hot	$MAT\geq 18$
		k	- Cold	$MAT<18$
C			Temperate	$T_{hot}>10$ & $0<T_{cold}<18$
	s		- Dry Summer	$P_{sdry}<40$ & $P_{sdry}<P_{wwet}/3$
	w		- Dry Winter	$P_{wdry}<P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot}\geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10}\geq 4$
		c	- Cold Summer	Not (a or b) & $1\leq T_{mon10}<4$
D			Cold	$T_{hot}>10$ & $T_{cold}\leq 0$
	s		- Dry Summer	$P_{sdry}<40$ & $P_{sdry}<P_{wwet}/3$
	w		- Dry Winter	$P_{wdry}<P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot}\geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10}\geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold}<-38$
E			Polar	$T_{hot}<10$
	T		- Tundra	$T_{hot}>0$
	F		- Frost	$T_{hot}\leq 0$

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

Figure 2-3. Köppen-Geiger climate type map of Africa with description of climate symbols and defining criteria (from Peel *et al.* (2007)).

The North African coast with its temperate "Mediterranean" climate is not considered as part of this study. Irrigated agriculture is unlikely until a latitude of approximately 18°N is reached and the climate of this area is well described by Nicholson (1984): "The sub-Saharan region immediately south of the Sahara Desert is characterized by low, highly variable rainfall and a landscape that undergoes a marked and abrupt change between wet and dry seasons within a year. Moving southwards, the rainfall increases along with the length of the rainy season. Rainfall gradients are steep; as much as 100 mm per 100 km in West Africa, passing from 100 mm in the northern region of the Sahelo-Saharan zone to over 1600 mm in the Guinean zone. The duration of the rainy season also varies greatly, ranging from 1-month in the desert margin to more than 8-months in the Guinean coastal zone. Hence, the transition from desert to the humid tropics is abrupt."

In the semiarid sub-Saharan zones, wet and dry seasons are controlled by the subtropical high-pressure zone and the inter-tropical convergence zone (ITCZ). The ITCZ lies at the convergence of the northeasterly and southeasterly trade winds; in Africa that relates to the transition between the dry northeasterly harmattan winds of the Sahara and the moist southwesterly monsoon flow originating from the tropical Atlantic. This convergence moves northward during May to October bringing heavy cloud and intense rainfall. Rainy season length at particular latitudes reflects the number of months that the ITCZ dominates the local climatology (Nicholson, 1984).

Moving southwards to equatorial latitudes within the Congo Basin the rainy season has a bimodal distribution peaking in April and again in October with short dry seasons running from December to February and June to August (Washington *et al.*, 2013). Further east towards the East African coast is anomalously dry for its equatorial latitude primarily due to the rain shadow effect of the Rwenzori Mountains and the Ethiopian Highlands.

As latitude increases in a southerly direction, a unimodal rainfall regime is again established during opposing months to that seen in the northern hemisphere. Rains are greatest during November to January decreasing south of approximately 20°S where the Namib and Kalahari Deserts are located, although the east coast at this latitude does not experience such aridity. The southern coast of the continent enjoys a temperate "Mediterranean" climate.

Figure 2-4 shows the mean annual rainfall distribution across the continent as described in the previous paragraphs.

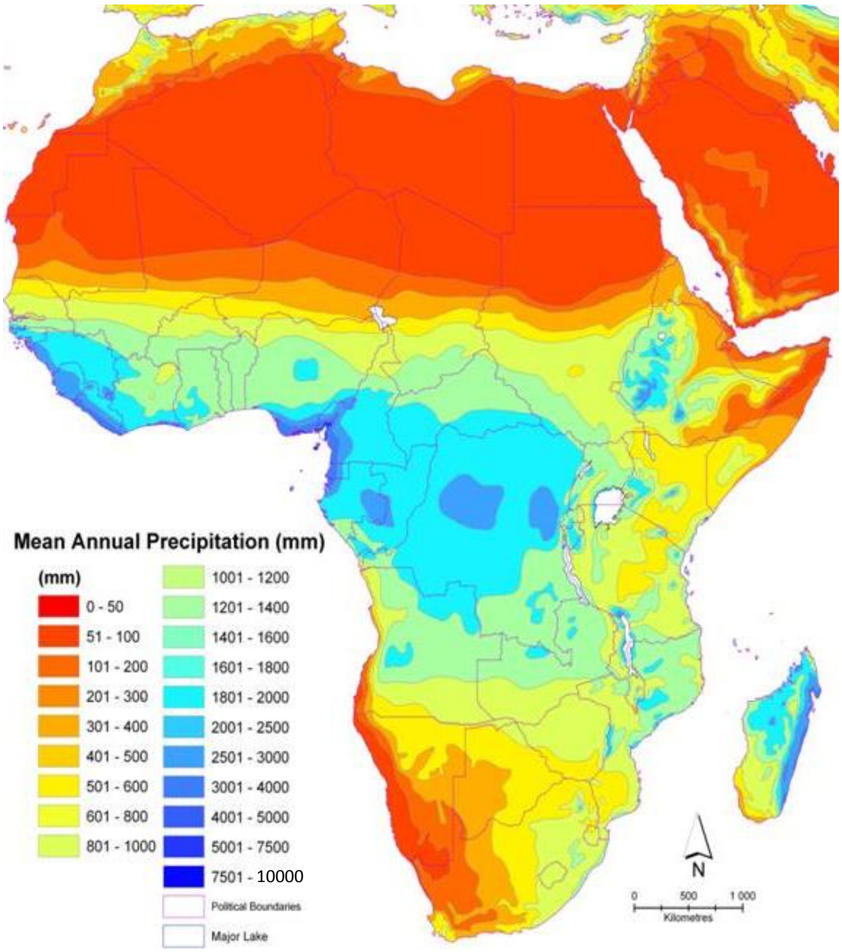


Figure 2-4. Mean annual precipitation map of Africa (from Kitamirike (2008)).

There are abundant publications on the climatic history of Africa, which describe observed trends in precipitation and temperature. Hulme *et al.* (2001) investigated how the African climate has changed over the last 100 years and report the following: "The continent of Africa is warmer than it was 100 years ago. Warming through the 20th century has been at the rate of about 0.5°C per century, with slightly larger warming in the June–August (JJA) and September–November (SON) seasons than in December–February (DJF) and March–May (MAM). The six warmest years in Africa have all occurred since 1987, with 1998 being the warmest. This rate of warming is not dissimilar to that experienced globally, and the periods of most rapid warming—the 1910s to 1930s and the post-1970s—occur simultaneously in Africa and the rest of the world." While most of the continent is experiencing warming, large areas of cooling are noted, such as along the coastal margins of Senegal/Mauritania and South Africa (of up to 1^{o}C per century), within Nigeria/Cameroon and in Somalia/Ethiopia/Sudan. In contrast, as can be seen on Figure 2-5, warming of nearly 2°C per century is observed over the interior of southern Africa and in the Mediterranean countries of northwest Africa.

A glance at African news on any particular day starkly reveals Africa's notorious climate variability. The following headlines all originated within the same 24-hour period on 29-30th December 2016: "Namibia drought threatens food security" (The Namibian, 2016), "DR Congo floods leave 50 dead in Boma" (BBC, 2016), "Uganda: Government to build Shs4 trillion irrigation scheme in Pallisa …to address a persistent dry spell" (All Africa, 2016), "Sahara Snow Falls Once Again After 37 Years!" (Travelers Today, 2016), "Drought mitigation package for Zim" (The Herald, 2016), and most tellingly though not exclusively considering Africa; "Freaky weather the new normal" (The Straits Times, 2016). The inherent and often extreme temporal and spatial variability of the African climate is well known (Nicholson, 1984; Cooper *et al.*, 2008; Washington *et al.*, 2013). Interannual rainfall variability is large over most of Africa with multi-decadal variability having been identified in many regions. Hulme *et al.* (2001) discuss three regions that exhibit contrasting rainfall variability characteristics: "the Sahel displays large multi-decadal variability with recent drying, East Africa a relatively stable regime with some evidence of long-term wetting, and southeast Africa also a basically stable regime, but with marked inter-decadal variability. There is no simple correlation between temperature and rainfall in these three regions." The pattern of rainfall trends presented in Figure 2-5 shows that parts of the eastern, and particularly the western, Sahel are drying by up to 25% per century. A moderate drying trend is also observed over a large part of southern Africa. A wetting trend can be seen across much of the rest of the continent especially over a wide zone south of the equator where wetting by over 10% per century is occurring.

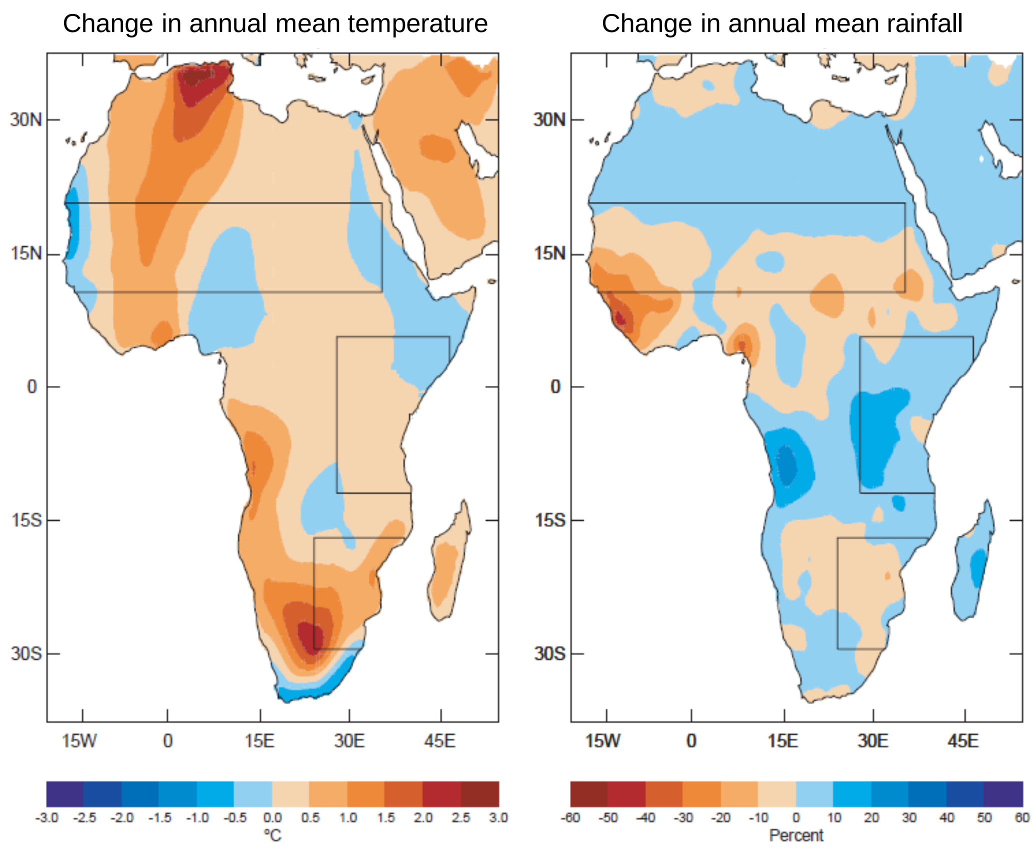


Figure 2-5. Mean linear trends in annual temperature (°C per century) and annual rainfall (% per century) over the period 1901-1995 (from Hulme *et al.* (2001)).

Looking further back into history by analysing varied records such as journals, diaries, tree rings, animal distributions and ice core data, Nicholson (1981) presents historical climatology for Africa. It is reported that droughts were widespread across Africa in 1820-1840, with higher than average rains during 1870-1895, followed by further droughts in 1895-1920 being particularly severe in 1913/14. African lake levels (e.g. Lake Chad, Malawi, Victoria, Tanganyika, etc.) were greatest around 1750 and again around 1850 with much lower levels in between, before 1750 and at all times since 1850. The Sahel region has become increasingly arid since the 1600s. Africa was very arid during the ice age peak 18000BP (before present) when the Sahara extended further south and the Kalahari reached further north (similar to the 1830s and the 1968-73 drought years). 6000-5000BP was wetter with a populated Sahara and greater humidity in east and southern Africa (like the end of the 1800s).

Sylla *et al.* (2013) explain how rainfall distribution is critical over Africa for applications such as drought and flood forecasting, water resources management and agricultural planning. Simulating and understanding the spatial and temporal precipitation variability at the necessary timescale is a challenge, as it requires high quality observation data.

Datasets are available for Africa blending satellite and ground observations but they suffer from likely uncertainty due to limitations in density and quality of available stations.

Maystadt and Ecker (2014) state how a growing body of evidence shows a causal relationship between extreme weather events and civil conflict incidence at the global level. For example, they estimate that a one standard deviation increase in drought intensity and length in Somalia raises the likelihood of conflict by 62%.

Buontempo *et al.* (2014) present an ensemble climate projection for Africa; a regional climate model (RCM) for Africa, which improves over the GCM. The model runs from 1949 to 2100 and, they state, it captures annual temperature and rain cycles well but slightly overestimates rainfall. For scenario A1b, rapid economic growth though with a balance of fossil and non-fossil energy sources (Nakicenovic and Swart, 2000), the predictions are:

- Temperature to increase everywhere in Africa by 3-4^{o}C
- General increase in rain between 8^{o}S and 8^{o}N
- Generally becoming wetter in the east, in particular in the Congo basin
- General drying in the west, especially the Guineas
- Reduction in rainfall seasonality, i.e. less rain in the wet season and more rain in the dry season.

Estimating the impact of climate change on water resources, Döll and Flörke (2005) used two climate scenarios (A2 and B2, a divided world of self-reliant nations and a divided but ecologically friendly world, respectively (Nakicenovic and Swart, 2000)) and two GCMs, to present a global-scale estimation of diffuse groundwater recharge. Their global scale maps of recharge quantities were validated against ground observations, though these were mostly streamflow hydrograph assessments, few comparison studies were from Africa, and those were predominantly in arid and semi-arid locations. The change in annual recharge from 1961-90 to the 2050s was predicted to be an increase of around 100 mm between the equator and 8^{o}N, as well as in the Horn of Africa and parts of East Africa, otherwise an increase of about 30 mm in the east. While annual recharge was predicted to decrease by 100 mm in Southwest Africa and the Mauritania coast area, and generally decrease by around 30 mm in the west.

However, many authors cast doubt on the predictive skill of GCMs for data-poor regions such as Africa (Hulme *et al.*, 2001; Cooper *et al.*, 2008; Taye *et al.*, 2015). Bonsor *et al.*

(2010) further state that from a water resources point of view, "the exclusion of daily or inter-annual climatic variability within GCMs is particularly important, as it is this very short-term climatic variability which is thought to be highly important in simulating the effect of intense rainfall events and the future frequency of droughts." What's more, translating the predicted estimates of precipitation totals and intensity into more useful variables, such as groundwater recharge, is extremely difficult (Bates *et al.*, 2008). As well as the direct impact of climate change on groundwater resources we also have to consider the impact of changes in human behaviour (Taylor *et al.*, 2013). For example, sometimes recharge will decrease due to increased evapotranspiration caused by warming, while sometimes recharge will increase due to increased irrigation as the growing season lengthens.

2.5 Land use change

Future changes to land use / land cover (LULC) may be entirely anthropogenic or could be climate related. Foster and Cherlet (2014) discuss the links between LULC and groundwater noting how deforestation will increase recharge on flat ground but on sloping ground there is a risk of soil erosion and eventual loss of recharge. This has been observed during field visits elsewhere in Ethiopia, such as in Robit Bata *kebele* near Bahir Dar and in Boloso Bombe *woreda* in SNNPR. In both cases, deforestation is said by local officials to be due to increasing demand for wood for charcoal by a growing population, in addition to overgrazing. Afforestation, not uncommon in Ethiopia due to increased demand for eucalyptus for house-building and for charcoal, is likely to decrease recharge as the evapotranspirative demand will rise (Jagger and Pender, 2003; Farley *et al.*, 2005). Conversion of native vegetation or pasture to cropped land would generally cause slight increases in recharge, especially during fallow periods. Obviously under irrigated conditions, especially flood irrigation, recharge significantly increases (Scanlon *et al.*, 2005).

Notable examples of the impact of land use change on groundwater can be found in West Africa. Most of the rivers in the region (except in the Sahel) have seen a significant decrease in discharge since the 1970s, due to a decrease in rainfall and consequent lowering of the water table and reduction in baseflow contribution (Mahé and Paturel, 2009). Conversely, the much-discussed "Sahelian paradox" concerns how, despite drought since the 1960s, groundwater levels in the Sahel and Niger River discharge have been increasing. For example, the water table in southwest Niger rose continuously by 4 m from 1963-2007 despite a ~23% reduction in monsoonal rains from 1970-1998

(Favreau *et al.*, 2009). This is due to vegetation clearance, mostly for firewood and livestock fodder, in addition to expansion of cropped lands and overgrazing leading to an increase in bare and crusted soils. Hortonian overland flow has increased forming temporary endorheic ponds, which then infiltrate creating groundwater "mounds". Leduc *et al.* (2000) estimate a 150% increase in groundwater storage since the 70s. The recharge rates measured in the Sahel are similar to those from similarly semi-arid regions of Australia following land clearance (Favreau *et al.*, 2002). Endorheic basins becoming exorheic have increased the contributing basin area giving rise to more intense but shorter annual floods creating flooding problems and shorter duration stream flow (Amogu *et al.*, 2010). Specifically, the Niger River now has a two-flood hydrograph: previously there was a single flood from June-September rains in the Guinea Highlands, which is delayed by the Inner Niger Delta so arrives downstream from November. Now there is an additional local (red) flood caused by August and September monsoons (Descroix *et al.*, 2012).

Lambin and Ehrlich (1997) showed using continental-scale remotely sensed surface temperature and vegetation indices that, for the period 1982-1991, climate variability is responsible for most LULC changes. However, human-driven LULC changes were observed to have a lower degree of reversibility and are, therefore, cumulative over time. Concerning the Ethiopian Highlands in particular, Ali *et al.* (2011) showed that wetter regions have seen a large shift since the 1970s with croplands replacing pasture. This is less significant in drier regions as water scarcity prevents a large shift to cropping.

2.6 Research gap

It is a commonly expressed view that the hydrogeology of sub-Saharan Africa (SSA) is under-studied and poorly understood (Robins *et al.*, 2006; Calow *et al.*, 2009b; Taylor *et al.*, 2009). In a review titled "Identifying the barriers and pathways forward for expanding the use of groundwater for irrigation in Sub-Saharan Africa" by Pavelic *et al.* (2013b), the first presented major obstacle is the inadequate knowledge of the aquifer systems. This view is prevalent not just among researchers but is shared by the host governments who could provide the most benefit to the SSA populace in the form of intervention planning with better understanding of the hydrogeology. For example, Ethiopia's Ministry of Water Resources state: "Ethiopia's hydrogeology is complex and at present only partly understood" (MoWR, 2011), and from Uganda's Ministry of Water and Environment: "Because of the limited knowledge on the groundwater,... movement of water across local, national and international boundaries are not known" (MoWE, 2009).

This research gap has been succinctly posed by Lapworth *et al.* (2013) discussing West Africa; “Ideally, a thorough quantitative understanding of aquifer properties and recharge mechanisms under a variety of climate, land use and geological environments is required to confidently assess current groundwater availability, and forecast future availability under different scenarios”.

Research remains limited into the impacts of climate on groundwater resources (Bovolo *et al.*, 2009; MacDonald *et al.*, 2009; MacDonald *et al.*, 2011). A significant disadvantage is the poor availability of groundwater data, e.g. groundwater levels and withdrawals. As a result, according to Taylor *et al.* (2013): “our ability to evaluate fully the responses of ground water to climate variability and change, to estimate directly groundwater replenishment, and to constrain models and satellite observations, is severely impaired. There is, for example, a profound lack of knowledge regarding the quantity of groundwater storage in most aquifers that may be sustainably used.”

The research gap is particularly apparent with regard to shallow groundwater, at least to shallow groundwater in aquifers at less than 25 m depth. A number of studies have been conducted on the resilience of African groundwater resources, particularly in the face of predicted climate change. A study by MacDonald *et al.* (2011) concluded that “…groundwater possesses a high resilience to climate change in Africa and should be central to adaptation strategies. Increasing access to improved groundwater sources based on handpumps is likely to be highly successful”. MacDonald et al reached similar conclusions in a 2009 study. However, in both cases “shallow” groundwater resources were considered those from boreholes of up to 50 m depth. Boreholes, especially at depths beyond 25 m, are unfeasible for the small-scale groundwater considered as part of this project, being beyond the technical and financial limit of poorer communities. As such, many of the conclusions reached by the aforementioned studies are less appropriate for poor rural communities. This view is shared by Lapworth *et al.* (2013) who state that “although shallow groundwater sustains the vast majority of improved drinking-water supplies in rural Africa, there is little information on how resilient this resource may be to future changes in climate.”

Shallow groundwater resources are particularly sensitive to variations in recharge. Such variations are highly likely with land use changes and increasing climate variability (Carter and Parker, 2009; Taylor *et al.*, 2013; Smerdon, 2017). General circulation model (GCM) simulations offer a range of possible future climate scenarios for SSA from increasing aridity to greater rainfall; both predicted for the western Sahel for example

(Hulme *et al.*, 2001; Sheen *et al.*, 2017). Most studies agree that an increase in extreme events, such as intense storms, is likely. How this will translate to changes in effective rainfall and the partitioning of this effective rainfall between different water resources through altered patterns of surface run-off, soil moisture and groundwater recharge, is unclear (BGR, 2008; Owor *et al.*, 2009; Bonsor *et al.*, 2010).

The few examples of published studies concerning shallow hydrogeological systems in SSA are often quite specific and include a recent paper on permeability variations in laterite soils in Nigeria by Bonsor *et al.* (2014), a method for estimating shallow groundwater availability in small South African catchments by Ebrahim and Villholth (2016), and many studies on groundwater quality in urban and peri-urban shallow aquifers (e.g. Onwuka *et al.* (2004); Kulabako *et al.* (2007); Takem *et al.* (2015)). These studies are in addition to several recharge studies to assess the sustainability of abstraction of shallow groundwater, such as Edmunds *et al.* (1991) in NW Senegal and several from Nigeria (e.g. Carter and Alkali (1996); Goes (1999); Akpan *et al.* (2013)). Sand rivers, particularly in Zimbabwe and Botswana, are one shallow aquifer type that has received more attention in the literature, though generally in the form of technical reports and it is still typically quoted that greater research is called for to increase understanding of the long-term sustainability of the resource (Owen, 1989; Davies *et al.*, 1998; Hussey, 2007). While these examples detail specific aspects of the shallow hydrogeology, there is a general lack of transferrable shallow hydrogeological studies. This shortcoming was identified by Taylor and Howard back in 1998 discussing the prevalent regolith shallow aquifer systems: "… basic questions regarding both the geochemical evolution and the hydrogeological nature of the regolith [in SSA] remain unsolved. Particular concerns are the hydrogeological characteristics of the aquifer material, the hydraulic interaction of the regolith with the underlying bedrock aquifer and the nature of groundwater recharge"; their study still remains one of very few on shallow regolith aquifers. Another notable example is the heavily studied 4.6 km^2 Romwe catchment in southern Zimbabwe (e.g. Macdonald *et al.* (1995); Bromley *et al.* (1999); Butterworth *et al.* (1999)). Groundwater level monitoring, pumping tests, and hydrochemistry analysis from multiple boreholes, piezometers and hand-dug wells revealed differences in aquifer properties and recharge quantities in different zones of the regolith aquifer dependent on the nature of the underlying crystalline basement. Zones with the greatest potential for well-siting were identified considering geology and topography and a successful (for domestic use and some small-scale irrigation) large diameter collector well was installed. It is noted that none of the studies cited in this paragraph investigated the resilience of the shallow groundwater resource beyond conducting a recharge assessment.

Reasons are occasionally suggested for the general lack of investigation of shallow aquifers. They include: hydrogeological complexity in the case of Ethiopia (MoWR, 2011; Kebede, 2013), and investigations being limited to areas of highest population density in the case of Ghana (Dapaah-Siakwan and Gyau-Boakye, 2000). Generally, authors simply state that a better understanding of the shallow hydrogeology from the point of view of potential agricultural use is a necessity (Giordano, 2006; Namara *et al.*, 2011; Evans *et al.*, 2012; Pavelic *et al.*, 2013a). A recent review of groundwater conditions in fifteen SSA countries by Pavelic *et al.* (2012) concluded that "Quantitative information on aquifer characteristics, groundwater recharge rates, flow regimes, quality controls and use is still rather patchy".

The aims of this PhD research clearly target a research gap that has been often identified by others. That is: insufficient understanding of shallow aquifers in sub-Saharan Africa, their potential for productive use, and their resilience. A study of smallholder shallow groundwater irrigation development in Ghana by Namara *et al.* (2011), though stated by the authors to be applicable throughout SSA, concludes that to get maximum benefit from groundwater, the following are required:

1. "Better understanding of the nature and extent of the existing use of groundwater, so that it is considered more in national planning and policy.
2. Better understanding of the hydrogeology, so that expansion can be profitably planned.
3. Reducing some of the other identified constraints, including:
    a. provision of land tenure security through innovative institutional arrangements;
    b. provision of decision support tools, such as easy to comprehend groundwater maps for assessing the precise sitting of wells;
    c. improving access to appropriate and affordable drilling technologies;
    d. introducing tube-well technology, where applicable;
    e. provision of research-based (or founded) extension advise on agronomic practices (i.e. soil fertility management, crop protection, etc.) and water management systems;
    f. training farmers in safety precautions regarding the handling of agro-chemicals;

g. improving the supply chain of complementary inputs (e.g. improved seeds, fertilizer, herbicides, etc.); and
h. improving output marketing systems by, for example, organising farmers using shallow groundwater irrigation into commodity value chains."

From the above list, points 1, 2 and 3b are directly targeted through this PhD research while points 3e, 3f and 3h were touched upon, though not always with prior intention in the case of coming across pesticide application without the use of protective equipment.

Chapter 3. Study site background

3.0 Chapter overview

Chapter 2 provided a background on the potential for a sustainable growth in the use of shallow groundwater for irrigation by rural communities in sub-Saharan Africa. Whether or not such an expansion is possible in sub-Saharan Africa is principally dependent on the hydrogeology and the climate. Following this broad continental-scale study, Chapter 3 will zoom in to the regional and local-scale, providing background information on the study site for which the research was conducted. Following a report on study site selection, information is given from desk study, including analysis of received data, concerning climate, agriculture, socio-economics, governance structures, geography and geology.

3.1 Site selection

The study site is Dangila *woreda* in northwest Ethiopia. A *woreda* is the second smallest administrative unit in Ethiopia, equivalent to a UK district. Dangila *woreda* was selected at the onset of the AMGRAF project in September 2013, 12-months prior to commencement of the PhD research. The field site was established in March 2014 with the aid of a catalyst grant under the NERC-DFID-ESRC UPGro research programme. See Appendix C for further details of UPGro and AMGRAF. Several areas of Ethiopia had been identified by the Ethiopian ATA (Agricultural Transformation Agency) for an intensification of agriculture, one of which being the southern portion of the Lake Tana basin. Several *woredas* in the basin were considered based on their accessibility, the dominant farming system, and their status within the Agricultural Growth Programme. In collaboration with in-country partners, the Geological Survey of Ethiopia (GSE) and International Water Management Institute (IWMI), Dangila *woreda* was selected as the study site. In terms of geology, climate, and level of socio-economic and agricultural development, Dangila *woreda* is considered representative of a wide area of upland Ethiopia. In particular, the study site was chosen to represent an important type of shallow aquifer. The distribution of this aquifer type can be seen in Figure 3-1 where volcanic rocks cover a large proportion (~50%) of Ethiopia. The representativeness of the study site climate can be seen in Figure 3-2 where high rainfall areas are widespread; approximately 50% of Ethiopia receives >1000 mm/a rainfall and the country-wide average is 817 mm/a (Fazzini *et al.*, 2015).

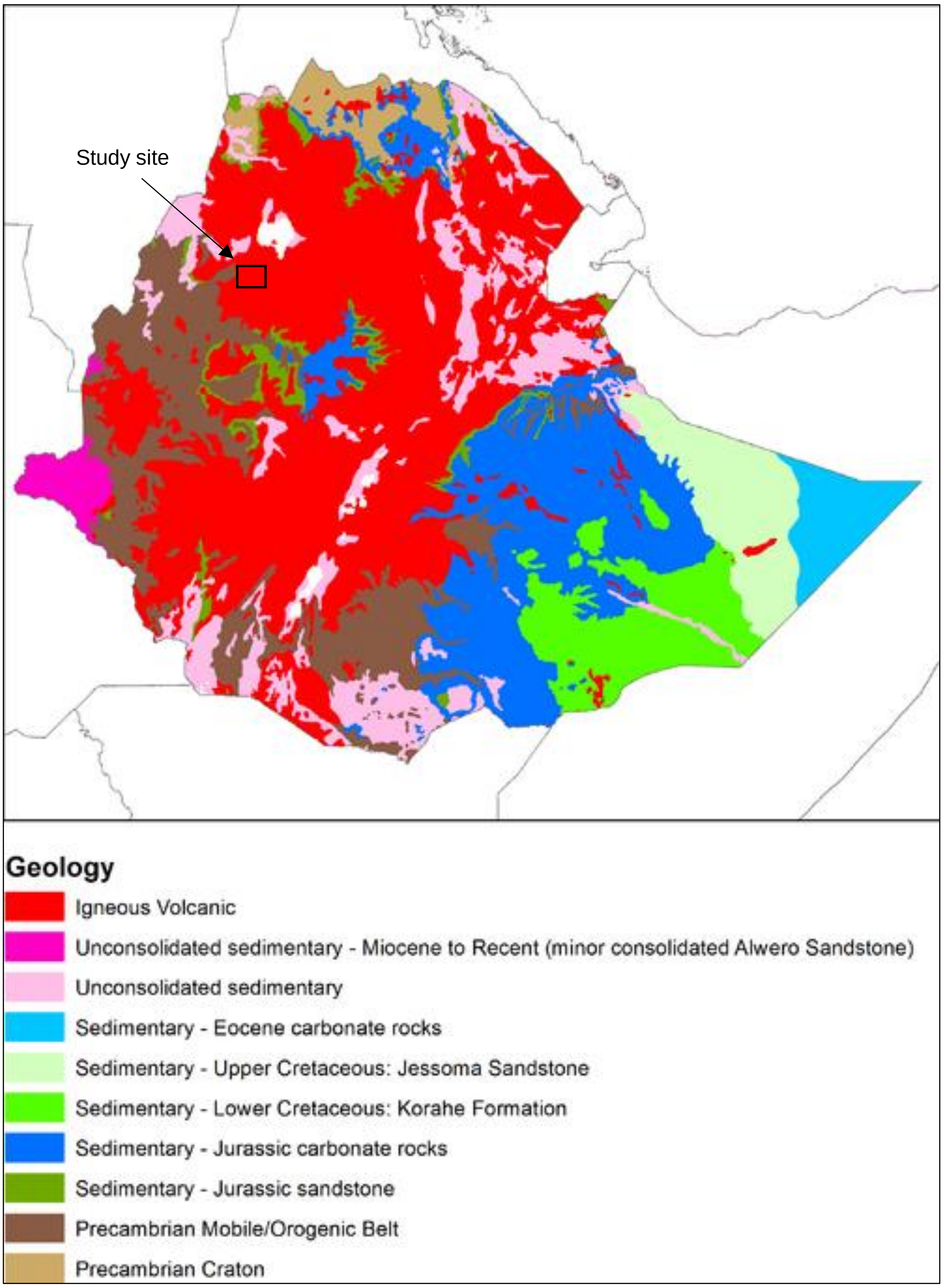


Figure 3-1. Ethiopia hydrogeological map (adapted from BGS (2018)).

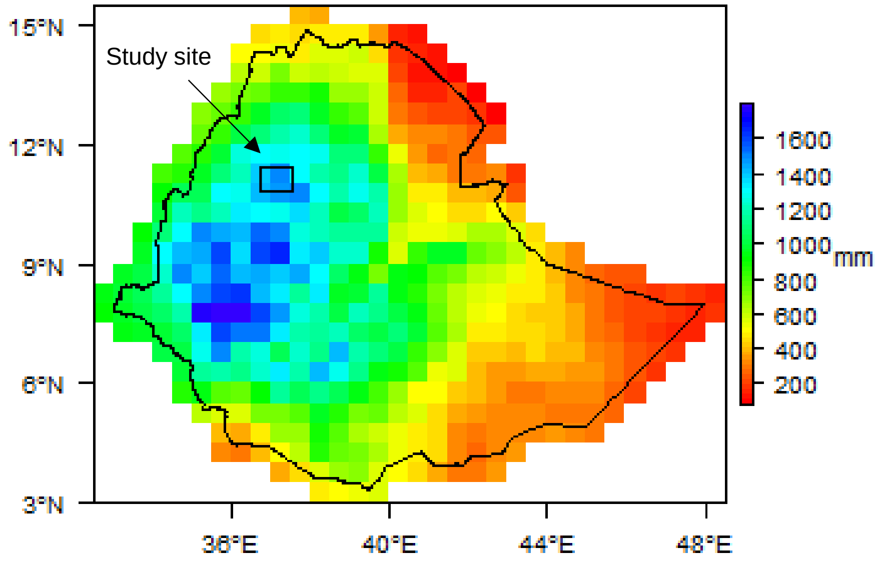


Figure 3-2. Ethiopia precipitation map (adapted from BGS (2018)).

Dangesheta *kebele* was chosen as a focus community within Dangila *woreda* to assess the potential of the shallow groundwater resource to support increased irrigation use. A *kebele* is the smallest administrative unit in Ethiopia, equivalent to a parish or ward. Dangesheta is one of 27 rural *kebeles* within Dangila *woreda*. The selection of Dangesheta *kebele* for hydrogeological study followed collaboration with GSE and IWMI, and a field visit in September/October 2013 by the AMGRAF research team prior to commencement of this PhD. The rural *kebeles* were ranked for intervention, according to:

(i) Access to market, i.e. proximity to an all-weather road and distance to market: both necessary for the adoption of groundwater irrigation

(ii) Experience in small-scale irrigation

(iii) Potential of shallow groundwater, i.e. evidence of existing shallow groundwater use. Shallow groundwater is here defined as <25 m: that which is accessible to poor rural communities using manual excavation methods.

3.2 Country context

Ethiopia is a large landlocked country in the Horn of Africa comprising mostly wet highlands though with large arid areas in the east and north. It is the second most populous country in Africa with a population of ~104 million in 2017 and a population growth rate of ~2.5% per year (World Bank, 2017b). Ethiopia is considered a low-income country by the World Bank with its per capita income of $590 being significantly lower than the regional average. However, the country has experienced remarkable economic growth and development in recent years, primarily attributed to two factors:

1. The absence of widespread drought; rainfall and gross domestic product (GDP) have been shown to be strongly linked in recent decades (Figure 3-3) (Grey and Sadoff, 2007).
2. A model of development that has driven investment in public infrastructure (World Bank, 2015).

As a result, Ethiopia has achieved an annual economic growth rate of 10% per year and has seen a reduction in its population living below the poverty line (income-based poverty) from 44% to 30% since 2000 (REACH, 2015). Between 1990 and 2015, in aiming to achieve Millennium Development Goal (MDG) #7 “To ensure environmental sustainability”, Ethiopia ranked fifth in the world in increasing clean water access to its rural population with an increase of 37.5 million people with safe access or from 3% to 49% (WHO, 2015). However, the multi-dimensional poverty index (MPI), that considers health, education and living standards, still places 87.3% of Ethiopia’s population in poverty (REACH, 2015).

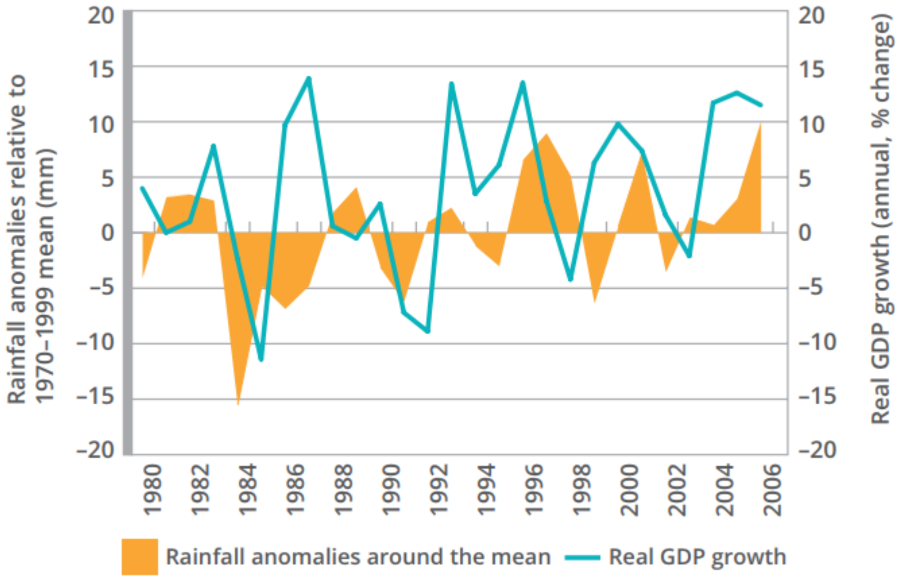


Figure 3-3. The link between annual rainfall and GDP growth in Ethiopia. Above average rainfall since 2006 has led to consistent GDP growth of around 10% (REACH, 2015).

3.3 Site description

Dangila *woreda* lies approximately 70 km southwest of Bahir Dar, the capital city of the Amhara Region, in northwest Ethiopia (Figure 3-4). The *woreda* has an area of approximately 900 km^2 with one significant population centre, Dangila town.

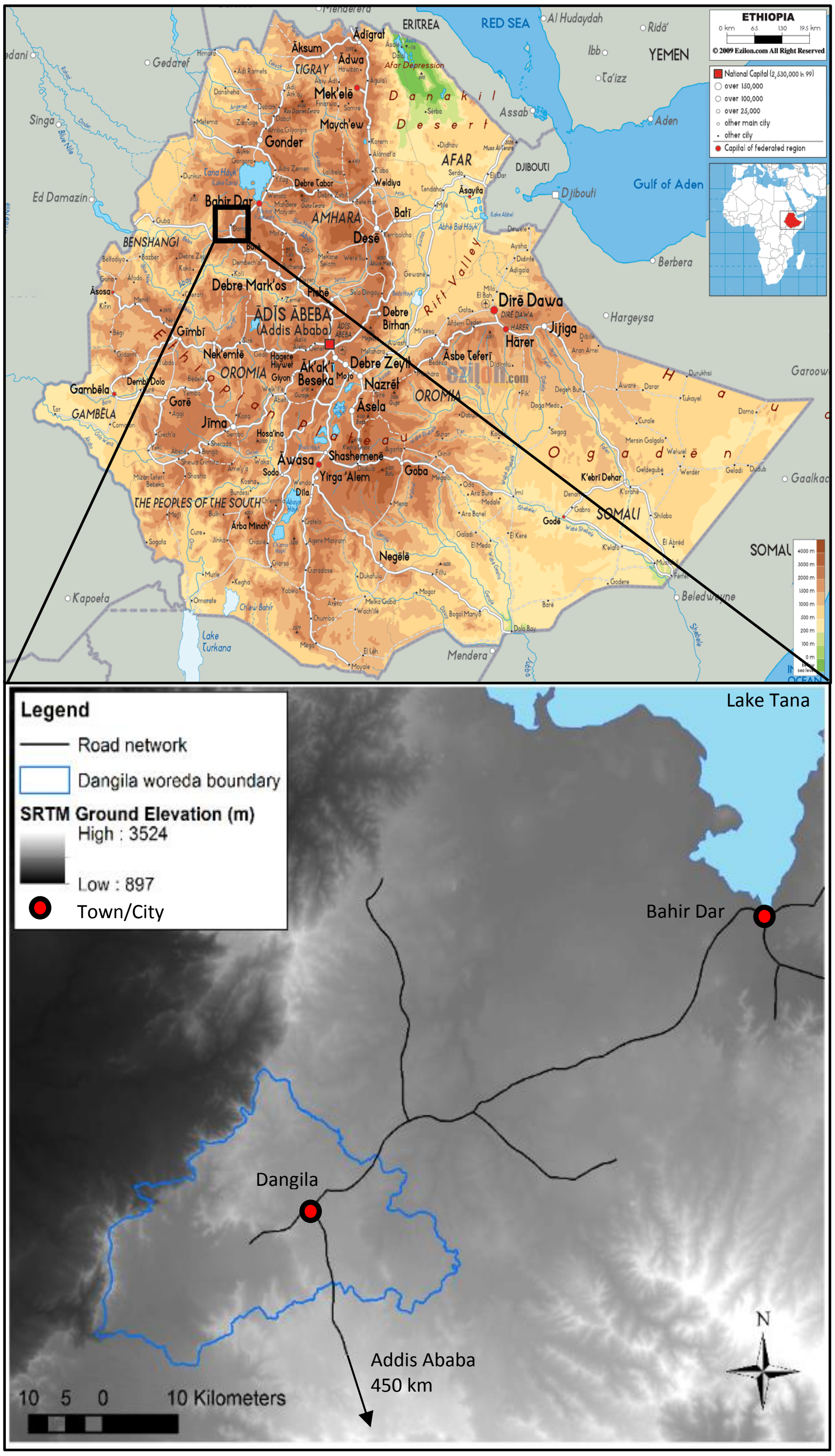
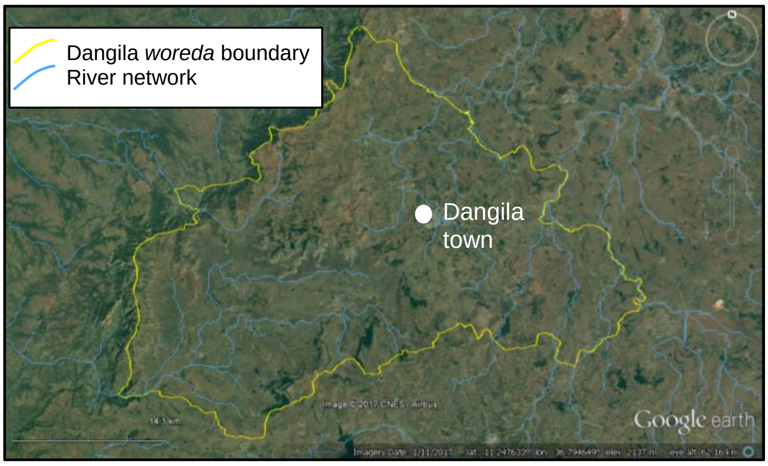


Figure 3-4. Location of Dangila *woreda* field site showing *woreda* boundary (blue) and position within Ethiopia (Geographical map of Ethiopia from Ezilon (2017)).

Dangila *woreda* ranges in elevation from around 1600 m in the southwest to 2400 m in a central hilly belt, dropping again in the east, which includes Dangila town, to around 2100 m. The northwestern border is formed by an escarpment, which falls over 700 m towards the Benishangul-Gumuz Region. Much of Dangila *woreda* is formed of low hills and expansive floodplains (Figure 3-5). West of the central hills drains to the Beles River, while the east of the *woreda* drains via the Gilgel Abay River into Lake Tana. The Beles and Lake Tana are both part of the Blue Nile, or Abay, river basin, the largest tributary of the Nile that contributes 65% of the total Nile flow (Yates and Strzepek, 1998).



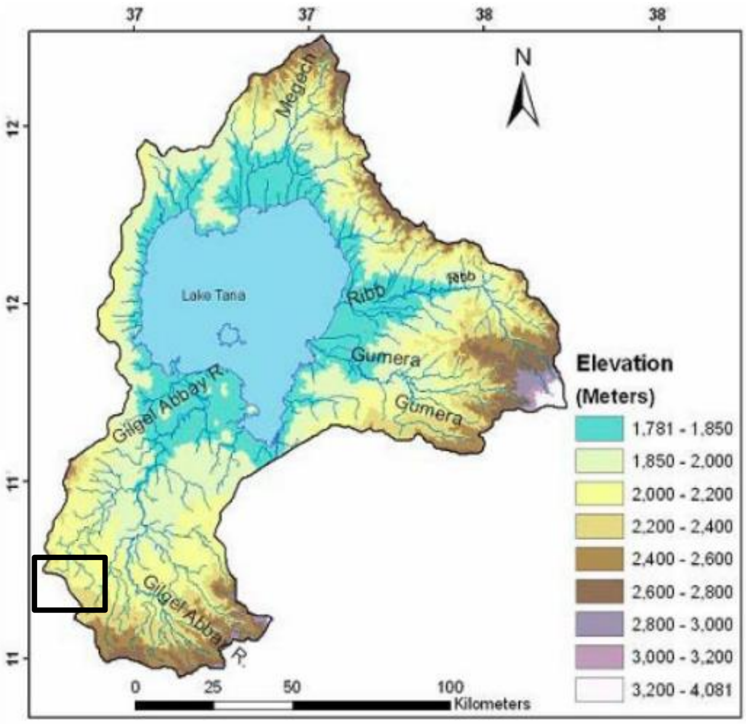


Figure 3-5. Geography of Dangila *woreda* study site (image source: Google.Earth; Imagery ©2017 DigitalGlobe), position within the Lake Tana Basin (map from MoWR), and position within the Nile Basin (map from PRI (2017)).

Dangila *woreda* has a population of around 175,000, of which 140,000 are rural (CSA, 2012). Most of the 35,000 urban population reside within Dangila town. Crop–livestock mixed subsistence farming is the primary source of livelihood.

Studies from nearby areas of the Amhara Region typically show an increasing trend in deforestation and an increasing trend in land converted to cultivation. For example, a study by Zeleke and Hurni (2001) in Dembecha *woreda*, 80 km southeast of Dangila, showed a 99% decrease in natural woodland since the 1950s and a 95% increase in cultivated land. In the Koga watershed, 30 km east of Dangila, Yeshaneh *et al.* (2013) report a 51% decrease in natural woodland over the same period and an increase in agricultural land of only 5%, despite an increase in settlement size of 2,733%. This increase in settlement size is a clear indication of the population pressures that the region is experiencing.

3.4 Agriculture

Rainfed agriculture predominates with the main crops of *teff (Eragrostis tef)*, maize, barley and millet together making up 90% of the area coverage. The products are mostly sold locally to local traders and brokers. The current product markets are regarded as satisfactory and farmers feel that they received a fair price (Belay and Bewket, 2013). Crop rotation and intercropping (less common) are practised. According to a survey by Belay and Bewket (2013), conducted in three rural *kebeles* of Dangila *woreda*, approximately 14% of cropland is irrigated, which equates to about 0.20 ha of irrigated land per household. Despite this small size, irrigated land is seen as important in terms of both cash income and household nutritional benefits. Irrigated crops are generally vegetables, fruits and cash crops, e.g. onions, chilli peppers, coffee, rather than the dominant cereals. In all cases in the survey, streams (86%) and springs (14%) provided the irrigation water, with diversions constructed from locally available materials, such as soil, tree branches, stones, and *teff* straw and chaff. Small groups of 5-10 households, who share irrigation water from a common source, construct and maintain such systems. Elected water user committees (WUCs) manage the rotational process of water sharing. Notable in the study by Belay and Bewket (2013) is the lack of shallow groundwater use from traditional hand-dug wells (HDWs). This is likely due to the high and hilly topography, and consequent abundance of streams, of much of the three *kebeles* studied.

A recent and broader study by Abera (2017) of the Lake Tana Basin revealed that of the Megech, Gumara-Rib and Gilgel Abay catchments, the latter of which includes the eastern half of Dangila *woreda*, around 84% of cultivated land relies solely on rainfall while 9% utilises flood recession and only 7% is irrigated. Similarly noted is that cereals dominate the rainfed season comprising over 74% of cultivated land. Abera (2017) reports "crop production and the rearing of livestock are closely integrated on the small farms, with livestock utilizing crop residue and providing draft power for ploughing and transport. Purchase of improved seed and use of chemical fertilizer is common, but per hectare application is low. Most farms use traditional methods of cultivation, harvesting and threshing. Only one crop is produced per year in rainfed areas. Crop losses are high both in the field and during harvesting and storage. The combination of a reliance on rainfed production, only one crop per year, small and degraded plots, a low use of purchased inputs, traditional cultivation methods and high post-harvest losses means that production is low and varies substantially from year-to-year. Most farm households in the [Lake Tana] Sub-Basin are accordingly exceptionally poor. They market only a small fraction of their total output, and often this is to meet urgent cash needs and requires the repurchase of staples later in the year." Whereas fertilizer application occurs for rainfed crops, pesticides are more common for irrigated crops, though communities are not adequately informed of the associated hazards. Therefore, farmers use such chemicals without thorough understanding of the health and environmental impacts. Similarly, farmers are apparently unaware of recommended seed rates for most crops. Too low or high seed rate, combined with poor land preparation, reduces productivity (Abera, 2017).

In December 2013 as part of the AMGRAF project, Dr Elizabeth Oughton (Newcastle University) and Dr Gebrehaweria Gebregziabher (IWMI), working with officers from the Dangila *Woreda* Agricultural Office, conducted focus groups in two rural *kebeles*. The investigations revealed that decisions over cropping, in both fields and backyards, are overwhelmingly made by males of the household, even though females and children provide labour for backyard agriculture. Secondly, there are a high proportion of female-headed households in this region, as women that have been widowed, divorced or abandoned are not permitted to remarry. Although women may retain legal ownership of fields, they require male labour to farm them. Clearly, changes in the availability and management of irrigation water could have very different effects on men and women affecting relative poverty, livelihood and environment (Oughton and Gebregziabher, 2014).

At the onset of the AMGRAF project, Dr Jaime Amezaga investigated the governance aspects of water use in the region: Ethiopia has a history of watershed management initiatives dating back to the 1970s. The basic approach has shifted from top-down planning to community-based approaches. There is now a supportive policy and legal framework in the form of policies that facilitate decentralised and participatory development, institutional arrangements that allow and encourage public agencies at all levels to work together, and an approach to natural resources that reflects local legislation and tenure practices. The institutional and legal framework designed by the Ministry of Water Resources (MoWR) promotes farmer-managed small-scale irrigation through the establishment of irrigation user communities (IUCs) under the national cooperative law starting from 2002. Recently, 233 IUCs were reported to have been established in the region, but their success is variable. Recently prepared (2010) draft regulations for Irrigation Water Users Associations are currently under consideration (Amezaga, 2014).

3.5 Climate

According to the Köppen–Geiger climate classification system, this region of Ethiopia is categorised as humid subtropical (Peel et al., 2007). There is little annual temperature variation though high diurnal variation due to the elevation. A median annual daily maximum temperature of 25 °C and minimum of 9 °C have been measured at the National Meteorological Agency (NMA) weather station in Dangila. The median annual total rainfall is 1541 mm, as measured (since 1987) at the Dangila NMA weather station, 91% of which falls during May to October (Figure 3-6). The main June-September rains, known in Ethiopia as *kiremt*, are principally controlled by the seasonal northward advance of the inter tropical convergence zone (ITCZ), in addition to the upper-level tropical easterly jet (TEJ) and convergence in the Red Sea region (Conway, 2000). Both the Choke Mountains to the east and Lake Tana to the north affect the pattern of rainfall in the study area. Most rain events are convective, have a duration shorter than 1-hour and often occur in the late afternoon (Haile et al., 2009).

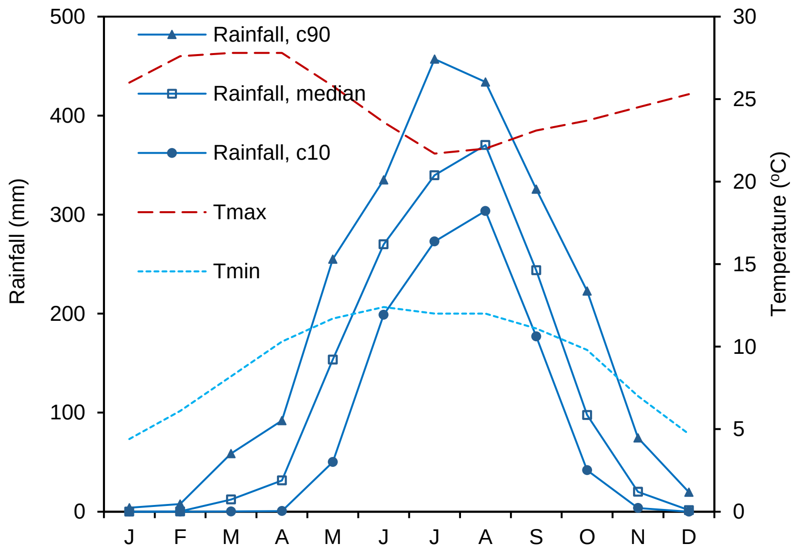


Figure 3-6. Monthly median, 10th and 90th percentile rainfall, and mean maximum and minimum temperatures as measured (since 1987) by the NMA at the Dangila weather station.

The region experiences high interannual variability in rainfall, with historical annual rainfall totals ranging from below 1000 mm to over 2000 mm. Interannual variations in rainfall total are related to cyclone development in the southwest Indian Ocean; specifically, a high frequency of tropical cyclones causes a delay in the onset of the rainy season, due to a failure of the early short, or *belg*, rains, throughout the Ethiopian Highlands (Shanko and Camberlin, 1998). Variation in *kiremt* rainfall total is related to the El Niño–Southern Oscillation (ENSO) and TEJ; specifically, a strong ENSO or a poor

TEJ often results in drought, though ENSO and TEJ may temper the effects of each other and the exact interrelationship remains uncertain (Seleshi and Zanke, 2004; Segele and Lamb, 2005; Diriba and Anthony, 2007). Analysis of this climate variability can be found in Chapter 8.

A single NMA weather station is present within Dangila *woreda*, situated in Dangila town. Another weather station, and the NMA regional office, is located in Bahir Dar. There are four further rain gauges in villages along the road between Dangila and Bahir Dar, and three rain gauges in the hills to the south of Dangila towards Addis Ababa. Further information and analysis of these monitoring sites is presented in Chapter 5.

3.6 Geology

The 1:2,000,000 scale Geological Map of Ethiopia by Tefera *et al.* (1996) states that the geology of the area predominantly consists of Quaternary basalt and trachyte above Eocene-Oligocene flood basalts and trachyte. There is much disagreement over the thickness of the flood basalts in northwest Ethiopia, ranging from 250 m (Hautot *et al.*, 2006) to 1500 m (Pik *et al.*, 1998) to ~4000 m (Hofmann *et al.*, 1997), though the generally accepted range is 500-3000 m (Mohr, 1983). There is further disagreement over the age of the flood basalt formations that cover 25% of Ethiopia’s land surface (Figure 3-7), with some studies stating the entire vast volcanic plateau sequence was erupted in an event lasting just a million years, approximately 30 million years ago (Hofmann *et al.*, 1997). These Ethiopian flood basalts are a classic example of mantle source continental flood volcanism and the youngest global example of a major continental volcanic plateau (Kieffer *et al.*, 2004).

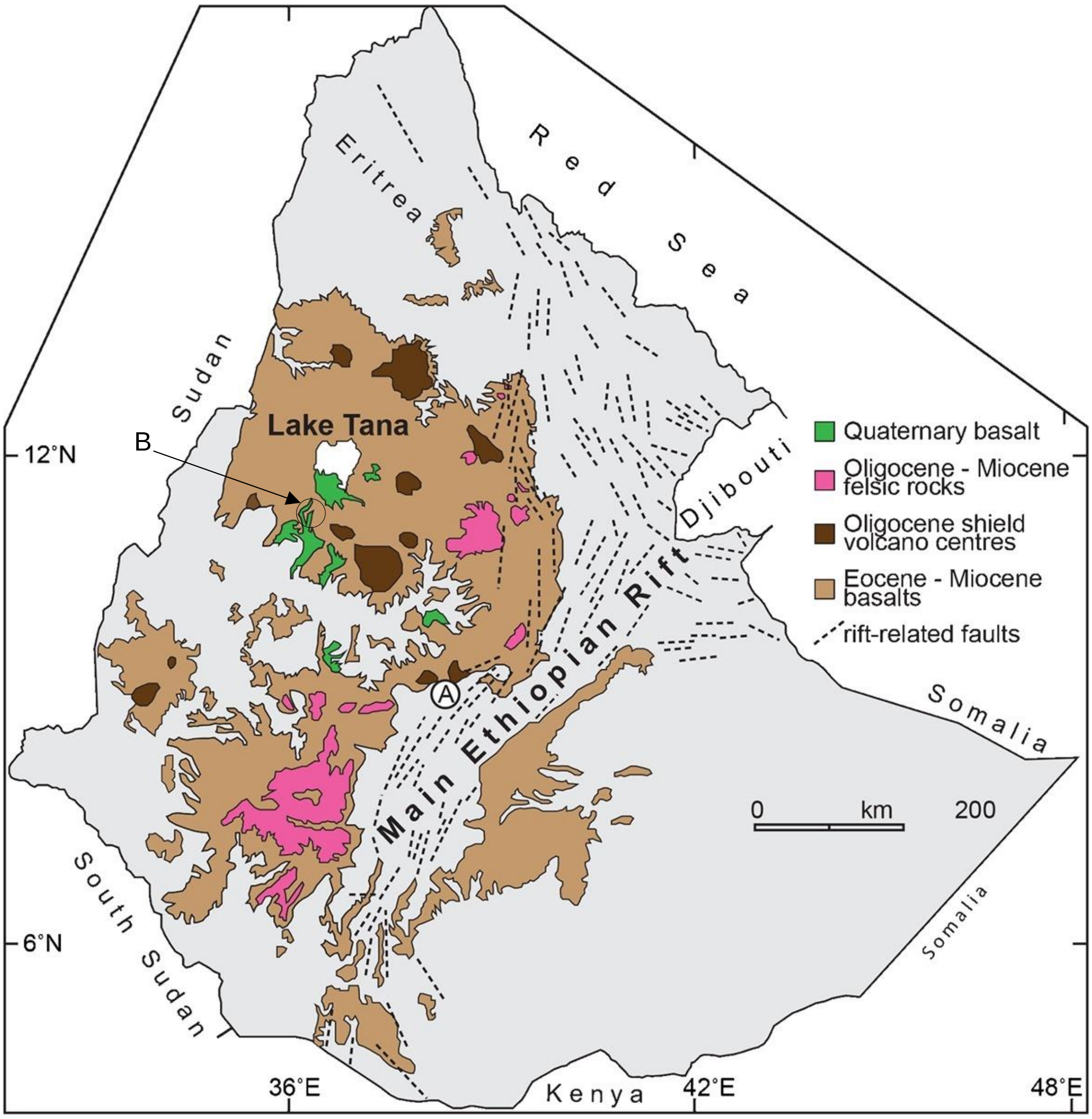


Figure 3-7. Generalised Cenozoic geology of the regions bordering the Main Ethiopian Rift (MER) system (simplified from the Geological Map of Ethiopia). Circled "A" is the location of Addis Ababa and "B" is the Dangila *woreda* study site. From Prave *et al.* (2016). Note that there are some discrepancies between the geological units, their ages and positions, on this map, the Figure 3-8 map, and the descriptions within the text. This reflects the lack of agreement in the published literature.

The deep geology at the study site was traditionally known as the Termaber flood basalts, though is more recently termed the Upper Basalt sequence (Kebede, 2013). Another series of volcanics are present in the area, though there is some uncertainty as to whether these are present above the flood basalts at the field site: The Miocene-Pliocene shield volcanics, erupted from large shield volcanoes (approximately 22 Ma) that today form the Choke Mountains to the southeast of Lake Tana (Figure 3-8), contain more rhyolitic, trachytic and ash layers than the flood basalts (Kieffer *et al.*, 2004; Kebede, 2013). Overlying this thick flood basalt and/or shield volcanic sequence across a large area south of Lake Tana are more volcanic rocks of middle-Pleistocene to Holocene age, i.e. 10,000 to 1 million years old (Mohr, 1963). These thinly bedded and often scoriaceous basalts and trachytes were erupted from relatively small and local Strombolian volcanoes (Kieffer *et al.*, 2004; Kebede, 2013), many of which are still visible, the locations are shown on Figure 3-8. Largely impermeable dykes, sills and faults are present within the region though these are most likely confined to the pre-Quaternary geology (Kebede, 2013) and, as such, should have little impact on the shallow aquifer.

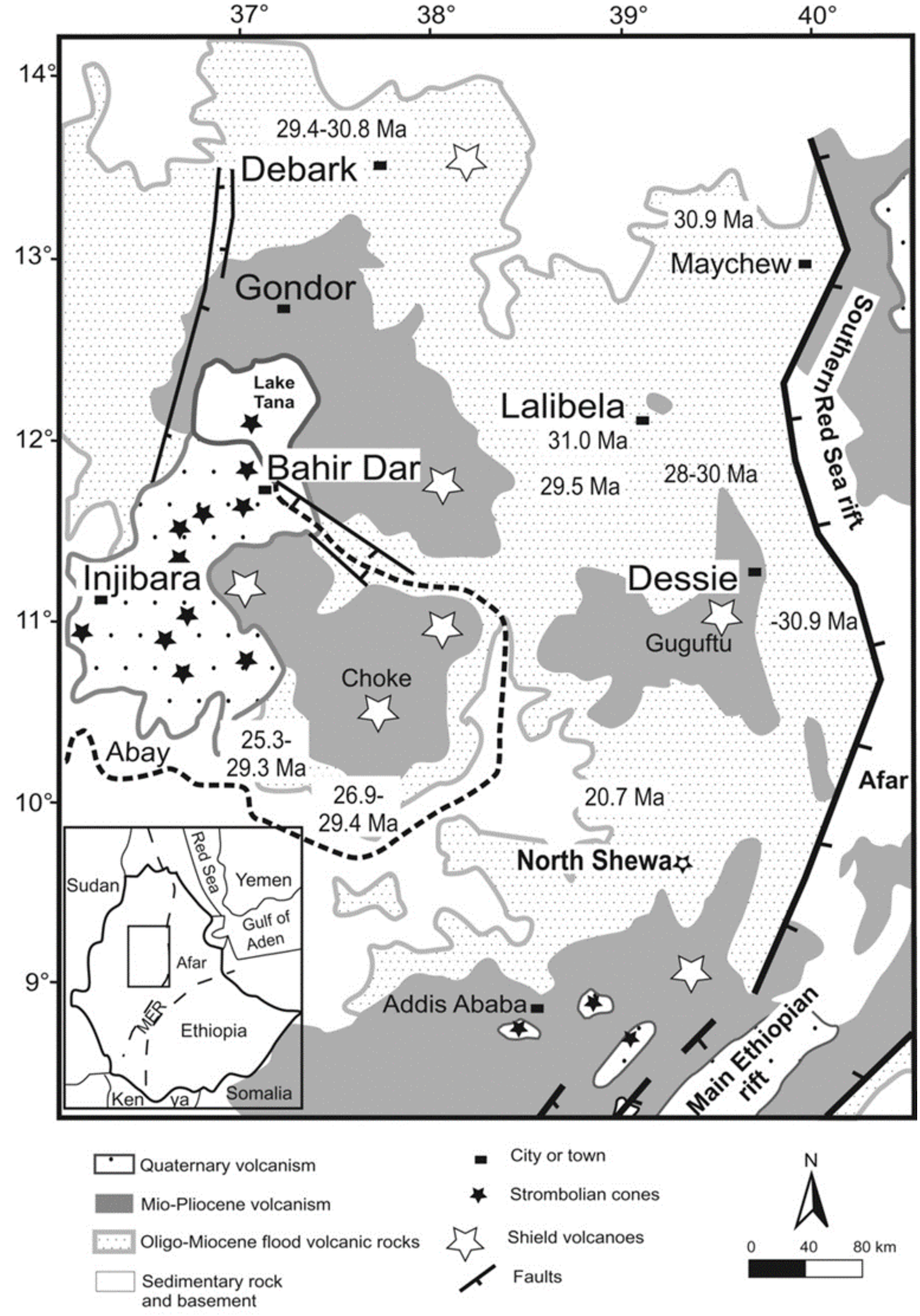


Figure 3-8. Geological map of the northern part of the Ethiopian plateau depicting the distribution of the volcanic rocks, shield volcanoes and Strombolian cones (from Ayalew (2011)). MER = Main Ethiopian Rift.

Lake Tana itself had been believed to have been formed by the intersection of three graben rift systems (Chorowicz *et al.*, 1998). However, a recent study suggests that Lake Tana is a collapsed caldera created during a super eruption around 30 million years ago (Prave *et al.*, 2016).

The basalts and trachytes found around Dangila *woreda* have had little time, less than 1 million years, for weathering and regolith formation in comparison to the majority of the African continent. However, a review of various physical and chemical weathering experiments of igneous rocks by Cawsey and Mellon (1983) indicates that significant physical weathering may occur over relatively short periods of time (years), whereas chemical weathering processes require much longer periods before the effects are readily observed, though still just 100s to 1000s of years. Indeed, the Pleistocene-Holocene volcanics south of Lake Tana have been observed to be more highly weathered than the 10-30 million years older flood basalts in the surrounding area (Poppe *et al.*, 2013).

3.7 Regolith hydrogeology

Weathered materials that can be considered regolith overlie the Cenozoic volcanic rocks of the study site. The generally accepted definition of "regolith" is the unconsolidated heterogeneous material, including soil, which overlies the bedrock (Merrill, 1897). Regolith consists of physically broken and, generally, chemically altered rocks (Scott and Pain, 2009). While sometimes considered a synonym, "saprolite" refers to in-situ weathered materials, whereas regolith may include transported materials (Taylor and Eggleton, 2001). In this thesis, "regolith", "weathered regolith" and "weathered mantle" are used interchangeably.

Acworth (1987) describes the typical weathered profile, which forms above crystalline (including volcanic) bedrock: Four weathering zones are present between the fresh rock and the soil (Figure 3-9). Each zone is always present but may be so thin as to be insignificant. The interface between zones is generally planar as it is related to the water table but the interface between zone 'd' and bedrock can be highly irregular. Zones 'a' and 'b' are generally clay-rich and have low hydraulic conductivity. Zone 'c' acts as storage and fractures in zone 'd' are the transmissive parts. If hydraulic conductivity is high in zone 'c', then drainage will occur from zone 'b' above.

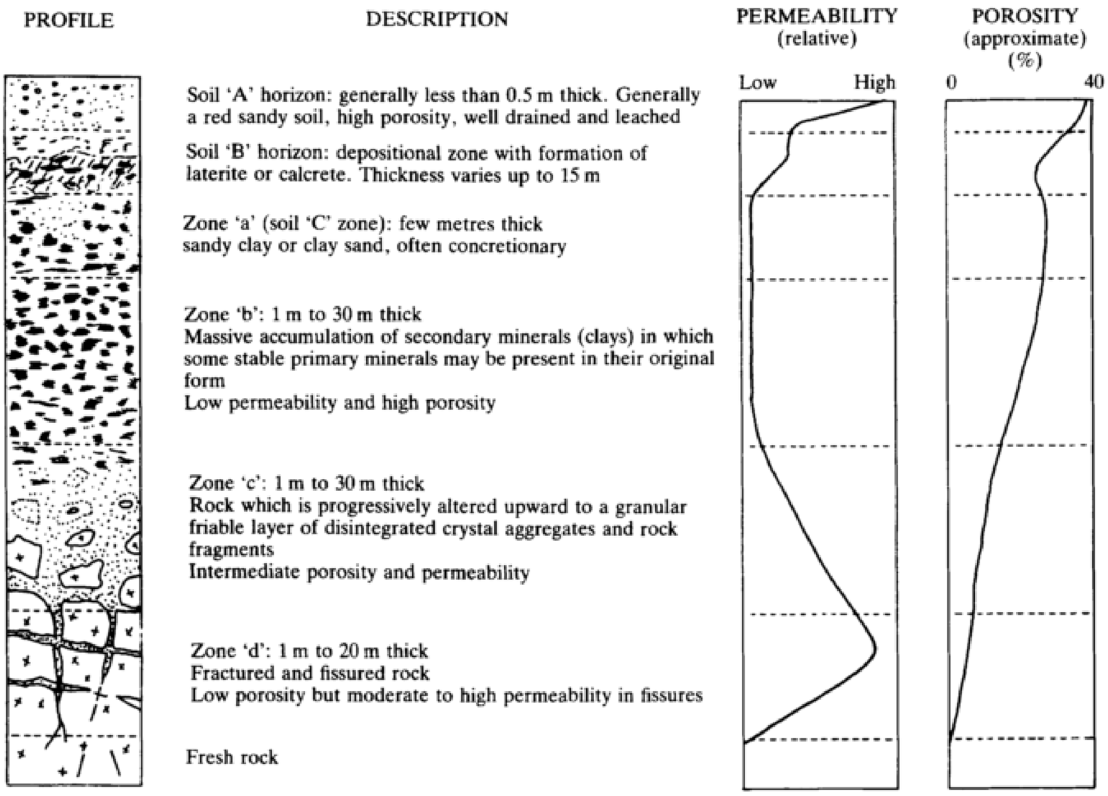


Figure 3-9. Typical weathering profile developed upon crystalline rocks (from Acworth (1987))

Acworth (1987) goes on to state that recharge is highest where zone 'd' directly underlies stony soils whereas minimal recharge occurs where thick zones 'a' and 'b' exist. However, there will be lateral flow between horizons. Hilly or plains areas have a higher groundwater potential as weathering basins will have coalesced laterally as relief has been lowered, with the result that an extensive zone 'c' saprolite aquifer has been produced extending into the area previously occupied by the zone 'd' fractured material. Reduction in relief also causes a reduction in groundwater flow as water table contours are a subdued reflection of surface topography. In general, well sites should be chosen towards the middle of the slope where the depth of weathering and saturated material is maximized.

Jones (1985) reports that saprolite profiles tend to have similar characteristics over a wide variety of rock types. This conclusion is extremely important for this PhD project. It means that findings from shallow hydrogeological assessments conducted at the field site may be transferrable across SSA, even to areas with different bedrock geology. Jones (1985) states that geomorphological development by cyclic erosion has resulted in a predictable distribution of the regolith aquifer and the analysis of data from over one thousand wells shows it to be hydrogeologically uniform. This uniformity is traced to the geomorphological development of the landscape; of lesser importance is the mineral composition of the parent rock. However, some studies have identified differences in regolith hydrogeological characteristics occurring over short distances related to local variation in parent geology (e.g. Macdonald and Edmunds (2014)). Jones (1985) description of a typical weathering profile above crystalline rocks in Africa is in agreement with Acworth (1987) (Figure 3-9) and he further adds that the lower part of the profile, the weathering front, if freely draining with active groundwater flow, will preserve a relatively clay-free, gravel-like texture. The grain size of the saprolite diminishes upwards until the clayey part of the saprolite is encountered and where the groundwater flow is impeded. Furthermore, chemical weathering occurs without significant volume change (indicated by undisturbed persistent quartz veins) though dissolution removes mass causing structural unloading allowing deeper joints and fissures to open, which allow deeper groundwater penetration. The transferability of the findings from this study to other types of geology in SSA is discussed in Chapter 9.

Chapter 4. Field investigations and development of conceptual model

4.0 Chapter overview

Chapter 3 presented background information on the study site. The process provided understanding of the climate, geology, agriculture, socio-economics and governance issues prior to the field visits and enabled planning of fieldwork. Chapter 4 provides descriptions and analysis of information from field investigations, essentially detailing how the hydrogeological conceptual model was derived.

4.1 Field visits

Three field visits were conducted to Dangila *woreda*, in March/April 2015 at the end of the dry season, in October/November 2015 at the end of the wet season, and in January/February 2017 during the dry season. The first two visits were for approximately a month with around 2-3 weeks in the field in Dangila and the surrounding area, the remaining time being spent with local partners in Addis Ababa and Bahir Dar. The third visit was for 2.5 weeks, principally spent in Boloso Bombe *woreda* in SNNPR Region in southwest Ethiopia for a different research project, though with a few days in Dangila *woreda*.

4.2 Aims

The aims of the field visit were to develop a conceptual model for use in subsequent recharge and modelling studies. The field investigations conducted during this process allowed the first research question from Chapter 1 to be evaluated, namely: Do shallow aquifers have the requisite properties, in terms of hydraulic conductivity, potential well yield, specific yield and aquifer geometry, for productive groundwater use?

4.3 Study site observations

Situated on the Addis Ababa to Bahir Dar highway, Dangila town is a popular transport stop with more services, such as; markets, hotels and banks, than are seen in similar sized towns in nearby *woredas*. Being well connected on the transport network, there is potential for an increase in agricultural production due to good access to markets. The majority of the *woreda* is devoted to agriculture. Seasonally inundated floodplains/grasslands are utilised as pasture with mixed cropping and dwellings occupying the adjacent slopes (Figure 4-1). Natural woodland is generally only found around hilltop churches and along more steeply sloping riparian strips. The higher steeper mountains often have thin soils and are covered with low scrub-like vegetation. Abera (2017) notes that much of the steeper highland areas have been degraded through overuse and erosion. Dangila town is by far the largest settlement in the *woreda* and, other than Abadira town to the north, and Chara and Giza in the west, dwellings and the population are quite scattered.

Figure 4-1. Typical wet season and dry season scenery in Dangila *woreda* of floodplain pasture surrounded by low hills with small (<1 ha) individual plots of rainfed agriculture.

The flatter *kebeles* in the east of the *woreda*, e.g. Dangesheta, Zelesa, Zeguda and Workit, that were most frequented for this PhD research exhibit very few stream diversions like those observed by Belay and Bewket (2013) during their study of irrigation in the *woreda*. However, most households have their own HDW for backyard irrigation. Such plots generally occupy <0.25 ha and are more likely to be planted with fruits, vegetables, coffee and *khat* (*Catha edulis*) than the main crops listed above. The typical observed backyard irrigation system involves a rope and bucket and a watering can. Some smallholders have the more efficient pulley and double bucket system while others have rope-and-washer pumps often supplied by NGOs. Only one treadle pump was observed among the hundreds of wells visited during the three field visits. Despite the advantages of being less energy-intensive, locally-made and low cost (1300-3000 Birr or $60-150), broken-down rope-and-washer pumps were frequently observed. Indeed, a study by MetaMeta (2014) revealed that 35-50% of rope-and-washer pumps in the areas of Ethiopia they surveyed were non-functional.

The main rainfed crops have a 5-8 month cropping cycle and are harvested in October following the first substantial dry spell at the end of the rainy season. This dry period is necessary to dry out the crop thus an extended wet season, according to the local community, is a hindrance. The generally flat and seasonally inundated floodplains are almost exclusively used for pasture for cows, sheep and goats, usually tended by local children. Other observed floodplain activities were occasional observations of harvesting wetland vegetation for animal fodder and small plant nurseries can sometimes be found beside perennial reaches of streams during the dry season. While the floodplain marginal areas are sought after for cropping to take advantage of residual moisture and shallow water tables, cropping is largely non-existent within Dangila *woreda* on the floodplains themselves.

4.4 Hydrology

During the dry season field visits, rivers were commonly observed to have dry reaches between areas of flow. Similarly, flowing springs often form small streams, which later dry up. Dry and low-flow reaches are commonly observed on large flat floodplains where the rivers are losing water to the underlying sediments whereas upstream in narrower steeper valleys there may be substantial flow. An example is the Amen River, which flows through the centre of Dangila town but later dries up upon reaching the large floodplain of the Kilti River (Figure 4-2).

Figure 4-2. The flowing Amen River at the gauge location in Dangila town (left) and the stagnant or dry Amen River (right) approximately 5 km downstream shortly after reaching the extensive Kilti floodplain.

The floodplains become inundated during the wet season from spring discharge at their edges and from pluvial flooding as opposed to overbank flow. These features appear akin to “dambos”, which are discussed in the following section.

To increase understanding of the hydrology, gauge boards were installed in the Kilti and Brante rivers that were monitored by the local community. Additionally, a manual raingauge was installed and groundwater level was monitored in five hand-dug wells. Further detail is provided of the community-based monitoring programme in Chapter 5.

4.5 Dambos

The definition of a "dambo" is under debate in earlier studies but is generally as described in a review paper by von der Heyden (2004): "… shallow, seasonally waterlogged depressions forming the headwaters of ephemeral and perennial streams in subtropical and tropical Africa." Dambo profiles are "primarily concave, with shallow slopes and gradients of less than 6^{o} (usually less than 2^{o}). The size and shape of the dambo surface in plan vary widely, with dambos ranging from several square kilometres of wide, oval wetland to narrow, tortuous structures barely 100 m in length." This definition matches the pervasive floodplain wetland land form observed in Dangila *woreda*, as do the characteristics, such as: (non-calcic) soils characteristics of 30-50% coarse sand, <10% clays, low EC, and pH 5.3-6.5, and; a clay layer from in-situ weathering that forces soil water to discharge at the level of the dambo at dambo verges.

Studies on dambos are predominantly from Malawi, South Africa, Zambia and Zimbabwe, and though the term appears in papers concerning Ethiopia, specific dambo studies are non-existent. Published literature on dambos generally ranges from the late 1980s to the early 2000s then dries up (attempted contact with authors has not revealed why this occurred).

Uncertainty and conflicting hypotheses exist in the literature concerning the role dambos play within catchments, relating to evapotranspiration (ET), dry season baseflow, and attenuation of flood flow. The review paper by von der Heyden (2004) states:

1. Evapotranspiration from a dambo will likely be greater than from interfluves when the latter is vegetated by short grasses and shrubs.
2. Baseflow and dry season flow augmentation is primarily a function of aquifer groundwater discharge, with a secondary contribution from surface water storage within a dambo. However, viewing the surface water as a separate entity from the groundwater system is illogical as the surface water is an above-ground extension of the groundwater table.
3. Storm flow is retarded and attenuated during the early wet season, through soil infiltration and dambo filling. The extent of this retardation and attenuation is a function of the soil characteristics. Following saturation of soils, the dambo effects little influence over storm flow, with flashy responses to rainfall events noted.

A geochemical study on a dambo in the Zambia copperbelt with long term monitoring by von der Heyden and New (2003) discusses the three issues in contention with the role of dambos, agreeing with the points presented above: ET is increased but the main outlet of a dambo is surface water flow; floods are retained at the onset of the wet season but the dambo quickly fills and has no effect on downstream floods; dambos only contribute to dry season surface flows until mid-dry season – later in the dry season dambos must be fed by deeper aquifers. The study site has a two-aquifer system – the shallow regolith and the deeper aquifer – akin to Dangila, and the hydrochemistry results for wetlands, deep groundwater and surface water also match.

An earlier review paper by Bullock (1992) generally matches the conclusions drawn by the von der Heyden (2004) review. Bullock states that ET is highest at dambo edges though these areas make up only 10% of a dambo. The paper agrees that dambos are not so significant for low-flow augmentation and references to this in many papers are from misunderstandings of available literature.

McCartney and Neal (1999) present a case study from Zimbabwe with coarse to medium loamy sand soils and a low-permeability clay lens. Low slope and low hydraulic conductivity (K) mean that when saturated most flow is over the surface rather than through the dambo. Deeper groundwater showed higher alkalinity indicative of weathering, whereas shallow groundwater did not, confirming that the clay lens acts as a barrier to upward flow. The study suggests pipe-flow is significant in natural pipes ~0.4 m below surface. During the wet season, 70% of storm flow is "new" water; 10 days following a storm event, most water is "return" water having passed through soils first. Contradictory to other studies, they state that most water loss is via ET, though they do note that there is still much uncertainty.

A lengthy technical report by McFarlane (1989) describes the contrasting theories of dambo formation: (i) fluviatile, with fining up sediments, or (ii) within irregularly lowered land formed by differential leaching with colluvium fill. McFarlane (1989)'s Malawi example argues against a fluviatile formation because some dambos are circular, others cross watersheds, others are discrete (endorheic); exactly as observed in Dangesheta (Figure 4-3). This is suggestive of formation due to irregular lowering of the land caused by differential leaching. Further arguments against fluviatile formation presented by McFarlane (1989) include:

- Dambos often contain smectite but it is not seen in interfluves because it is from local weathering

- Some dambos have stepped forms which would have required multiple climate change episodes
- There is a lack of sufficient energy in low gradient streams with little higher catchment for formation of such features
- There is a lack of stratification of sediments with often vein quartz within clays.

Also described is the dambo-peripheral zone being characteristically sandy, which “shows up well on the air photos as a light toned belt”; this can be seen on Google.Earth satellite imagery around Dangila (Figure 4-3). At the Malawi study site, the dambo peripheral belts are preferred localities for HDWs because the water table is near to the surface; again, such a pattern can be observed in Dangila. Mechanisms for dambos in-setting in the landscape include: 1) repeated dissolution and deposition (i.e. as seen in African bauxite and laterite terrains), 2) physical subsidence as saprolite loses mechanical strength, 3) upstream retreat of gully head and subsequent deposition on downstream dambo. The lack of bauxite and laterite terrains makes mechanism 1 inapplicable at Dangila. The geomorphology of the narrower, steeper dambos in hilly areas are suggestive of mechanism 3, though mechanism 2 is likely to be dominant in Dangila *woreda*. When discussing mechanism 2, McFarlane (1989) talks about HDWs in dambos being notorious for collapsing; this may be another reason why the Dangila local communities do not excavate wells in dambos and the only HDWs observed in dambos are concrete-ring-lined MoWR installed handpumps. Many authors suggest grass slows surface water flows off of dambos at the onset of the wet season, a delay of around a month (McCartney and Neal, 1999), though McFarlane (1989) suggests it actually takes a month for cracks to be closed by swelling clays before runoff is promoted. Interfluve runoff would penetrate a dambo at the sandy periphery rather than over the surface; the lack of surface deposits is evidence of this.

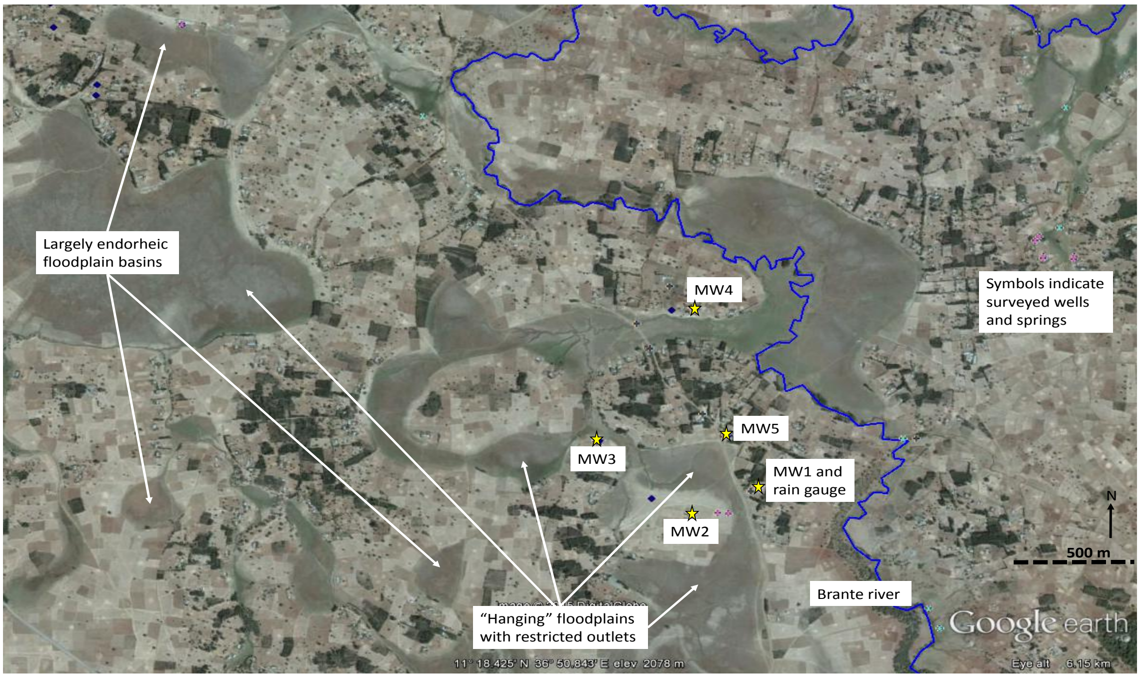


Figure 4-3. "Hanging" floodplain basins above the Brante river valley and the locations of the community monitored raingauge and hand-dug wells, Dangesheta *kebele*. Image source: Google.Earth; Imagery ©2015 DigitalGlobe).

4.6 Geology

Outcrops are visible in riverbeds, occasionally on steeper slopes and in a few man-made excavations. Examples of the geology are more commonly visible as large boulders within superficial materials, particularly in riverbeds and banks (Figure 4-4). The basalts are variously massive, fractured and vesicular with variations occurring in short distances. The more massive basalt often forms higher ground with valleys and floodplains overlying more fractured and vesicular basalt, which is more easily weathered and eroded.

Figure 4-4. Vesicular basalt boulders in the Brante riverbed, Dangesheta *kebele* (left). As-dug weathered basalt beside a well under construction on the edge of the Brante river floodplain.

Above the solid geology lies weathered basalt regolith, itself overlain by red clayey loam soils. The red soils become more lithic and clayey with depth, grading into the regolith usually with no obvious boundary. As-dug materials beside wells under construction show the degree of weathering decreasing with depth. The regolith becomes greyer, stronger, and must be chiselled as it deepens though it is still quite friable (Figure 4-4). Local communities report there are rarely problems with well sidewall collapse. The most friable and excavatable regolith is the result of weathering of low-density vesicular or scoriaceous basalt. Often solid geology is reached abruptly and well excavation is halted.

The superficial materials underlying the floodplains are often browner in colour being more organic-rich. Deep and wide desiccation cracks suggest a high clay content, though the alluvial materials are occasionally very sandy and gravelly.

Depth to the top of the solid geology is variable. Wells are typically excavated until further excavation becomes impossible, therefore, the location of rockhead can be inferred from well depth. Over all the field visits, 80 wells were measured for estimation of regolith thickness; more wells were visited but access for measurement, such as in the case of wells fitted with handpumps, was not always possible. Rockhead was generally found to be deeper in more steeply sloping areas and shallower in floodplains. For example, in the north of Dangila *woreda* in Afafe Eyesus *kebele*, a hilly area with large slopes, wells were found to be 14 to 17 m deep (Figure 4-5), whereas wells adjacent to the floodplains in much flatter Dangesheta *kebele* are often just 3 to 4 m deep. Rivers have often incised to the level of the rockhead where solid basalt forms the riverbed with banks of only 1 to 3 m in height (Figure 4-5). Measurements and information from the well and river surveys are presented in Appendix F.

Figure 4-5. Very deep (approximately 15 m) exposure of regolith in a gully on a large slope, which leads to the Amen River, Kuandisha *kebele* (left). Massive and fractured basalt bedrock exposed in the bed of the Gizani River, Sehara *kebele*. Note the low (~1 m) river banks in this floodplain.

In a study of gully formation and upland erosion by Tebebu *et al.* (2010) at a site south of Lake Tana, approximately 50 km from Dangila *woreda*, they note that the area consists of vertisols, which comprise only soils' A-horizon then 'C' (no soil B-horizon) (see Figure 3-9). The study further reports that the area is underlain by shallow highly weathered and fractured basalt. The fractures are highly interconnected with limited clay infillings. Surface exposures of weathered basalt (saprolite) can be found on the hilltops and in mid-slope areas on the hillsides. A black clayey layer, regolith zone 'b', (note this is different to the soil B-horizon as shown in Figure 3-9) is often present above the basalt and a brown silty loam is common (zone 'a'), as well as a compact stony friable layer (zone 'c'). These observations match those made during fieldwork for this PhD project in both Dangila *woreda* and north of Bahir Dar at Robit-Bata *kebele* (when assisting a Bahir Dar University student with his PhD fieldwork); these two locations being either side of the study area of Tebebu *et al.* (2010). Such complementary observations indicate that the "typical" regolith profile reported by Acworth (1987), Jones (1985), and others, is applicable to this study site and the surrounding area.

4.7 Hydrogeology

In addition to season, topography appears to govern shallow groundwater availability. The variations in geology are sufficiently subtle, particularly concerning the regolith, which forms the shallow groundwater aquifer, to be less of a control on the hydrogeology than geomorphology.

Near the end of the dry season in March/April within the floodplains where the solid geology is at a depth of around 4 m, the water table lies at 2-4 mbgl (metres below ground level). The water table can often be seen as a seepage face at this depth within riverbank sections in floodplain sediments (Figure 4-6). However, on the larger and steeper slopes where rockhead is around 15 m deep the water table is at a depth of 12-15 m. Thus, the shallow aquifer is thicker on slopes giving deeper water tables and generally greater saturated aquifer thickness though possibly with lower hydraulic conductivity (as suggested by pumping tests). Superficial deposits are thinner in floodplains and the material has higher hydraulic conductivity due to the visible sand and gravel content and the possible presence of enhanced fracturing below the floodplains (refer to the earlier discussion on dambos).

Figure 4-6. Visible water table in the banks of the Amen River, Dangila *kebele* (left). Massive basalt boulders visible within regolith in a cutting for an irrigation canal near Giza.

It is noted that farmers often talk of a well excavation striking rock at a shallow depth and being dry, then when the well is relocated a short distance away (~10 m) rock is struck at greater depth and the well fills with water. Such a situation is commonly ascribed to heterogeneous rockhead, however, the unsuccessful wells are perhaps more likely to be due to the presence of large and massive basalt boulders lying higher in the weathered profile as are often visible in riverbank sections (Figure 4-6).

Despite the shallow aquifer being considered the regolith above the solid geology, it is likely that fractures in the upper layers of the bedrock are influential to the hydrogeological regime. However, fissure flow is unlikely as any fractures are probably filled with weathered material with similar properties to the overlying regolith. The precise depth and degree of fracturing of the solid geology is very difficult to estimate without subsurface investigations or geophysics. Heterogeneities within the weathered basalt regolith, such as the clay content and the fractured or vesicular nature of the pre-weathered rock, determine the productivity of a well, though this is similarly very difficult to assess prior to excavation.

During the AMGRAF catalyst period in February and March 2014, 143 hand-dug wells were surveyed by Demis Alamirew of GSE. A further 64 wells were surveyed by me during field visits in March/April 2015 and October/November 2015. The surveys included GPS location, depth and water level measurements, description of geology, topography, land use, pump/lifting device and cover, in-situ measurement of water temperature, pH and electrical conductivity, and discussions with local community over the well’s use, seasonality and history. The information gathered during the water point surveys is tabulated in Appendix F.

Water point surveys also included assessment of springs, many of which are used by the local community, whether developed or not, to collect water for domestic and potable use. Flow rates vary from over 20 l/s at Lunk in Sehara *kebele*, where water is piped to tanks to supply the towns of Giza and Chara, to unmeasurably small seepages, though often over a large area giving a combined high total flow rate and often forming streams (Figure 4-7). Where springs and seepages emerge from gullies they commonly occur at contacts between regolith and bedrock or gravelly regolith and more solid regolith (Figure 4-7). Springs and seepages are also very common around the edges of floodplains where the water table from the surrounding slopes intercepts the ground surface (Figure 4-8).

Figure 4-7. Small spring emerging from contact between gravelly and more solid regolith (left). Large area of seepages emerging at contact between regolith and massive basalt bedrock forming the riverbed.

Figure 4-8. Developed spring in the centre of a floodplain, which is completely submerged in the wet season (left). Spring emerging at the end of the wet season around the edge of a floodplain.

4.8 Pumping tests

Eight pumping tests were conducted on shallow hand-dug wells in order to gain information on the shallow aquifer properties. This particular aspect of the field investigations was presented at the 7th RWSN (Rural Water Supply Network) Forum

"Water for Everyone" in Abidjan, Côte d'Ivoire, in November/December 2016. The resulting peer-reviewed conference paper titled "Properties of shallow thin regolith aquifers in sub-Saharan Africa: a case study from northwest Ethiopia" (Walker, 2016), is presented as Appendix A. The paper essentially states that the drawdown and recovery were analysed separately, applying the Moench (1985) and Barker and Herbert (1989) methods respectively, providing consistent results, confirming suitability of methods. Hydraulic conductivity estimates ranged from 0.2 to 6.4 m/d (mean = 2.3 m/d, median = 1.6 m/d) in the dry season and ranged from 2.8 to 22.3 m/d (mean = 9.7 m/d, median = 6.5 m/d) in the wet season when the water table was higher. This difference indicates the importance of excavating wells as deeply as possible to increase the likelihood of intercepting more transmissive layers. Specific yield estimations have a wider range (0.00001 to 0.32) and are more uncertain though the mean of 0.09 (median of 0.08) is reasonable. Estimates of well yield average 0.5 l/s though this increases to >1 l/s in the wet season; giving optimism that small-scale abstraction and irrigation is achievable.

4.9 Hydrochemistry

A water sampling and in-situ testing programme was undertaken with the aims of: identifying water types, assessing aquifer connectivity, groundwater aging, assessing recharge mechanism, analysing the consistency of the hydrochemistry, and to identify losing and gaining reaches of surface water. The water sampling and in-situ testing programme undertaken during the field visits is described in Appendix B and details of the sampling and testing locations can be found in Appendix F. In summary, 49 samples of shallow and deep groundwater, surface water and rainwater were sampled during the first two field visits; many of these being repeat samples from the same locations. Laboratory analysis involved measurement of major ions, some trace elements, and stable isotopes oxygen-18 and deuterium ($\delta^{18}O$ and $\delta^{2}H$). In-situ testing involved measurement of pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, and radon-222 concentration.

The shallow groundwater is consistent in chemistry both spatially and temporally. Residence time is low, indicated by low EC and ionic concentrations, suggesting that the resource could be vulnerable to drought. Surface water and shallow groundwater belong to the "bicarbonate calcium" type typical of recent recharge. The deep groundwater is of "bicarbonate sodium" type indicative of higher mineralisation due to longer residence time and greater distance of flow. The shallow groundwater samples from the wet season are very similar in chemistry to surface water samples indicating a high degree of and rapid interconnectivity. This was expected in the wet season from the observed very shallow water table. There is no hydrochemical evidence to suggest mixing between the shallow and deep groundwaters; they belong to clearly different water types. What's more, Radon-222 measurements showed the opposite of what would be expected if surface water and shallow groundwater were being drawndown by abstraction from the deep boreholes: ^{222}Rn concentrations would be lower in the vicinity of the abstracting boreholes as groundwater discharge would be prevented but the reverse was measured. Radon-222 measurements did suggest that the large floodplains in river valleys are areas of groundwater discharge from the shallow regolith aquifer, whereas the narrower valleys with basalt riverbeds are not discharge areas. However, it should be noted that the faster, more turbulent flow through rocky reaches would have a degassing effect on the river water thus reducing radon-222 concentrations (Cook *et al.,* 2003).

Other interesting findings resulted from comparing individual samples collected during the same visit. Wells reported by the community to have good year-round supply often showed greater stable isotope enrichment and higher ionic concentrations than would be expected from their topographic position close to a flow divide. Often, across the flow divide, there was a dambo. The higher enrichment (through evaporation when inundated) and higher concentrations (due to the longer residence time) suggest the sampled water originated in the dambo, which provides continuous groundwater supply through the dry season with groundwater flow paths contradicting surface water flow paths.

Considering only hydrochemistry and not microbial content, the analyses indicate that the shallow groundwater tested is suitable for both irrigation and domestic use: Ethiopia is known for having problems with fluorosis caused by excess fluorine in groundwater (though the issue is typically confined to the Rift Valley and deep boreholes, (Tekle-Haimanot *et al.*, 2006)) but here F^- levels were below the WHO recommended maximum; nitrate was suspected to be a possible contaminant due to the proximity of pit latrines and wells but NO_3^- levels were also below the WHO limit, and; sodium adsorption ratios (SAR) were well below the acceptable limit for irrigation water.

4.10 Conceptual model

The shallow and deep aquifers have little interconnectivity while the shallow aquifer and surface water are in connection particularly during the wet season when large expanses are inundated. Recharge is rapid and groundwater residence time is low.

The clay content of the floodplain sediments means that early rains may quickly create a low-permeability layer at shallow depth, which may exacerbate flooding as surface water would pass overland into the river systems and local recharge would be restricted. However, the constricted floodplain outlets restrict discharge, thus creating wetlands that increase infiltration through coarser lenses or slowly through the low-K layer. If there is a surface water / groundwater disconnection, it probably only occurs at the beginning of the wet season and during dry season rains when the water table is deeper. During the wet season, because the shallow aquifer under floodplains is only a few metres thick, sufficient water would enter this aquifer laterally, even if not vertically, to create a single connected surface and groundwater body.

The floodplains fully saturate and flood during the wet season and discharge in directions not necessarily matching surface water flow paths. Groundwater flows laterally from floodplain basins and probably also flows into and through regolith-filled fractures in the upper portion of the basalt bedrock. Numerous surveyed wells were said to have good perennial supplies despite appearing to be close to watershed boundaries. Further investigation often reveals up-gradient floodplains that may lie across a surface watershed divide though the solid bedrock topography promotes groundwater flow in the direction of the well. Stable isotope results of groundwater from wells in such locations show evaporation at recharge consistent with infiltration below a floodplain wetland. Published literature on regolith and saprolite hydrogeology supports this hypothesis where shallow low-K layers direct infiltration perpendicular to surface contours whereas groundwater flow predominantly occurs in the deeper higher-K layers immediately above the solid bedrock and may be in a different direction, as shown in Figure 4-9. The literature indicates that regolith is often thickest on slopes and this has been confirmed by surveys of well depth. The greater saturated thickness of aquifer in these areas leads to greater well yield, as there is more likelihood of intercepting more transmissive layers.

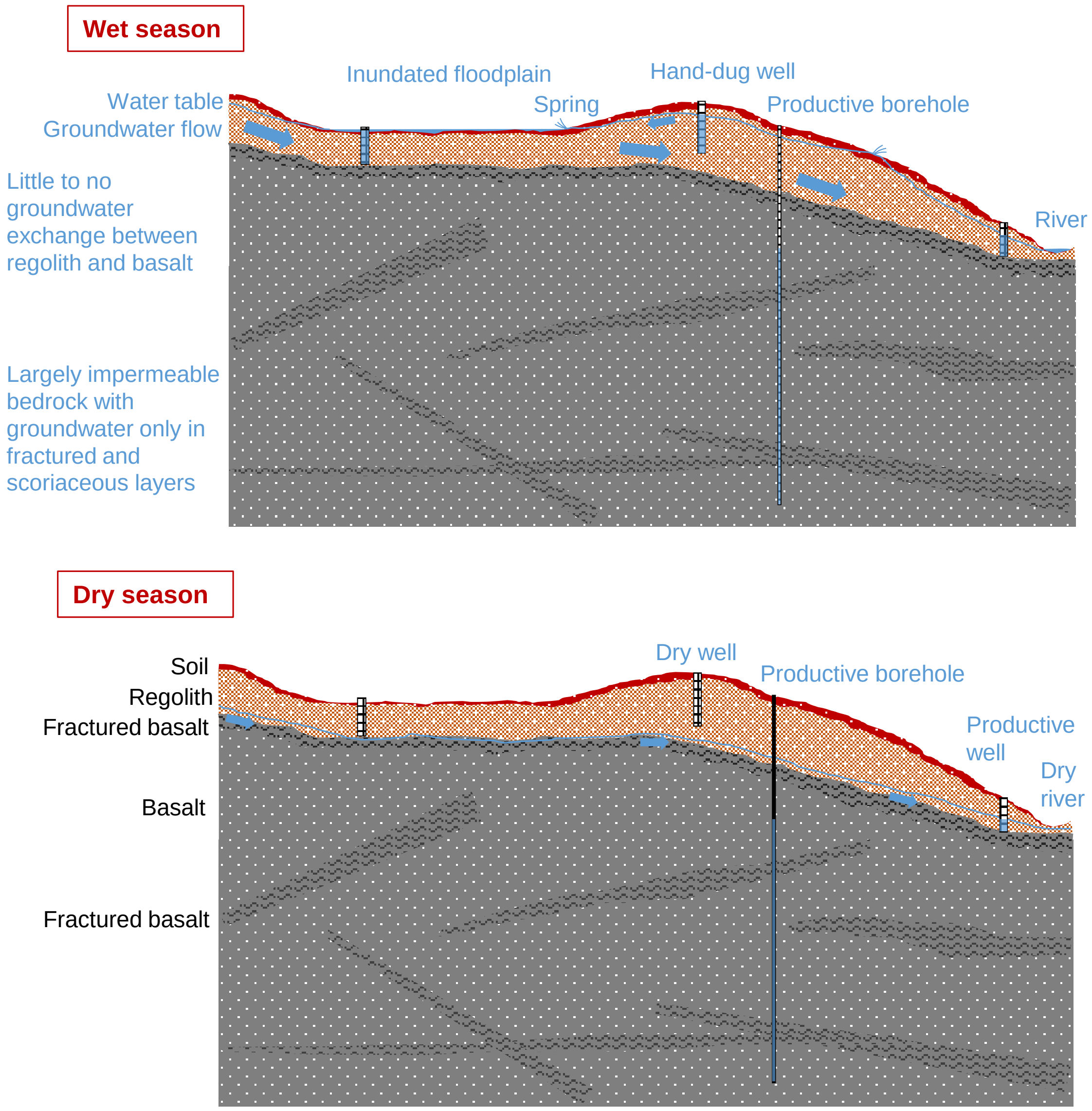


Figure 4-9. Cross sections showing the conceptual model during the wet and dry seasons. The cross section represents a situation common in Dangesheta, such as a west-east section from the floodplain containing MW2 and MW3, through MW1 to the Brante River (Figure 4-3). Note the unsaturated zone flow and very shallow groundwater flow in contradictory directions to the dominant regolith aquifer groundwater flow during the wet season. Note the dominant regolith aquifer groundwater flow direction disregarding the surface water flow divide during the dry season.

The situation of the wet season in the conceptual model in Figure 4-9 of seemingly having groundwater flow in two different directions at the same place is an example of shallow-flow in the upper soil and regolith layers after storm events but with the main groundwater flow in the opposite direction, which would be exacerbated by a low-K layer higher up within the regolith as much of the literature describes. Such a situation was first described by Toth (1963) where local groundwater flow systems are at odds with regional flow systems and diagrams based on his paper are found in most hydrogeology textbooks (Figure 4-10).

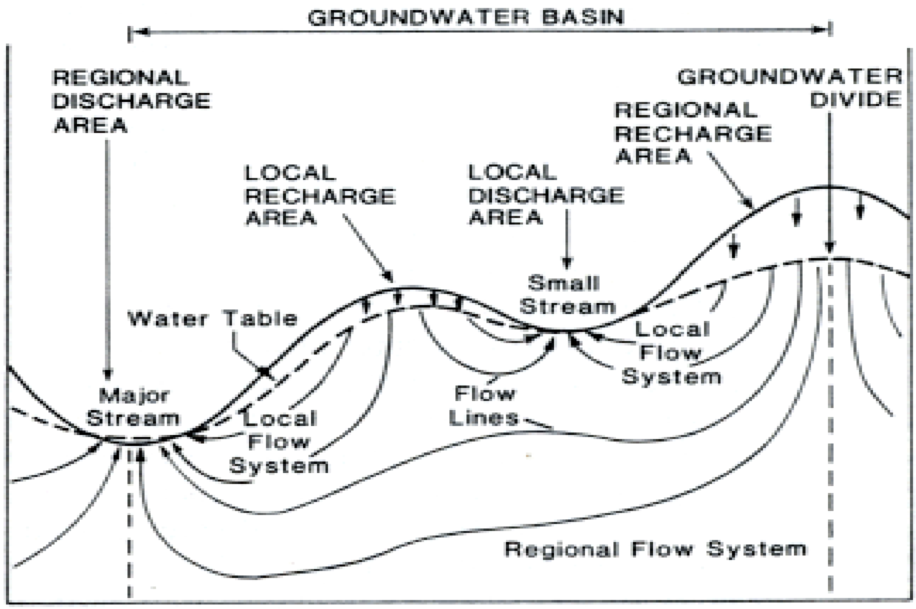


Figure 4-10. Schematic diagram of a regional groundwater flow system (from van der Heijde (1988)).

4.11 Conclusions

In addition to allowing development of the conceptual model described in the previous section, the field investigations indicated that the shallow aquifer has suitable properties for an increase in productive groundwater use. While hydraulic conductivity and consequently well yield are quite low, systems of multiple or large diameter wells providing storage of water could be employed. Aquifer thickness and specific yield are also quite low but not too low to prevent productive shallow groundwater use.

Chapter 5. Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme

5.0 Chapter overview

Chapter 4 described the field investigations that led to development of a hydrogeological conceptual model. To enable resource assessment, time series data was also required; the acquisition and analysis of such data is the basis of Chapter 5. This chapter shows how community-based hydrometeorological monitoring programmes can provide reliable high-quality measurements comparable to formal observations, thus answering research question 2 from Chapter 1. Time series of daily rainfall, river stage and groundwater levels obtained by a local community in Dangila *woreda*, have passed accepted quality control standards and have been statistically validated against formal sources. In a region of low-density and declining formal hydrometeorological monitoring networks, a situation shared by much of the developing world, community-based monitoring can fill the observational void providing improved spatial and temporal characterisation of rainfall, river flow and groundwater levels. Such time series data are invaluable in water resource assessment and management, particularly where, as shown here, gridded rainfall datasets provide gross under or over estimations of rainfall and where groundwater level data are non-existent. Discussions with the local community during workshops held at the setup of the monitoring programme and since have demonstrated that the community have become engaged in the project and have benefited from a greater hydrological knowledge and sense of ownership of their resources. This increased understanding and empowerment is at the relevant scale required for effective community-based participatory management of shallow groundwater and river catchments.

This aspect of the research was published in Journal of Hydrology in 2016:

Walker, D., Forsythe, N., Parkin, G. and Gowing, J. (2016) 'Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme', *Journal of Hydrology*, 538, pp. 713-725. https://doi.org/10.1016/j.jhydrol.2016.04.062

The co-authors provided support in planning and final editing of the paper; all the analysis, writing the paper and preparing figures was conducted by David Walker.

The text and figures comprising the published manuscript are provided here with little alteration. The study area section has largely been deleted to avoid repetition with Chapters 3 and 4 while the supplementary material is provided in full as Appendix C.

5.1 Introduction

Continuous time series of rainfall, river flow and groundwater level vary in their availability. For many areas of, particularly the developing, world, such data is patchy or non-existent. Unfortunately, the areas of greatest data scarcity typically coincide with areas that suffer the greatest impacts from adverse hydrological conditions where more data could be used to better assess the current situation and to forecast future scenarios allowing for better mitigation and adaptation strategies. The importance of quantitative information on the rainfall, which controls spatially and temporally variable water resources, and of measurements of the surface/groundwater resources themselves is not in doubt (Washington *et al.*, 2006; Conway *et al.*, 2009; Bonsor and MacDonald, 2011). Satellite and reanalysis rainfall products are often promoted as the solution to low-density gauge networks, however, the greatest accuracy of such products is achieved in areas with abundant ground observation data to aid calibration (Fekete *et al.*, 2004; Dinku *et al.*, 2008; Symeonakis *et al.*, 2009). What's more, the necessary spatial averaging means spatial resolution is commonly insufficient for smaller than regional scale hydrological and hydrogeological studies. Datasets at the relevant scale to inform local resource management strategies are increasingly being obtained by local communities providing a low-cost and highly useful source of hydrometeorological time series data where they would be otherwise unavailable (Liu *et al.*, 2008a; Gomani *et al.*, 2010). The numerous additional benefits of such community-based monitoring programmes include the engagement and empowerment of local communities in their own water resources (Conrad and Hilchey, 2011; Buytaert *et al.*, 2014). A recent editorial in *Nature* discussing the rise of "citizen science" in various fields states that data quality is the prime concern of critics (Nature, 2015). The majority of the literature presenting community-based monitoring programmes has sought to detail the benefits brought to the community though few (if any) papers have attempted to quantitatively validate the collected data in a statistical manner akin to the abundant literature validating remote sensing products against ground observations. It will be determined here whether community-based monitoring can provide data that can be satisfactorily validated against formal sources to provide improved spatial and temporal resolution, and whether it can supply reliable hydrogeological data where there are no formal alternatives. As formal monitoring networks continue to decline in many parts of the world, we determine if community-based monitoring programmes can be a viable complement.

5.2 Sub-Saharan Africa context

Rain gauge distribution across sub-Saharan Africa (SSA) is sparse, particularly in comparison with Europe, North America and South Asia. There are 1152 World Meteorological Organization (WMO) World Weather Watch stations in Africa at an average station density of just one per 26,000 km^2, 8 times lower than the WMO minimum recommended level (Washington *et al.*, 2006). Figure 5-1 shows the network of WMO stations clearly indicating the sparsity of stations in Africa and their uneven distribution resulting in substantial areas going unmonitored. Within SSA, rain gauge densities are highest in coastal West and Southern Africa, and the East Africa Highlands of Kenya and Uganda, whereas areas of greater aridity are underrepresented. Furthermore, it is widely reported that rain gauge networks in SSA are in decline as weather services make cut backs (Nicholson, 2001; Washington *et al.*, 2004; Maidment *et al.*, 2014). Willmott *et al.* (1994) report a peak in African rain gauge density occurring in the 1950s and a sharp decline after 1970. South Africa has generally been commended for its relative abundance of rain gauges although Pegram and Bardossy (2013) report that even South African rain gauge records are dying off; after mid-2000 they found that out of the 279 gauges in the 5 regions only 180 survived until 2008. A more extreme example is Angola which had over 500 meteorological stations as a Portuguese colony which were all but destroyed during four decades of civil war until a government rebuilding programme had increased the number to eight by 2007 (Cain, 2015).

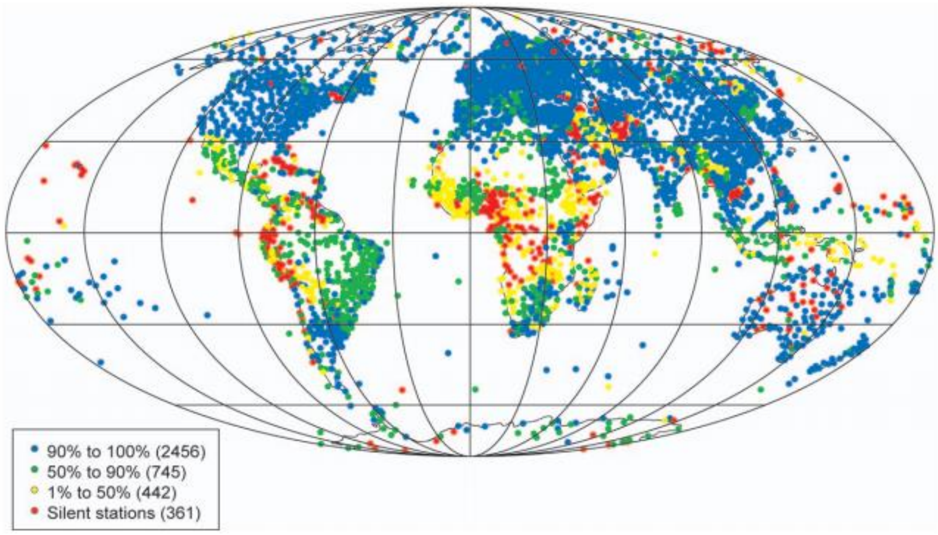


Figure 5-1. The global network of World Weather Watch stations colour-coded to show reporting rates (from WMO, 2003)).

River flow monitoring networks in SSA are unfortunately experiencing a similar decline to meteorological monitoring networks. Monitoring stations globally have been decreasing in number over the last few decades. Tourian *et al.* (2013) note that among the 8424 identified gauging stations in the Global Runoff Data Center (GRDC) database only 40% of stations provide discharge data after 2003. Many of these monitoring stations going offline were located in SSA. The requirement to reverse the trend of decreasing hydrological monitoring is a widely held view (Kundzewicz, 1997; Owor *et al.*, 2009; Taylor *et al.*, 2009).

Even so, surface water is densely monitored in comparison with groundwater. There is general agreement that a better understanding of the shallow hydrogeology of SSA from the point of view of potential agricultural use is a necessity (Giordano, 2006; Namara *et al.*, 2011; Evans *et al.*, 2012; Pavelic *et al.*, 2013a). Lapworth *et al.* (2013) state the issue succinctly; “Ideally, a thorough quantitative understanding of aquifer properties and recharge mechanisms under a variety of climate, land use and geological environments is required to confidently assess current groundwater availability, and forecast future availability under different scenarios”. A recent review of groundwater conditions in 15 SSA countries (Pavelic *et al.*, 2012) concluded that: “Quantitative information on aquifer characteristics, groundwater recharge rates, flow regimes, quality controls and use is still rather patchy”.

Invariably simultaneously reported alongside comments on the need for greater understanding of SSA hydrogeology is the dearth of observations of groundwater systems, in particular sustained time series data (Martin and Van De Giesen, 2005; Calow *et al.*, 2009b; MacDonald *et al.*, 2009; Taylor *et al.*, 2009; Ethiopian ATA, 2013). The situation with groundwater data is different to the aforementioned decreasing meteorological and hydrological time series data because there have never been many monitoring systems in place. For example; considering the hydrogeology atlas of the SADC region (the Southern African Development Community which includes fifteen member states south of and inclusive of the Democratic Republic of Congo and Tanzania), Robins *et al.* (2006) report that only six of the member states (Lesotho, Mauritius, Namibia, South Africa, Swaziland and Zimbabwe) have formal monitoring networks involving water level and some type of water quality measurements. In the remaining countries, sporadic measurement occurs though in an ad hoc fashion with little or no data reaching the national groundwater authority. This issue is not restricted to southern Africa as Martin and Van De Giesen (2005) report that the only data on shallow aquifers in Ghana and Burkina Faso is the total number of wells in a region while even production figures for small formalised piped groundwater supplies are not recorded. Dapaah-Siakwan and Gyau-Boakye (2000) who conducted broad-scale hydrogeological research in this region of West Africa chose to ignore shallow aquifers altogether because: "Even though many hand-dug wells have been constructed in various hydrogeologic formations (a total of about 60,000 as of March 1998; Ministry of Works and Housing, 1998), these were not taken into consideration in the analyses for this paper due to the dearth of data from these sources." The limited groundwater data available in SSA is almost exclusively from deep abstraction boreholes, however, shallow groundwater is the resource that is accessible and exploited by the majority of rural communities via hand-dug wells.

5.3 Community-based monitoring

It is increasingly advocated that community involvement should be strongly supported by the scientific community to improve links between science and local level planning policy (Ridder and Pahl-Wostl, 2005). While there are an increasing number of published works on stakeholder participation in environmental decision-making, there are few concerning a participatory approach in quantitative environmental monitoring. The potential benefits of community-based monitoring are listed by Conrad and Hilchey (2011), compiled from an extensive literature review across a variety of fields, and include:

- Increasing environmental democracy (sharing of information).
- Scientific literacy (Broader community/public education).
- Social capital (volunteer engagement, agency connection, leadership building, problem-solving and identification of resources).
- Citizen inclusion in local issues.
- Data provided at no cost to government.
- Ecosystems being monitored that otherwise would not.
- Government desire to be more inclusive is met.
- Support/drive proactive changes to policy and legislation.
- Can provide an early warning/detection system.

Published studies of data collection from non-specialists, often termed "citizen science", commonly involve the collection of "snapshots" of, for example; wildlife, soil type, or plants (Roy *et al.*, 2012; Vianna *et al.*, 2014; Rossiter *et al.*, 2015). Monitoring of bird populations in programmes such as eBird (Sullivan *et al.*, 2009), where several million species/date/location records are added monthly from around the world and believed to be the largest citizen science project in existence (Hochachka *et al.*, 2012), are the only known studies where time series data is collected by non-specialists though the data are not necessarily gathered at regular times from the same locations. These momentary observations are less useful for most hydrological applications where complete time series of transient data are required. The theory and practice of citizen science in hydrology and water resources management has emerged mainly through experiences in developed countries in response to growing environmental activism. To date its scope is limited and there are only a few published examples within the hydrology and water resources literature of successfully implemented community-based monitoring programmes:

The APWELL project, instigated in the 1990s, developed participatory monitoring including 230 rain gauges and 2100 observation wells across 370 villages in the most drought-prone region of Andhra Pradesh, India. The project provided farmers with the necessary knowledge, data and skills to understand and manage their groundwater resource. The outcome was more efficient groundwater use, increased crop yield, and poverty reduction (Garduño *et al.*, 2009; Garduño and Foster, 2010).

Gomani *et al.* (2010) detail an "integrated participatory approach" in setting up a monitoring network in a large (2780 km^2) catchment in Tanzania as part of a project with an overall aim of assessing climate change impacts and land use options. The approach aimed to assimilate local and expert knowledge with some voluntary monitoring by the community including weather, river flow and groundwater measurements.

A smaller scale community-based monitoring programme in South Africa with the overall objective of watershed management for the increase of food production and improving rural livelihoods is detailed by Kongo *et al.* (2010). This monitoring network was extremely equipment intensive and involved monitoring weather, river flow, deep and shallow groundwater, sediment load, overland flow, soil moisture and crop transpiration. It is claimed that the participatory aspect led to an appreciation of the research, which sustained the goodwill of the community to safeguard the instruments and structures comprising the network. It is stressed that there is always a process to be followed when engaging stakeholders that needs to be based on trust, honesty and friendship.

Buytaert *et al.* (2014) present case studies detailing the benefits of community involvement in hydrological issues from Peru; identifying the hydrological impacts of land use change on ecosystems in remote upland areas beyond the range of formal monitoring networks, from Ethiopia; engaging farmers to rehabilitate gullies following soil erosion caused by poorly implemented land management practices, from Nepal; where communities have taken the lead in water sharing arrangements in an arid region, and from Kyrgyzstan; where water users associations (WUAs) are being set up who are installing monitoring schemes to replace those which died out at the end of the Soviet period.

The few other published case studies of water resource community-based monitoring programmes generally concern monitoring of water quality for various applications. They include; water quality monitoring in rural Mexico for public health where no professional assessments exist (Burgos *et al.*, 2013); for monitoring river sediment load and nutrient contamination to assess the impact of soil erosion in a remote area of Mindanao, the Philippines (Deutsch *et al.*, 2005), and; biological measurements (faecal coliform levels and macroinvertebrate indices) for protection of aquatic habitats in Georgia, USA (Conners *et al.*, 2001).

This paper presents a case study of a community-based monitoring programme in Ethiopia and aims to show that community measured hydrometeorological data can pass strict published quality control procedures. Such data can be validated against formal sources proving that the data is reliable, of high quality, and can offer improved spatial and temporal resolution over formal ground observation and gridded datasets. To our knowledge, there are no other published examples of attempts to rigorously validate data from community-based monitoring programmes.

5.4 Project context

5.4.1 AMGRAF research project

The AMGRAF (Adaptive Management of shallow GRoundwater for small-scale irrigation and poverty alleviation in sub-Saharan AFrica) research project commenced in 2013 with the overarching aim of establishing whether development of shallow groundwater resources for small-scale irrigation (and other purposes) can be used sustainably to alleviate poverty in SSA. The first field site selected was Dangila *woreda* in northwest Ethiopia; an area identified by the Ethiopian ATA (Agricultural Transformation Agency) for an increase in irrigated agriculture. Further information on the AMGRAF research project can be found in Appendix C.

5.4.2 Study area

The Dangila *woreda* study area was described in Chapters 3 and 4; the location is shown again in Figure 5-2 with nearby hydrometeorological monitoring stations.

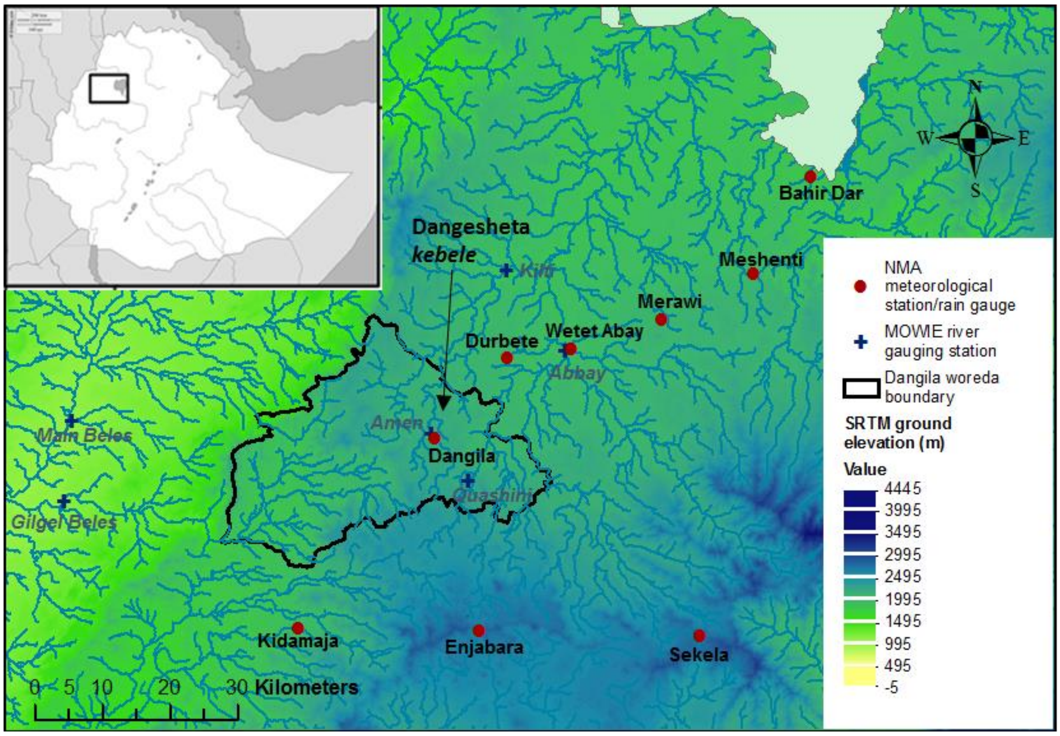


Figure 5-2. Location map of the study area in the Amhara region of Ethiopia. Map shows formal rain gauges and river gauges near to Dangila woreda. Lake Tana is visible at the top of the map.

The community-based monitoring programme was initiated in February 2014. The community were consulted and involved in siting the rain and river gauges and identifying the wells to be monitored (Figure 5-3 and Figure 5-4). Hydrologically suitable areas were identified, i.e. narrow channels and valleys for the river gauges where river stage fluctuations would be most pronounced and open areas with no overhead obstructions for the rain gauge. Certain locations were excluded for being too open where the community expressed concern over the security of the equipment. Ultimately, the rain gauge was situated within the smallholding of the community member who would monitor the gauge. The monitored wells were chosen to provide a transect from close to the river and floodplain up towards a watershed boundary that would include successful wells with perennial supply and also unreliable seasonal wells. Another influence on monitoring well selection was the route that could be taken by the community member who would measure well level, which leads in a broad circle from his house to his place of work (Figure 5-3).

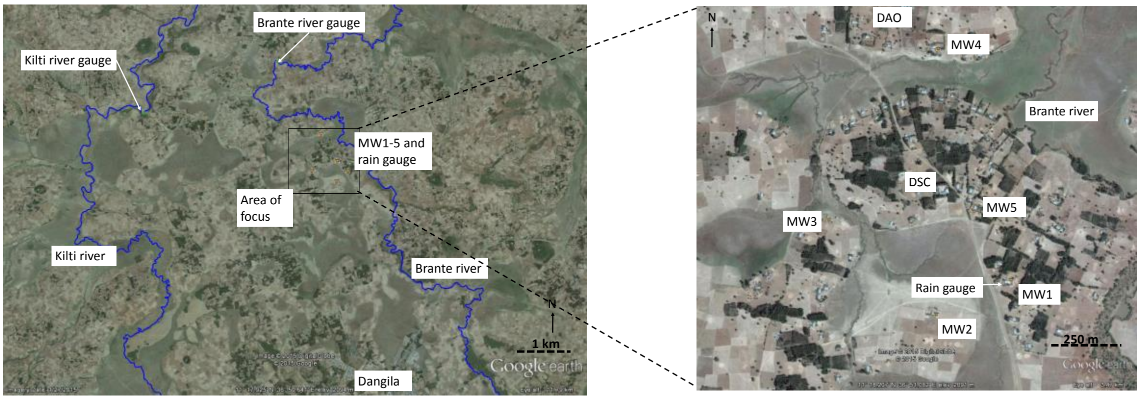


Figure 5-3. Locations of monitoring points (close to arrowhead in Figure 5-2). MW = monitoring well, DSC = Dangesheta Service Cooperative, DAO = Dangesheta Agricultural Office. (Image source: Google.Earth; Imagery ©2015 DigitalGlobe).

The five monitoring wells are manually dipped every two days with a dip meter and the rain gauge is measured daily at 9am by reading the level of the internal graduated cylinder. The river gauges are monitored daily at 6am and 6pm by reading the river stage from the permanently installed gauge boards. Hard copy records of measurements are provided by community monitors on a monthly basis to the Dangila *woreda* office, where they are transferred to an Excel spreadsheet and forwarded to the research team. Further information on the monitoring network can be found in Appendix C.

Figure 5-4. Photographs of (left to right) the Kilti River gauge, the rain gauge, and measuring groundwater level at monitoring well MW5.

5.5 Data analysis methods

5.5.1 Sources of error

Potential errors in rainfall measurements can broadly be divided into two categories; sampling error and observational error. Sampling error results from spatial and temporal variability of rainfall. Sampling error increases with increased rainfall and decreases with increased gauge density and duration of rainfall event (Huff, 1970). Therefore, warmer regions where convective storms of high-intensity and short duration are common will see the greatest errors, particularly where rain gauge density is low (the Ethiopian

Highlands fit this category). Observational error can be due to inaccurate measurements on individual days arising through observer errors, either during measurement or transcription. Detecting such errors is problematic because the skewed distribution of daily rainfall quantities signifies that in all but the most extreme cases a suspect measurement has a considerable likelihood of being correct (New *et al.*, 2001). Measurement biases arise through gauge undercatch caused mostly by wind turbulence around a gauge though splash and evaporation can also have an effect (Legates and Willmott, 1990; Peterson *et al.*, 1998; New *et al.*, 2001).

The sources of error presented above are similarly applicable to river stage and groundwater level measurements. Biases can arise from taking measurements relative to poorly chosen reference points or due to equipment maintenance issues. Other observational errors which may be more likely to result from measurements by non-professionals include family or work commitments necessitating adjustments to observation time or a temporary change in observer.

5.5.2 Quality control

The quality control procedures of WMO, as presented in their "Guide to climatological practices", have been followed in order to verify whether a reported data value is representative of what was intended to be measured and has not been contaminated by unrelated factors (WMO, 2011). Checks recommended by WMO comprise:

- Format tests, e.g. impossible dates or words in numeric fields, typically caused by transcription errors.
- Completeness tests, e.g. missing data, which may or may not be important; a missing daily rainfall total during a wet period could have a significant effect on the monthly rainfall total whereas a single missing groundwater level measurement would not be crucial.
- Consistency tests, further divided into four types of check:
    - internal consistency checks, e.g. do maximum measurements exceed minimum or is wind direction between 0^{o} and 360^{o} (such tests are less applicable for this community data);
    - temporal consistency checks, where the amount of change with prior and subsequent values is not greater than might be expected for the given time interval;

- spatial consistency checks, comparing observations with what would be expected based on observations from neighbouring locations;
- summarisation consistency checks, e.g. do annual rainfall totals equal the sum of monthly and daily totals (this is less applicable for the community data where only daily measurements are received).

- Tolerance tests, which set upper and lower limits on possible values with recourse to historical values or via spatial interpolation methods.

Similar to temporal and spatial consistency checks, care must be taken with tolerance tests to avoid excluding correct and particularly informative extreme values, such as happened with the Boscastle flood of 2004 in Cornwall, UK and the Great Storm of 1987 in southeast England when seemingly anomalous measurements could have improved forecasts to provide more warning of what became disastrous weather events (Woodroffe, 1988; Golding *et al.*, 2005).

Considering the community data received in this case study, the initial screening procedure would reveal any gross errors, which may simply be typographical errors revealed by format and consistency tests, or extended gaps in the measurements revealed by completeness tests. Errors were revealed by this visual inspection including; received spreadsheets often had a mixture of English and Amharic characters which were not recognised by all computers, commas were often used in place of decimal points or spaces were present either side of decimal points, and there were occasional errors in the conversion from the Ethiopian to the Gregorian/Western calendar. Such errors were simple to rectify.

An additional quality control procedure is the double mass check, which involves plotting the cumulative data of one station against the cumulative data of another nearby station. If the data records are consistent, a straight line is obtained. Data from stream flow gauges can be compared with data for other flow gauges in the same general area, and, similarly, data for rainfall gauges can be compared. Where an inconsistency is observed, such as a break in the slope of the line, an investigation into the cause should be performed. Relocation of weather stations and dam constructions are examples of causes of such breaks in slope in rainfall and river flow data respectively (O'Donnell, 2012).

5.5.3 Validation of hydrometeorological data

There is much published literature which aims to validate alternative sources of rainfall measurements against ground observations from formal institutions (Robinson *et al.*, 2000; Nicholson *et al.*, 2003; Wolff *et al.*, 2005; Ebert *et al.*, 2007). The validation methodologies used are similar and consist of statistical comparisons typically evaluating correlation coefficient, error and bias. The alternative rainfall sources comprise satellite and reanalysis products. Specific examples covering Ethiopia include validation of different gridded rainfall datasets by Dinku *et al.* (2007) and Dinku *et al.* (2008). Published literature concerning validation of river flow and groundwater level data generally compares modelling simulations to observations (Beven, 1993; Refsgaard and Knudsen, 1996; Motovilov *et al.*, 1999). No examples have been found in the literature of validation of data from community-based monitoring.

For this study, the community and formal data were compared using the Pearson correlation coefficient (PCC) and bias. PCC is the typical standard (including in all the studies cited in the previous paragraph) used to validate data from an alternative source against a formal source: a negative or low value indicating poor performance and questionable validity. However, because PCC simply measures the strength of the linear relationship between the datasets, a high PCC would result from a match in the structure of the data even if absolute values varied significantly. Therefore, bias is also computed to determine whether variation is systematic and could therefore be reduced with bias correction, or is due to random error. High seasonal variation between absolute measurements mean bias is a more useful descriptive indicator than other methods of calculating error such as mean error and RMS error. Gridded datasets have been evaluated using the same methodology in order to compare their performance with that of the community data.

$$\boldsymbol{PCC} = \frac{\boldsymbol{N}\sum \boldsymbol{C}.\boldsymbol{F} - (\sum \boldsymbol{C}).(\sum \boldsymbol{F})}{\sqrt{(\boldsymbol{N}\sum \boldsymbol{C}^{\boldsymbol{2}} - (\sum \boldsymbol{C})^{\boldsymbol{2}}).(\boldsymbol{N}\sum \boldsymbol{F}^{\boldsymbol{2}} - (\sum \boldsymbol{F})^{\boldsymbol{2}})}} \quad (5\text{-}1)$$

$$\boldsymbol{Bias} = \frac{\sum \boldsymbol{C}}{\sum \boldsymbol{F}} \quad (5\text{-}2)$$

Where C = community monitored data or gridded data set, F = formal ground observation data, and N = number of data pairs.

The seasonality of the climate in this region means high correlations would be expected during the long dry season when little to no rainfall occurs and surface/groundwater levels are relatively static. Therefore, statistical comparisons were separately conducted for the wet season onset (May-June), wet season peak (July-August), wet season retreat

(September-October), and the dry season (November-April), as well as for the full time series.

5.5.4 Behavioural differences in data

It is important to note that the formal and the community monitoring locations are not immediately adjacent and, as such, near-perfect correlations and zero bias are not expected. Variations in groundwater and river levels and in rainfall due to geographic position provide insights into local hydrogeology, hydrology and meteorology and the lower PCC derived from such variations does not call for rejection of data as long as the quality control procedures are passed. What's more, seemingly extreme values should not always cause the rejection of data during the quality control process but should be investigated properly. Local knowledge gained through field visits combined with anecdotal evidence from contacts in the area means extreme observations highlighted for rejection during tolerance tests may be correctly incorporated and are highly valued.

5.6 Rainfall

5.6.1 Formal ground observations

Rainfall data in Ethiopia is collected by the NMA. The density of rain gauges is low, as can be seen in Figure 5-2, with only one rain gauge within 900 km^2 Dangila *woreda* and only an additional eight within a surrounding area of 5000 km^2. All the rain gauges outside of the *woreda*, particularly those to the south, lie at significantly different altitudes to Dangila *woreda*. In addition, the rain gauges to the northeast of the *woreda* lie along a straight line; the Dangila to Bahir Dar highway, which leads to unconfident extrapolation of rainfall data either side of the highway via methods such as Kriging or Thiessen polygons. Rainfall data has been collected for the nine rain gauges shown in Figure 5-2 with the available datasets varying in length. Dangila is the closest NMA rain gauge to Dangesheta at 5.7 km distant to the south and at approximately the same altitude (~11 m difference). The Dangila rainfall record is the third longest (since 1987) but more importantly is the most complete while all other rain gauges have significant data gaps, often for a year or more. For these reasons of proximity and completeness, the Dangila rainfall record is used to evaluate the performance of the alternative rainfall sources (see Appendix C for further information substantiating the use of Dangila data for validation purposes).

5.6.2 Community data

At the time of writing, 18-months of data were available; March 2014 to October 2015, which span two wet seasons. The wet season is pronounced with approximately 85% of rainfall recorded between May and October. However, the wet season of 2014 was atypical in that it started earlier, ended later, and had a less pronounced peak in July and August compared to historical records from the NMA for all nearby rain gauges. A double mass check conducted for rainfall from the community-based monitoring programme against Dangila NMA confirms a reliable record (Figure 5-5); based on double mass checks it appears more reliable than records from most of the alternative formal rain gauges.

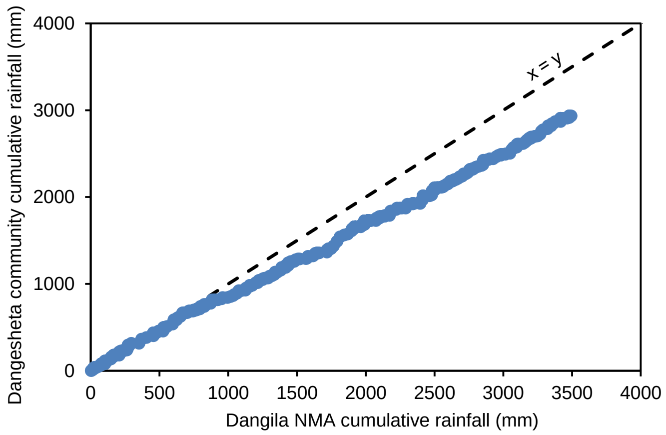


Figure 5-5. Double mass check of rainfall for Dangila NMA with Dangesheta community showing a good linear relationship indicating a consistent record. Note that a good record is considered to be a straight line and not necessarily x=y.

Closer to the community rain gauge than the NMA formal rain gauge is an electronic automatic weather station, which is 960 m to the north beside the Dangesheta Agricultural Office (DAO on the map in Figure 5-3) and at approximately the same altitude (~14 m difference). Installed by Bahir Dar University in March 2015, the electronic weather station incorporates a tipping bucket rain gauge, though unfortunately it stopped recording during the peak of the wet season leading to limited data with which to conduct comparisons.

5.6.3 Gridded datasets

The gridded remote sensing and reanalysis rainfall datasets that have been considered are TRMM, ERA-Interim, NASA MERRA, JRA-55 and NCEP (see Appendix C for further information). The spatial resolution of these gridded datasets varies from 0.25^{o} x 0.25^{o}, or ~28 x 28 km, (TRMM) to 1.25^{o} x 1.25^{o}, or ~140 x 140 km, (JRA-55) though this coarsest dataset provides the longest time series; since 1958. Such large grid squares over this region of Ethiopia necessarily comprise large altitudinal ranges, often of several thousand metres, and where multiple NMA rain gauges are present within a grid square the observed variations in rainfall totals can be very high.

5.6.4 Performance of alternative rainfall sources

Spatial consistency testing conducted as part of the quality control procedure involved plotting daily rainfall totals from Dangila NMA, Dangesheta community, and Dangesheta electronic rain gauges. The plots were very similar but with a slight shift in the peaks. It was immediately apparent that there had been an error in conversion from the Ethiopian to the Gregorian/Western calendar and when the community rainfall time series was shifted by a day the peaks matched. Further investigation of rainfall data from the electronic rain gauge revealed that daily totals were summed from a 24-hour period spanning midnight to midnight. When the totals were recalculated for a 9 am to 9 am period, as per the formal and community measurements, the timing of peaks from all three datasets were in agreement. Values for the tolerance tests could be taken from the extensive formal rainfall datasets from the nine nearby rain gauges, which were also used for consistency testing. All community rainfall data passed quality control testing.

Before correlating daily rainfall from the community gauge with the formal source, it was necessary to determine what PCC could be considered good performance. By correlating rainfall from the other nearby NMA rain gauges with that from Dangila, variations in PCC would show the degree of spatial and temporal variation in rainfall. The PCC was calculated using as long a time series as available for each rain gauge; the results are presented in Figure 5-6a. As would be expected, the PCC increases as distance from the Dangila rain gauge decreases because error due to spatial and temporal variation lessens. The trendline is projected to the distance of the community rain gauge (5.7 km) and it can thus be stated that a PCC below this line (less than approximately 0.68) likely includes a degree of observational error.

Because the community data is available only from March 2014, the same period was used to evaluate the relative performance of the gridded datasets. JRA-55 and NCEP are excluded because the data were not available for this evaluation period. Where multiple seasons have occurred, i.e. wet season peak in 2014 and 2015, the mean PCC is taken; nowhere was it necessary to take means of markedly different values (Figure 5-6b).

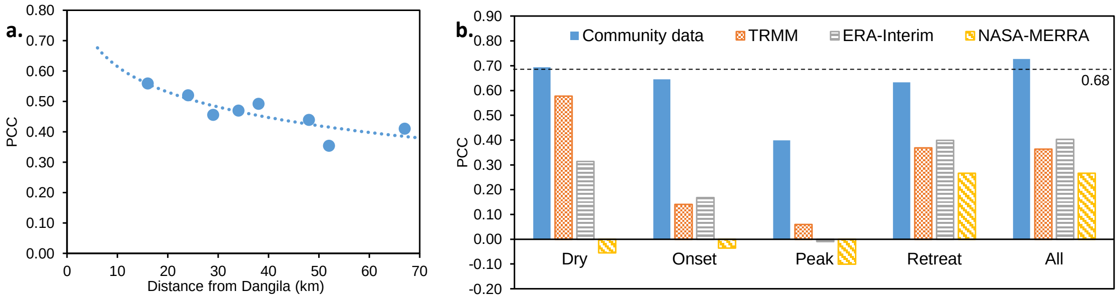


Figure 5-6. Variation with distance of Pearson correlation coefficient (PCC) between daily rainfall from Dangila NMA rain gauge and other NMA rain gauges close to Dangila woreda (a). Pearson correlation coefficient (PCC) between daily rainfall from Dangila NMA rain gauge and alternative sources (b).

Immediately apparent from Figure 5-6b is that the community data outperforms the gridded datasets for all seasons. Localised short-lived storm events leading to high spatial and temporal variability are proposed for the reason behind the poor correlation of all alternative sources of rainfall data during the wet season peak. When all the data is considered (the far right of the graph), the PCC of 0.73 for the community data is greater than the value predicted in Figure 5-6a and the discrepancies with the formal dataset can therefore be considered sampling rather than observational error. Because they are just 900 m apart, it would be expected that the community rain gauge and the electronic rain gauge would correlate better than the dataset pairs presented in Figure 5-6b; indeed the calculated PCC is 0.84.

Analysis of bias is presented in Figure 5-7a. Again, the community data shows the least bias and, importantly, the greatest consistency, suggesting that the bias is due to systematic error. This error could be due to undercatch as the community rain gauge is close to a small tree, which may provide some sheltering. However, when compared to the nearby electronic rain gauge which is in an open position like the Dangila NMA rain gauge, bias is just 1.05, suggesting that the bias of ground observations in Figure 5-7a is primarily due to spatial variability.

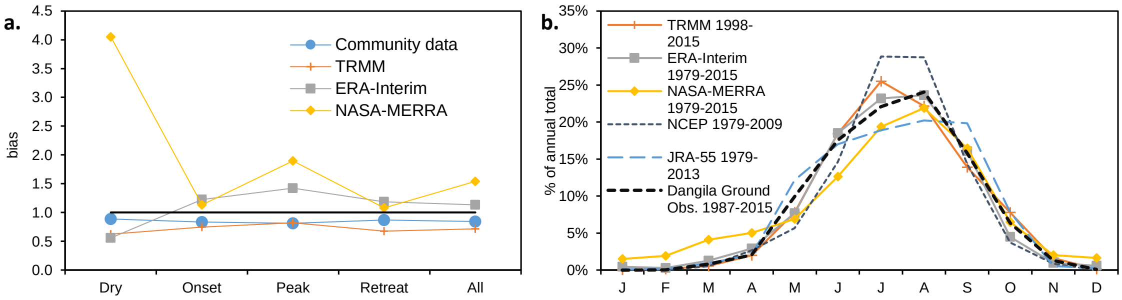


Figure 5-7. Bias between daily rainfall from Dangila NMA rain gauge and alternative sources (a). Note that bias is computed as a ratio and the bold line at 1.0 represents zero bias. Median monthly rainfall totals as percentage of annual total for Dangila NMA rain gauge and gridded datasets (b).

Figure 5-6 and Figure 5-7a suggest that the gridded datasets perform poorly for this location, particularly in comparison to the community-based monitoring. To test whether the gridded datasets always perform poorly or solely for the period of overlap with the community data, the full available time series were analysed and monthly totals are considered in order to smooth out extreme events that reduce the PCC during daily rainfall analysis. When median monthly totals are normalised to annual total (Figure 5-7b) the performance of the gridded datasets is improved. However, capturing the wet season peak still appears to be problematic which could have serious consequences for water resource assessment if these datasets were to be relied on in place of ground observations.

5.7 River flow

5.7.1 Formal observations

River flow data in Ethiopia is collected by the Ministry of Water, Irrigation and Electricity (MoWIE). It can be seen in Figure 5-2 that two river gauges lie within Dangila *woreda* though the most useful for this project are named "Amen @ Dangila", which is upstream of the community Kilti gauge, and "Kilti Nr Durbete", which is downstream of the community Kilti and Brante gauges and situated outside the *woreda*. Measurement of river stage at these locations is taken from depth gauge boards and the available time series spans 1988 to 2014 though with some significant gaps in the data lasting from months to years.

5.7.2 Community data

The two MoWIE monitored river gauges within Dangila *woreda* are located on ephemeral streams and it appears that either measurement does not always take place or monitoring records have not yet been completely digitised. A continuous time series of river stage measurements is therefore only available from the community-based monitoring programme. Following a decision taken by the community themselves, measurements take place twice a day as opposed to the daily formal river monitoring. In addition, with no external prompting, the community members who conduct the monitoring regularly add notes to their river stage records noting if a flood peak passed at a particular time and at what level. Such information is not available from formal sources.

The full time series of rainfall and river stage measurements collected by the Dangesheta community are presented in Figure 5-8. It can be seen that the rivers are very flashy with sharp peaks in river stage quickly following rainfall events.

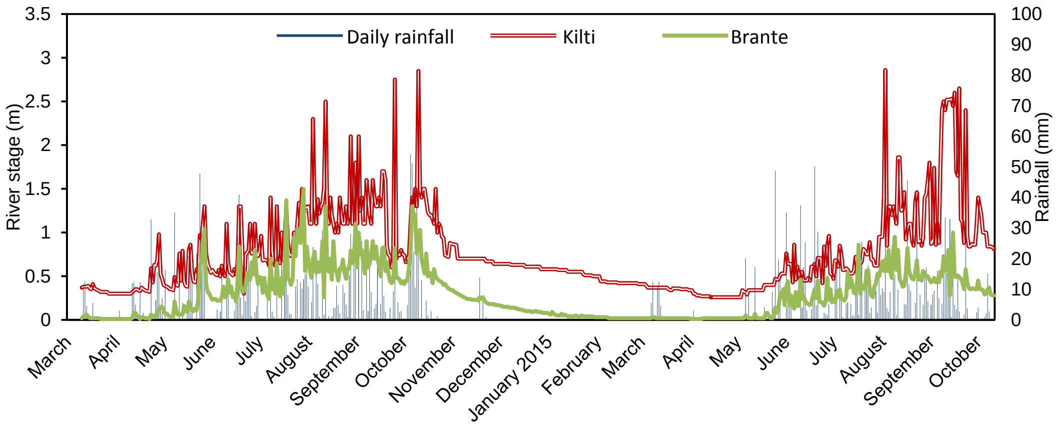


Figure 5-8. Complete time series to date of daily Kilti and Brante river stage, and rainfall measurements from the community-based monitoring programme (2014-2015).

5.7.3 Performance of alternative river flow sources

A complete twice-daily record of river stage is held which is straightforward to cross-examine between rivers and with rainfall to determine if all peaks and troughs pass consistency tests. Suitable values for tolerance testing were derived from anecdotal and physical evidence obtained during field visits to the monitoring sites; such as the Kilti River's maximum peak in October 2014, which damaged the river gauge. Quality control procedures were passed for all of the community monitored river data.

Unfortunately, there is only a very short period of overlap between the formal and the community river flow data. Therefore, correlations with formal sources are not considered the principal method of validating the river flow data. However, correlating the overlapping data between formal (Kilti and Amen) and community (Kilti and Brante) daily totals gives 0.52-0.58, similar to the correlation between the two formal river flow sources for their complete daily records, PCC = 0.58.

A unit runoff check involves dividing the (monthly) runoff by the catchment area in order to determine the runoff as a depth. This is compared for consistency with values obtained from nearby hydrologically similar catchments. This check is particularly useful in identifying abrupt changes in river flows resulting from river basin management activities (O'Donnell, 2012). Unit runoff checks were conducted for the Kilti and Brante flow measurements from the community-based monitoring programme and for the formal flow measurements for the Kilti and Amen (Figure 5-9). The differences in unit runoff depths from the formal sources are increasingly significant from 1997 to 2001 and 2007 to 2010. This may be due to a period of unreliability of the rating curve and ongoing revision efforts which was the explanation given by MoWIE for considering the 2014 data to be unreliable (S. Mamo, personal communication, 10 December 2015). Thus, no conclusions should be drawn from the poor match with the community data during the 6-month overlap in 2014 (Figure 5-9). It can be seen on the unit runoff check that there is a reasonable match between the two community monitored rivers, at least as good a match as has typically been seen between the two formally monitored rivers in previous years.

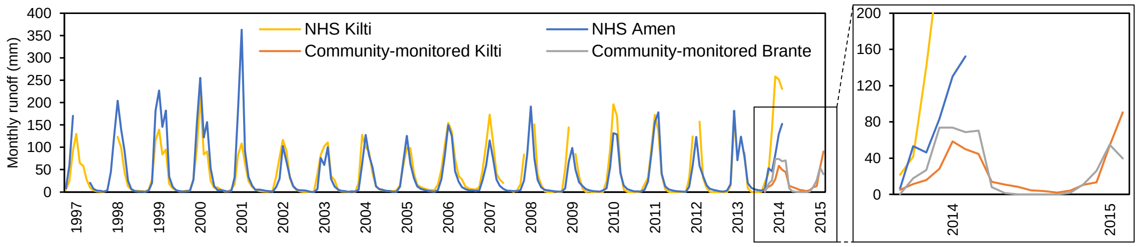


Figure 5-9. Unit runoff checks for river flow data from community-based monitoring and formal sources. Gaps indicate insufficient flow measurements to calculate monthly totals. Note that the 2014 formal measurements are considered by MoWIE to be unreliable.

When river flows (daily totals) are correlated against rainfall from the NMA Dangila rain gauge, the PCCs are lower for all seasons and for all gauges (Figure 5-10) than was achieved when validating rainfall and groundwater data. The low values reflect the geography and hydrogeology of the catchments where peak floods have been observed to occur with a very short time lag after the onset of a rainfall event. Very heavy overnight storms were experienced during fieldwork though when the rivers were visited early the following morning the river stage had already dropped from the level still visible on the banks to the level observed the previous day. Because rainfall measurements are cumulative and river stage measurements are momentary, monitoring would have to be undertaken at a much higher frequency in order to achieve better correlations with rainfall. However, the PCCs in Figure 5-10 are similar for both the formal and the community measurements particularly when all seasons are considered.

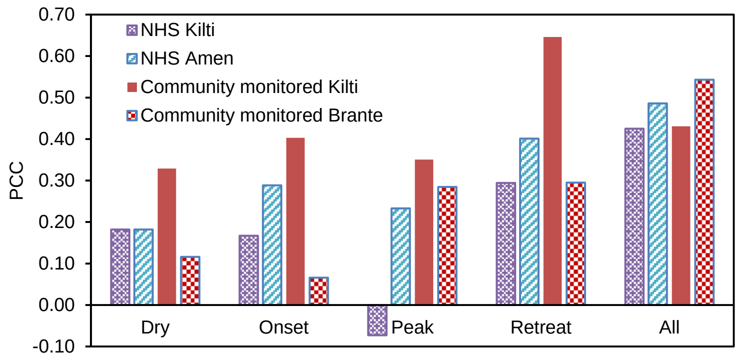


Figure 5-10. Pearson correlation coefficient (PCC) between daily rainfall from Dangila NMA rain gauge and river flow measurements (daily totals) from formal and community sources. Note that "All" includes incomplete months excluded from other seasons explaining the contrast in relative PCC of, in particular community monitored Kilti, data from individual seasons to "All".

5.8 Groundwater level data

5.8.1 Formal observations

The community monitored groundwater level data is the only means of assessing water table depth and recession anywhere within Dangila *woreda*. Extremely limited data on boreholes and groundwater are available from formal sources (see Appendix C).

5.8.2 Community data

It would be expected, given that the monitoring wells are in close proximity (maximum separation of 970 m), that groundwater levels from different wells would follow a similar pattern of seasonal variation. Peaks in water level during dry spells or plateaus spanning numerous rainfall events would suggest unreliable data. It is immediately obvious from Figure 5-11 that the patterns in water level response are consistent, quality control procedures have been passed (with a single exception discussed below) and the validity of the data is confirmed when statistical comparisons are conducted between wells and with river stage.

Minor abstraction occurs from the monitoring wells at the level of a few buckets (20-50 litres) per day for domestic use. If abstraction took place immediately prior to measurement then a drawdown of a few centimetres may be incorporated into the observation. Such discrepancies between aquifer and well groundwater level are likely within the expected measurement error. Furthermore, measurement took place as much as possible early in the morning prior to well abstraction.

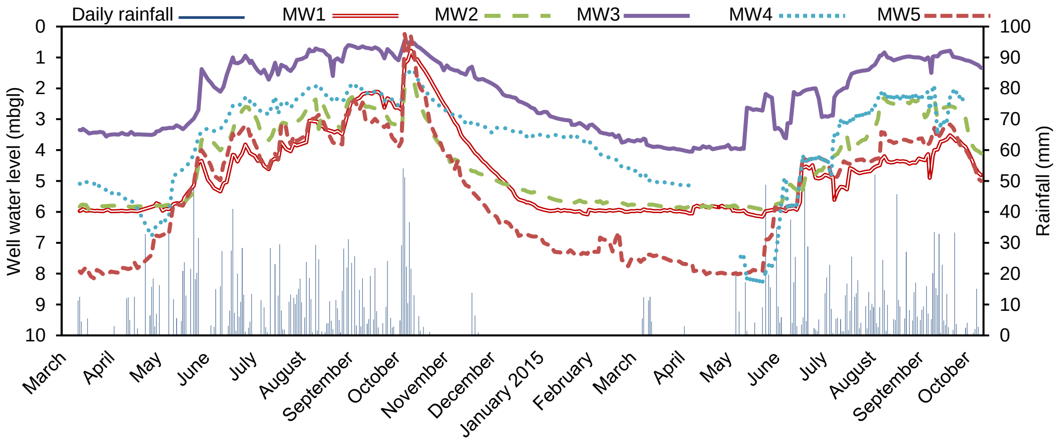


Figure 5-11. Complete time series to date of groundwater level and rainfall measurements from the community-based monitoring programme (2014-2015). It is noted that wells MW1, MW3 and MW5 dry out in the dry season and their minimum groundwater levels represent the basal level of the well. The gap in the well MW4 time series is discussed in Section 5.8.3.

Differences in amplification of water level responses to particular rainfall events have physical reasons: either due to features of the well itself, e.g. MW1 and MW5 peak the most significantly as they are open to direct precipitation and overland flow, or due to aquifer characteristics, e.g. MW4 declines the most gradually, proposed to be due to a lack of high-transmissivity layers, such as fractured bedrock within the shallow weathered regolith aquifer, which are present in other well bores (during workshop discussions the local community spoke of not striking rock when excavating MW4 unlike in other wells, particularly MW1 and MW5 where a rapid decline in water level is observed at the onset of the dry season). Analysis of the differences in well responses and discussions during community workshops have been invaluable in gaining a greater understanding of the shallow hydrogeology in the area.

5.8.3 Performance of alternative groundwater level sources

The quality control procedures had to be most carefully applied to the groundwater level data. Completeness tests showed occasional gaps of two days rather than the expected measurements every other day with some gaps of three days and one exceptional gap of eight days. It is noted that these larger gaps occur during the dry season when there is little groundwater level fluctuation and there are just as many measurements at a higher than required frequency on consecutive days. No groundwater level dataset was excluded for reasons of completeness. Consistency tests often highlighted errors where large “steps” in the data were present from one month of measurements to the next. Further investigations typically revealed that a spreadsheet had been labelled incorrectly and when the data was switched to the correct well the consistency test was passed. One such step in the data which failed according to spatial consistency (neighbouring wells do not show such a large drop at that time) and temporal consistency (such a large overnight drop has no physical explanation) has yet to be resolved and the excluded month can be seen in well MW4 in Figure 5-11. Other than this single month of data for one particular well and following some corrective reorganisation of datasets, the groundwater level data passes quality control procedures.

The groundwater level data cannot be validated against formal sources as no such data exists. Figure 5-12 shows the Pearson correlation coefficient between water level responses of different monitoring wells. Bias is inapplicable because the response of each well is expected to vary in absolute value; such variations are due to differing well and water table depths, variations in aquifer properties and differences in position on the groundwater flow path. Accordingly, precise agreement, i.e. correlations of 1, would not be expected. Indeed, it is the subtle differences in groundwater level response that are aiding understanding of the shallow hydrogeology of the area. Analysis was conducted for individual seasons and for the full time series.

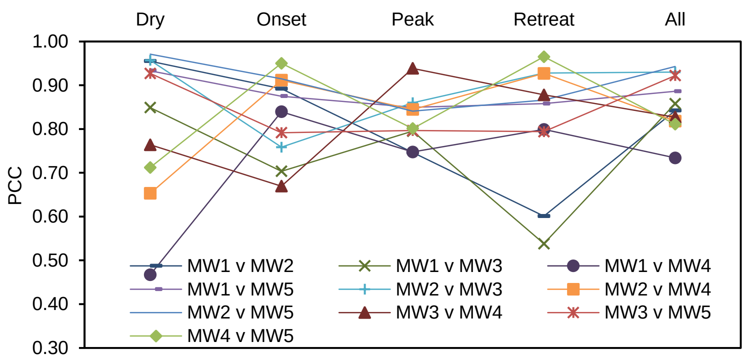


Figure 5-12. Pearson correlation coefficient (PCC) between community monitored groundwater level data from monitoring wells MW1-5.

Figure 5-12 shows that there is very good correlation between monitoring wells; the mean PCC between all wells for the full time series is 0.86. The raw data was investigated where the PCC is below 0.75 and in all cases a physical reason was apparent such as comparisons between wells during a period where one was predominantly dry (e.g. MW1 for long periods).

To further validate the groundwater level data, correlations were conducted with river stage from the two nearby community-monitored gauges. River depth is being compared to depth to groundwater thus when river stage is high it would be expected that depth to the water table would be low and a perfect correlation would yield -1. However, the flashy response of the rivers to rainfall events and the lag until groundwater responds means it is unlikely that very close to -1 would be obtained but the results should still be high in the negative. The results of the correlations are presented in Table 5-1 and show highly satisfactory correlations with an average of -0.73.

Table 5-1. Pearson correlation coefficient (PCC) between community monitored river stage and groundwater level from monitoring wells MW1-5 for the entire time series.

	Brante river stage vs;					**Kilti river stage vs;**				
Well:	MW1	MW2	MW3	MW4	MW5	MW1	MW2	MW3	MW4	MW5
PCC:	-0.75	-0.80	-0.76	-0.63	-0.83	-0.70	-0.76	-0.73	-0.64	-0.74

5.9 Discussion

5.9.1 Qualitative and quantitative value of community-based monitoring observations

The qualitative value of the community data is in contributing to the conceptual understanding of the shallow groundwater system. Conceptual understanding has only been possible with a combination of fieldwork and analysis of differences in well and river responses using data from the community-based monitoring programme. Slow declines in groundwater levels following rainfall events can indicate high storativity of the aquifer and significant river baseflow throughout the dry season can indicate an aquifer with the potential for exploitation.

The community data has quantitative value through providing complete time series spanning numerous seasons. For the purpose of understanding the shallow hydrogeological system to enable simulation of the impacts of increased abstraction, land use change, and climate variability; physically-based numerical models are being constructed using SHETRAN (Ewen *et al.*, 2000). Construction and calibration of these necessarily transient models at scales useful for local management of water resources is only possible with the time series of river flow and groundwater level gathered by the community. Alongside traditional methods such as chloride mass balance (CMB), recharge assessments for the Dangesheta area are being conducted using the RIB model (Xu and van Tonder, 2001; Sun *et al.*, 2013) and water table fluctuation method; neither of which would be possible without the time series of groundwater level. The close agreement of the community-gathered and nearest formal rainfall dataset gives confidence that the formal rainfall dataset can be used in the models to extend the time series prior to the commencement of the community-based monitoring programme. Consistency of anomaly patterns as evidenced by the PCC between community gathered and gridded rainfall datasets enables selection of the most appropriate gridded dataset for infilling gaps in formal ground observation rainfall totals, which occurred historically.

A key value of community-based monitoring programmes is the engagement of the local community, which, as the wider research programme progresses, will hopefully evolve to active management of their resources. The value to the local community has been expressed as a feeling of partnership in the project rather than constantly being subjects of research. Questions posed by the Dangesheta community during recent workshops involving the dissemination of findings demonstrated a level of engagement and an increase in hydrological knowledge that was not observed during workshops at the project onset. Proffered reasons for differences between recession curves for groundwater levels from various wells, e.g. zones of aquifer with greater storage properties, have been incorporated into conceptual models. The community also speak of a sense of pride that their community are participating in the programme that may have implications beyond Dangesheta.

This research has shown that high quality hydrometeorological data for various applications can be collected by non-specialists from local communities. The data can reliably supplement that from formal sources or provide time series where no formal alternatives are available.

5.9.2 Recommendations for ensuring quality data production

The potential for community-based monitoring programmes to infill gaps in sparse, declining or non-existent formal monitoring networks is clear. However, there are numerous critical factors for ensuring quality data production. The early involvement of the local community is important to instil a sense of ownership of the equipment and the project. Assistance in site selection for monitoring points is an ideal way to engage the community early and was achieved in this case via the focus groups and participatory mapping workshops. Variations in well level responses indicate the monitoring wells were successfully identified to provide information on aquifer zones with varying potential for exploitation. Selection of the community members to be involved in the programme is particularly crucial. The completeness of these community datasets and their success in passing the WMO quality control standards indicates selection of monitoring personnel was successful in this case. Known and respected community members who live or work in close proximity to the monitoring points should be selected, if willing to participate, to ensure security of the equipment and to demonstrate to the community, simply by their involvement, that the programme has value. We are aware of community-based monitoring programmes in other areas of Ethiopia that have suffered issues such as vandalism of equipment (Zemadim *et al.*, 2014) and falsification of data (D.L. Yiak, personal communication, 5 April 2015). In these cases, monitoring or in-situ downloading of data has been conducted by outside (unknown to the community) people or a casually selected community member who may have been purely interested in the financial incentive. Notably, these examples were more equipment intensive and offered higher financial incentives than the Dangesheta case. Vandalism or data falsification have not been encountered during this study further confirming the value of community participation in site selection and nomination of community members to undertake the monitoring. The importance of feedback has been reported to us concerning Dangesheta and other examples of community-based monitoring programmes in Ethiopia: this could be delivered through visits and support as well as workshops presenting the collected data, eliciting from the community what the data reveals, explaining what the data is being used for, and giving the community the opportunity to ask questions, provide their own explanations for patterns in the data, and give suggestions for improving the community-based monitoring programme. The continued performance of the community-based monitoring programme in generating high-quality observations is evidence of the value of the workshops.

5.9.3 Wider application of community-based hydrometeorological monitoring

It has been shown that community-based monitoring can be used to provide improved spatial density of measurements in areas of sparse and/or declining formal monitoring networks. In addition, where there exist relatively high densities of formal hydrometeorological monitoring points, community-based monitoring still has much to offer.

Gridded datasets are a viable alternative source of rainfall data in many regions though it has been shown here that over complex terrain with large differences in altitude gross over and under estimations of rainfall totals are possible, especially where grid size is large. Community-based monitoring can provide data of sufficient quality to add to the ground observation datasets used to calibrate and validate these gridded datasets.

5.10 Conclusions

The research shows that high-quality daily rainfall totals, sub-daily river stage and daily to sub-weekly groundwater level measurements are achievable by an astutely implemented and managed community-based monitoring programme. Formal rain gauge networks in many regions of the world are inadequately dense to provide confident interpolation of rainfall quantities. Gridded datasets with their necessarily low resolutions often cannot achieve good agreement with ground observations particularly in areas of spatial heterogeneity of intense convective precipitation and particularly when sub-monthly rainfall totals are required. Formal river monitoring networks are also insufficient with few available datasets for use in modelling catchments at less than the regional scale. Furthermore, formal river monitoring networks, along with formal rain gauge networks, are in decline as national institutions embark on cost-cutting practices; an issue which is particularly severe in less economically developed countries. In sub-Saharan Africa, groundwater level monitoring networks are essentially non-existent when it comes to shallow groundwater – the resource used by the majority of poor rural communities. It has been shown that community-based monitoring can provide high quality data to help fill these observational voids. Data screening for quality control indicates reliable and consistent measurements, as good as formal monitoring, can be obtained by local communities. Community-based monitoring can improve spatial and temporal characterisation of rainfall, river flow and groundwater level, reducing the uncertainty of using extrapolated/interpolated values from formal and gridded datasets or from modelling simulations. Statistical comparisons of the community-based monitoring data against formal sources and against other data simultaneously gathered by the local community validate their quality for use in further study. Our research has shown that benefits to the community include a greater understanding of their local hydrology and hydrogeology, a sense of ownership of their water resources, and a sense of being a research partner as opposed to a subject. Such increased hydrological understanding in sub-Saharan Africa provides the basis for communities to manage their own resources, which could increase food security by reducing reliance on rainfed agriculture.

It is noted here that the community-gathered data from Dangesheta beyond the period covered in this chapter (collected after publication of the associated paper) passed through the same quality control procedures. This longer time series of consistently high-quality data was utilised in subsequent chapters.

Chapter 6. Insights from a multi-method recharge estimation comparison study

6.0 Chapter overview

Chapter 5 showed that high quality hydrometeorological time series can be obtained from community-based monitoring programmes, in addition to informing the conceptual model. The community gathered data was therefore approved for use in resource evaluations. Chapter 6 concerns the recharge assessment conducted for Dangila *woreda* that aimed to answer research question number 3 from Chapter 1: Can shallow groundwater be considered a renewable resource, and; which recharge assessment methods provide the highest confidence in the calculated recharge amounts when applied to these types of aquifers?

Although most recharge estimation studies apply multiple methods to identify the possible range in recharge values, many do not distinguish clearly enough between inherent uncertainty of the methods and other factors affecting the results. We investigated the additional value that can be gained from multi-method recharge studies through insights into hydrogeological understanding, in addition to characterising uncertainty. Nine separate groundwater recharge estimation methods, with a total of 17 variations, were applied. These gave a wide range of recharge values from 45 to 814 mm/a. Critical assessment indicated that the results depended on what the recharge represents (actual, potential, minimum recharge or change in aquifer storage), and spatial and temporal scales, as well as uncertainties from application of each method. Important insights into the hydrogeological system were gained from this detailed analysis, which also confirmed that the range of values for actual recharge was reduced to around 280-430 mm/a. This chapter demonstrates that even when assumptions behind methods are violated, as they often are to some degree especially when data are limited, valuable insights into the hydrogeological system can be gained from application of multiple methods.

This aspect of the research was published in Groundwater journal in 2018:

Walker, D., Parkin, G., Schmitter, P., Gowing, J., Tilahun, S.A., Haile, A.T. and Yimam, A.Y. (2018) 'Insights from a multi-method recharge estimation comparison study', *Groundwater (in press).*

The co-authors provided support in planning and final editing of the paper, or were involved in data collection; all the analysis, writing the paper and preparing figures was conducted by David Walker.

The paper is provided here with little alteration; the study area section has been largely reduced to avoid repetition with Chapters 3 and 4, though some climatic and geological information is repeated where particularly important for the recharge study. The supporting information is provided in full as Appendix D. It is noted that one of the recharge estimation methods applied utilised SHETRAN modelling, which is not described in detail until Chapter 7. Brief information on the SHETRAN modelling is provided in this chapter and in Appendix D.

6.1 Introduction

Estimates of groundwater recharge allow quantification of renewable groundwater resources and can be used to indicate aquifer vulnerability to contamination or drought, assess groundwater contribution to streams (baseflow) and wetlands, and identify the implications of changes to land use, land cover or climate (Misstear, 2000; de Vries and Simmers, 2002; Healy, 2010). Several notable reviews published over the past decades discuss various methodologies of estimating groundwater recharge (Simmers, 1988; Lerner *et al.*, 1990; Scanlon *et al.*, 2002; Healy, 2010). It is well known, and stated by these reviews, that groundwater recharge estimates often vary between methods due to the uncertainties inherent with each method, the different spatiotemporal scales at which they operate, and the type of recharge they represent. It is normally recommended, therefore, that multiple methods be used. However, recharge estimation methods are often chosen in practice according to data availability even though the method may not be the most suitable for the particular climate or hydrogeological conceptual model. Often, the violation of a method's assumptions may only become apparent when the recharge result is compared to results from different methods. In addition, some recharge estimation studies do not make a clear distinction between the reasons why the recharge results differ, whether it is due to genuine uncertainties in data and methods, unsatisfied assumptions, different spatiotemporal scales, or if the method is actually computing a different type of recharge. However, recognising these distinctions in multi-method recharge estimation comparison studies can help to provide useful insights into the hydrogeological system.

A recharge assessment was conducted at a study site in northwest Ethiopia (Dangila *woreda*, a local administrative district), in the context of an investigation into the resilience of shallow groundwater resources used for irrigation by rural communities. Following recommended approaches, e.g. Scanlon *et al.* (2002) and Healy (2010), several techniques were initially applied, and it was found that they gave a wide range of recharge estimates. This is commonly reported in the literature, e.g. Berehanu *et al.* (2017) and Afrifa *et al.* (2017), although it is less common for studies to report investigation of the reasons for the range of values. Some previous studies, typically using at most three to five recharge estimation techniques, have considered the basis for differing recharge estimates in more detail, and concluded that the range of recharge estimates contains useful information to inform further understanding of the conceptual model (e.g. Coes *et al.* (2007); King *et al.* (2017)). For our study, there were sufficient data of suitable quality to apply a larger number of recharge estimation methodologies at a single site, so a wider investigation was made to assess which of the most commonly applied recharge estimation methods could help to provide insights and increase understanding of the hydrogeological system. Nine different recharge estimation techniques were applied, with a total of 17 variations, including variants of methods and variations in how input data were derived. The methods are presented here in order of increasing data requirement and complexity: an empirical method, streamflow hydrograph methods (three variations), soil moisture balance (two variations), basin water balance (three variations), chloride mass balance, water table fluctuation (two variations), rainfall infiltration breakthrough, and physically-based modelling. The ninth method is large-scale mapping and modelling (three variations) from which recharge values have been obtained for comparison from published studies.

The three aims of this paper are to:

1. Demonstrate quantitatively the range of recharge results that can be calculated from as many methods as feasible for the study site, and analyse the underlying reasons for the different recharge values
2. Assess the utility of applying multiple methods in order to gain insights on the hydrogeological system
3. Provide a recharge estimate with uncertainty for Dangila *woreda*.

The study highlights and analyses the general problem of interpretation of variability in recharge estimates obtained from different methods. It is noted that all methods were applied even if assumptions may not be fully complied with, since this is a factor relevant to uncertainty in recharge estimation in many published studies. It is not uncommon for recharge results to be reported without explicit statement of assumptions and limitations or the type of recharge being computed (Sophocleous, 1985; Wood, 1999; Halford and Mayer, 2000). It may only be through identifying significant discrepancies between recharge results from different methods that violation of a method's assumptions are realised and the hydrogeological conceptual model can be amended and better understood. Additionally, this study provides a useful recharge estimate for a shallow aquifer in northwest Ethiopia. Published recharge estimation studies from sub-Saharan Africa are not great in number, not well geographically distributed, and many are grey literature (Bonsor and MacDonald, 2010; Wang *et al.*, 2010; Pavelic *et al.*, 2012; Chung *et al.*, 2016). The majority of studies are concentrated in arid and semi-arid regions due to water scarcity in these areas. However, many regions of apparent high rainfall also experience water scarcity during the dry season (Rijsberman, 2006) and when sub-Saharan Africa's variable climate unpredictably delivers low wet season rains (Van Koppen, 2003; Bonsor *et al.*, 2010).

6.2 Groundwater recharge

Lerner *et al.* (1990) provide the classical definition of recharge: "the downward flow of water reaching the water table, forming an addition to the groundwater reservoir". This defines "actual recharge" and is referred to as such by many authors, e.g. Scanlon *et al.* (2002); Misstear *et al.* (2007); Healy (2010). According to Rushton (1997), the term "actual recharge" is used to distinguish it from *potential* or *minimum* recharge. *Potential* recharge is water passing downward through the unsaturated zone that could potentially contribute to the aquifer. *Potential* recharge is the term used by many authors for recharge computed from unsaturated zone methods as this infiltrated water may be subject to losses (e.g. root zone uptake, interflow then surface discharge) before contributing to the aquifer (e.g. Simmers (1988); Rushton (1997); Healy (2010)). *Minimum* recharge refers to groundwater discharge to rivers or springs, when the two quantities are considered to be in balance. It is termed *minimum* recharge because other losses (e.g. evaporation from the saturated zone, seepage to deeper aquifers) may have occurred since the water was recharged (e.g. Szilagyi *et al.* (2003); Vegter and Pitman (2003); Risser *et al.* (2005)).

In humid regions characterised by shallow water tables and gaining rivers, diffuse (or direct) recharge dominates. In arid regions characterised by deep water tables and losing rivers, recharge is usually focussed (or indirect) along river corridors with rates generally limited by water availability at the surface (Allison, 1988; Scanlon *et al.*, 2002). The factors that influence the amount and type of recharge (diffuse or focussed) include: precipitation (volume, intensity, duration); topography (slope, above ground storage);

vegetation (cropping pattern, rooting depth) and evapotranspiration; soil and subsoil types; flow mechanisms in the unsaturated zone (uniform or preferential); bedrock geology; available groundwater storage; presence of influent rivers, and; presence of karst features (Misstear, 2000).

6.3 Recharge estimation methods

Various techniques are available for estimating recharge, the selection of which is not straightforward (Lerner *et al.*, 1990; Scanlon *et al.*, 2002). Each technique has different assumptions as well as limitations. Therefore, it is recommended to use multiple methods to reduce uncertainty and to improve conceptual understanding of recharge at a study site (de Vries and Simmers, 2002; Healy and Cook, 2002). Generally, selection of a technique is dependent on data availability, which is often lacking in many regions. Such data scarcity can lead to the selection of a less suitable recharge estimation method as well as no additional methods to corroborate the findings. Rather than data driving the methodology used, the user should select methodologies depending on the desired spatiotemporal resolution. This is easier for primary data collection but less obvious when dependent on secondary data sources. Then the user must determine what the recharge result represents, according to the fundamental theory of the method applied and the satisfaction of the assumptions.

6.4 Study area

6.4.1 General description

The study site is Dangila *woreda* within the Amhara Region of northwest Ethiopia, 70 km southwest of Bahir Dar on the Addis Ababa to Bahir Dar road (Figure 6-1).

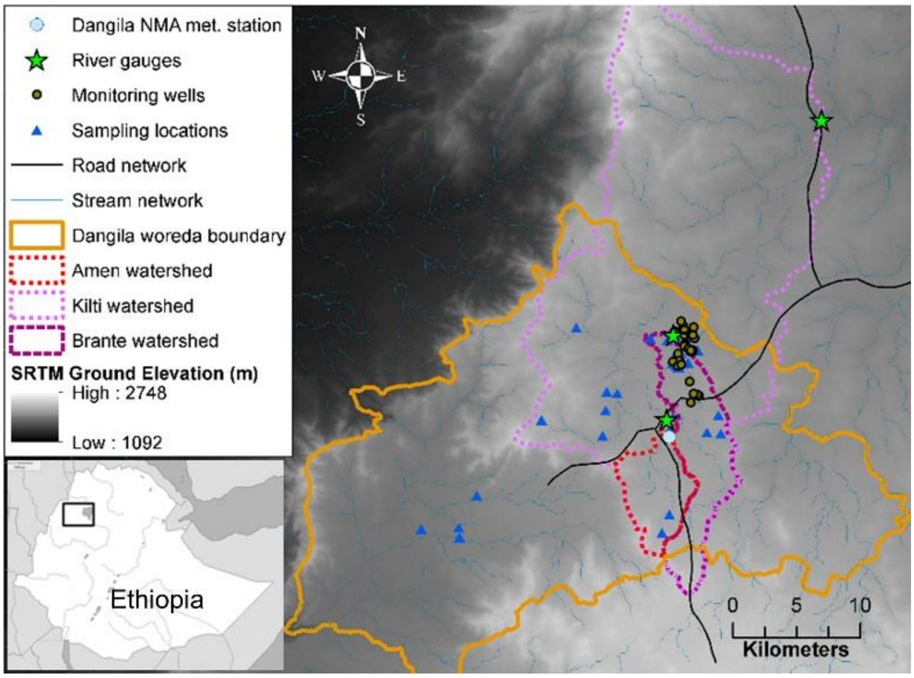


Figure 6-1. Location map of the study area.

6.4.2 Climate

The climate of the region is moist subtropical with little annual temperature variation though high diurnal variation. The median annual total rainfall is 1541 mm, as measured (1987-2017) at the National Meteorological Agency (NMA) weather station in Dangila town, 91% of which falls during May to October (Figure 6-2). Both the mountains to the east and Lake Tana to the north affect the pattern of rainfall in the study area. Most rain events have a duration shorter than 1-hour and often occur in the late afternoon (Haile *et al.*, 2009).

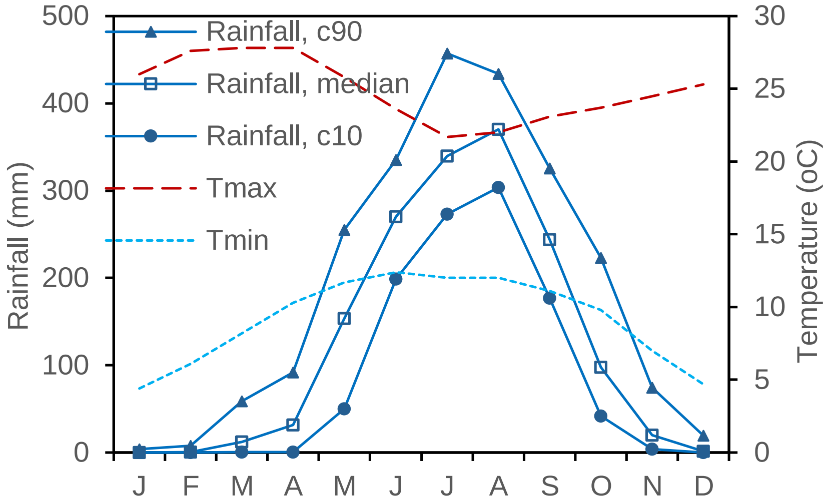


Figure 6-2. Monthly median, 10th and 90th percentile rainfall, and mean maximum and minimum temperatures as measured (1987-2017) by the NMA at the Dangila weather station.

6.4.3 Hydrogeology

Bedrock geology consists of Cenozoic basalt and trachyte (Tefera *et al.*, 1996) that are variously massive, fractured and vesicular. Above the bedrock lies weathered basalt regolith, itself overlain by red clayey loam soils (nitisol). The superficial materials of the floodplains are occasionally very sandy and gravelly though deep and wide desiccation cracks suggest a high clay content (vertisol).

Diffuse (direct) recharge dominates across the study site (Figure 6-3) with quantities likely to vary according to local position. Upslope areas will receive less recharge due to higher runoff and interflow gradients whereas overland flow, interflow and groundwater flow collect in the topographic lows. The large floodplains, which are prevalent in the landscape, become waterlogged in the wet season from direct rainfall and spring discharge (rather than from overbank flooding).

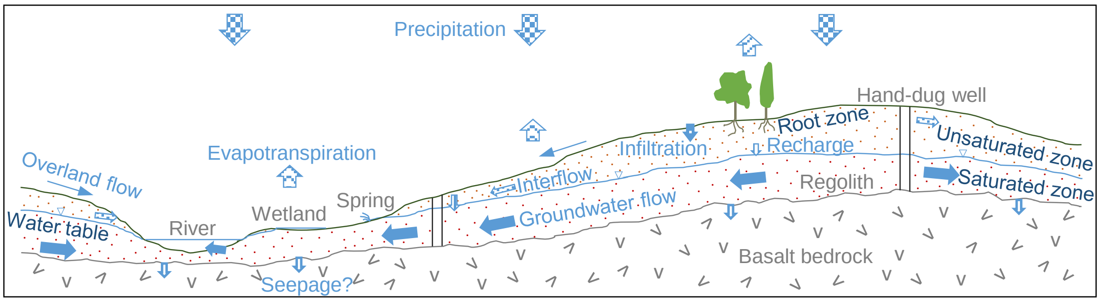


Figure 6-3. Conceptual model of the study site.

6.5 Data used in the study

In this study, nine frequently used methods were applied using data from all possible hydrological zones. Additional methods were explored and rejected for various reasons, as discussed in Appendix D. The data requirements for the various methods applied are shown in Table 6-1. Meteorological data was measured by the NMA weather station in Dangila town: the only formal weather station in the district. River flow data in Ethiopia is collected by the Ministry of Water, Irrigation, and Electricity (MoWIE): Amen and Kilti river flow data were utilised, the latter catchment forming a large portion of Dangila district, even though the gauging station lies outside the district (Figure 6-1). The available time series date from 1988 (Amen) and 1997 (Kilti) to late 2014, though there are occasional gaps in the data. In addition to these formal data sources, hydrometeorological time series are available from a community-based monitoring programme at Dangesheta village from March 2014 to January 2017. River stage in the Brante river was measured twice-daily, rainfall was measured daily in a manual raingauge, and groundwater levels were measured bi-daily in five wells since March 2014 and daily in 25 wells since February 2015. The hand-dug wells have an average diameter of 1 m with depths ranging from 3-21 m. Rainfall and river stage from the community-based monitoring have been validated against formal sources confirming the quality of the data (Walker *et al.,* 2016). The Amen (37.0 km^2) and Brante (65.5 km^2) are sub-catchments of the Kilti (631.7 km^2). The catchment-scale recharge assessment methods were applied to all three catchments. Thirty-one shallow groundwater samples were collected for chloride analysis, from locations distributed throughout the study site, in March/April 2015 and October/November 2015. Rain could only be sampled during the second field visit because it did not rain during the four weeks of the earlier dry season visit, nor during a third visit in January 2017. Three samples were collected from two sites and occurred whenever rainfall was sufficient to enable direct sampling. All samples were filtered upon collection and, to prevent evaporation, the nalgene bottles were completely filled and kept in a refrigerator prior to laboratory analysis by Dionex ion chromatography. Additional data used in development of the conceptual model and required to parameterise models resulted from three periods of fieldwork, which included pumping tests on hand-dug wells (Walker, 2016), geological surveys, hydrochemistry and stable isotope sampling, radon-222 measurements, water point surveys, and workshops with the local community (further information is provided in Appendix D). Proportions of different land use land cover (LULC) types were taken from ADSWE (2015).

Data from three large-scale mapping and modelling recharge studies were also assessed. The global-scale WHYMAP (WHYMAP, 2016) by BGR (the German Federal Institute for Geosciences and Natural Resources) and UNESCO gave recharge values of 20-100 mm/a for the study site, the continental-scale map by Altchenko and Villholth (2015) gave 100-300 mm/a, and a national-scale map by Ayenew *et al.* (2008b) gave 250-400 mm/a. Further information on the large-scale mapping and modelling can be found in Appendix D.

Table 6-1. Hydrological zone, spatial scale, and data requirements of the applied recharge estimation techniques.

	Hydrological zone	Spatial scale of the method	Meteorological averages	Meteorological time series	River flow time series	Groundwater sampling	Rainfall sampling	Groundwater level time series	Aquifer properties	Soil properties	Vegetation properties	Geological surveys or maps	Land use/land cover surveys or maps	Digital elevation model (DEM)	Access to literature
Empirical	A	D	✓												✓[a]
Stream hydrograph	SW	C			✓										
SMB	UZ	D		✓											
Water balance	A	C		✓	✓										
CMB	SZ	D	✓			✓	✓								
WTF	SZ	L						✓	✓						
RIB	SZ	L		✓				✓	✓						
Phys. based modelling	A	C		✓	✓			✓	✓	✓	✓	✓	✓	✓	
Large-scale mapping	A	R													✓[b]

A = all zones, SW = surface water, UZ = unsaturated zone, SZ = saturated zone, R = regional (1000s km^2), D = district (*woreda*), C = catchment (10s-100s km^2), L = local (100s m^2).

[a] Access to literature only required if developing a new empirical equation.

[b] Assuming consideration of published studies as opposed to developing new large-scale maps.

6.6 Recharge estimation methodologies

6.6.1 Empirical method

In an attempt to establish a rainfall-recharge relationship for Ethiopia, a thorough and systematic literature search was conducted. Appendix D provides detailed information on the literature search and a map of the study site locations, which were distributed around Ethiopia (Figure D1). Forty-nine quantitative studies were located that provided 102 annual recharge estimates to plot against annual rainfall (Figure 6-4). A quadratic trendline, reflecting an increase in recharge disproportionate to increasing precipitation, achieved the best R^2 and standard error. The resulting relationship is presented as Eqn. 6-1. Separating the data into the geographic (and consequently, climatic and geological) regions as shown in Figure 6-4 and fitting linear trendlines gave similar recharge values as the trendlines plot close to the quadratic regression line. Additional analysis of site-specific, rather than regional, rainfall intensity, topography, soils and vegetation is beyond the scope of this study. The regression line is not extended to rainfall below

500 mm/a as this is considered the lower limit of applicability of Eqn. 6-1. Where rainfall is below 500 mm/a, the relationship with recharge is more complex (Bonsor and MacDonald, 2010) and there were insufficient studies from which a relationship could be established.

$$\boldsymbol{R = 136.6 - 0.3005P + 0.000271P^2} \qquad (6\text{-}1)$$

Where *R* is recharge and *P* is annual precipitation.

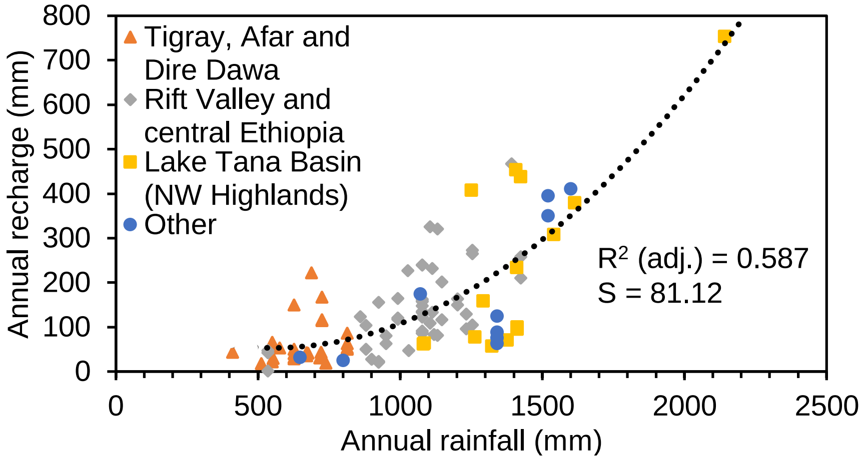


Figure 6-4. Plot showing the relationship between annual rainfall and annual recharge in Ethiopia based on 102 recharge estimates from 49 studies across the country. *S* = standard error, R^2 *(adj.)* = adjusted coefficient of determination. The Tigray, Afar, Dire Dawa group has semi-arid climate and highly heterogeneous geology ranging from Precambrian crystalline to Mesozoic sandstones and limestones to Quaternary volcanics, generally overlain by leptosols with sparse and herbaceous vegetation. Rift Valley and central Ethiopia have subtropical highland and tropical savanna climate with Quaternary volcanic geology, highly heterogeneous soils and rainfed cropland and mosaic forest and grassland. The Lake Tana Basin has a tropical highland monsoon climate and Cenozoic volcanic rocks overlain by luvisols or vertisols closer to the lake with mosaic cropland/grassland/shrubland/forest (Tefera *et al.*, 1996; Peel *et al.*, 2007; Arino *et al.*, 2012; Jones *et al.*, 2013).

6.6.2 Streamflow hydrograph analysis (three methods)

Recharge estimation using streamflow hydrograph methods typically involves separating the baseflow component (Figure D2 in Appendix D) and idealising that precipitation entering the aquifer as recharge must be balanced by groundwater discharge into rivers that forms baseflow. However, there are several ways in which groundwater can be depleted without contributing towards baseflow, including abstractions, leakage to deeper aquifers, and evapotranspiration from the saturated zone. Without quantifying these fluxes, equating baseflow to recharge will lead to underestimation of recharge. It is important to remind, therefore, that quantifying baseflow is an estimate of groundwater discharge and provides a *minimum* estimate of recharge (Szilagyi *et al.*, 2003; Vegter and

Pitman, 2003; Risser *et al.*, 2005). Three streamflow hydrograph methods were used in this study, the baseflow recession method presented by (Meyboom, 1961), and two digital recursive filter tools, the Web GIS based Hydrograph Analysis Tool (WHAT) (Lim *et al.*, 2005) and WETSPRO (Willems, 2009). Details of the application of these methods are presented in Appendix D.

6.6.3 Soil moisture balance (SMB)

The Thornthwaite-Mather (1955, 1957) (T-M) method is essentially a water balance of the root zone performing monthly book-keeping of precipitation, evapotranspiration and soil moisture. Deep infiltration below the root zone occurs only when field capacity is exceeded (see Steenhuis and Van Der Molen (1986)). The direct runoff component is dealt with by applying a runoff factor or by subtracting a portion of soil moisture surplus; both methods were applied here. Details of the parameterisation and the tabulated calculations can be found in Appendix D.

A key assumption of unsaturated zone methods, such as the SMB method, is that the soil moisture surplus will infiltrate to the water table. However, this water may flow laterally through the unsaturated zone as interflow without necessarily recharging the aquifer (Misstear, 2000; Hendrickx and Flury, 2001). Hence, Simmers (1988), Rushton (1997), Healy (2010) and others refer to the recharge computed from unsaturated zone methods as *potential* recharge.

6.6.4 Basin water balance

The water balance, or water budget, simplifies the full water balance equation by neglecting Q_{in}, A, Q_{out} and ΔS in

$$\boldsymbol{P + Q_{in} = RO + AET + R + A + Q_{out} + \Delta S} \quad (6\text{-}2)$$

Where P is precipitation, Q_{in} is groundwater flow into the basin, RO is runoff (i.e. overland flow and interflow out of the basin), AET is actual evapotranspiration (from the unsaturated and saturated zones and from surface water), R is recharge, A is abstraction, Q_{out} is groundwater flow out of the basin, and ΔS is the change in storage. The assumptions are that ΔS is balanced over long time-periods (this appears valid from groundwater level records), Q_{in} and Q_{out} are negligible as these are headwater catchments with thin aquifers and rivers founded on bedrock (hence no groundwater flow beneath the gauge), and abstraction is negligible due to sparse wells with manual-lifting technology. AET is not straightforward to estimate and was calculated with three methods for comparison: (1) The T-M method; (2) Application of Turc's formula (Turc, 1954), and;

(3) A value estimated by Allam *et al.* (2016) for this region of the Tana Basin by combining remote sensing and river flow records. The average AET values were 789, 831 and 931 mm/a, respectively. See Appendix D for details of the AET and runoff estimations. Accurate quantification of all the fluxes is always troublesome though is required in order to leave an accurate residual that is equated to *actual* recharge (Scanlon *et al.*, 2002).

6.6.5 Chloride mass balance (CMB)

The CMB method requires mean annual precipitation, chloride concentration of that precipitation and chloride concentration of the groundwater, is independent of whether recharge is diffuse or focussed, and integrates recharge rates both spatially across a region and temporally over long time-periods. The method has several assumptions (Bazuhair and Wood, 1996):

- All chloride within groundwater originates from precipitation, i.e. there are no alternative chloride sources such as evaporites or pollution.
- Chloride is conservative in the system (this is generally the case as chloride is not adsorbed, is unlikely to form salts, and has rare biochemical interaction).
- Recycling of chloride does not occur within the basin area.
- The chloride concentration in runoff is equal to that in precipitation.
- Evaporation of groundwater does not occur upgradient of groundwater sampling points.

The basic equation applicable for evaluation of recharge using the CMB is

$$\boldsymbol{R} = \frac{(\boldsymbol{P_{eff}})(\boldsymbol{Cl_{wap}})}{\boldsymbol{Cl_{gw}}} \tag{6-3}$$

Where R is annual recharge, P_{eff} is average annual effective precipitation (rainfall minus direct runoff), Cl_{wap} is the weight-average chloride concentration in precipitation including dry deposition, and Cl_{gw} is the average chloride concentration in groundwater. Cl_{gw} averaged 2.10 mg/l with a standard deviation of 1.33 mg/l and Cl_{wap} averaged 0.68 mg/l (standard deviation = 0.32 mg/l). Details of the parameterisation can be found in Appendix D.

6.6.6 Water table fluctuation (WTF)

In the WTF method, the upward movement of groundwater level with respect to time is an indication of recharge and the downward movement indicates recession of groundwater; no assumptions are made regarding recharge mechanism (see Healy and

Cook (2002) for details). Groundwater recharge R is calculated for a particular well by multiplying the change in water level of two successive groundwater level readings by the specific yield S_y of the aquifer:

$$\boldsymbol{R = S_y * {}^{\Delta h}/_{\Delta t}} \qquad (6\text{-}4)$$

Where h is water level and t is time. To correctly estimate Δh, it is necessary to extrapolate the antecedent recession curve to the point below the peak, i.e. the point that the groundwater level curve would have reached without precipitation (Figure D5). This extrapolation was conducted manually on each of the 30 well hydrographs, following the graphical method described by Delin *et al.* (2006). For comparison, another approach was followed that involves calculating the water level rise from one day to the next with a negative rise, i.e. a fall in groundwater level, counting as zero. This method would be expected to underestimate recharge because groundwater recession with the absence of recharge is not considered (e.g. Delin *et al.* (2006); Choi *et al.* (2007); Varni *et al.* (2013)). S_y of 0.08 was used, obtained from 11 pumping and recovery tests in the area (Walker, 2016).

6.6.7 Rainfall infiltration breakthrough (RIB)

The RIB method is a model for groundwater recharge estimation developed by Xu and Beekman (2003) based on the cumulative rainfall departure (CRD) method (Wenzel, 1936). The conditions at the field site fit well the requirements detailed by (Sun *et al.*, 2013): "… the RIB model is best suited for shallow unconfined aquifers with relatively low transmissivity". The model considers not only rainfall from a single event but the series of preceding events that influence breakthrough of water at the water table (for details see Xu and van Tonder (2001) and Sun *et al.* (2013)). Time series of rainfall are required, plus groundwater level and aquifer S_y. The RIB method utilised data from the 30 community-monitored wells and raingauge in addition to S_y of 0.08 (Walker, 2016). Further details can be found in Appendix D. As with the WTF method, there is the possibility of accounting for groundwater level rise from lateral flows in recharge estimation.

6.6.8 Physically-based modelling

SHETRAN (Système Hydrologique Européen TRANsport) is a physically-based spatially distributed finite difference modelling system for coupled surface and subsurface water flow in river basins and is openly available at http://research.ncl.ac.uk/shetran/. SHETRAN is well established in the literature, having been applied to a variety of situations (e.g. Birkinshaw and Ewen (2000b); Bathurst *et al.* (2011a); Starkey *et al.* (2017)), however, it has not previously been used to quantify recharge. Model setup requires a DEM, catchment mask, geological, soil, vegetation and LULC information. Further details of SHETRAN, including how recharge is computed within the model and how the models were parameterised, can be found in Appendix D. Three nested catchments were modelled, details of which are in Table 6-2. The calibration procedure involved adjusting geological layer thicknesses, aquifer properties, channel characteristics, Strickler overland flow roughness coefficient, and evapotranspiration characteristics until satisfactory matches with observed groundwater level and river discharge data were achieved. The nested nature of the catchments meant a final matching set of optimum parameters was selected to satisfy the calibration requirements of all catchments. Table 6-2 shows calibration statistics for a calibration period; subsequent simulations during a validation period were deemed acceptable (see Appendix D).

Table 6-2. Details of the three catchments modelled using SHETRAN (see Figure 6-1 for locations).

Catchment	**Area (km^2)**	**Resolution (m)**	**Run length**	**Calibration**	**NSE**	**RMSE**
Amen	37	100x100	17 years (Jan 98 to Sep 14)	River flow	0.79	0.19 m^3/s
Kilti	632	500x500	18 years (Apr 97 to Oct 14)	River flow	0.78	1.47 m^3/s
Brante	66	100x100	3 years (Mar 14 to Jan 17)	GW levels	0.69	2.01 m

NSE = Nash-Sutcliffe efficiency. *RMSE* = root mean square error.

6.7 Recharge results

Recharge estimates from the various methods show high variability: 45-814 mm/a or 3-53%MAP (median annual precipitation) for the median annual recharge (Figure 6-5 and Table 6-3). The WHYMAP and Meyboom methods were rejected for this study with full reasoning provided in Appendix D.

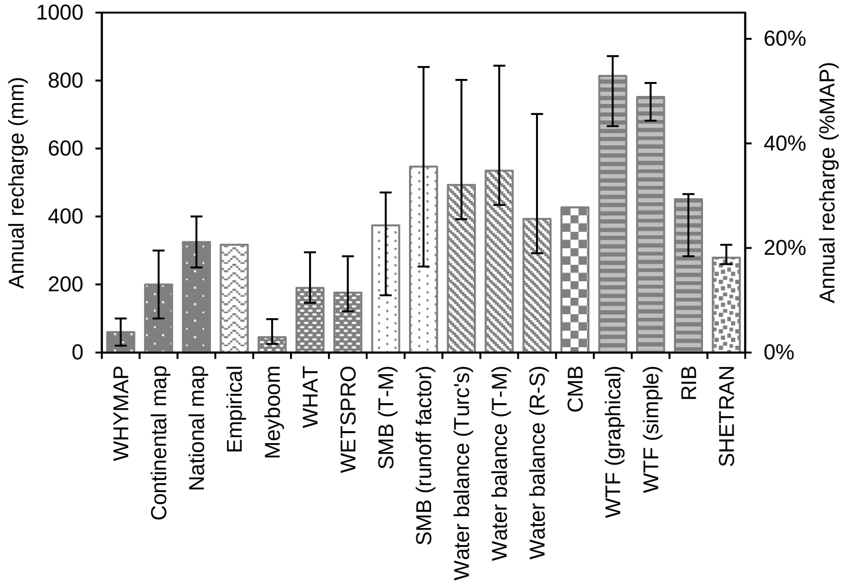


Figure 6-5. Median annual recharge estimates from all the techniques. The error bars give the interannular recharge range. *T-M* = Thornthwaite-Mather method of runoff or AET estimation. R-S = Remote sensing method of AET estimation.

Table 6-3. Tabulated recharge results shown on the plot in Figure 6-5.

	Annual recharge (mm)		
Technique	**Minimum**	**Median**	**Maximum**
WHYMAP	20	60	100
Continental map	100	200	300
National map	250	325	400
Empirical		317	
Meyboom	25	45	98
WHAT	146	190	295
WETSPRO	121	176	283
SMB (T-M)	168	374	471
SMB (runoff factor)	253	547	840
Water balance (Turc’s)	392	493	802
Water balance (T-M)	434	535	844
Water balance (R-S)	292	393	702
CMB		427	
WTF (graphical)	666	814	872
WTF (simple)	682	752	793
RIB	283	451	466
SHETRAN	260	279	317

6.8 Sensitivity analyses

Measured input data and modelling parameters were individually adjusted by ±10% to assess sensitivity. For some methods, only measured input data could be adjusted, e.g. rainfall or groundwater level fluctuation. For other methods, it was possible to adjust modelling parameters determined during additional investigations, calibration or by "expert opinion", e.g. the recession constant for WHAT and WETSPRO analysis. Additionally, to suggest the range of uncertainty, recharge was computed by each method using the likely maximum deviation in parameter values. Table 6-4 details the parameter adjustment and Figure 6-6 shows the sensitivity and uncertainty for each method.

Table 6-4. Parameters and input data adjusted for the sensitivity and uncertainty analysis.

Method	**Parameters/input data individually adjusted by ±10%. Most sensitive parameter underlined.**	**Maximum likely deviation of parameters/input data giving the uncertainty range.**
Empirical	Annual average rainfall	95% prediction interval from the rainfall-recharge relationship curve
WHAT	River flow, BFI_{max}, recession constant	Derived BFI_{max} and maximum/minimum recession constant that still gave an acceptable baseflow separation
WETSPRO	River flow, recession constant, w	Maximum/minimum recession constant and w that still gave an acceptable baseflow separation
SMB (T-M)	Rainfall, PET, MC, LULC proportions, % surplus to runoff	Combined adjustment by ±10% of % surplus to runoff, MC and LULC proportions*
SMB (runoff factor)	Rainfall, PET, MC, LULC proportions, runoff factor	Combined adjustment by ±10% of runoff factor, MC and LULC proportions*
Water balance (Turc's)	Rainfall, temperature (for AET), runoff	Combined adjustment by ±10% of rainfall, temperature (for AET) and runoff*
Water balance (T-M)	Rainfall, AET, runoff	Combined adjustment by ±10% of rainfall, AET and runoff*
Water balance (R-S)	Rainfall, AET, runoff	Combined adjustment by ±10% of rainfall, AET and runoff*
CMB	Annual average rainfall, Cl_{gw}, Cl_{wap}	Measured range of Cl_{wap} (0.38-1.12 mg/l)
WTF (graphical)	Water level fluctuation, S_y	Measured range of S_y (0.05-0.3)
WTF (simple)	Water level fluctuation, S_y	Measured range of S_y (0.05-0.3)
RIB	Water level fluctuation, rainfall, S_y	Measured range of S_y (0.05-0.3)

SHETRAN (phys. based modelling)	Rainfall, PET, Strickler coefficient, S_y, hydraulic conductivity, layer thicknesses, AE/PE ratio	Combined adjustment of layer thicknesses and AE/PE ratio by ±10%, and S_y and hydraulic conductivity within measured range that still gave an acceptable calibration

BFI_{max} = maximum value of long-term ratio of baseflow to total streamflow. *w* = portion contributing directly to runoff. *PET* = Potential evapotranspiration. *MC* = root zone storage. *AE/PE* = actual to potential evaporation ratio. See methodological descriptions in Appendix D for more information on these parameters.
* The range in parameter/input data was uncertain, i.e. there was no constraining measured range nor calibration targets.

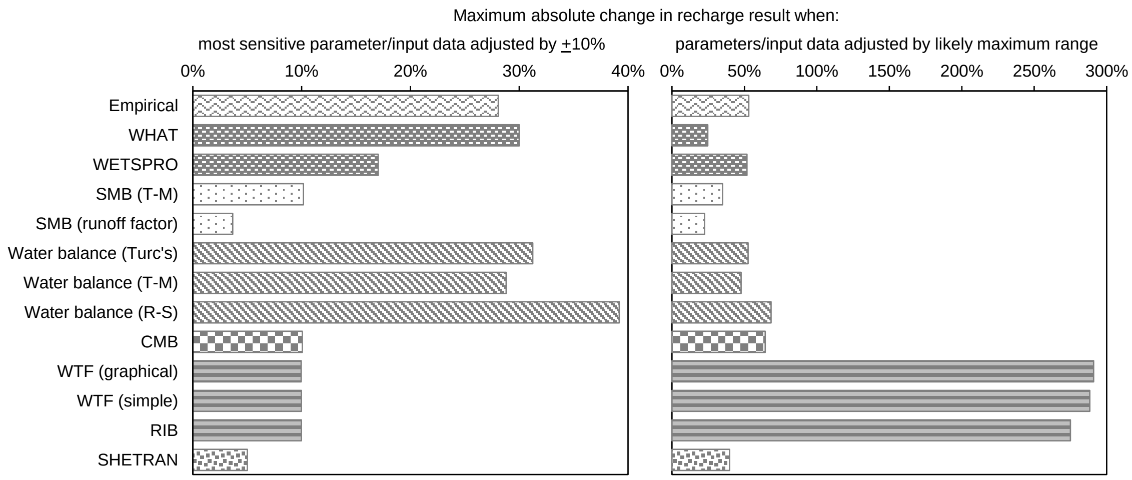


Figure 6-6. Comparison of the sensitivity of each recharge estimation method to ±10% adjustment in measured input data and modelling parameters (left) and range of uncertainty when the maximum likely deviations are applied (right).

The left plot in Figure 6-6 highlights the varying sensitivity of the methods. For example, it shows the water balance methods' high sensitivity to rainfall input and, essentially, lower sensitivity to any single parameter when the number of parameters increases (e.g. SMB and SHETRAN). The right plot in Figure 6-6 highlights the varying range of uncertainty in recharge result from different methods, which is dependent on the degree of uncertainty in the input parameters. For example, while the WTF and RIB methods show low sensitivity to a 10% variation in parameters, the recharge result has high uncertainty because the measured range in S_y was high; S_y is commonly uncertain due to the difficulties in accurate measurement and the heterogeneous nature of many aquifers. Uncertainty reduces with those methods that involve calibration, e.g. WHAT and SHETRAN, as the maximum possible deviation in parameter values decreases.

Additionally, when there is high uncertainty in input data, Figure 6-6 suggests which methods may be better selected.

6.9 Discussion

6.9.1 Reasons for the range in results

The range of recharge results presented in Figure 6-5 does not necessarily mean that some results are incorrect, as they need to be considered in the context of their spatiotemporal scale, what they represent, and the limitations of each method. A recharge value that is comparatively high or low can provide insights on the conceptual model, especially if previously the conceptual model expected the method to provide an *actual* recharge estimate, and insights on uncertainty. A summary of the methods is provided in Table 6-5.

Table 6-5. Summary of methods and suggestions for lessening uncertainty in the recharge results. It should be restated here that while the specific methods usually compute the specified type of recharge, this is particular to the conceptual model of the study site.

Method	**Type of recharge computed**	**Under/over estimates**[a]	**Uncertainty**[b]	**How to lessen uncertainty**[c]
WHYMAP	Actual	Under	Rejected because its scale is inappropriate for this study resulting in gross underestimation of recharge	
Continental map	Actual	Under	High	Use other methods
National map	Actual	Applicable	High	Use other methods
Empirical	Actual	Applicable	High	Increase number of recharge studies considered with greater geological, soils, vegetation and climate detail
Meyboom	Minimum	Under	Rejected due to problems of application on the study site hydrographs resulting in gross underestimation of recharge	
WHAT	Minimum	Under	Low	Utilise longer river flow time series and additional series from nested catchments
WETSPRO	Minimum	Under	Low-medium	As above
SMB (T-M)	Potential	Applicable	Medium	Increase rainfall and PET measurement density, utilise higher resolution soil and vegetation mapping and use a daily computation time step
SMB (runoff factor)	Potential	Over	Low-medium	As above
Water balance (Turc's)	Actual	Over	Medium-high	Increase rainfall and PET measurement density, utilise higher resolution vegetation mapping for better AET estimation, and use a daily computation time step
Water balance (T-M)	Actual	Over	Medium	As above
Water balance (R-S)	Actual	Applicable	Low-medium	As above
CMB	Actual	Applicable	Medium	Increase rainfall chloride sampling frequency

WTF (graphical)	Change in storage	Over	High	Obtain more S_y estimates, utilise piezometers that are not biased towards good groundwater supply
WTF (simple)	Change in storage	Over	High	As above
RIB	Change in storage	Over	Medium-high	As above
SHETRAN (phys. based modelling)	Actual	Applicable	Low	Increase rainfall and PET measurement density, obtain more S_y and hydraulic conductivity estimates, and aquifer geometry measurements (e.g. with geophysics), utilise more river flow and groundwater level records for calibration

[a] In comparison to the estimated actual recharge range for the study site of 280-430 mm/a.

[b] This relates to the sensitivity and uncertainty ranges in Figure 6-6 and the robustness of the method.

[c] The suggestions present a best-case scenario should time and budget allow.

As previously stated, unsaturated zone methods may overestimate recharge, explaining why the SMB methods applied here show high recharge values, i.e. they are calculating potential recharge. The other uncertainty relates to which method to choose to determine the amount of runoff; application of a runoff factor based on measured river flows has lower uncertainty.

The streamflow hydrograph methods provide the lowest recharge estimates, supporting their classification as computing *minimum* recharge. While the Meyboom method was rejected (see Appendix D), the similarity of the WHAT and WETSPRO recharge results provides confidence in their *minimum* recharge estimates.

Considering the WTF and RIB methods, the suggestion by Healy and Cook (2002) that monitoring wells should be positioned in a “representative” location is reasonable for purposely installed piezometers, but hand-dug wells will naturally be excavated where generations of experience indicate has good potential for groundwater abstraction, i.e. there is a bias towards areas that receive lateral in addition to vertical recharge. It is unsurprising then that the WTF methods give the highest recharge estimates of all methods as they are actually computing the change in aquifer storage on a much smaller scale (10s of metres) than the other methods. The RIB method utilised the same groundwater level datasets and S_y, though is constrained by the incorporation of a rainfall time series thus giving lower recharge estimates.

The empirical method is simple, but is built upon a substantial quantity of work by the authors of the studies used in the development of the method. However, confidence in the recharge result is low, due to several factors:

- Confidence in the quality of the published studies: The generation of the rainfall-recharge relationship considered recharge estimates from all identified studies, even though 56% used only a single recharge estimation method and there was often uncertainty if the conceptual model meant applicability of assumptions or the type of recharge computed.
- Confidence in the transferability of the results: Figure D1 in Appendix D shows that the geographical distribution of the studies is biased to the Lake Tana Basin, Tigray, Dire Dawa, and around Addis Ababa. These four regions have specific rainfall intensity, evapotranspiration, hydrogeological and topographic characteristics that control the recharge rate.
- Confidence in the appropriateness of using annual rainfall total: Considering only the annual total rainfall fails to recognise the importance of rainfall intensity and distribution throughout the year. For example, a unimodal and a bimodal rainfall pattern would give different recharge rates even with the same annual total rainfall (Kingston and Taylor, 2010).

The water balance methods should give *actual* recharge *if* the other fluxes are accurately quantified. While we may have a degree of confidence in values used for runoff and precipitation, AET is difficult to estimate, as the range in AET estimates from the three applied methods attests. The relatively high recharge estimates from the water balance methods are likely to be a symptom of underestimation of AET and greater uncertainty comes with decreasing robustness of AET estimation.

There is some uncertainty in the CMB recharge result due to the small number of rainfall chloride measurements and the assumption that chloride is not introduced into groundwater from any other source but precipitation. This assumption is valid at the study site regarding pollution and evaporites, which are not present, however, evapotranspiration from the saturated zone or from seepages that re-infiltrate may cause an increase in the chloride concentration of groundwater. The discrepancy in recharge result of the CMB method may be because it averages over a longer period and larger area than the other applied methods.

SHETRAN modelling computes the change in aquifer storage for each cell, which becomes *actual* recharge when integrated over the catchment area as adjacent lateral inflows cancel. There is high confidence in these recharge estimates due to: substantial locally derived data was used to set up and calibrate the models as opposed to relying on just a few, potentially highly localised, input datasets or relying on averages; interannual variations in recharge totals correlate well between catchments with $r = 0.81$, and; recharge estimates are not sensitive to adjustments in individual parameter values. The spatially distributed nature of the model means that spatial variations in recharge due to lateral groundwater flow can be observed and understood, rather than providing misleading recharge estimations. Similarly, interannual variations in storage can be observed and measured rather than assumed to be negligible. However, this robustness of method depends on quantity and quality of data available for model setup, calibration and validation in addition to requiring a skilled operator with the necessary time available. Exploring the models' mass balances indicated why the SHETRAN recharge estimates are lower than those from other methods: recharge is reduced because, unlike other methods here presented, SHETRAN computes canopy and open water evaporation, both of which are significant at this site.

The map presented by Ayenew *et al.* (2008b) was produced only at Ethiopian national-scale and incorporates more local studies and experience than is possible with global or continental-scale maps. Therefore, assuming that those local studies were conducted robustly, the national map gives a recharge estimate for which we have greater confidence.

6.9.2 Insights gained on the conceptual model

The obvious insights gained from the multi-method comparison was that not all methods were computing *actual* recharge or the results would be more similar (given similar spatiotemporal scale). Therefore, some assumptions must have been unsatisfied, which, rather than invalidating a method altogether, meant that the method was computing *potential* or *minimum* recharge or change in aquifer storage. Insights gained on the conceptual model mostly concern the amount and type of evapotranspiration, and the spatial variability of groundwater availability. High recharge values from the SMB methods indicate that all infiltration, which unsaturated zone methods are actually measuring, does not form recharge and there is likely to be interflow followed by discharge and/or evapotranspiration. The streamflow hydrograph methods' lowest recharge estimates indicate that groundwater is depleted prior to contributing to baseflow. Evapotranspirative losses from the saturated zone must be significant, which was thought likely given the shallow wet season water tables and spring/seepage-fed inundated floodplains. High recharge values from the water balance methods are also suggestive that evapotranspiration may have been underestimated. Further evidence for this is the lower recharge estimate from SHETRAN that is due to its comprehensive simulation of canopy and open water evaporation and transpiration from the unsaturated and saturated zones resulting in greater total evapotranspiration losses. The high recharge values from the water table fluctuation methods, and high variability between wells, demonstrate the spatial variability in groundwater availability. The results show that groundwater flow, interflow and storage in certain areas can provide high potential for abstraction. Examples of other studies where fewer methods were applied and useful insights were gained are included in Appendix D.

6.9.3 Recharge estimate for Dangila woreda

Considering which types of recharge and spatiotemporal scales are relevant to this study, we restate the purpose as being to determine the resilience of shallow groundwater resources used for irrigation by rural communities in the Dangila area of Ethiopia; estimates of long-term annual *actual* recharge at multiple catchment-scales are therefore of primary interest. Although spatial assessments of aquifer storage change for small-scale shallow aquifers, particularly at the seasonal-scale, are also of significant interest to identify areas with the greatest potential for groundwater abstraction.

Considering the different types of recharge (see Table 6-5), while the median recharge values from all of the methods used range from 45 to 814 mm/a, we expect that the long term *actual* recharge averaged over the general study area lies somewhere between the *minimum* and *potential* values of 176 and 547 mm/a, given by the lowest streamflow hydrograph and highest SMB methods, respectively. The range of median values given by all *actual* recharge methods is 279-535 mm/a.

With regard to spatial scales, the methods based on groundwater level time series are highly localised and dependent on lateral inflows and other local factors, with values of recharge for individual wells from the RIB and the WTF methods ranging from under 100 to over 1600 mm/a. At the catchment-scale, recharge values for the three catchments for each method used were generally consistent (see Appendix D), indicating some spatial consistency at this scale.

Having separated out and considered results by different types of recharge and spatial scales, determination of reliable *actual* recharge estimates for the general area around Dangila requires consideration of the confidence given to each relevant method. This can be based on factors discussed earlier, including: temporal representativeness of time-series data; spatial representativeness of data; errors and uncertainties in input data; sensitivity of models to parameter values and input data; whether assumptions of methods are met. We have greatest confidence in the water balance method using the higher AET rate, the CMB method, and the SHETRAN modelling. Thus, we identify a reliable recharge range for the Dangila area of 280-430 mm/a, which is consistent with the range from the national map (Ayenew *et al.*, 2008b).

6.10 Conclusions

Nine methods, with 17 variations, of groundwater recharge estimation were applied for a shallow aquifer in Ethiopia resulting in a wide range of median annual recharge values from 45 to 814 mm. This research shows that application of a range of methods may give a broad range of recharge values, but that it may not be necessary to discard results that appear to be outliers as these provide useful information. Consideration must be given to exactly what the "recharge" value represents: *potential, minimum*, or *actual* recharge, or change in aquifer storage. It is clear from the results presented that some methods providing estimates of *potential* recharge or storage change are likely to deliver overestimates of *actual* recharge while others that represent *minimum* recharge will deliver underestimates of *actual* recharge. Considering each method's spatiotemporal scale and uncertainty, we conclude that the most reliable recharge estimates for *actual* recharge in the general Dangila area are in the range 280 to 430 mm/a.

Insights gained from the multi-method comparison study, including in particular assessment of results from methods where the usual assumptions were not strictly valid, enabled the hydrogeological system be better understood. Firstly, by indicating that evapotranspiration is significant from a) the saturated zone, and b) the unsaturated zone following infiltration past the root zone due to interflow and seepage. Secondly, by revealing the spatial variation of the change in aquifer storage, which locally can be significantly higher than *actual* recharge estimates, giving further insight and confidence that areas could be identified with high potential for abstraction for small-scale irrigation. Even though our recharge range is comparable to the national map results, we now have much higher confidence in the results and better understanding of our catchments and aquifers from our analyses.

This study has demonstrated for an extensive range of commonly used recharge methods applied at a single site that, in addition to quantifying uncertainty of recharge estimations, results from multi-method comparisons should be clearly interpreted in relation to the types of recharge and spatiotemporal scale they represent, but can also provide additional benefits through improved hydrogeological understanding.

Chapter 7. Modelling the shallow aquifer

7.0 Chapter overview

The recharge assessments in Chapter 6 showed that the Dangila *woreda* shallow aquifer has the potential to support development of small-scale irrigation. How the resource availability varies spatially and temporally is the subject of Chapter 7. This chapter presents information on the many catchment-modelling options and explains why SHETRAN was chosen and how the program works. Details are provided on model construction and parameterisation followed by a description and results of the calibration process. The modelling aims were to simulate observed historical conditions to improve understanding of the hydrogeological system; this improved understanding is described. The resulting maps of shallow groundwater potential for irrigation are shown and discussed.

7.1 Catchment modelling

7.1.1 Introduction

The conceptual model of the study site, presented in Chapter 4 and developed though field investigations and observations, illustrates our understanding of the shallow aquifer system. However, the static nature of the conceptual model means it alone is insufficient to enable us to inform water resource management strategies. Due to the standard issue of paucity of observational data, we cannot confidently make predictions for areas or time-periods where data is unavailable. While Chapter 6 gave an estimation of recharge – the renewable portion of aquifer storage – that is also insufficient to inform water resource management strategies. Bredehoeft (2002) stated quite clearly, following on from works by Theis (1940), Brown (1963) and Sophocleous (2000): "The idea that knowing recharge is important in determining the size of a sustainable groundwater development is a myth… The important entity in determining how a groundwater system reaches a new equilibrium is capture. How capture occurs in an aquifer system is a dynamic process. For this reason, hydrologists are occupied in studying aquifer dynamics. The principal tool for these investigations is the groundwater model." To understand the dynamic nature of a hydrogeological system it must be modelled numerically, which allows the conceptual model to be tested and consequently updated. Spatial variation of fluxes and storage can be analysed. What's more, potential changes to conditions at the study site can be simulated for assessment of impacts (see Chapter 8).

7.1.2 Purpose of the modelling

The initial aim of the modelling was to increase hydrogeological understanding of the shallow groundwater system to aid in development of the conceptual model. The following research questions were posed:

a. Are the models satisfactorily reflecting reality in terms of river flows and groundwater levels?
b. Are the parameter values appropriate considering field investigations and published literature?
c. What effect does incorporating various hydrogeological features presented in key regolith and dambo literature, but not necessarily identified in the field, have on the simulations?
d. Is groundwater availability recharge controlled or storage controlled?

Once these questions were answered satisfactorily and the models were considered to be simulating current conditions well, the objective was then to answer research question 4 from Chapter 1: Are there easily identifiable zones that show the greatest potential for sustainable intensification of agriculture through shallow groundwater irrigation?

7.1.3 Model types

A model is by definition a simplified representation of a real-world system or process (Fetter, 2001; Wagener, 2003). A conceptual model, such as that described for the Dangila study site (presented in Chapter 4), aims to describe the hydrogeological/hydrological system with a much reduced complexity reflecting a qualitative understanding of how the system works. On the other hand, a numerical model applies equations to link the quantitative inputs and outputs of a system in order to emulate observations enabling us to better understand the spatial and temporal variation (Refsgaard and Abbott, 1990). Numerical hydrogeological and hydrological models have a broad range of applications: from large-scale studies of impacts of climate change on groundwater resources, e.g. Goderniaux *et al.* (2009); Jackson *et al.* (2011); Ali *et al.* (2012); to small-scale flood frequency estimation, e.g. Prudhomme *et al.* (2003); Blazkova and Beven (2009); Calver *et al.* (2009); to multi-scale studies of aquifer contamination (e.g. Conan *et al.* (2003); Harvey *et al.* (2006); Karatzas (2017). In these cases and many others, numerical modelling is a useful tool to aid decision-making concerning water resource management, adaptation planning, risk mitigation, hydraulic structure design, and remediation strategy, amongst other applications.

Hydrological models are generally classified in three main groups: (1) empirical "black box", (2) lumped conceptual or "grey box", and (3) physically-based distributed or "white box" (Refsgaard and Knudsen, 1996; Devia *et al.*, 2015). Empirical black box models are based entirely on mathematical relationships between observed data and hydrological inputs/outputs (Refsgaard, 1996), examples include data-driven approaches and neural network models (e.g. Sudheer *et al.* (2002); Wu and Chau (2010); Kan *et al.* (2015)). The next class of models are more physically-meaningful with mathematical functions describing fluxes between different storages (Todini, 2007) such as SIMHYD (Peel *et al.*, 2000) or TOPMODEL (Beven *et al.*, 1984). Physically-based models are the most complex of the numerical hydrological model types, being the most extreme in their detailed representation of physical processes and in the number of parameters that must be evaluated (Parkin *et al.*, 1996). Physically-based models have been in use for catchment hydrology for almost 50 years, following the blueprint proposed by Freeze and Harlan (1969). Owing to their distributed nature and implication of sound physical reasoning, physically-based models have often been considered to be particularly applicable to modelling changes to catchments (e.g. climate or land use) and spatial variation of inputs and outputs (e.g. Beven and O'Connell (1982); Abbott *et al.* (1986a); Bathurst (2011)). For these reasons, a physically-based model was selected for use in this study.

Probably the most commonly used groundwater model is the MODFLOW program from the U.S. Geological Survey, used in various guises for over 40 years by academics and consultants (McDonald and Harbaugh, 1988; Refsgaard *et al.*, 2010; Hughes *et al.*, 2017). MODFLOW was not selected for this study for several reasons. Firstly, it only simulates flow in the saturated zone and is not recommended for use when there are important surface water processes such as floods to consider (Cushman and Tartakovsky, 2016). Consequently, the U.S. Geological Survey developed GSFLOW by combining MODFLOW and their precipitation runoff modelling system (PRMS) to better simulate surface/groundwater interactions. Secondly, evapotranspiration packages (e.g. ETS and EVT) allow limited vegetation specific adjustment, essentially only evapotranspiration extinction depth and the rate of evapotranspiration per hydraulic head (i.e. from the saturated zone). Given the climate of the study site with its long dry season and the low storage volume of the aquifer due to its thinness, it is important from a water resource assessment perspective to have accurate representation of evapotranspiration. Parameterisation of rooting depth, leaf area index, and proportional vegetation cover are desirable, as well as simulation of evapotranspiration rates according to soil moisture levels and pressure, particularly when the land use / land cover (LULC) change simulations are expected to most strongly impact on the surface and groundwater regimes through changes to evapotranspiration. Thirdly, time series data available to calibrate a model are sparse, in spatial and temporal extent. A physically-based model allows investigation of the conceptual model and spatial responses of the system, constrained by sensitivity analyses and the available observational data. Fourthly, the graphical user interfaces on which MODFLOW is run are expensive. An important criterion of this PhD project is that all the shallow groundwater investigations should be able to be repeated in different regions of sub-Saharan Africa by local researchers; hence, freely available software was prioritised.

7.1.4 SHETRAN

SHETRAN is a physically-based spatially distributed finite difference modelling system for modelling coupled surface and subsurface water flow in river basins (Ewen *et al.*, 2000). The main advantages of SHETRAN over alternative physically-based spatially distributed river basin modelling systems are its comprehensive nature and capabilities for modelling subsurface flow and transport. The subsurface is treated as a variably saturated heterogeneous porous medium, and fully three-dimensional flow and transport can be simulated for combinations of confined, unconfined, and perched systems. The ‘‘unsaturated zone’’ is modelled as an integral part of the subsurface, and subsurface flow and transport are coupled directly to surface flow and transport (Ewen *et al.*, 2000). SHETRAN is freely available at http://research.ncl.ac.uk/shetran/.

SHETRAN originated from SHE (Système Hydrologique Européen), which was developed in the 1980s by the British Institute of Hydrology, Danish Hydraulic Institute (DHI), and SOGREAH, France (see Abbott *et al.* (1986a)). The program has since evolved in two directions, as MIKE-SHE, further developed by DHI on a commercial trajectory, and as SHETRAN, developed at Newcastle University (Refsgaard *et al.*, 2010). The improvements over the original SHE program were in the incorporation of fully three-dimensional subsurface components in additional to solute and sediment transport modules (Ewen *et al.*, 2000). The main physical processes represented in the water flow component of SHETRAN (the sediment and solute transport components were not used for this study) are shown in Table 7-1. These physical processes are represented by physical, mostly partial differential, equations that are listed in Table 7-2.

Table 7-1. Main processes represented in the water flow component of SHETRAN (after Ewen *et al.* (2000)).

Water flow component	Processes
Surface water flow on the ground surface and in stream channels; soil-water and groundwater flow in unsaturated and saturated zones, including systems of confined, unconfined and perched aquifers	Canopy interception of rainfall
	Evaporation and transpiration
	Infiltration to subsurface
	Surface runoff (overland, overbank, and in channels)
	Snowpack development and snowmelt
	Storage and 3D flow in variably saturated subsurface
	Combinations of confined, unconfined, and perched aquifers
	Transfers between subsurface and river water
	Groundwater seepage discharge
	Well abstraction
	River augmentation and abstraction
	Irrigation

Table 7-2. Flow equations for SHETRAN applicable in this study (after Ewen *et al.* (2000)).

Process	Equation	Reference
Subsurface flow	Variably saturated flow equation (3D)	Parkin (1996)
Overland flow	Saint-Venant equations, diffusion approximation (2D)	Abbott *et al.* (1986b)
Channel flow	Saint-Venant equations, diffusion approximation (flow in a network of 1D channels)	Abbott *et al.* (1986b)
Canopy interception and drip	Rutter equation	Abbott *et al.* (1986b)
Evaporation	Fraction of potential evaporation derived from Penman-Monteith equation	Abbott *et al.* (1986b); Allen *et al.* (1998)

A SHETRAN model is divided into a grid with each cell comprising a column of finite difference cells (Figure 7-1). Where geological layer thicknesses vary between adjacent columns, the number of cells may differ; to minimise computational difficulties, yet give a very flexible system, each cell in each column exchanges water with a maximum of two cells in each adjacent column (Figure 7-1) (Ewen *et al.*, 2000). The columns, along with channel links, form the main computational structures in SHETRAN. Channel links run along the edges of grid elements (as shown for the four modelled catchments in Figure 7-4) and are assigned widths and cross-sections. Stream-aquifer interaction occurs through a channel's bed, which is handled in the same way as flows at the ground surface, and through channel sides, where a time-varying lateral head boundary condition is prescribed (Parkin, 1996).

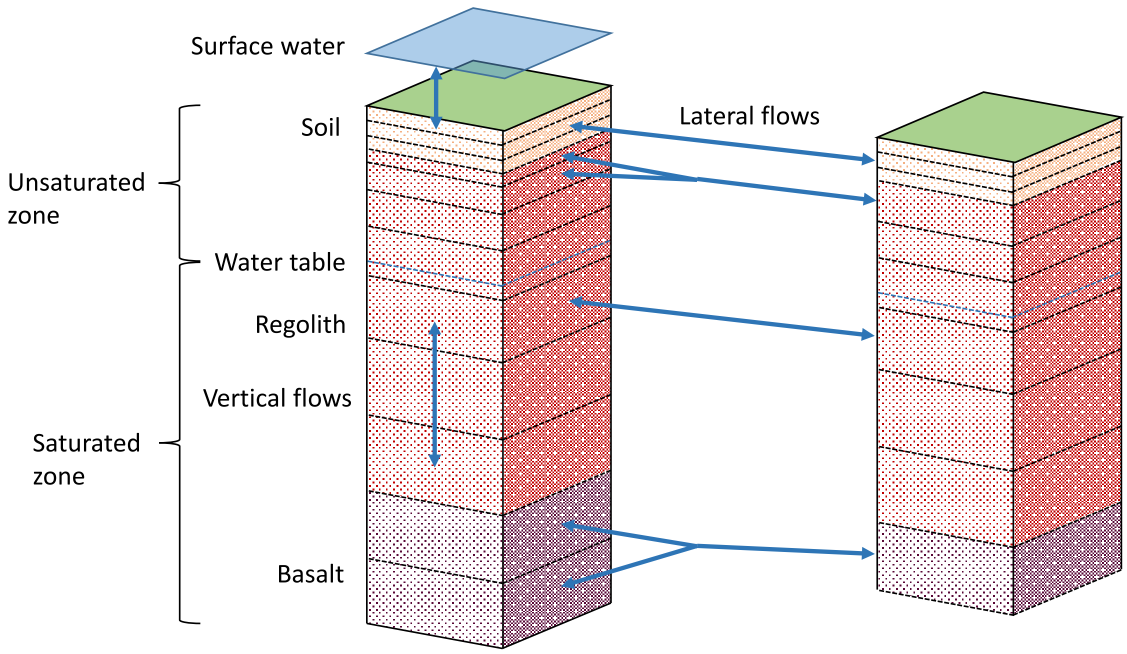


Figure 7-1. SHETRAN columns of finite difference cells showing modelled processes and geological layers consistent with the four modelled catchments, including lateral connections between layers of differing thickness.

SHETRAN has a high data requirement; the datasets required for parameterisation are listed below:

- Meteorological time series
- Mask delineating the catchment
- Topography including presence of lakes
- Size and location of columns, river links and finite-difference cells
- Soil/rock types and depths
- Porosity and specific storage of soils/rocks
- Hydraulic conductivity for soils/rocks
- Land use/vegetation
- Canopy drainage parameters and storage capacities
- Ground cover fractions
- Vegetation root density over depth
- Human-controlled:
    - channel flow diversions and discharges

- Rates of abstraction and artificial recharge

The datasets are combined as layers for the construction of a SHETRAN model (Figure 7-2).

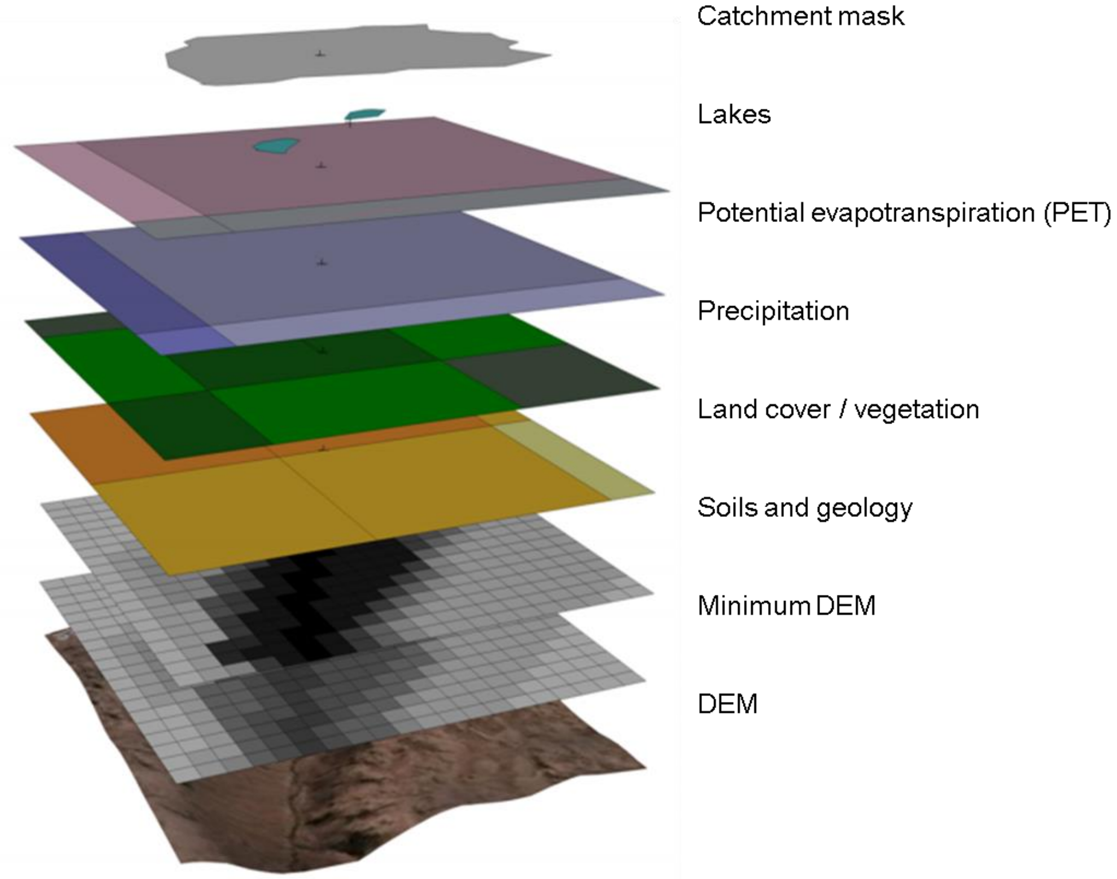


Figure 7-2. The data layers incorporated into a SHETRAN model (after Lewis (2016)).

SHETRAN is proven in the literature, having been used for a variety of catchment modelling studies. Examples include modelling nitrate transport in a catchment in southwest England (Birkinshaw and Ewen, 2000a), modelling landslide sediment yield in the Spanish Pyrenees (Bathurst *et al.*, 2006), and estimating runoff and flood peaks in a catchment in Maharashtra, India (Naseela *et al.*, 2015). Chapter 6 included a novel use of SHETRAN for recharge assessment, for which new code was required for the SHETRAN program (Walker *et al.*, 2018). The use of SHETRAN detailed in this Chapter is similar to previous uses available in the literature that have assessed impacts of climate variability and LULC change. For example, Lukey *et al.* (2000) used SHETRAN to estimate the impact of reforestation on a heavily eroded "badlands" environment in southeast France showing how runoff and sediment yield would decrease. Bathurst *et al.*, (2011a and 2011b) modelled four Latin American catchments with SHETRAN to show the degree of forest cover required for different-sized catchments to affect peak discharge from extreme rainfall events. Schmidt *et al.* (2008) modelled various LULC scenarios, adjusting the area of pasture and native vegetation, for a catchment in New Zealand to assess changes to sediment yield. Two independent studies for southern Iberia used downscaled global circulation model (GCM) and regional climate model (RCM) outputs with SHETRAN to simulate potential runoff reduction due to climate change (Mourato *et al.*, 2014; Guerreiro *et al.*, 2017). Notably, of all the mentioned studies, only that by Guerreiro *et al.* (2017) had a significant consideration of hydrogeology, the other studies essentially only considered shallow soil water in their subsurface component. While SHETRAN has been used to assess the impacts of groundwater abstraction on river flows (Parkin *et al.*, 2007), it has not (knowingly) previously been used to assess the potential for groundwater abstraction nor the impacts of the onset of groundwater abstraction on surface and groundwater resources nor the impacts of climate variability and LULC change on those resources. Similarly, SHETRAN has had limited application in Africa with only a single study found in the literature that assessed soil erosion at a catchment in Burkina Faso (Op de Hipt *et al.*, 2017). In addition, a conference paper was identified online of uncertain origin and date detailing a study from Uganda where it was shown that land use change to increased agricultural land has a had a greater impact on flood occurrence and surface water availability than a slight upward trend in precipitation (Bernard *et al.*, ?). Again, neither of these African studies had a significant groundwater component.

7.1.5 Methodology

Catchment models were built using SHETRAN based on the conceptual model and data from field investigations and open source remote sensing products. Calibration of uncertain parameters against groundwater levels and river flow led to further development of the conceptual model. Once the models were considered to be satisfactorily representing the natural system, post-processing of spatially distributed SHETRAN outputs could be used to create maps of varying potential for shallow groundwater abstraction for irrigation.

7.1.6 Similar modelling studies

Modelling studies from the Lake Tana Basin are not uncommon in the literature, with a predominance in the use of the SWAT (Soil and Water Assessment Tool) catchment modelling system. Frequent studies involve predicting flows and sediment yields of the rivers that feed Lake Tana, often for assessment of land degradation (e.g. (Setegn *et al.*, 2008; Easton *et al.*, 2010; Setegn *et al.*, 2010; Addis *et al.*, 2016)). SWAT is highly used being freely available, applicable on geographic information system (GIS) interfaces on which much of the required data is also freely available, and is straightforward to set up and calibrate. However, van Griensven *et al.* (2012) are critical of SWAT's application in the Upper Nile Basin countries due to reported use of unrealistic parameter values, a lack of reporting of parameter values making critical evaluation impossible, a general lack of attention to vegetation parameters, and comparison of SWAT applications at the same study site by different research teams and/or model versions giving very different results. Less common from the Tana Basin are modelling studies with explicit consideration of groundwater. Chebud and Melesse (2009) used MODFLOW to estimate the groundwater contribution of the Gumera watershed to Lake Tana. Even though Kebede *et al.* (2006) and Kebede *et al.* (2011), using a water balance and chemical isotopes, also showed groundwater contribution to Lake Tana, most modelling studies consider the lake and groundwater as separate entities in order to simplify the modelling by including an empirical groundwater component (e.g. Wale *et al.* (2009); Dargahi and Setegn (2011)).

Further afield in a small (2 km^2) sub-basin of the Zenako-Argaka basin Tigray, with a shallow aquifer similar to Dangila (vertisol and colluvium above trap basalts), Walraevens *et al.* (2009) used a combination of a runoff model and a soil moisture balance model to estimate recharge and a MODFLOW groundwater flow model calibrated against occasional groundwater level measurements from six piezometers. This study increased hydrogeological understanding and gave insights into recharge and discharge mechanisms of the aquifer to improve the effectiveness of the implemented water conservation measures. Also in Tigray, in the 5260 km^2 Geba Basin, Gebreyohannes *et al.* (2013) used the spatially distributed water balance model WetSpass to produce maps of long-term average runoff, evapotranspiration and recharge. The maps showed where a groundwater could be abstracted during the wet season to supplement rainfed agriculture when rains are poor. However, the safe yield was simply calculated as 25% of groundwater recharge for the particular location; groundwater flow was not modelled and no aquifer parameters (transmissivity or specific yield) were incorporated into the model.

This study appears to be the first in the region that explicitly models shallow groundwater, coupled with surface water, in order to assess the potential of the shallow aquifer resource for productive use.

7.2 Model construction

7.2.1 Modelled catchments and resolution

The four modelled catchments are shown in Figure 7-3. Table 7-3 provides information on the catchments. The decision to model four nested catchments of different sizes was to assess if optimum parameters achieved through calibration could satisfactorily be applied to all the models giving confidence in the optimum parameter uniqueness, to assess if there was any scale dependency in results, and to assess the required resolution for mapping of groundwater abstraction potential and impacts of changes. The smaller models (Brante and Amen) have a resolution of 100 m while the smaller Kilti model, "Kilti-Dangesheta", has a resolution of 200 m, and the larger "Kilti-Durbete" has a resolution of 500 m (Figure 7-4). As high a resolution as possible was chosen within the limits of the expected simulation run time, and considering the DEM had a resolution of ~90 m.

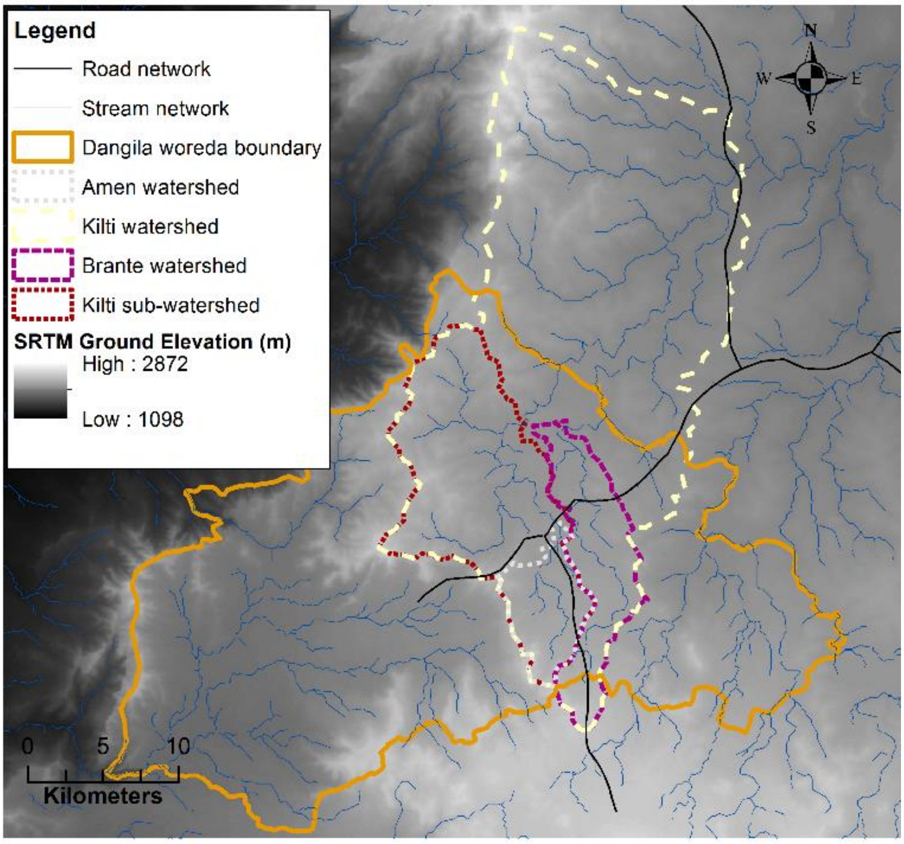


Figure 7-3. Location map of the four modelled catchments.

Table 7-3. Information about the catchments modelled with SHETRAN.

Name	Referred to as:	Gauge	Monitored by:	Area	Model resolution	Sub-catchment of:
Kilti	Kilti-Durbete, larger Kilti model	Kilti@Durbete	MoWIE	632 km^2	500 m	Gilgel Abay
Amen	Amen	Amen@Dangila	MoWIE	37 km^2	100 m	Smaller Kilti model
Kilti	Kilti-Dangesheta, smaller Kilti model, Kilti-sub	Dangesheta community	Dangesheta community	165 km^2	200 m	Larger Kilti model
Brante	Brante	Dangesheta community	Dangesheta community	66 km^2	100 m	Larger Kilti model

7.2.2 Digital elevation model (DEM) and catchment masks

The original SHETRAN model constructed by Dr G. Parkin during the one-year AMGRAF project under a NERC catalyst grant used an ASTER GDEM with a 25 m resolution from The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It was determined during the first field visit in March/April 2015 that this DEM was inaccurate. The stream network is created within SHETRAN according to DEM elevations and many of the created streams were not observed on the ground or streams that run parallel had been merged by SHETRAN. This ground-truthing led to the selection of an alternative DEM from NASA’s Shuttle Radar Topography Mission (SRTM) which, while of a lower resolution (3 arc-seconds, or approximately 90 m), proved to give the best representation of the topography of the area of focus. The DEM and minimum DEM were resampled from the SRTM DEM using QGIS, an open source geographic information system application, to the required resolution for each model. The catchment boundaries, or catchment masks, were delineated and resampled using tools within the QGIS GRASS-GIS toolbox. Lakes layers were unnecessary as no lakes are found within the catchments.

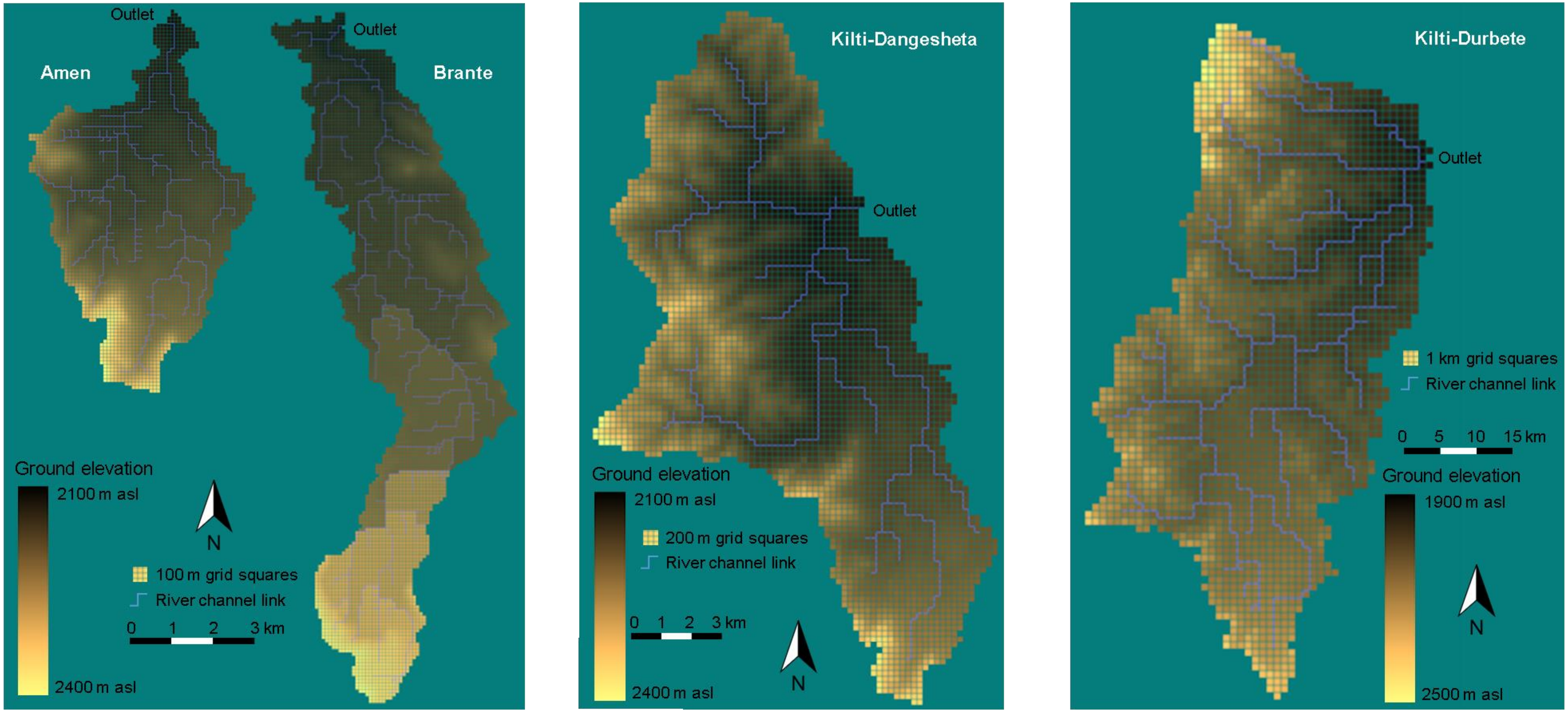


Figure 7-4. SHETRAN grid, DEM and stream networks for the four modelled catchments. Note the different horizontal and vertical scales of the catchments.

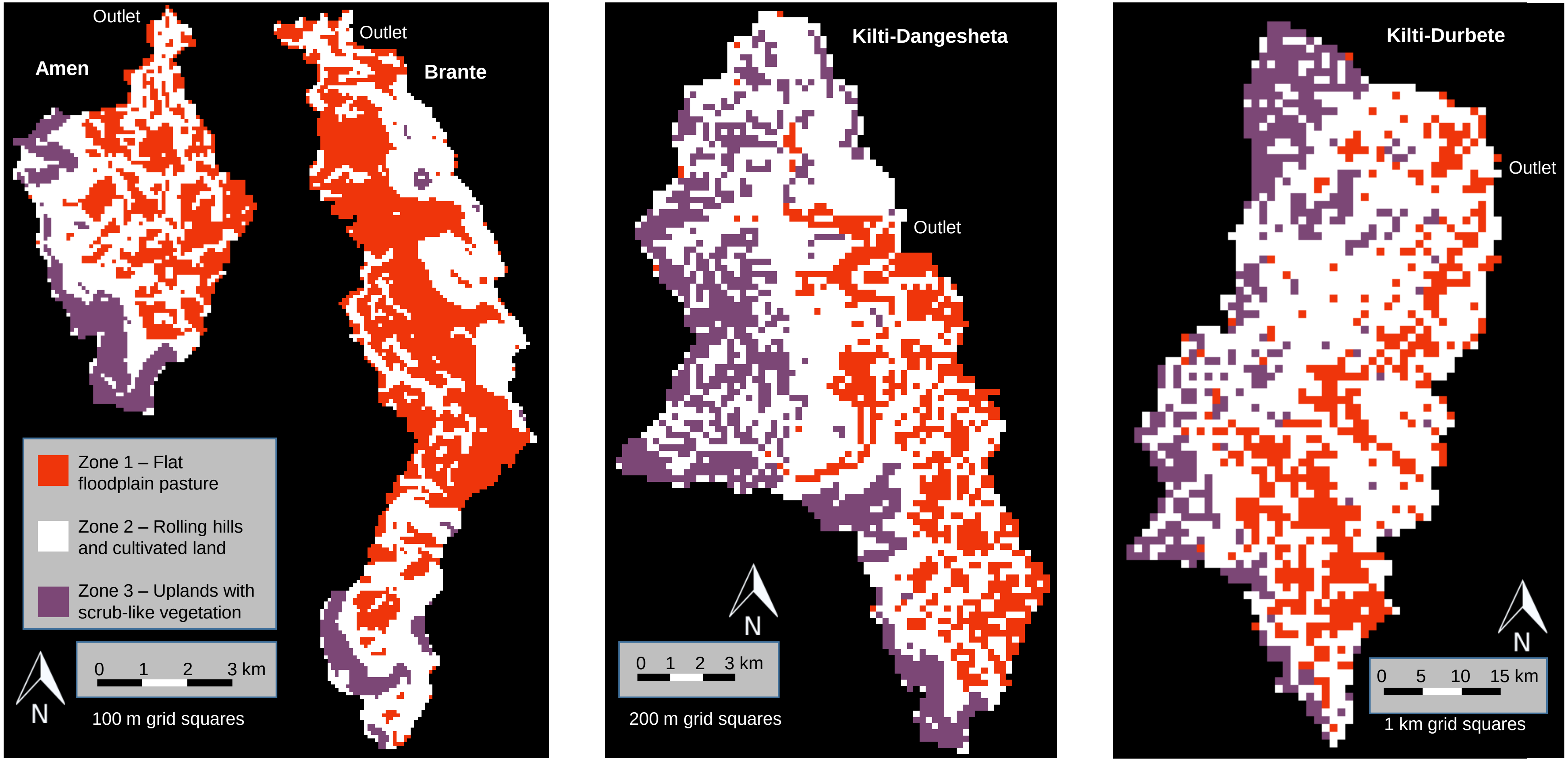


Figure 7-5. Maps showing the distribution of the hydrogeological and LULC zones of the four modelled catchments.

7.2.3 Meteorology

SHETRAN models require time series of precipitation and potential evapotranspiration (PET). Daily precipitation was available from the Ethiopian National Meteorological Agency (NMA) for the weather station within Dangila town from 1st January 1994 to 31st October 2015. The Dangila town weather station is the only formal monitoring station within Dangila *woreda* and any of the modelled catchments. Daily precipitation is also available from the Dangesheta community-based monitoring programme from 10th March 2014 to 8th January 2017. The quality of the data from the community-based monitoring programme was confirmed by statistical comparisons with data from formal sources as described in Chapter 5 and in Walker *et al.* (2016). PET was calculated using the standardised FAO-56 Penman-Monteith reference evapotranspiration (Allen *et al.*, 1998), which requires maximum and minimum daily temperatures, wind speed, sunshine hours and relative humidity. These parameters were available from the NMA for the Dangila weather station at a monthly time-step from January 1985 to December 2006 and daily from 10th January 2010 to 31st October 2015. Attempts to obtain the missing (2007-2009) PET data and obtain precipitation and PET data since November 2015 proved unsuccessful; despite visits to the NMA regional office in Bahir Dar and promises made by their staff. In order to fill the gaps in the PET data, it was determined that using average monthly values was satisfactory: The interannual variation in monthly PET totals is low, as can be seen in Figure 7-6; the coefficient of variation for interannual monthly values ranges from only 3.4% (September) to 6.8% (June). The single meteorological monitoring station operating at any one time within the catchments means the precipitation and PET layer for SHETRAN was homogenous across the whole catchment.

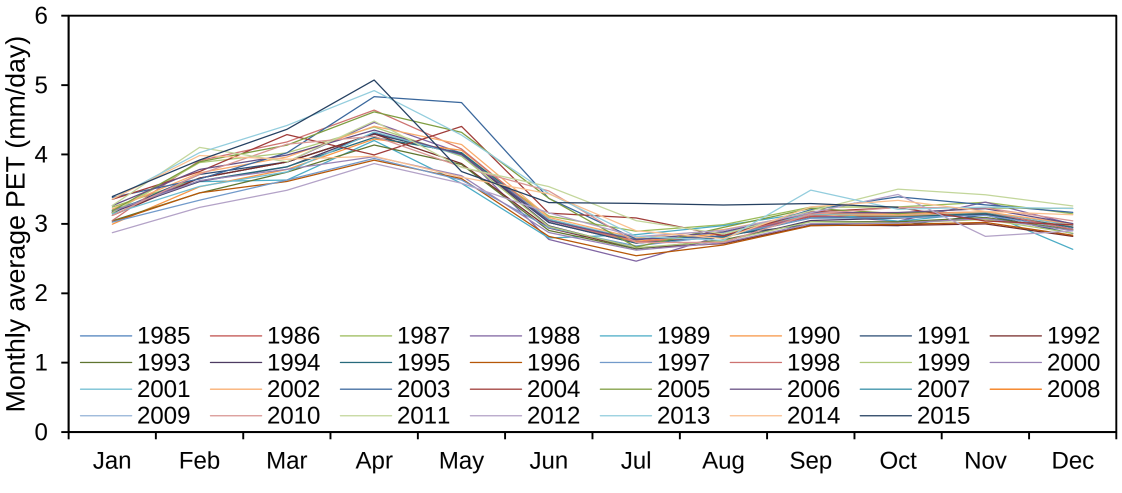


Figure 7-6. Interannual variation in monthly PET at Dangila.

7.2.4 Soils and geology

Hydrogeological zones

Chapter 4 provided details of the geological investigations. Essentially, loamy soils overlie regolith that overlies very low permeability basalt. The soils and geology layer for input into SHETRAN relied on field investigations as soil and geological mapping of the area is not available at sufficiently high resolution. The observed variation in well depths, differences in monitored well responses, variation in well pumping/recovery test results, geological and soil observations, and discussions with local communities led to the definition of three hydrogeological zones. It is noted that each zone is a land type and not a specific location, i.e. there are multiple locations designated as each zone.

1. The first zone comprises the widespread and often expansive floodplains. These features are flat or of very low gradient and provide year-round pasture for livestock. Desiccation cracked surfaces during the dry season indicate a clay-rich composition though sandy and gravelly patches are observed, particularly closer to flowing channels. The floodplains are generally waterlogged during the wet season, more from spring discharges at their edges and pluvial flooding rather than from streams bursting their banks. The regolith of zone 1 is considered to have a lower hydraulic conductivity than other zones due to the presence of the clays (this was also reported by McCartney and Neal (1999) following slug testing at dambos in Zimbabwe). Riverbank sections were observed to be homogenous, therefore, an additional soil layer above the regolith is not incorporated. The basalt bedrock of zone 1 may have a higher hydraulic conductivity than other zones because an area of preferential leaching leading to the formation of the dambo must have greater fracturing or a higher content of more permeable materials, however, such fracturing may be filled with clays from the enhanced weathering once again reducing the hydraulic conductivity.
2. The second and most abundant zone comprises all areas that are neither floodplains (zone 1) nor hillslopes (zone 3). The zone is characterised by low rolling foothills with shallow slopes comprising the highest population density and greatest agricultural intensity. Expanses of zone 2 may be split by zone 1 floodplains or such floodplains may sit or “hang” within higher areas of zone 2 thus being both up and down gradient of zone 2. Numerous small sub-basins are formed within the low hills of zone 2 generally draining to a zone 1 feature. Hydraulic conductivity of the zone 2 regolith has been determined from well

pumping and recovery tests and is considered higher than in zone 1 due to a lower clay content and less settlement, which would close pores and fractures. The basalt bedrock of zone 2 may be of lower hydraulic conductivity than zone 1 because differential leaching has not occurred in these areas.

3. The third zone comprises the upland areas. This zone is characterised by higher relief and ephemeral streams, often deeply incised into thicker regolith. While agriculture may be present, more common is scrub-like vegetation. Dwellings are fewer as population density is lower. Wells are deeper and generally poor providers of water during the dry season. Zone 3 typically forms the perimeter of the catchments. Well pumping and recovery tests were not conducted in areas that fit the zone 3 definition, however, discussions with local communities suggests that regolith hydraulic conductivity is less in zone 3 as wells recover slower than elsewhere. The basalt bedrock is considered similar to that of zone 2.

Delineation of the zones was conducted by analysis of ground-truthed Google.Earth imagery and slope analysis using QGIS. The zone 1 floodplains are simple to visually identify on Google.Earth though ground-truthing was conducted during the field visits to confirm the ease of identification and delineation. A sample area of ground-truthed floodplains were digitised by hand by drawing polygons on Google.Earth then importing into QGIS. Using the "slope" tool within the terrain analysis toolbox and applying it to the DEM, the gradient thresholds were varied until the delineated zones matched the digitised floodplains. The same methodology was used to define the zone 3 hillslope areas. The gradients selected to delineate the three zones are presented in Table 7-4. The distribution of the zones is shown in Figure 7-5.

Table 7-4. The slope gradients used to delineate the three zones using ArcGIS analysis of the SRTM DEM, and, based on field measurements, the mean well depths used to determine the base of the regolith, and the regolith aquifer properties.

Zone	**Gradient**	**Mean well depth (m)**	**Mean hydraulic conductivity (m/d)**	**Mean specific yield (-)**
1	0 – 1.4^{o}	6.64	7.5	0.09
2	1.4 – 6^{o}	7.59	2.1	0.09
3	> 6^{o}	12.00	1.1	0.09

Layer thicknesses

As described above, the models were constructed with three layers: soil, regolith and basalt bedrock. Soil layer thickness was varied during modelling from 0 to 2.5 m in accordance with sections that could occasionally be observed in riverbanks and well bores. The thickness of the regolith layer was determined from well surveys. Wells are typically excavated until manual excavation is no longer possible due to the presence of strong rock, therefore, well depth is inferred to be the base of the regolith layer, which is the top of the basalt bedrock. Demis Alamirew of GSE surveyed 143 hand-dug wells during the AMGRAF catalyst period in February and March 2014 and I surveyed 64 wells during the field visits in March/April 2015 and October/November 2015. Where wells had been re-visited only the most recent measurements of depth were considered for inference of the regolith thickness. Access to the well bore below hand pumps and, with some exceptions, rope-and-washer pumps was not possible, therefore, recorded measurements were often provided word-of-mouth. Such word-of-mouth measurements have not been accepted for analysis of regolith depth because when such measurements could be tested, large discrepancies were common. Typically, this is due to the traditional local measuring unit of the cubit simply being doubled to provide the depth in metres or being translated directly into metres rather than cubits. Such measurements are also reliant on good memory as the particular well may have been excavated and sealed many years previously. Following exclusions, 80 wells could be used for estimating regolith thickness. The average well depths per zone are shown in Table 7-4; these depths are analogous to the top of the basalt bedrock.

The underlying basalt is 500-3000 m thick (Mohr, 1983). Only the upper part of this sequence was incorporated in the models; the part which is considered to interact with the shallow aquifer where fracturing and weathering are enhanced. Basalt layer thickness was varied during modelling from 0 to 10 m with zero corresponding to a completely impermeable bedrock and 10 m being the likely maximum limit of hydrogeological interaction with the regolith aquifer. As the depth of fracturing of the basalt bedrock was not observable, 10 m was selected based on discussion with local expert opinion (Demis Alamirew, GSE hydrogeologist, personal communication, 17th March 2015); ultimately this value was reduced during the modelling process.

Aquifer properties

Pumping tests were undertaken during the first and second field visits as described in Chapter 3 and in Walker (2016). Hydraulic conductivity estimates averaged 2.29 m/d in the dry season and 9.65 m/d in the wet season when the water-table was higher. This difference indicates vertical heterogeneity of the regolith with more transmissive layers occurring at shallower depth that are only intercepted when the water column is higher. Specific yield estimations have a wider range and are more uncertain with an average of 0.09.

The tested wells were categorised into the three hydrogeological zones, according to slope gradient, land use and observable geology, then the mean hydraulic conductivity, considering both dry and wet season tests, was determined. The specified hydraulic conductivity and storage values for each zone are presented in Table 7-4. It is noted that most of the wells lie in zone 1 from a point of view of slope gradient though they are situated immediately on the edge of floodplains rather than within them. The calculated hydraulic conductivity for these zone 1 wells is higher than for zone 2 and 3 wells even though the floodplain regolith is considered to be clay-rich and of lower permeability. It has been reported that the floodplain or dambo edges are typically sandy and quite permeable (McFarlane, 1989) which may explain these high values from the pumping tests. The hydraulic conductivity values are not considered representative of zone 1 as a whole and were reduced for the modelling. The same specific yield value was used for regolith in all zones due to the greater uncertainty in its estimation.

7.2.5 Land use land cover (LULC)

LULC was divided into three zones matching the hydrogeological zones described previously. Zone 1 is characterised as grassland as the floodplains are almost always and entirely utilised as pasture. Zone 2 is categorised as arable because the majority comprises land devoted to rainfed agriculture. The crops planted are 87% cereals (39% maize, 35% *teff* and 13% millet), with the rest being pulses, oilseeds, sugarcane, potatoes, vegetables, fruits, onions, garlic, and tomatoes (Belay and Bewket, 2013), the latter few generally occupying backyard plots. In addition to these crops within zone 2, the vegetation actually ranges from grassland to Eucalyptus plantations with some areas of bare ground near areas of habitation. Zone 3 with its higher gradients is categorised as shrub due to the characteristic scrub-like vegetation, though in reality the hillslopes also contain lesser amounts of crops, grassland and forest, with dense native forest occurring around churches. How SHETRAN converts the potential evapotranspiration time series into actual evapotranspiration is specific for each of these zones. Each zone within SHETRAN differs in rooting depth and root density at different depths, ground coverage at maximum seasonal extent, canopy storage capacity, leaf area index, and AET/PET at particular soil moisture tensions. These parameter values were estimated from ground observations in order to generalise vegetation and crop types followed by consultation of the key instructional texts for calculating water demand; FAO24 (Doorenbos and Pruitt, 1975) and FAO56 (Allen *et al.*, 1998), and other published studies providing detail of particular vegetation types, particularly, Canadell *et al.* (1996); Dardanelli *et al.* (1997); Cain (1998) and; Fan *et al.* (2016).

7.3 Model calibration

7.3.1 Introduction

Theoretically, all parameters could have been measured in the field, though in reality, this is rarely possible due to cost, time and experimental constraints, as well as problems of scaling (Beven *et al.*, 1980). Therefore, some calibration of parameters is required to provide confidence that the catchment model is representing reality. Calibration of physically-based models can be complex and expensive/time-consuming due to sophisticated model structures, computation requirements and the large number of parameters (Blasone *et al.*, 2007; Zhang *et al.*, 2013). Manual calibration requires rigorous and purposeful adjustment of parameter values, is extremely time-consuming, tedious and can be subjective (Refsgaard, 1997). However, this time is well spent as, in addition to achieving satisfactory calibration statistics, hydrogeological understanding is greatly increased and the conceptual model can be updated and validated.

7.3.2 Calibration data

Datasets from two sources were used to quantitatively calibrate the models:

1. The Dangesheta community-based monitoring programme
    a. Groundwater levels from five wells
    b. River stage for the Brante and Kilti rivers, converted to river flow
2. Formal data from the Ministry of Water, Irrigation and Electricity (MoWIE)
    a. River flow records for the Kilti and Amen rivers

The community-based monitoring data was discussed in Chapter 5 and Walker *et al.* (2016). The time series used span 10th March 2014 to 8th January 2017. River flow records are available from MoWIE for the Kilti and Amen rivers from 17th April 1997 to

4th October 2014 and 26th April 1988 (though are continuous only from 1998) to 27th September 2014 respectively.

In addition to the quantitative calibration of modelled to observed groundwater level time series, a qualitative groundwater calibration took place in other areas of the catchments. The groundwater data used were occasional groundwater level measurements taken around the catchments on multiple field visits, and anecdotal or observational evidence of areas prone to flooding in the wet season or of dry wells in the dry season.

An issue with calibrating modelled against observed discharge is that the Brante and Amen rivers were observed to have ephemeral reaches. During dry season field visits when there was flow at the gauge sites, reaches both upstream and downstream of the gauges were observed to be dry. Generally, the rivers appeared to be losing through the flat floodplains where the rivers were dry and gaining through the narrow basalt riverbed flowing reaches. Incidentally, radon-222 measurements during the wet season field visit suggested that this pattern is reversed in the wet season with groundwater discharge in the floodplains (see Chapter 4).

Concerning calibrating modelled to observed groundwater levels, the individual well responses are often controlled by features unique to those wells. For example, rapid rises in water level of monitoring well MW5 are due to overland flow directly entering the well via termite and rat holes (such information was proffered during community workshops) and MW3 has no lid meaning direct precipitation will influence the groundwater hydrograph. Some features that are hydrogeologically significant, such as MW4 maintaining its groundwater level longer into the dry season due to its position directly at the foot of a slope and recharge area, are not represented at the resolution of the models; even at the 100 m resolution of the finest models. Given that the monitoring wells often dry out in the dry season, it is known that the water table is below the well base at their locations but the precise water table depth is uncertain. In addition, the wells are subject to abstraction for domestic and agricultural use (water for livestock and backyard irrigation). Abstracted volumes may be low in total and have minimal effect on the overall well response but the timing of abstraction could be immediately prior to measuring, i.e. first thing in the morning, therefore some measurements may not be showing natural aquifer response to recharge and discharge. What's more, the monitoring wells are clustered in a small area of around 0.5 km^2, though their positions were selected to be representative of the wider area.

7.3.3 Calibration methodology

The five community monitored wells are within the Brante catchment that is within the larger Kilti catchment. However, only the Brante model is of sufficiently fine resolution that all the wells lie in different cells. Therefore, the Brante model was chiefly calibrated against groundwater level data, as well as against the community river flow data. At the same time, the Amen and Kilti models were calibrated against their longer period river flow records. A set of optimum parameters was selected iteratively that satisfied the groundwater level calibration of the Brante and the river flow calibration of the Amen and Kilti rivers. This was while also considering the river flow of the Brante and smaller Kilti model and the qualitative groundwater level observations. The search for matching optimum parameters to suit all four modelled catchments is justified due to the nested and overlapping nature of the catchments in addition to the observed similarities in soils, geology and LULC.

The calibration parameters are those identified from literature to be sensitive in SHETRAN modelling (e.g. Bathurst *et al.* (2004); Bathurst *et al.* (2011a); Starkey *et al.* (2017)) in addition to parameters considered uncertain for this study site:

- The Strickler coefficient is the inverse of the Manning roughness coefficient and controls the speed of runoff. It is essentially a friction factor representing raindrop impact, flow channelization, obstacles such as rocks and vegetation, surface frictional drag, and erosion and transport of sediment (Engman, 1986). The Strickler coefficient value was initially selected based on literature review of modelling studies in similar environments. The adjusted range was from 0.5 to 10.0 $m^{-1/3}/s$.
- The AE/PE ratio controls the amount of evaporative loss. The values were adjusted with consideration of the SHETRAN mass balance output in order to achieve satisfactory long-term discharge totals. The ratios reduce with depth and were adjusted between 0.1 and 1.0.
- Hydraulic conductivity, specific yield and specific storage values were adjusted within the range estimated from the pumping tests and based on hydrogeological experience and textbook values in the case of soils and basalt (e.g. Fredlund *et al.* (1993); Fetter (2001)). The adjusted ranges for hydraulic conductivity were: soil 10-100 m/d, regolith 0.2-22.3 m/d, and basalt 1×10^{-5} to 1×10^{-2} m/d. for specific yield the adjusted ranges were: soil 0.05-0.4 and regolith 0.03-0.32. Specific storage of basalt was adjusted between 1×10^{-3} to 1×10^{-6} m^{-1}.

- Soil and geological layer thicknesses were adjusted within the range observed in the field: soil 0-3 m, regolith 3-15 m and basalt 0-10 m.

Calibration and validation periods were selected to give "typical" ranges of hydrological conditions and ran from the end of a wet season recession to the same point one, two or three years later. In addition to visual comparison of plotted observed and simulated data, the following performance indicators were utilised: Nash-Sutcliffe Efficiency (NSE) coefficient (Nash and Sutcliffe, 1970), where a value greater than 0.5 is considered acceptable (Moriasi *et al.*, 2007), and root mean square error (RMSE), with units matching the compared data thus the value should be as low as possible. NSE is very sensitive to peak flows (Krause *et al.*, 2005), therefore, given the flashy nature of the rivers with short-lived and relatively extremely high peaks, NSE (and RMSE) were calculated on baseflow following hydrograph separation. For the Brante model, NSE and RMSE were calculated on groundwater levels in the five monitoring wells, excluding the periods when the wells were dry as during this time the piezometric surface was at an unknown level below the well base. A validation period was run to confirm that the calibrated parameters still produced a satisfactory simulation for independent input datasets. However, it is inappropriate to calibrate the models purely against absolute values of the observed river flow and groundwater level time series using standard statistical techniques such as NSE and RMSE because high skill will not necessarily mean the model is representative of the natural system and vice versa. The purpose of the modelling is to assess availability of groundwater for productive use outside of the wet season, therefore, a realistic representation of groundwater seasonal response is deemed the most important process to simulate, rather than precise and entire groundwater level time series at five specific points. Simulated river flow was also assessed by comparing cumulative monthly flow totals using the full model run rather than calibration and validation periods). Monthly rather than daily flow totals are used for calibration in order to negate the aforementioned effects of temporarily dry reaches and flashy peaks. Achieving good daily matches between observed and simulated flows was not particularly important in this study; rather, understanding of the long-term water balance was critical. Comparing simulated to observed river flow purely using NSE proved an unsatisfactory calibration methodology as a good NSE could be achieved even when annual flow totals or cumulative monthly flow totals were mismatched.

7.3.4 Calibration results

The groundwater level calibration of the Brante model gave acceptable NSE values, however, RMSE was quite large (Table 7-5). This is suspected to be due to the varying well depths indicating heterogeneous aquifer thickness while the cells in which the wells lie have uniform aquifer thickness. Consequently, the model was simulating greater groundwater fluctuation where the aquifer is specified thicker than the wells indicate is the reality and vice versa (Figure 7-7). Correct simulation of the groundwater behaviour was the main calibration criterion for the model. Sample groundwater hydrographs are shown in Figure 7-7 that are representative of the three zones: Zone 1 floodplains areas known to have shallow water tables, flood during the wet season though often dry out in the dry season, Zone 2 cultivated and inhabited interfluve areas with groundwater response somewhere between Zones 1 and 3, and Zone 3 hilly areas observed to have deep water tables and known anecdotally to suffer water scarcity in the dry season. These observed and anecdotal responses can be seen in the simulated groundwater hydrographs, therefore, calibration was deemed satisfactory. The difference in the observed and simulated hydrograph for monitoring well MW3 in Figure 7-7 is due to the model output being the groundwater fluctuation of a 100 m x 100 m cell whereas the observed hydrograph is at a point with unique soil and geology parameters, particularly regarding layer thicknesses and elevations. What's more, the particular well is located just beyond the edge of a floodplain whereas the simulated output represents the floodplain itself. It is common at the study site for backyard agriculture plots of <0.1 ha to have multiple wells all with different depths and water levels, therefore, it was unsurprising that a better match could not be achieved between the simulated and observed groundwater hydrographs. The further semi-quantitative groundwater level calibration was also considered satisfactory for the Amen, Kilti and Kilti-sub models as SHETRAN correctly simulated Zone 1 floodplain areas (shallow water tables and wet season floods), and zone 3 hilly areas (deep water tables and dry season water scarcity).

Table 7-5. Details and statistics of the calibration and validation periods.

Catchment	Calibration period	No. of days	NSE	RMSE
Brante*	Mar 2014 to Mar 2015 (year 1)	365	0.69	2.01 m
Amen	Apr 1999 to Apr 2001 (years 2-3)	731	0.79	0.19 m^3/s
Kilti	Apr 1998 to Apr 2000 (years 2-3)	731	0.78	1.47 m^3/s
Kilti-sub	Mar 2015 to Mar 2016 (year 2)	365	0.64	0.27 m^3/s

Catchment	Validation period	No. of days	NSE	RMSE
Brante*	Mar 2015 to Mar 2016 (year 2)	365	0.53	2.08 m
Amen	Mar 2010 to Mar 2013 (years 13-15)	1096	0.75	0.13 m^3/s
Kilti	Apr 2004 to Apr 2007 (years 8-10)	1096	0.67	2.30 m^3/s
Kilti-sub	Jan 2016 to Jan 2017 (year 3)	365	0.08	1.17 m^3/s

* Calibration is against groundwater levels rather than river flow.

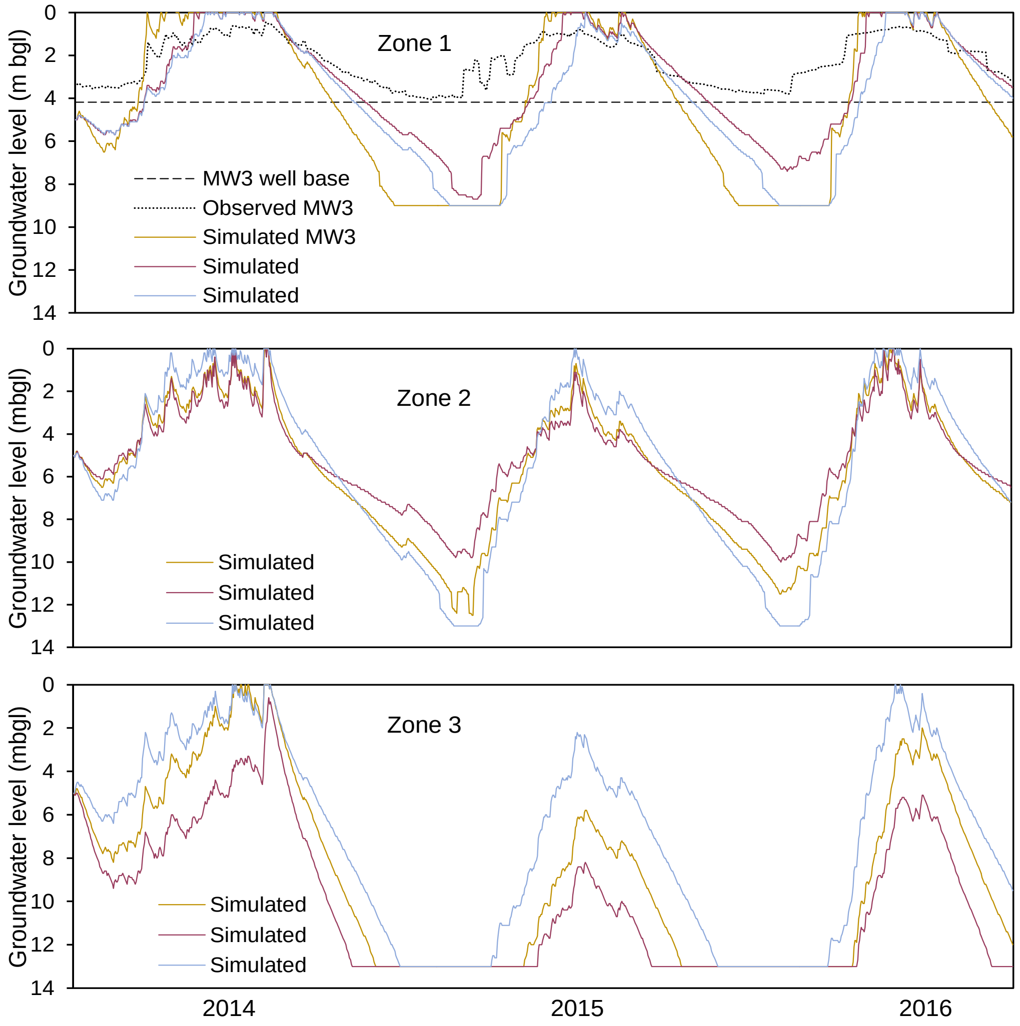


Figure 7-7. Simulated groundwater hydrographs from the Brante model showing three typical and representative hydrographs for each zone. Top: Representing Zone 1 floodplains and showing observed groundwater hydrograph for monitoring well MW3. Middle: Representing Zone 2 inhabited and cultivated foothills. Bottom: Representing Zone 3 hilly areas. It is restated that the monitoring wells all lie within Zone 1 cells, therefore, observed hydrographs cannot be included in the Zones 2 and 3 plots.

The observed and simulated river flow hydrographs match well for the Amen and Kilti-Durbete models (Figure 7-8) and both have good NSE and RMSE values for the calibration and validation periods (Table 7-5). More importantly, the simulated cumulative flow totals match well with observed (Figure 7-9). Using the optimum calibrated parameter values in the Kilti-Dangesheta model gave good calibration statistics for the calibration period but not for the validation period. However, the cumulative flow totals comparison is good, as it is for the Brante. Therefore, the calibration was considered satisfactory and confidence was given in the uniqueness of the optimum parameter values as a satisfactory calibration was achieved for all the nested catchments utilising the same values.

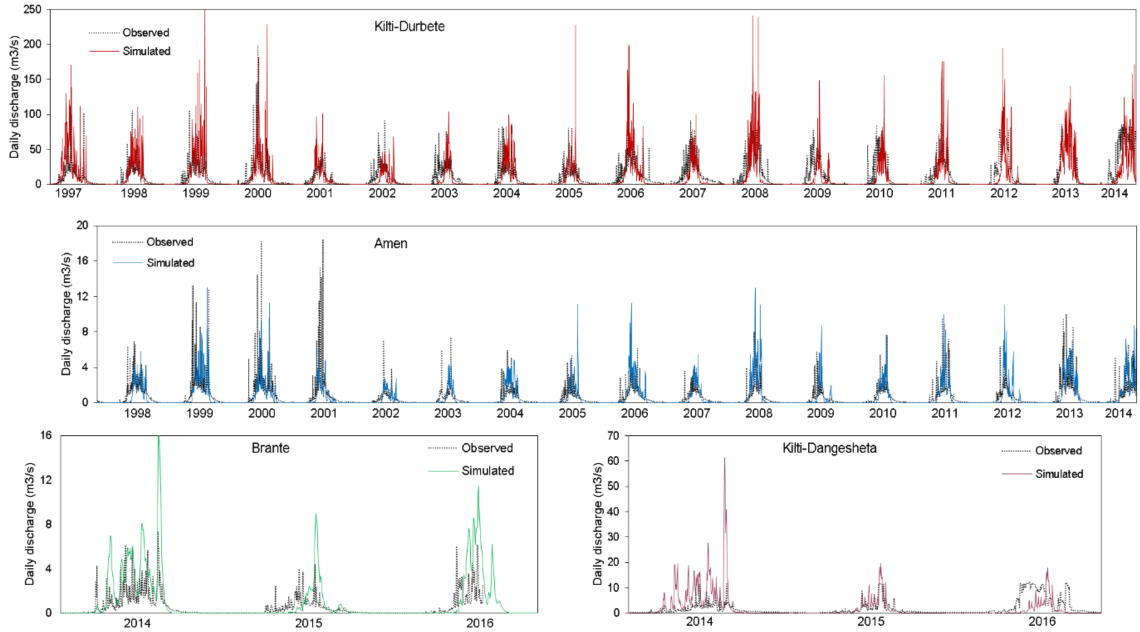


Figure 7-8. Simulated and observed river flow hydrographs.

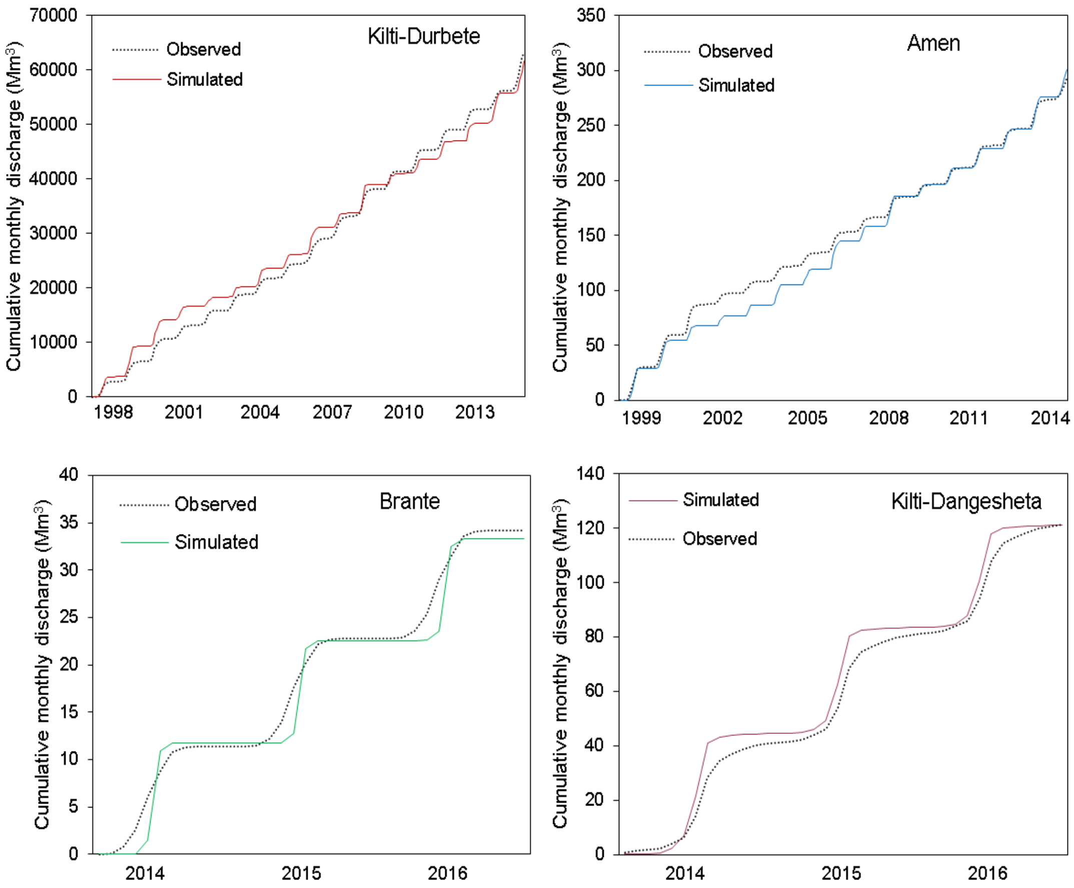


Figure 7-9. Simulated and observed cumulative monthly flow totals.

7.3.5 Optimum parameter values

The optimum parameter values are considered those that gave satisfactory calibration of both groundwater levels in the short duration (3-year) Brante model and river flows in the longer duration (17 and 18-year) Amen and Kilti-Durbete models. Further validation occurred when satisfactory calibration statistics and simulated vs observed plots were achieved from running the set of optimum parameter values in the Kilti-Dangesheta model. Calibration occurred for all models concurrently; therefore, while slight adjustments to parameter values could give slightly better individual calibrations, the differences were minor. The optimum parameter values are presented in Table 7-6. The aquifer properties remain similar to the observed and measured values, and to literature values in the case of basalt (e.g. Fetter (2001)). Strickler coefficients are at the low end of literature values (e.g. Engman (1986)) reflecting the hummocky tussocky floodplains, the rough surfaces produced by ox ploughing in small plots that are not conducive to forming rills, and the often dense underbrush of the shrub (Figure 7-8). The relatively high AE/PE for the arable zone reflects the high proportion of tall crops such as maize and sugar cane that have high water demand, i.e. PET would be greater than the grass reference value calculated using the Penman-Monteith FAO56 method (Doorenbos and Pruitt, 1975; Allen *et al.*, 1998).

Figure 7-10. Photographs of hummocky tussocky floodplain (left) and rough surface left by ox ploughing.

Table 7-6. Optimum calibrated parameter values for the SHETRAN models.

Zone	Layer / vegetation	Parameter	Optimum value
1 Floodplains	Regolith	Hydraulic conductivity	0.5 m/d
		Specific yield	0.08
		Depth	6.6 mbgl
	Basalt	Hydraulic conductivity	0.0003 m/d
		Specific storage	0.001 m^{-1}
		Depth	8.6 mbgl
	Grassland	Strickler coefficient	1.0 $m^{-1/3}/s$
		AE/PE	1.0 (at soil moisture tension of -0.1 m) 0.85 (-1.0 m) 0.65 (-10.0 m) 0.45 (-20 m) 0.25 (-50 m)
2 Cultivated and populated areas	Soil	Hydraulic conductivity	20 m/d
		Specific yield	0.1
		Depth	0.5 mbgl
	Regolith	Hydraulic conductivity	0.25 m/d
		Specific yield	0.08
		Depth	11.0 mbgl
	Basalt	Hydraulic conductivity	0.0003 m/d
		Specific storage	0.001 m^{-1}
		Depth	13.0 mbgl
	Arable	Strickler coefficient	1.5 $m^{-1/3}/s$
		AE/PE	1.0 (at soil moisture tension of -0.1 m) 0.9 (-1.0 m) 0.8 (-10.0 m) 0.6 (-20 m) 0.4 (-50 m)

3 Upland areas	Soil	Hydraulic conductivity	20 m/d
		Specific yield	0.1
		Depth	0.25 mbgl
	Regolith	Hydraulic conductivity	0.5 m/d
		Specific yield	0.08
		Depth	12 mbgl
	Basalt	Hydraulic conductivity	0.0001 m/d
		Specific storage	0.00001 m^{-1}
		Depth	12.5 mbgl
	Shrub	Strickler coefficient	1.0 $m^{-1/3}$/s
		AE/PE	1.0 (at soil moisture tension of -0.1 m) 1.0 (-1.0 m) 0.8 (-10.0 m) 0.6 (-20 m) 0.4 (-50 m)

7.4 Improved hydrogeological understanding from the calibration

7.4.1 Sensitivity to certain parameters

Adjustment of geological layering and of parameter values during calibration not only informed and confirmed the conceptual model but also was essentially a sensitivity analysis. The parameter to which the models were most sensitive was layer thickness with a few metres adjustment to soil, regolith or basalt depth leading to large changes in groundwater and river flow hydrographs. Therefore, the likely heterogeneous thickness of the soil and regolith layers, as indicated by variations in well depth, has significant impacts on local groundwater flow and river level. It would be extremely difficult to simulate these very local impacts accurately; it would require very high resolution modelling following widespread geophysical investigations to three-dimensionally map the layers.

7.4.2 Absence of a clay-rich low hydraulic conductivity layer

The key regolith literature (Jones (1985) or Acworth (1987)) place a clay-rich low-K layer within the regolith profile below the soil (zones ‘a’ and ‘b’ of Figure 3-9). This layer was simulated in the model runs, placed between the soil and regolith at thicknesses of 0.5-1.0 m with hydraulic conductivity of 0.001 to 0.01 m/d. However, the model repeatedly crashed due to excessive river discharges and drying out of aquifer cells, i.e. rainfall could not sufficiently infiltrate. This suggests that such a low-K layer is absent at this depth, or at least there are preferential flow pathways to the aquifer. Observed storm peaks in discharge are not at such high levels that suggest infiltration does not occur during intense rainfall events. The regolith has a high clay content throughout and the absence of a layer of particularly high clay and consequent very low hydraulic conductivity may be due to the relatively young age of the bedrock (Benvenuti *et al.*, 2002).

7.4.3 Absence of fractured bedrock high hydraulic conductivity layer

The key regolith literature also describe a fractured bedrock high-K layer at the base of the regolith profile (zone 'd' of Figure 3-9). Inclusion or exclusion of fractured basalt as a thin (<1 m) high hydraulic conductivity (20-75 m/d) layer between the regolith and basalt does not have a significant impact on the model results. When the fractured layer was ascribed a hydraulic conductivity >40 m/d, the model would only run when the basal basalt hydraulic conductivity was significantly reduced, and it was this adjustment to the basal basalt that had a greater impact on the simulation. The relatively young age of the basalt bedrock may mean that significant fracturing has not had time to occur.

7.4.4 Hydrogeological importance of the basal basalt bedrock

The greatest impact on simulated river flows and groundwater levels resulted from adjustment of basal basalt hydraulic conductivity. Decreasing the hydraulic conductivity increases the wet season baseflow significantly while decreasing the specific storage and porosity decreases recession length. Prior to the modelling, it was suspected that the basalt bedrock was impermeable, therefore, no basalt was simulated in the model and the base of the regolith formed the base of the model. However, the simulations gave unsatisfactory river flow and groundwater levels. To achieve a better simulation, some permeability had to be applied to a basalt basal layer. The thickness of this layer has less of an influence than the hydraulic conductivity. When the layer was simulated to be thick (>10 m) the model would not run, even when transmissivity was equal to a thinner layer, suggesting that underlying the regolith of the catchments is a thin, slightly weathered and fissured, basalt layer above impermeable basalt bedrock.

7.4.5 Absence of leakage to a deeper aquifer

The conceptual model was of a shallow thin perched aquifer with possible leakage to a deeper aquifer. That deeper aquifer is likely to comprise fractured and scoriaceous zones within the deeper basalts and trachytes (Kebede, 2013). Leakage to a deeper aquifer was simulated by allowing gravity drainage through the base of the model. This was initially applied only below the zone 1 floodplains because the dambo literature suggests more fractured bedrock may be present there (McFarlane, 1989). Allowing gravity drainage had little effect on the simulations until the zone 1 basalt hydraulic conductivity was increased to allow greater groundwater flow out of the model. It was clear from the hydrographs that the adjustment of the basalt hydraulic conductivity had a greater effect on the simulation than leakage as groundwater flowed laterally into streams more rapidly. Therefore, the modelling suggests that leakage to a deeper aquifer is not significant at these scales; a conclusion supported by field evidence described in Chapter 4.

7.4.6 Evapotranspiration from groundwater

The heavy wet season rains lead to very shallow water tables across much of the study site for 4-6 months of the year. This was most apparent at the seasonally inundated floodplains that were generally still too wet to cross on foot during the second field visit in October 2015 a month or so after significant rains had ceased. Springs and seepages remain active for much of the year and the shallow water tables support phreatophytes. Consequently, it was suspected that the evapotranspiration loss from the saturated zone would be significant. This was confirmed by SHETRAN modelling during the recharge assessment method comparison presented in the previous Chapter.

7.5 Mapping the potential of shallow groundwater for irrigation use

7.5.1 Methodology

Once the models were considered to be simulating natural conditions well, analysis could be conducted on the model outputs. Because SHETRAN is fully spatially distributed, variations in groundwater level across the catchments could reveal areas that have the best potential for exploitation of the shallow groundwater resource for irrigation (Figure 7-11). Such areas could be identified by slow groundwater recessions at the end of the wet season and an abstractable saturated thickness of aquifer throughout the dry season.

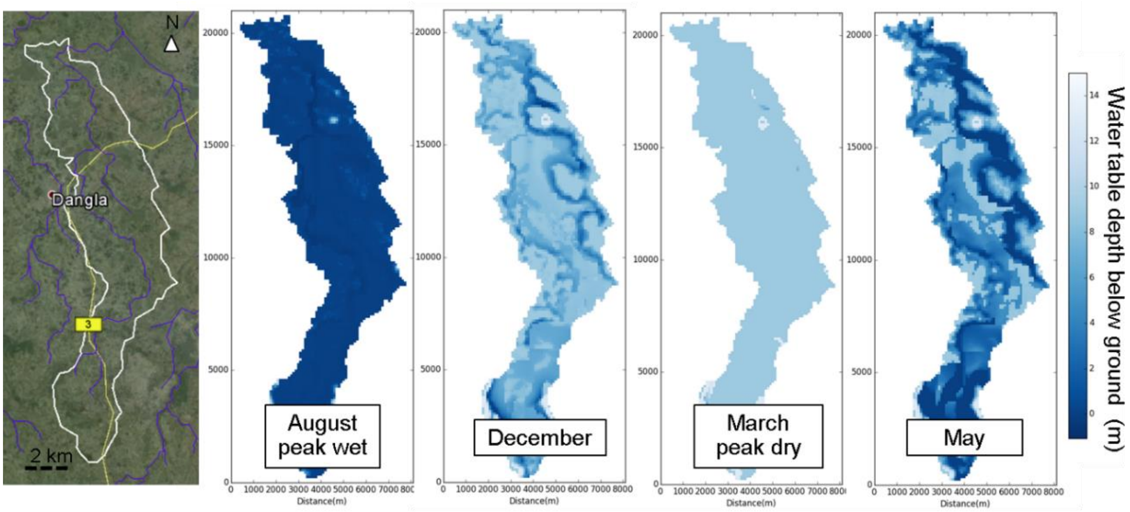


Figure 7-11. Maps showing The Brante catchment and SHETRAN model outputs of water table depth at the peak of the wet and dry seasons and the transition between the two seasons.

Post-processing was conducted using a Python script that analysed the groundwater level in every cell during every day of a simulation. The script counted the number of days per hydrological year that groundwater was available for abstraction in each cell. This was defined as a groundwater level >0.5 m above the base of the regolith, i.e. the groundwater level was not in the basal basalt layer below the base of wells and a sufficient water column was present to allow pumping by mechanical or motorised means. The annual counts of groundwater availability were averaged for the full model runs and groundwater potential zones were assigned as follows:

High: <10 days per year when groundwater is unavailable – Irrigation is possible year-round.

Medium: 10-100 days per year of groundwater unavailability – Irrigation is possible for a second growing season in addition to the main rainfed growing season.

Low: 100-200 days per year when groundwater is unavailable – Irrigation is unlikely to be possible outside of the wet season.

Very low: >200 days per year when groundwater is unavailable – Irrigation outside of wet season impossible.

It may seem that the criteria are strict as very low potential areas may still have available groundwater for 165 days of the year. However, this period of groundwater availability would obviously coincide with the wet season when no irrigation is required due to the rains.

7.5.2 Groundwater potential maps

The maps of potential for groundwater abstraction are presented in Figure 7-10. The patterns of zoning make most sense when the maps are overlain on Google.Earth and the viewing angle, or tilt, and transparency are adjusted to enable simultaneous viewing of topography and land use.

Figure 7-13, Figure 7-14 and Figure 7-15 show examples of the commonly observed relationships between the groundwater potential zoning, topography and land use. The high potential areas are found at the foot of hillslopes and in narrow valleys. Medium potential zones typically surround areas of high potential or are themselves surrounded by areas of low potential. Low-lying land and floodplains are typically areas of low potential and small hills in their midst are often medium potential. Very low potential zones are mountainous areas and ridges, typically around the catchment boundaries. Commonly, the low potential areas clearly appear lighter in colour and drier on Google.Earth while medium and higher potential areas appear darker. These observations were ground-truthed during the January 2017 field visit. At that time of year, only Eucalyptus is cultivated and plantations were noticeably less water-stressed in the areas of high potential than those in low potential zones (Figure 7-16).

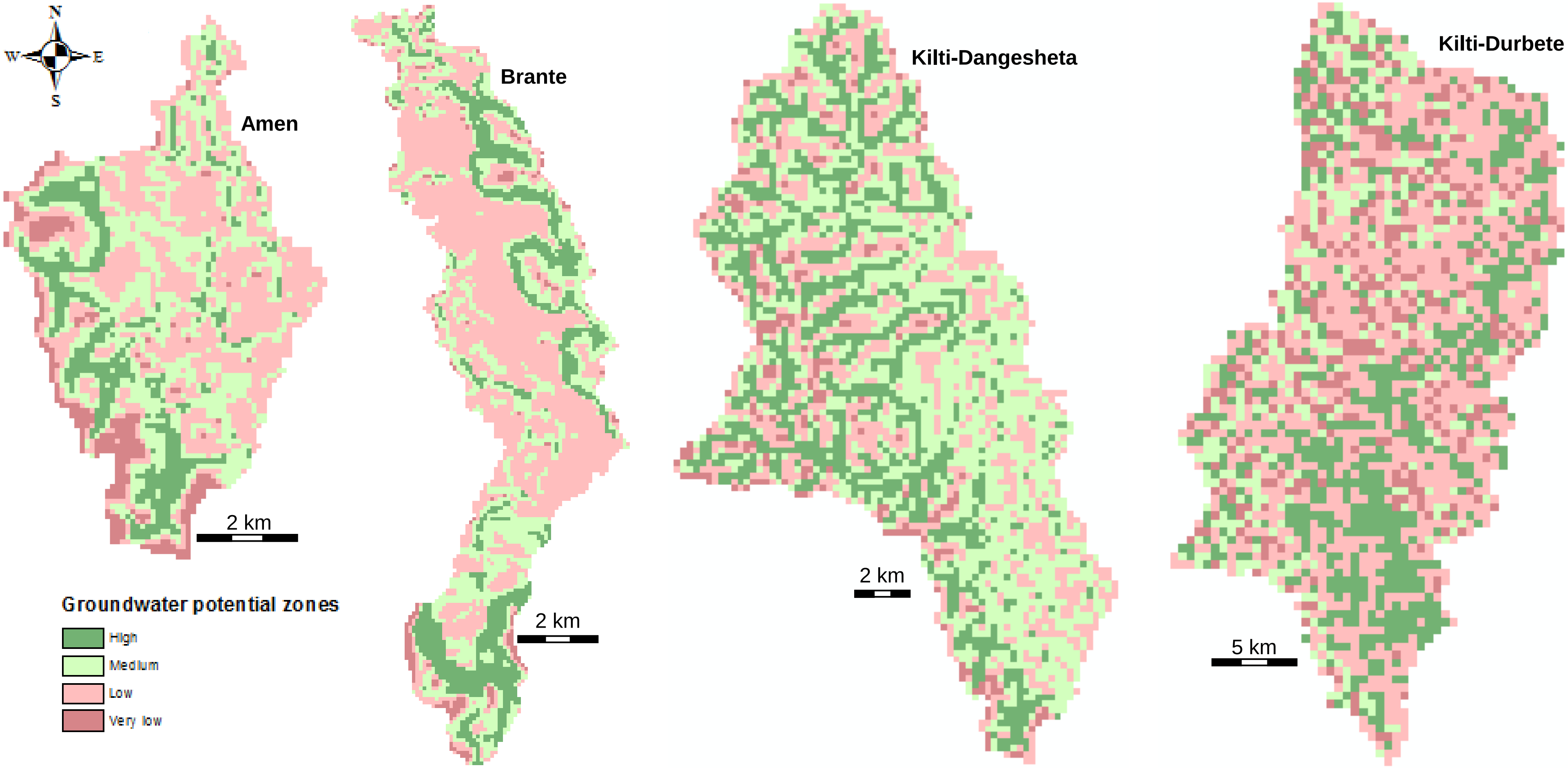


Figure 7-12. Maps showing potential of shallow groundwater for irrigation use.

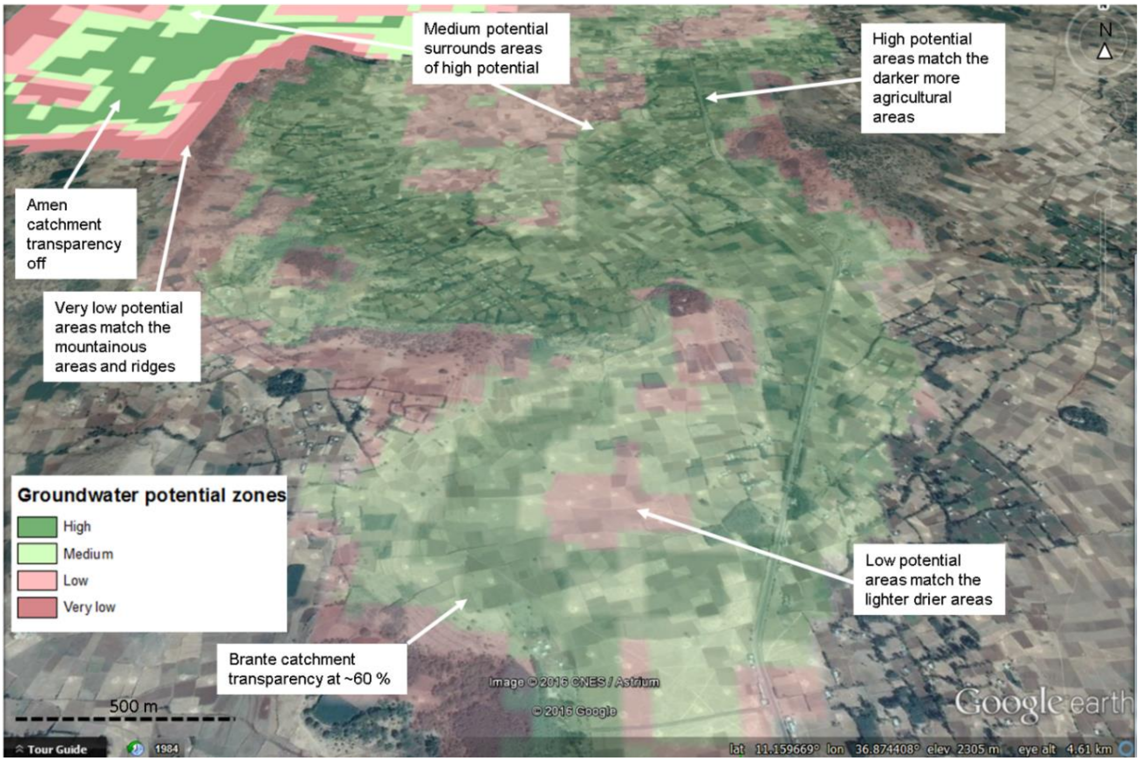


Figure 7-13. Southern extremes of the Brante and Amen groundwater potential maps overlain on Google.Earth.

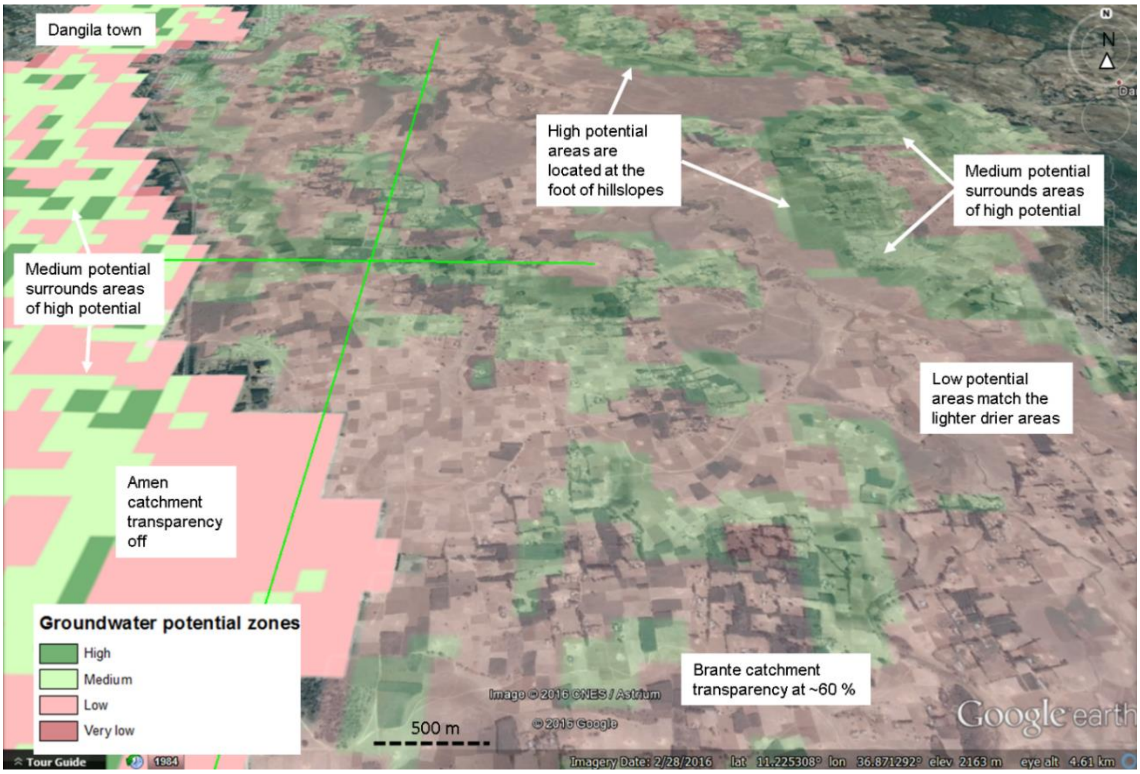


Figure 7-14. Central portion of the Brante and Amen groundwater potential maps overlain on Google.Earth.

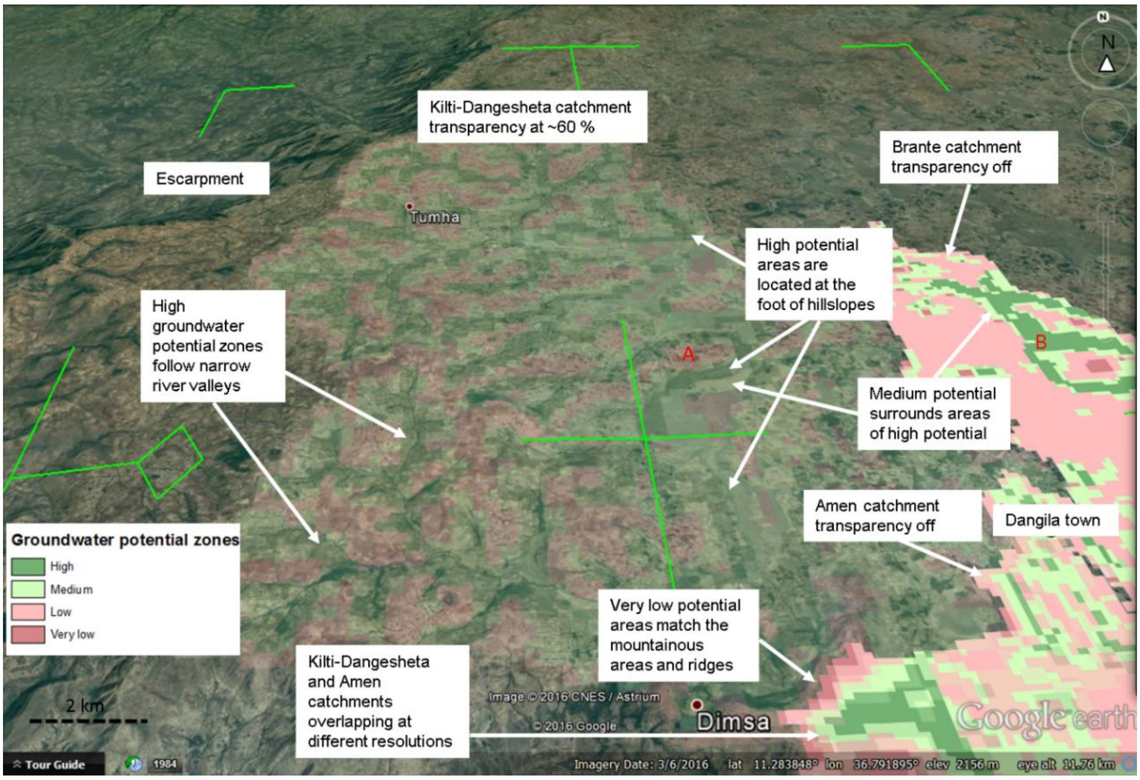


Figure 7-15. Northern portions of the Kilti-Dangesheta, Amen and Brante groundwater potential maps overlain on Google.Earth. A and B are the locations of the photographs in Figure 7-16.

Figure 7-16. Photographs taken during the dry season (January 2017) showing water-stressed Eucalyptus in a low potential zone (left) and healthier Eucalyptus in a high potential zone at the foot of a slope. See Figure 7-15 for the photograph locations.

Production of the groundwater potential maps revealed that the 500 m resolution of the Kilti-Durbete model was too coarse to correctly locate the different potential zones. There was agreement in potential zone correspondence to topography and land use for the other three models and general agreement in the overlapping portions of the Kilti-Dangesheta and Amen models. However, the Kilti-Durbete model could not identify the high potential zone narrow valleys and thin strips at the foot of slopes, nor the very low potential ridges around catchment boundaries. Figure 7-17 compares the potential maps produced from the different catchment models illustrating that the Kilti-Durbete model gives contrasting results of high potential in low-lying and floodplain areas. Slight variations in topography that have been revealed the controlling factor on groundwater availability cannot be picked up at coarse resolution. Therefore, no confidence could be given to the Kilti-Durbete potential map for advising on most suitable well locations for productive use. The 200 m resolution Kilti-Dangesheta potential map appears to perform well, though the 100 m resolution Amen and Brante maps are preferable for making intervention recommendations given the small-scale agriculture of typically <1 ha plot size that dominates the area. These maps are of use should a government ministry, private investor, NGO, or other organisation wish to implement irrigation in the area; resources could be focussed in the zones with highest potential. The groundwater potential maps were provided to relevant stakeholders during the January 2017 field visit; including the Dangesheta *kebele* office, the Dangila *woreda* office, the Abay River Basin Authority (ARBA) in Bahir Dar and the Ministry of Agriculture and Natural Resources (MoANR) in Addis Ababa. The response was positive and a follow up research project is underway with these partners with workshops planned for May 2018 where the maps will be further presented and described.

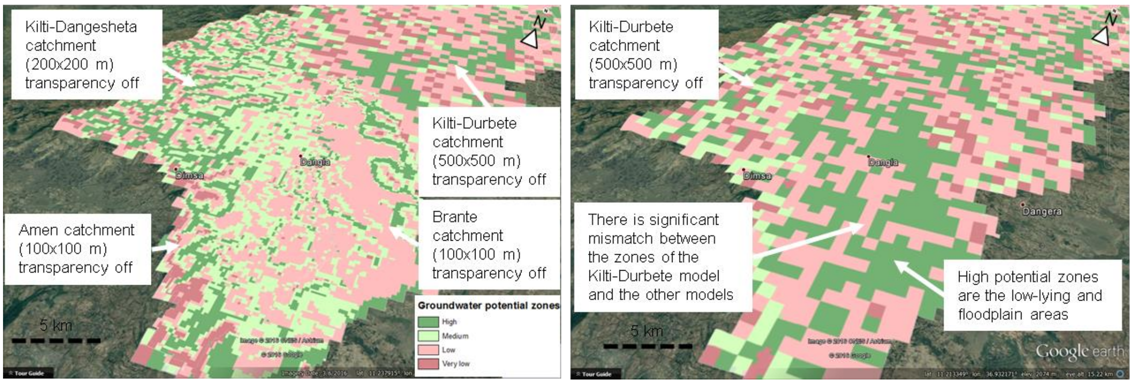


Figure 7-17. All four catchments' groundwater potential maps overlain on Google.Earth (left) and the same view but showing only the Kilti-Durbete potential map.

7.6 Discussion and conclusions

SHETRAN was chosen to model the shallow aquifer due to its comprehensive nature, ability to model coupled surface and subsurface, saturated and unsaturated components, and because the spatially distributed outputs would aid in understanding the behaviour of the hydrogeological system in all parts of the catchments.

Four catchments were modelled at different resolutions, from 100 m to 500 m, and their nested nature meant one set of parameter values should satisfy calibration for all the models. Calibration was chiefly against groundwater levels for the Brante model and river flows for the Kilti-Durbete, Amen and Kilti-Dangesheta models, though with qualitative calibration of groundwater levels for all models.

The initial aim of the modelling, to increase hydrogeological understanding of the shallow groundwater system, was certainly achieved. Referring back to the specific research questions posed in Section 7.1.2: Are the models satisfactorily reflecting reality in terms of river flows and groundwater levels?

Calibration was satisfactory in terms of the long-term behaviour and water balance. However, short-term (daily) response was not necessarily picked up and groundwater level calibration was problematic due to the point locations of the observational time series vs cell-wide simulated outputs that could not incorporate monitoring well specificities such as: very local elevation and topography, geological heterogeneities (soil and regolith layer thicknesses, hydraulic conductivities and specific yields), and direct water ingress via precipitation and overland flow. This is a generic problem in spatial models representing point measurements. The models did produce the general range of observed responses and were considered valid for the scenarios analysis presented in Chapter 8.

Again from 7.1.2: Are the parameter values appropriate considering field investigations and published literature?

The calibration procedure and sensitivity testing adjusted parameters within either measured ranges or, where impossible to measure, within published ranges. The optimum values were similar to those measured and were deemed appropriate. Model outputs are sensitive to geological layer thicknesses. The few exposures available in well bores and riverbanks, and the depths to bedrock inferred from well depth measurements, suggest layer thicknesses are heterogeneous even within short distances. Therefore, the layer thicknesses are ascribed in the models with uncertainty, which further explains the problematic groundwater level calibration given the sensitivity to this parameter.

From 7.1.2: What effect does incorporating various hydrogeological features presented in key regolith and dambo literature, but not necessarily identified in the field, have on the simulations?

The calibration and sensitivity testing process allowed update and confirmation of the conceptual model, revealing a lack of a clay-rich low permeability layer beneath the floodplains and lack of a high permeability fractured layer at the top of the basalt. However, there is evidence supporting a permeable horizon, although not with very high permeability that may be associated with fractured basalts; seepage through this layer to a deeper aquifer is minimal. Likelihood of the presence of such features was determined by their improvement or worsening impact on, in terms of comparisons between simulated and observed, groundwater levels and river flows. The use of SHETRAN to provide recharge estimates as described in Chapter 6 confirmed that evapotranspiration from the unsaturated zone is significant.

From 7.1.2: Is groundwater availability recharge controlled or storage controlled?

Assessment of the spatiotemporal variability of recharge and storage indicated that shallow groundwater availability is storage rather than recharge controlled. This was unsurprising given the high recharge estimates presented in Chapter 6 and the thinness of the aquifer as described in Chapter 4.

The final objective, to identify areas that show the greatest potential for the onset of irrigation using shallow groundwater, was achieved with production of the groundwater potential maps. Maps of the potential to utilise shallow groundwater for irrigation were produced by processing the SHETRAN water table depth outputs using Python, which were then overlain on Google.Earth. Areas described as being of high potential were where groundwater was on average available year-round, allowing just 10 days of unavailability. Such zones were typically found at the bases of hillslopes and in narrow valleys, corresponding to around 17% of the study site. Medium potential zones had 10-100 days of unavailability and were found surrounding areas of high potential or formed "islands" of higher relief areas within low-lying floodplains (corresponding to approximately 31% of the study site). Low potential areas (100-200 days of groundwater unavailability) comprised much of the low-lying land including the floodplains (~46% of the study site) while very low potential zones (>200 days of unavailability) were located in mountainous areas and ridges (~6% of the study site). These maps could be utilised for intervention planning and were provided during the third field visit in January 2017 to local, regional and national stakeholders, who showed interest and requested follow up discussions and possible workshops (planned for May 2018 as part of a subsequent research project).

While a complete SHETRAN modelling study would not be feasible to evaluate the abstraction and irrigation potential for every new site, the topographic and geological identifiers of high potential zones can be located during desk study analysis of topographic and geological maps followed by ground truthing, e.g. geological observations, well depth measurements and dry season well productivity assessments.

Chapter 8. Resilience of shallow groundwater resources

8.0 Chapter overview

Chapter 7 provided justification for the use of SHETRAN and described the model construction, parameterisation and calibration processes. The models could next be used to simulate potential future scenarios, which is the basis of Chapter 8. This chapter details the likely future scenarios that may affect surface and shallow groundwater resources. A multimethod drought analysis is presented revealing the historical climate variability in the area. SHETRAN modelling of the potential future climate, land use and abstraction scenarios is described and results are presented of the impacts on surface and groundwater availability.

8.1 Introduction

8.1.1 Context

Groundwater is often considered a potential saviour for sub-Saharan Africa's unfortunately prevalent issues of food security, poverty and vulnerability to climate change (Carter and Bevan, 2008; Calow *et al.*, 2009b; Taylor *et al.*, 2009; MacDonald *et al.*, 2012a). Rural communities, being poorer and more vulnerable, have the most to gain from increased groundwater use, and these communities are most likely, or only have the capacity, to exploit shallow groundwater. Reports are common of water table decline in parts of the world like India, China and Pakistan where a rapid growth in abstraction for small-scale irrigation, not only increased food security and alleviated poverty, but has caused a worryingly drastic depletion of groundwater resources (Konikow and Kendy, 2005; Aeschbach-Hertig and Gleeson, 2012; Reshmidevi and Nagesh Kumar, 2014). It is also well known qualitatively and empirically the likely effects of climate and land use land cover (LULC) change on water resources, e.g. increased storm intensity and urbanisation and/or cultivation encroaching on natural vegetation, all of which would increase rapid runoff and decrease recharge and baseflow (Meyer and Turner, 1992; Arnell, 2004; Liu *et al.*, 2008b). However, few (if any) studies have been conducted at community scales in sub-Saharan Africa to determine what will happen quantitatively to the shallow groundwater resource if smallholders actually start abstracting it, and in the face of climate variability and LULC change.

8.1.2 Purpose of modelling

Chapter 7 showed how the modelling aims were achieved, in terms of increasing hydrogeological understanding of the shallow groundwater system, developing the conceptual model, and identifying areas with the greatest potential for sustainable intensification of agriculture through irrigation. The objective for the second phase of the modelling was to answer research question 5 from Chapter 1: How will climate variability, LULC change and increased abstraction impact the shallow groundwater resource and surface water?

The groundwater potential maps give satisfactory guidance under current conditions in terms of the recent climate, current land use and likely slow initiation of shallow groundwater abstraction for irrigation. But going forward, climate variability is predicted to become more extreme (Bates *et al.*, 2008; Taye *et al.*, 2015) and population pressures will likely lead to reductions in natural vegetation cover (Hurni *et al.*, 2005; Amsalu *et al.*, 2007) and increased groundwater abstraction (Awulachew *et al.*, 2007; Evans *et al.*, 2012). It is important to understand how these changes will impact the surface and groundwater resources. Further modelling of potential future scenarios was conducted to determine the resilience of the shallow groundwater resource.

8.1.3 Methodology

The second part of the modelling study involved simulating the potential impacts of future scenarios on surface and groundwater resources. As discussed in Chapter 2, the likely causal changes are climate, land use, and abstraction. The initial step was to assess existing climate variability by conducting a drought analysis of historical data. A literature review was also conducted of trends identified in highland Ethiopia meteorology and projected climate change. The aims of these climate variability assessments were the derivation of synthetic rainfall and potential evapotranspiration (PET) time series for incorporation into the SHETRAN models presented in Chapter 7. Ground observations, remote sensing analysis and literature review of LULC change trends determined LULC scenarios for incorporation into the SHETRAN models by adjusting the original land cover/vegetation layer. Groundwater abstraction and irrigation were simulated by SHETRAN at calculated rates in distributed locations. The simulations were run for 200 years in order to observe a full range of impacts on surface and groundwater. Variations in shallow groundwater and surface water availability were analysed to assess the impacts of the potential future scenarios.

8.1.4 *Similar modelling studies*

Many studies have investigated hydrological response to climate and LULC change in Ethiopia. Legesse *et al.* (2003), for the Lake Ziway area of central Ethiopia, used the physically based distributed Precipitation Runoff Modelling System (PRMS) to simulate predicted changes in rainfall, temperature and transition between cultivated/grazing land and native forest. Despite problems of data scarcity and calibration of peak river flows, suspected to be due to errors from extrapolation of ratings when flow was above the gauge, their simulations saw changes of 20-30% in stream discharge. Koch *et al.* (2012) conducted a study using the SWAT model, which is very widely used in Ethiopian studies (see Chapter 7), evaluating LULC change against hydrological response in the northwest Highlands of Ethiopia, approximately 120 km from Dangila. Poor input data (gaps in hydrometeorological time series and a coarse DEM) meant the model could only achieve an acceptable calibration with monthly river flows (Nash and Sutcliffe efficiency (NSE) daily = 0.24, NSE monthly = 0.71). The authors also stated that SWAT struggled with the strong seasonality, i.e. floods in the wet season and dry streams with only subsurface flow in the dry season. Cultivated land had increased in proportional coverage from 53 to 70%, largely at the expense of grasslands, shrubs and bushes and simulations showed higher peak runoffs and decreased low flows, but it is stated that the results are unreliable and further modelling should be conducted. These studies, and similar for various catchments around Ethiopia giving similar results, have no explicit simulation of groundwater flow nor its response to climate and LULC change. While there are groundwater modelling studies evaluating formal abstraction on deep aquifers in Ethiopia (e.g. Ayenew *et al.* (2008a); Asrie and Sebhat (2016); Kerebih and Keshari (2017)), no examples of modelling studies have been found from anywhere in Africa simulating the effects of potential increases or onset of shallow groundwater abstraction.

8.2 Identifying potential future scenarios

8.2.1 *Climate variability*

Taye *et al.* (2015) state that when an ENSO (El Niño Southern Oscillation) event is followed by La Niña in the same year, there is a 67% chance of an extreme flood occurring in the Upper Blue Nile region. Conversely, they found that 83% of ENSO events starting in April–June cause droughts in the Upper Blue Nile region. Seleshi and Zanke (2004) found only links between ENSO events with summer droughts. Seleshi and Zanke (2004) demonstrated no trends in total annual rainfall, seasonal rainfall, or the number of rainy days per year in the Ethiopia Highlands. Meze-Hausken (2004) similarly detected no trends in rainfall data for the same region; however, interestingly, farmers' perceptions indicate progressively unfavourable conditions over the previous 20-30 years. While trends have not been identified in rainfall in the Upper Blue Nile Basin, the considerable interannual rainfall and river flow variation is well reported, e.g. Conway (2000); Hurni *et al.* (2005); Kebede *et al.* (2006). For example, annual rainfall totals measured at weather stations in the area of the study site range from a minimum of 1185 mm/a to a maximum of 2009 mm/a at Dangila (1987-2015) and from 1059 to 2043 mm/a at Meshenti (1987-2013). The annual flow totals of the Kilti measured at the Durbete gauge ranges from a minimum of 206 Mm^3/a to a maximum of 396 Mm^3/a (1997-2014), though this range is an underestimate as there is missing data during very wet periods due to the gauge being overtopped or damaged. The local climate variability was analysed further and is discussed in later sections.

8.2.2 Climate change

Buontempo *et al.* (2014), using a regional climate model (RCM), predicted for this region of Ethiopia by 2100: an increase in rainfall of 2 mm/d from September to May (the dry season) and a decrease of 2 mm/d in June-August (wet season), in other words a decrease in rainfall seasonality, while the IPCC (Intergovernmental panel on climate change) predict an intensification of extreme rainfall events for Ethiopia as a whole (Bates *et al.*, 2008). Laprise *et al.* (2013), using combinations of GCMs and RCMs, project no change in this region in January-March precipitation up to 2100, whereas for July-September precipitation the various models give projections from -1 to +1 mm/d. Clearly, there is significant uncertainty in climate change projections. This arises from underlying uncertainties in the emissions scenarios used to force the climate models and in the assumptions made of physical processes of climatic systems within GCMs (Bonsor *et al.*, 2010). Hulme *et al.* (2001) state that while GCMs simulate changes to African climate due to increased greenhouse gas concentrations, two very important climate drivers either are represented poorly in the case of the influence of ENSO or are not represented at all in the case of LULC change. Bonsor *et al.* (2010) agree that the predictive capability of GCMs in data-poor regions like Africa has significant limitations. They give the example of the Sahel where some GCMs predict significant drying and others predict progressive wetting. These uncertainties are evident at the smaller regional scale as Taye *et al.* (2015) report various rainfall projections for the Upper Blue Nile Basin from studies using GCMs, some of which predict a wetter climate after the 2050s while others predict drying. Similarly, Mengistu and Sorteberg (2012) in modelling changes in streamflow in the Blue Nile due to climate change could not give confident predictions because the 47 temperature and precipitation scenarios they applied from 19 GCMs disagreed in both the strength and the direction of future precipitation changes.

There is general agreement that temperatures in Africa will rise with climate change (e.g. New *et al.* (2001); Mitchell *et al.* (2004); Buontempo *et al.* (2014)). According to Hulme *et al.* (2001), based on the median of seven GCM experiments, temperatures around the continent will rise by around 1-2 ^{o}C by the 2080s with the B1-low scenario, or around 4-7 ^{o}C by the 2080s with the A2-high scenario. While these temperature increases will certainly increase evapotranspiration, the uncertainties regarding changes to rainfall described in the previous paragraph mean the effects of temperature on soil moisture and water bodies are more problematic to forecast.

Initial ideas for the future climate change scenarios involved downscaling multiple GCM and RCM outputs for the study site, or a simpler method of bias-correction of GCM/RCM outputs for an observed period then applied to projected data. However, as described above, the uncertainties in climate change prediction for the region and consequent scepticism in the projections meant it was decided not to incorporate a climate change scenario. What's more, the observed climate variability shown in a later section is much greater than the projected daily average increases/decreases due to climate change. Simulating the observed extremes of climate variability is much less speculative than utilising GCM projections for which there is little confidence.

8.2.3 Land use land cover (LULC) change

From 1950 to 2000, the population of the Ethiopian highlands is estimated to have quadrupled, from approximately 16 million to 65 million; of which about 26 million reside in the Blue Nile Basin (Hurni *et al.*, 2005). Such population increases lead to intensification of land use, including shortening and eventual abandonment of fallow periods, expansion of cultivated land into grazing land, and deforestation (Lambin *et al.*, 2001). A literature review by Taye *et al.* (2015) reported that generally seen in the Ethiopian Highlands is a decrease of low flows and an increase of high flows, i.e. trending towards more hydrological extremes. The proposed cause is land use change: a decrease in natural vegetation and an increase in cropped land, overgrazing, and Eucalyptus planting. The result of these changes being greater transpiration and, consequently, reduced baseflow. Contrastingly, a comparison of a series of photographs by Nyssen *et al.* (2009) taken in the Rift Valley in 1868 by the British military expedition to Abyssinia and in 2008 show improved land management and vegetation cover, albeit often from Eucalyptus plantations, despite a ten-fold increase in population density, all of which would decrease rapid run off. Past and future changes to LULC may be entirely anthropogenic or could be climate related. Either way, the trend towards less forest and increased coverage of cultivated land is widely reported, e.g. Abate (1994); Zeleke and Hurni (2001); Amsalu *et al.* (2007).

Land degradation could be a threat at the Dangila study site as soil erosion has been observed to be occurring during field visits elsewhere in Ethiopia, such as in Robit Bata *kebele* near Bahir Dar and in Boloso Bombe *woreda* in SNNPR (Southern Nations, Nationalities and Peoples' Region). In both cases, according to local officials, deforestation is due to increasing demand for firewood and charcoal production by a growing population, which is often followed by overgrazing. The rate of population growth in Dangila *woreda* is increasing; the total population increased from 149,000 to 160,000 to 175,000 between the 1994, 2007 and 2012 censuses, respectively (CSA, 1994; 2008; 2012). Even between field visits, the first in March 2015, the second in October 2015, and the third in January 2017, expansion of house-building was observed at the edges of Dangila town on formerly cultivated land. This development can be observed using the "time slider" on Google.Earth (Figure 8-1), in addition to both deforestation of native woodland for house-building and afforestation of cultivated land for Eucalyptus (Figure 8-2). Analysis of Landsat imagery by Jaleta *et al.* (2016) for the Meja watershed (~200 km south of Dangila) revealed that Eucalyptus coverage had expanded from <1 to 15% between 1976 and 2015, and farmers intended to plant more. The community around Dangila regularly speak of how the growing number of Eucalyptus plantations is negatively affecting water level in their hand-dug wells. The Eucalyptus is not only utilised locally for house building and charcoal, but, according to the Dangesheta *kebele* office agronomist and Abiyu *et al.* (2016), is transported to Tigray and exported to Sudan. Similar Google.Earth time slider assessment of the rural *kebeles* sees a growing number of houses, though they are still sparse, increases in Eucalyptus plantations in cultivated areas, and little conversion of pasture or shrubland to cultivated land. This latter observation is suggestive that the hydrological/agricultural regime is stable, therefore, encroachment onto the floodplain pasture to plant crops is considered too risky due to likely flood damage (this has been stated by the local community) and that highland areas are cultivated as much as they can be according to the gradient.

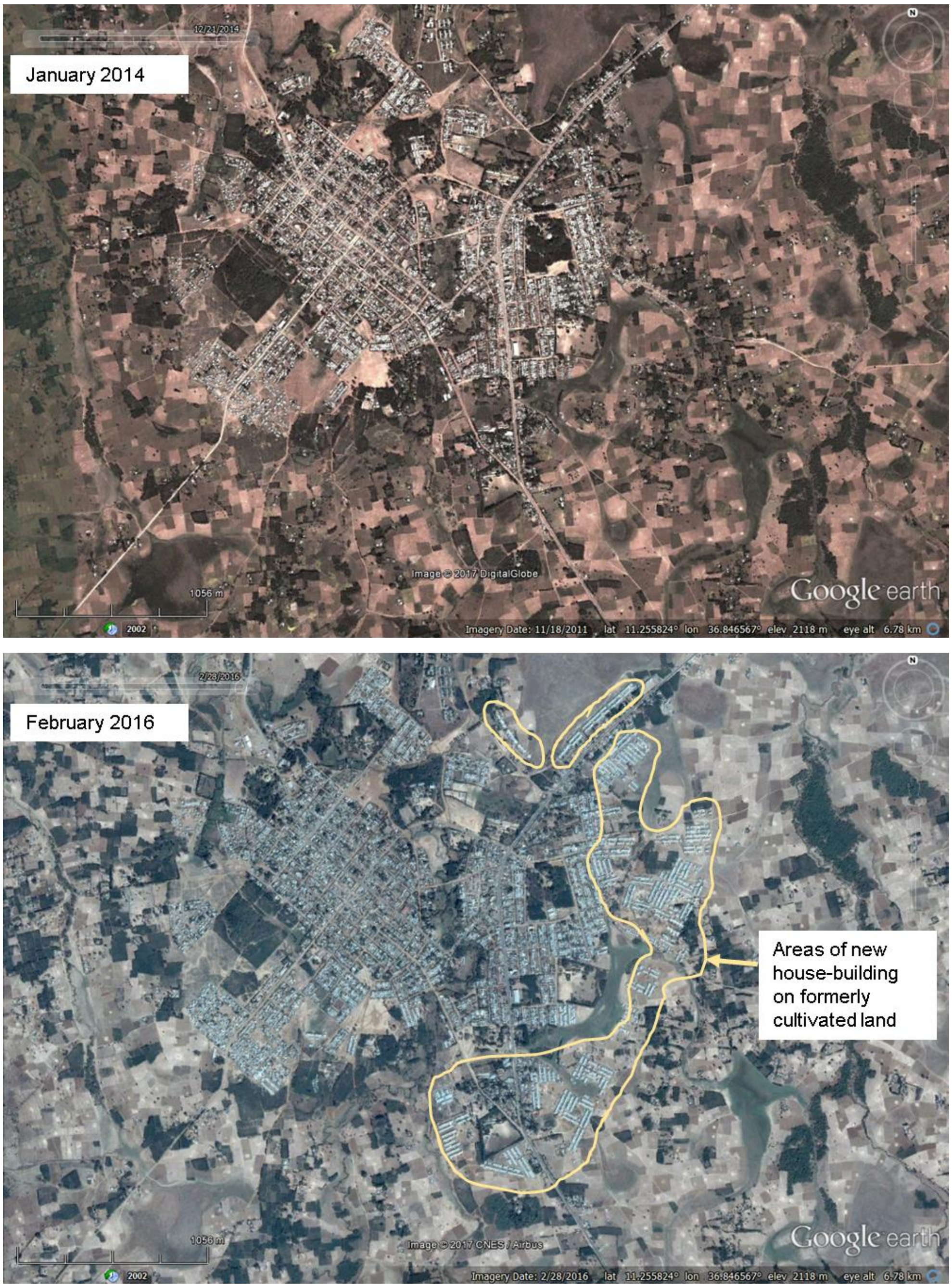


Figure 8-1. LULC change around Dangila town: increased house-building. (Image source: Google.Earth; Imagery ©2014 and 2016 DigitalGlobe).

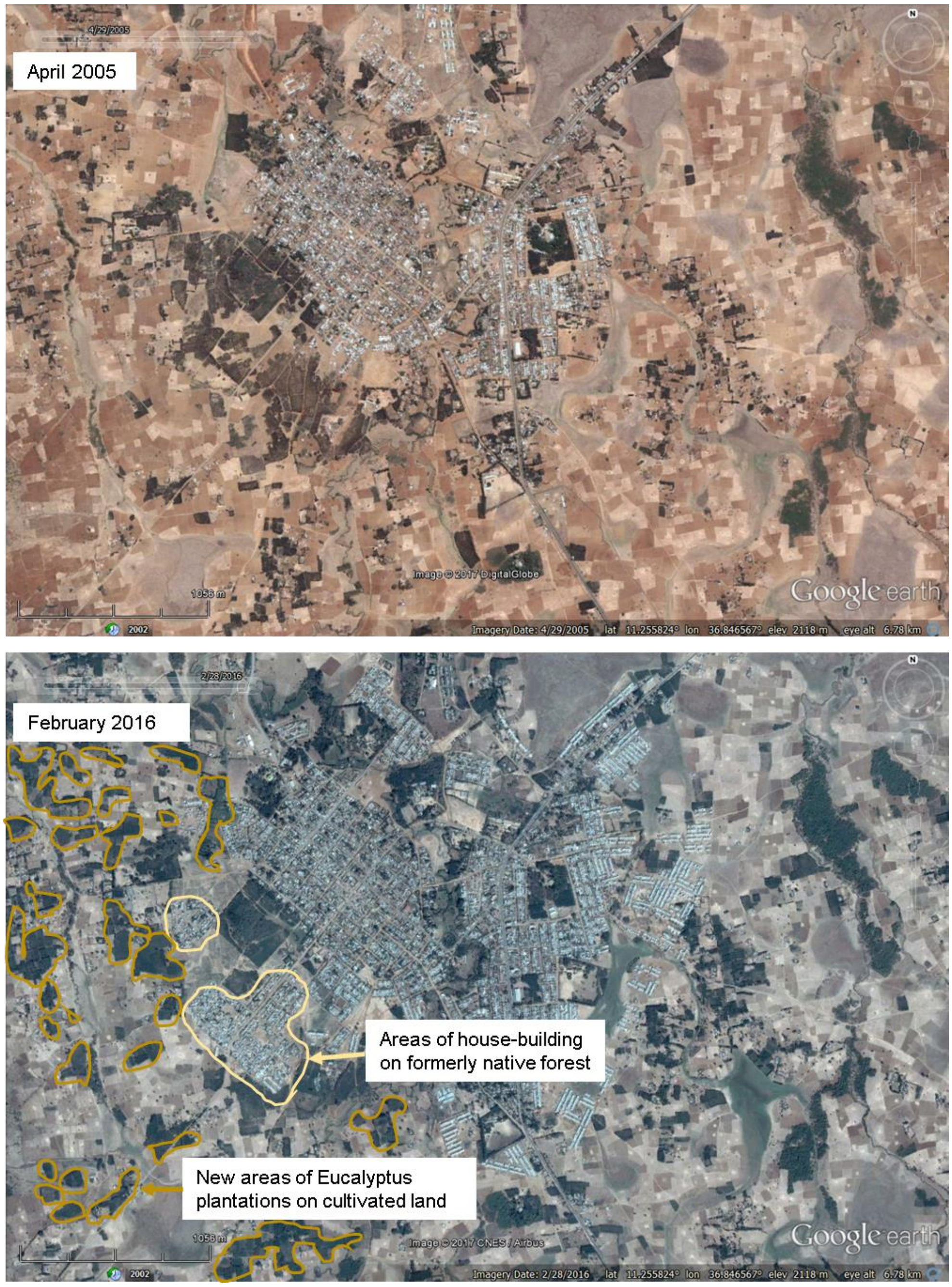


Figure 8-2. LULC change around Dangila town: deforestation for conversion to house-building and afforestation of cultivated land for Eucalyptus. The forest types have been ground truthed. (Image source: Google.Earth; Imagery ©2005 and 2016 DigitalGlobe).

There are several studies concerning the eco-hydrological impact of Eucalyptus in the Lake Tana Basin. Soil analysis and farmer surveys by Chanie *et al.* (2013) at Koga, 30 km northwest of the study site, revealed nutrient depletion and springs drying up following Eucalyptus planting. Growers were aware of these impacts but insisted on continued Eucalyptus planting due to the cash income generated. Simple plot experiments by Alebachew *et al.* (2015) at Mecha, 20 km northwest of the study site, showed large yield and biomass reduction (up to fifteen-fold) in maize and finger millet grown adjacent to

Eucalyptus plantations. The effects were not statistically significant beyond 20 m from tree stands. Enku *et al.* (2017a) monitored hourly groundwater level fluctuations in Eucalyptus plantations at Fogera and calculated dry season evapotranspiration of 2300 mm, almost double the reference evapotranspiration, compared to 900 mm without Eucalyptus. The potentially negative impact of Eucalyptus led to its planting on farmland being banned in the Tigray Region in 1999 (Hagos *et al.*, 1999). However, many authors claim its planting should be encouraged in marginal areas due to its general utility and potential to alleviate poverty among growers, even stating it could dry saturated lands for food production (Pohjonen and Pukkala, 1990; Jagger and Pender, 2003; Zegeye, 2010). Looking at the impact of Eucalyptus across all Ethiopia, there are many more studies available though most are conference proceedings and master's theses and their impact assessments were generally conducted with community questionnaires. As they all state, further research is required on the impact of Eucalyptus on water resources.

8.2.4 Groundwater abstraction

Groundwater abstraction is currently minimal, only for domestic use and for backyard irrigation predominantly utilising rope and bucket technology. Should abstraction increase, the quantities and rates would depend on:

(i) Irrigation water requirement – controlled by irrigation method, crop type, growing season length and climate
(ii) Well yield – controlled by aquifer properties
(iii) Water-lifting technology – controlled by availability, capital costs and running costs
(iv) Area under irrigation – controlled by population size, access to water-lifting technology, market demand and access, and land available

(i) A typical irrigation requirement would be 1 l/s/ha, pumping continuously 24 hours per day, based on the crop water demand of typical crops in the climate of the Ethiopian Highlands (Brouwer *et al.*, 1992). The growing season length varies from up to 6-months for the main rainfed crops, to ~100 days for the short-cycle crops that would be most likely to be planted should a second irrigated growing season be possible (FAO, 2017). (ii) The pumping tests described in Chapter 4 and Appendix A suggest that abstraction at 1 l/s/ha may not always be achievable. Although, the ease of well digging reported by the community and confirmed by the small backyard plots that often have several wells, means the required yield per hectare could be achieved by abstracting from multiple wells (one at a time abstracting from storage, allowing other wells to refill). (iii) The general desire among farmers in Ethiopia is for motorised pumps, the barriers being capital costs and running costs (Evans *et al.*, 2012). The shallow water tables and very short distance from well to crop mean simple motorised pumps could be utilised and fuel costs would be minimised. However, it must be borne in mind that at this altitude of ~2000 m, centrifugal/suction pumps will have a lift of only around 2-3 m and are likely to be unsuitable. (iv) Dangila has its own busy market and is around an hour from the important city of Bahir Dar on a good road; therefore, distance/time to market is not a restricting factor for agricultural expansion here. What's more, rainfed land lies fallow for much of the year and would be available for dry season irrigation. Population growth is occurring, as described previously. An initiative offering water-lifting technologies directly or through credit would likely have to occur to kick-start irrigation in the area.

The literature includes many studies on the impacts of water use on the Ethiopian Rift Valley lakes (e.g. Legesse and Ayenew (2006); Ayenew (2007)), and modelling studies on the impacts potential hydropower and irrigation schemes could have on Lake Tana (e.g. Alemayehu *et al.* (2010); McCartney *et al.* (2010)). However, no studies have been identified from Ethiopia assessing or simulating the likely increase of abstraction and irrigation nor impacts on shallow groundwater resources.

8.2.5 Khat production

Field visits to Robit-Bata *kebele*, approximately 8 km northeast of Bahir Dar, while assisting a Bahir Dar University project, revealed that since irrigation infrastructure had become available, much of the (observed) agricultural land had been given over to *khat* farming. This trend has been reported elsewhere in Ethiopia where the preference with irrigation is to opt for a cash crop such as *khat* (Meshesha *et al.*, 2014). The infrastructure consists of tanks raised on Eucalyptus scaffolds or on topographic highs above hand-dug wells. The tanks are filled using rope-and-pulley double-bucket systems with irrigation then conducted manually with hoses (Figure 8-3). The leaves of the *khat* bush (*Catha edulis* Forsk) are a mild stimulant and have been chewed in parts of East Africa and Southern Arabia for centuries, reducing feelings of fatigue and hunger (Kalix and Braenden, 1985). *Khat* is chosen for its high profitability, its return during the same year as planting, and because it can be harvested, thus provide an income, year-round (Dube, 2014). *Khat* accounts for 13.4% of Ethiopia's export earnings (third after coffee and oil seed), Ethiopia being the primary global producer (Megerssa *et al.*, 2014). Studies from Jimma zone in southwest Ethiopia have shown that *khat* chewing causes social problems such as family disintegration, health issues, lack of education when consumed by school children, and increasing use of *khat* by 18-30 age group has negatively affected labour productivity (Dube, 2014; Megerssa *et al.*, 2014). Some studies claim *khat* is grown at the expense of vegetables thus increasing food insecurity (Gebissa, 2010; Gezon, 2012). However, other studies claim the potential export earnings (unlike the regular fluctuations in the internationally controlled coffee price) and the fact that *khat* can be intercropped with vegetables and grown on marginal (steep or poor soil) agricultural land, mean its planting should be encouraged (Hailu, 2005; Klein *et al.*, 2009). Studies explicitly researching the impact of *khat* growing on water resources have not been identified, though its year-round water demand is reported to have had negative impacts on lake and groundwater levels elsewhere in Ethiopia where exploited for irrigation, causing wells to require deepening and conflict between water users (Lemma, 2011; Meshesha *et al.*, 2014).

Figure 8-3. *Khat* production in Robit-Bata kebele.

Khat has only been observed in backyard plots within Dangila *woreda* for home consumption and consumption generally does not appear to be prevalent in Dangila compared to Bahir Dar; the local population has confirmed this anecdotally. The travel time to a major population centre from the rural *kebeles* of Dangila *woreda* may restrict the popularity of *khat* growing, unlike for Robit-Bata where the highest value freshly picked leaves can be at market in Bahir Dar very quickly. What's more, though popular in Bahir Dar, especially with the young student population, *khat* production and consumption is prevalent mainly in the Islamic east of the country; namely Oromia and Harar Regional States (Lemessa, 2001; Gebissa, 2008). Therefore, an increase in *khat* production was not considered a potential future scenario for simulation.

8.3 Historical drought analysis

8.3.1 Purpose, definition and methodology

A drought analysis was conducted using methods that would also identify particularly wet periods. The purpose of the drought analysis was to assess the climate variability of the study site. Analysis of all types of drought, rather than focussing on rainfall quantities alone, would increase understanding of the likely impacts of climate variability. Consideration of extreme wet periods, in addition to droughts, is also important due to stakeholders reported (anecdotally) and observed negative impacts of high rainfall and floods. A comparative drought analysis of a nearby area would confirm that the study site meteorological time series spans sufficient climate variability extremes experienced in the region. These drought analyses would enable the generation of future climate variability scenarios for simulation in the models.

According to the European Drought Centre (EDC, 2016): "Drought is a sustained and regionally extensive occurrence of below average natural water availability. Drought affects all components of the water cycle from a deficit in soil moisture, through reduced groundwater recharge and levels, and to low streamflows or dried up rivers…Drought should not be confused with aridity, which is a permanent feature of a dry climate. Neither with water scarcity which implies a long-term imbalance of available water resources and demands." Sheffield *et al.* (2013) consider meteorological drought, agricultural drought (soil moisture), ecological drought, and hydrological drought (streamflow). Clearly, assessment of annual rainfall totals alone is insufficient in determining the presence and strength of a drought or wet period. The methods used here to evaluate dryness and wetness were:

- SPI (standardised precipitation index)
- SPEI (standardised precipitation-evapotranspiration index)
- Annual river flow totals (unit runoff)
- Growing season length – 2 methods: Segele and Lamb (2005) and Stern *et al.* (2006)
- NDVI (normalized difference vegetation index)
- LST (land surface temperatures)
- Annual rainfall from ground observation, remote sensing and reanalysis products
- Annual potential evapotranspiration (PET) from ground observation
- SPI and SRA (standardised rainfall anomaly) from other published studies

- Local community perception

The analyses were principally conducted for Dangila, with application of some methods at Bahir Dar to determine if years not represented within the Dangila hydrometeorological datasets were extreme drought or extreme wet years and, as such, should be incorporated into climate variability projections for Dangila. Note that all annual computations consider the hydrological year: 1st March to 28th/29th February. The following sections describe the methods and show results while a synthesis and comparison of results from all methods is provided last.

8.3.2 Available hydrometeorological data

In addition to the 22 years (1994-2015) of daily observations from the Dangila NMA weather station used for SHETRAN modelling, monthly rainfall totals are available from 1987, though with abundant missing months of data prior to 1993. Historical monthly rainfall records were obtained from the Global Historical Climatology Network (GHCN) via the NOAA (National Oceanic and Atmospheric Administration) website (NOAA, 2017). Two periods were available for Dangila: 1955-1969 (with many missing months) and an almost complete record from 1922-1934.

Bahir Dar weather data is commonly analysed in the literature due to its long available time series. It was obtained for this study for comparison with the Dangila data, especially to assess climate variability during periods when Dangila data is unavailable, i.e. the infamous early 1980s droughts. The available daily data from the Bahir Dar NMA weather station is from 2007 to 2015, and monthly data from 2002, though there are long (12+ months) missing periods. Daily rainfall and average temperature data has been sourced from the NOAA website for 1961-2000.

The other local raingauge observations (see Chapter 5) were not utilised due to their short and discontinuous records. The NOAA website does not have data for these raingauges.

River flow records were available from MoWIE for the Kilti and Amen rivers from April 1997 to October 2014 and April 1988 (though are continuous only from 1998) to September 2014 respectively.

Remote sensing and reanalysis rainfall products were downloaded from online open sources for the grid squares containing the Dangila and Bahir Dar weather stations respectively. The following products and periods were utilised: TRMM (1998-2014), ERA-Interim (1979-2014), NASA-MERRA (1979-2014), NCEP (1979-2008), and JRA-

55 (1979-2013); see Chapter 4 for more detail on these remote sensing and reanalysis products.

Normalised difference vegetation index (NDVI) and land surface temperature (LST) were obtained from MODIS (moderate-resolution imaging spectroradiometer) on-board the Terra and Aqua satellites. The data availability is dictated by the operational periods of the satellites: 2001 (NDVI) and 2003 (LST) to 2013. The data products are available at a 16-day timestep and a resolution of 250 m that were spatially averaged across Dangila *woreda*.

8.3.3 SPI (standardised precipitation index)

SPI is a normalised index of precipitation deficit or excess at specified time-scales, first presented by McKee *et al.* (1993). It is the method recommended by the World Meteorological Organisation (WMO) for monitoring drought severity (WMO, 2012) because when using a long time-step it is stated that it identifies agricultural and hydrological drought. A probability density function is determined to describe the observations, then, once the distribution is established, the cumulative probability of an observed precipitation amount is computed and the inverse normal (Gaussian) function is applied to the probability resulting in the SPI (Guttman, 1998). Open source code is available to run SPI analyses using R requiring monthly rainfall totals for a suggested minimum of 30-years. A drought event is defined as a period in which the SPI is continuously negative and reaches a value of -1.0 or less. The drought begins when the SPI first falls below zero and ends with the next positive value (McKee *et al.*, 1993). The gradations are 0 to -0.99 = mild drought, -1 to -1.49 = moderate drought, -1.5 to -1.99 = severe drought, ≤-2 = extreme drought. The same gradations are applied in the positive for wet periods.

When considering the impact of drought on agriculture, it is most applicable to analyse SPI for particular seasons. Poor spring rains would delay planting or prevent crops from developing whereas poor summer rains would damage crops and shorten the growing season. Obviously when poor spring rains are followed by poor summer rains, the impact is exacerbated. Spring in this region is defined as March to May (13% of long-term mean annual rainfall) in accordance with the onset of some rain; late November to February experiences almost zero rainfall. Summer is considered June to October (84% of long-term mean annual rainfall) when the onset of the wet season is clearly visible in late May-early June rainfall totals, peaking in July and August, and dropping off in late October. Thus, for spring the SPI is analysed at a 3-month time-step and calculated for May (the end of the time-step) while for summer the SPI is analysed at a 5-month time-step and analysed for October. SPI was calculated with all available years combined in a single series (deleting the gaps) for the most robust probability density function estimate (Figure 8-4). SPI indicates extreme droughts in Dangila for spring 2003 and summer 1995. While there are a few severe droughts and wet periods, mostly the SPI oscillates between mild and moderate, wet and drought.

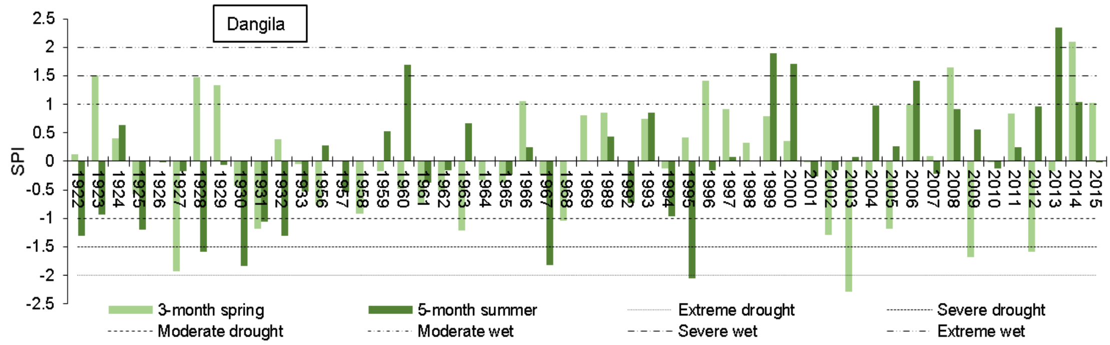


Figure 8-4. SPI calculated for Dangila for spring (3-month, March-May) and summer (5-month, June-October). Note the non-continuous year sequence.

8.3.4 SPEI (standardised precipitation-evapotranspiration index)

SPEI, developed by Vicente-Serrano *et al.* (2010), builds on SPI by incorporating evapotranspiration. It is mathematically similar to SPI though computes a climatic water balance with the addition of temperature data. Like SPI, open source code is available to run SPEI analyses using R requiring monthly rainfall totals. The drought and wet period gradations match those for SPI. Analysis was similarly conducted for spring and summer seasons with all available years combined in a single series (Figure 8-5), though the lack of historical temperature data restricted the time series length. SPEI is applied with less confidence than SPI due to the shorter time series. SPEI indicates extreme drought in Dangila for summer 1995, otherwise, there are a few severe droughts and wet periods but mostly SPEI oscillates like SPI between mild and moderate, wet and drought.

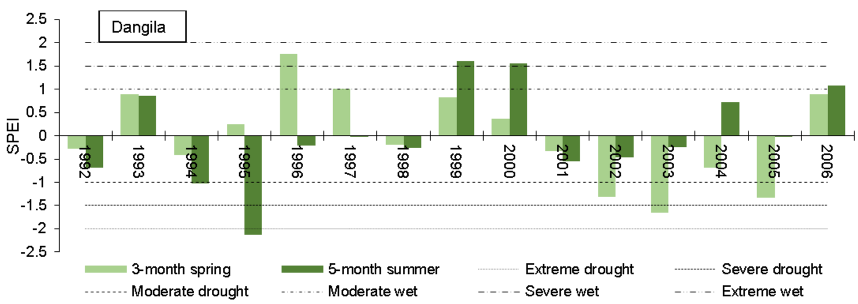


Figure 8-5. SPEI calculated for Dangila for spring (3-month, March-May) and summer (5-month, June-October). Note the non-continuous year sequence, which is different to the SPI plot in Figure 8-4.

8.3.5 River flow totals

To directly assess hydrological drought, river flows were converted to unit runoff (total annual flow divided by basin area) and the percentage variation from the mean was computed. Figure 8-6 shows that there is high interannual variation in river flow, though with consistently lower flow in both rivers from 2002-2005. The Amen is a small (37 km^2) catchment nested within the much larger (632 km^2) Kilti catchment, therefore, it is intriguing that in 2001, 2007, 2010 and 2012, the two rivers show divergence from mean unit runoff in opposite directions. It could be explained by the small size of the Amen catchment meaning localised intense storms would significantly affect the flow records whereas the effects would be diluted within the large catchment.

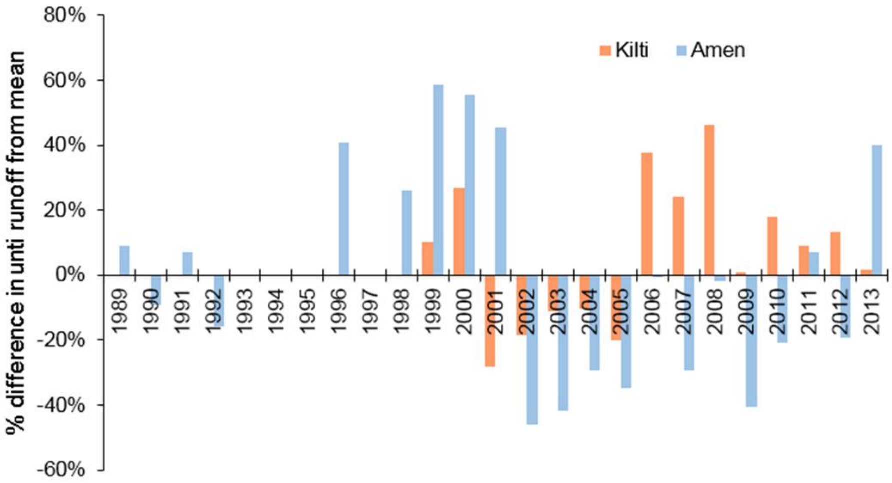


Figure 8-6. Kilti and Amen Rivers' percentage variation in unit runoff from the mean.

8.3.6 Rainfed crop growing season length

Segele and Lamb (2005), in investigating wet season variability as a cause of drought and famine in Ethiopia, proposed a method for identifying growing season length. Assessment is conducted on daily rainfall totals with thresholds of onset, cessation and dry-spell determined by reported crop requirements and research of Ethiopian meteorology and agriculture. Onset is defined as the first day of the year's first wet-spell of at least three days totalling 20 mm or more rainfall, provided there were no sequences of eight or more dry (<0.1 mm) days in the subsequent 30 days. Cessation is the first day of a dry-spell (<0.1 mm/d) of at least 20 days. A similar method of measuring growing season length, proposed by Stern *et al.* (2006), was also applied. Onset is defined as the first occasion with more than 20 mm of rainfall in a 2-day period after 1st April and no dry spell of 10 days or more within the following 30 days. Cessation is the first day after 1st September that the water balance drops to zero. The daily water balance is computed with effective rainfall (rainfall minus PET) and soil capacity. The soil capacity value was specified as

150 mm/m based on the FAO-UNESCO world soils database and mapping (see Batjes (1997) and Nachtergaele *et al.* (2010)). Figure 8-7 shows that the interannual variability in growing season length is significant, ranging from 140-237 days with Segele and Lamb (2005) and 156-252 days with Stern *et al.* (2006). The typical range is April/May to October/November with the few cessations in December mostly estimated by the Stern *et al.* (2006) method, which generally predicts a later cessation. The Segele and Lamb (2005) cessations match observed and anecdotal evidence better, which is understandable as the method was tuned specifically for Ethiopian climate and agriculture.

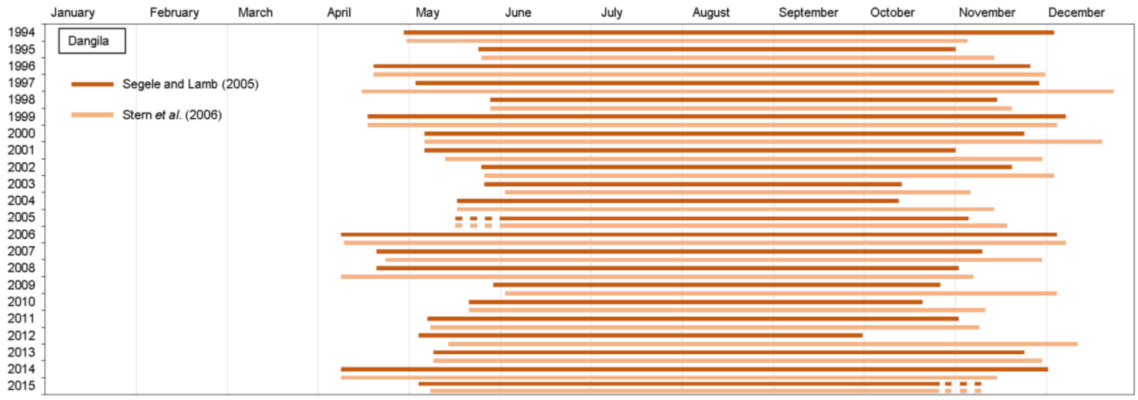


Figure 8-7. Growing season length at Dangila. Dashed lines indicate where onset or cessation lies within missing data.

8.3.7 NDVI (normalized difference vegetation index)

The NDVI is derived from the red/near-infrared reflectance ratio from the amounts of near-infrared and red light reflected by vegetation and captured by the satellite sensor (Pettorelli *et al.*, 2005). The index is based on the fact that chlorophyll absorbs red light whereas the mesophyll leaf structure scatters near-infrared (Myneni *et al.*, 1997). Therefore, NDVI values range from −1 to +1, where negative values equate to vegetation absence. NDVI may be able to identify droughts by revealing lengthy periods of low greenness or, conversely, periods of high greenness could indicate the length of the wet season (Peters *et al.*, 2002). Simple methods were derived to conduct the analyses. NDVI data at 250 m spatial and 16-day temporal resolution was downloaded from the NASA-MODIS website (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php). The absolute NDVI values per pixel were then averaged across Dangila *woreda* for each time step. To reveal possible droughts the number of 16-day periods with NDVI in the lowest 10th percentile and lowest 20th-percentile were counted for each year. To estimate wet season length the number of 16-day periods with NDVI above the 50th percentile and 75th percentile were counted for each year. Figure 8-8 shows the high interannual variability in greenness and little correspondence between the two plots (which is not unexpected as the left plot assesses the dry season and the right plot assesses the wet season).

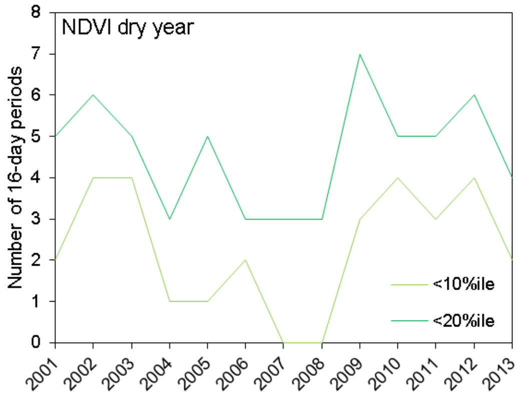


Figure 8-8. Counts of 16-day periods of spatially averaged absolute NDVI values above/below thresholds to identify dry and wet years. High counts in the NDVI dry years plot (left) indicate prevalent dry conditions and low counts in the NDVI wet season length plot indicate short growing seasons.

8.3.8 LST (land surface temperatures)

The data used is the difference in LST between the MODIS Terra satellite measurement at 13:30 and MODIS Aqua satellite measurement at 10:30, spatially averaged across the *woreda*, again on a 16-day cycle. A high positive difference when LST is greater at 13:30 means low soil (or canopy) moisture; this would be expected in the dry season. A high negative difference means LST is greater at 10:30, therefore, there is evaporative cooling at 13:30; this would be expected in the wet season. Daily difference in LST may be able to identify droughts by revealing long periods of high positive difference, which equate to low soil or canopy moisture. Figure 8-9 shows there is little variation in mean LST daily difference during the dry season and spring; however, there is greater interannual variation during the wet season with clearly wetter and drier years.

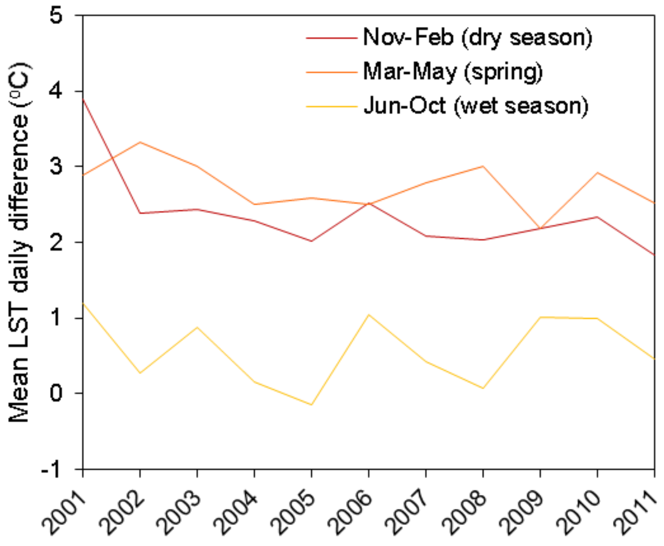


Figure 8-9. Mean of LST daily difference per season. The greater the positive value the lower the soil and canopy moisture content.

8.3.9 *Annual rainfall totals*

To assess purely meteorological drought and to make interesting comparison to other drought analysis methods, annual rainfall totals from ground observations, remote sensing and reanalysis were compared. Apparent from Figure 8-10 and Figure 8-11 is the interannual variability in rainfall total and the overestimation in totals from most of the reanalysis products. The Pearson correlation coefficients between annual totals from remote sensing and reanalysis against ground observations are <0.60 for all the products.

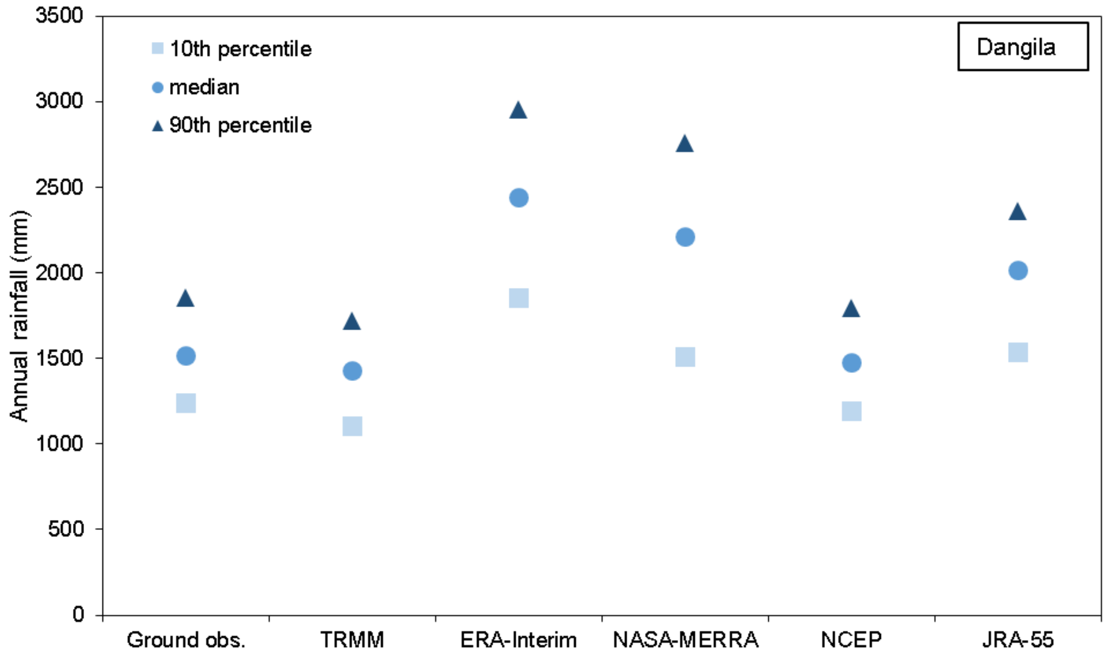


Figure 8-10. Median and percentile annual rainfall totals for Dangila from ground observations, remote sensing and reanalysis products.

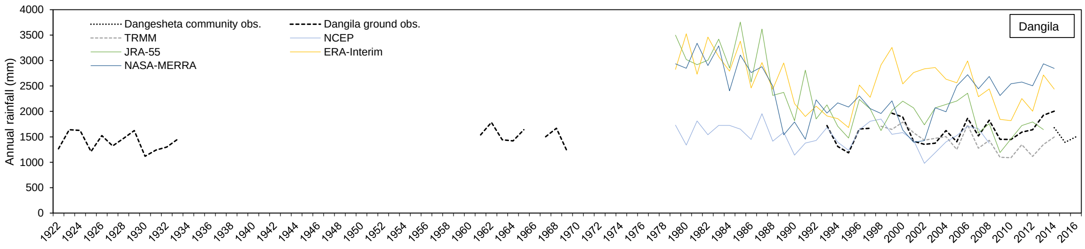


Figure 8-11. Annual rainfall totals for Dangila from ground observations, remote sensing and reanalysis products.

8.3.10 Annual potential evapotranspiration (PET) totals

PET was calculated using the Penman-Monteith FAO56 method (Allen *et al.*, 1998) with meteorological data from the Dangila NMA weather station. It can be seen in Figure 8-12 that there is little interannual variability in PET totals; the coefficient of variation is just 3%.

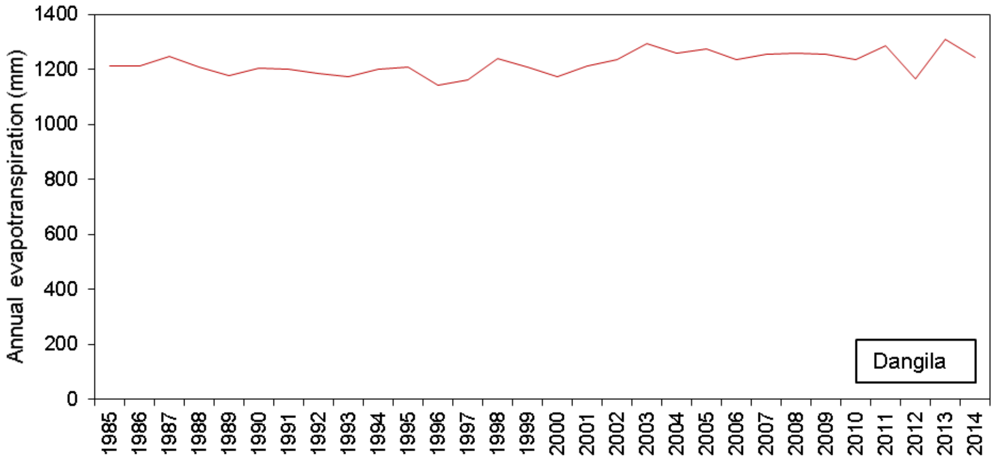


Figure 8-12. Annual potential evapotranspiration totals from Dangila.

8.3.11 SPI (standardised precipitation index) and SRA (standardised rainfall anomaly) from other published studies

Regional and nearby drought assessments appear in the literature and these were compared with the Dangila analyses. SPI analysis of the northwest highlands of Ethiopia was conducted by Viste *et al.* (2013) for spring and summer periods 1972-2010. Bewket and Conway (2007) applied the SRA method (annual rainfall minus mean annual rainfall all divided by standard deviation of annual rainfall) to several raingauge records of which the 1962-2003 Bahir Dar assessment was considered here. The Bahir Dar SRA assessment by Ayalew *et al.* (2012) was also considered as the different time series, 1979-2008, gives different results to the previous study.

8.3.12 Local community perception

Rather than being conducted systematically, whenever the opportunity arose during field visits, such as at community workshops (Figure 8-13), questions were put to the local community regarding historical droughts and wet periods. Given that the great majority of the agriculture is rainfed and domestic water comes from shallow wells; local farmers and communities would be uniquely aware of all types of drought. Common responses were that Dangila *woreda* does not suffer the type of droughts for which Ethiopia is renowned, though the early 80s droughts were felt, and that the climate is becoming less predictable. Indeed, there was a frost for the first time in living memory a few nights prior to the January 2017 field visit, which caused visible damage to banana plants (Figure 8-13). It was commonly stated that 2014 was wet and 2015 was dry, these being in recent memory. Memory triggers were given to the community for earlier suspected wet and dry years with mixed results. A number of people remembered that 2012 was a poor growing season because it was quite recent and due to the memory trigger of the death of Prime Minister Meles Zenawi and the succession of Hailemariam Desalegn. The year before millennium of the Ethiopian calendar, 2006 in the Gregorian calendar, was remembered as being very wet in Dangila and causing flooding across Ethiopia. Earlier memory triggers included elections, the war with Eritrea, football world cups and the Olympics but there was little agreement in dry/wet years, perhaps complicated by Ethiopia's unique calendar and usually having to converse through a translator. Furthermore, Meze-Hausken (2004) explains how statistical rainfall anomalies do not always create memorable droughts as more depends on the preceding environmental, socioeconomic and cultural conditions (preceding soil moisture, crop prices, increased population densities due to migration, low soil fertility, low seed availability, poor crop choice, low availability of aid, etc.) that impact people's preparedness.

Figure 8-13. Community workshop in Dangesheta (left) and frost damage to banana plant in January 2017.

8.3.13 Synthesis of results

The different spatial and temporal scales of the drought analysis methods mean they cannot be compared quantitatively to rank years in terms of dryness. However, a qualitative comparison can be conducted using Table 8-1. There were many interesting findings from this drought analysis:

- There is general agreement between methods; often enough to justify their applicability for drought/wet period analysis in this area.
- Prior to the early-1990s, there are insufficient data to apply multiple methods to confidently identify drought/wet years.
- Drought years are identified as: 1995, 2002-2003, 2009, 2012
- Wet years are identified as: 1999-2000, 2006, 2013-2014
- The requirement for using more complex drought analysis methods rather than relying only on annual rainfall totals is illustrated by 2012, which had above average annual rainfall, but the timing of the rainfall meant it was one of the worst years, in terms of drought, on record.
- The reanalysis products perform particularly poorly in the early-80s where the famous drought years are recorded as being especially wet.

Table 8-1. Identification of drought/wet years and comparison of drought analysis methods for Dangila. X = insufficient data for analysis. v = very. Note the jump from 1933 to 1956. For SPI, SPEI and SPI/SRA from other studies: v dry and v wet are <-2 and >2 respectively, dry and wet are <-1.5 and >1.5 respectively. For river flow: v high and v low are >±40% difference in unit runoff from the mean, high and low are >±20% difference in unit runoff from the mean. For growing season length: v long and v short are >±20% difference from mean length in days, long and short are >±10% difference from mean length in days. For NDVI dry year: dry is >3 16-day periods in the 10%ile and >4 in the 20%ile, wet is <2 16-day periods in the 10%ile and <4 in the 20%ile. For NDVI wet season length: long is >12 16-day periods in the 50%ile and >8 in the 75%ile, short is <11 16-day periods in the 50%ile and <7 in the 75%ile. For LST wet season daily difference: dry and wet are >±70% difference from the mean daily difference. Annual rainfall: dry is rainfall total <10%ile, wet is >90%ile.

Year	**SPI**		**SPEI**		**River flow**		**Growing season length**		**NDVI**		**LST**	**Annual rainfall**						**Annual PET**	**Viste *et al.* (2013) NW Highlands ***		**Bewket and Conway (2007) Bahir Dar SRA**	**Ayalew *et al.* (2012) Bahir Dar SRA**	**Local community perception**
	spring	**summer**	**spring**	**summer**	**Kilti**	**Amen**	**Segele and Lamb (2005)**	**Stern *et al.* (2006)**	**dry year**	**wet season length**	**wet season daily difference**	**ground obs.**	**TRMM**	**NCEP**	**JRA-55**	**ERA-Interim**	**NASA-MERRA**		**spring SPI**	**summer SPI**			
1922			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1923			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1924			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1925			X	X	X	X	X	X	X	X	X	dry	X	X	X	X	X	X	X	X	X	X	
1926			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1927	dry		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1928		dry	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1929			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1930		dry	X	X	X	X	X	X	X	X	X	dry	X	X	X	X	X	X	X	X	X	X	
1931			X	X	X	X	X	X	X	X	X	dry	X	X	X	X	X	X	X	X	X	X	
1932			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1933			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1956			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1957			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1958			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1959			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1960		wet	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1961			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
1962			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	

1963			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	
1964			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	wet	X	
1965			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	dry	X	
1966			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	
1967		wet	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	
1968			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	
1969			X	X	X	X	X	X	X	X	X	dry	X	X	X	X	X	X	X	X		X	
1970	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	
1971	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	wet	X	
1972	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	dry			X	
1973	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			v wet	X	
1974	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			v wet	X	
1975	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	dry			X	
1976	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	
1977	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	
1978	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	
1979	X	X	X	X	X	X	X	X	X	X	X	X	X		wet		wet	X					
1980	X	X	X	X	X	X	X	X	X	X	X	X	X		wet	wet	wet	X			dry	dry	
1981	X	X	X	X	X	X	X	X	X	X	X	X	X		wet		wet	X					
1982	X	X	X	X	X	X	X	X	X	X	X	X	X		wet	wet	wet	X		v dry	v dry	v dry	v dry
1983	X	X	X	X	X	X	X	X	X	X	X	X	X		wet	wet	wet	X					
1984	X	X	X	X	X	X	X	X	X	X	X	X	X		wet			X		dry		dry	v dry
1985	X	X	X	X	X	X	X	X	X	X	X	X	X		wet	wet	wet			dry			
1986	X	X	X	X	X	X	X	X	X	X	X	X	X		wet		wet		v dry				
1987	X	X	X	X	X	X	X	X	X	X	X	X	X		wet	wet	wet			v dry	dry		
1988	X	X	X	X	X	X	X	X	X	X	X	X	X										
1989			X	X	X		X	X	X	X	X		X		wet							wet	
1990	X	X	X	X	X		X	X	X	X	X	X	X	dry					dry				
1991	X	X	X	X	X		X	X	X	X	X	X	X				dry		dry				
1992					X		X	X	X	X	X	X	X							v dry			
1993					X	X	X	X	X	X	X		X									wet	
1994					X	X	long		X	X	X		X								dry	dry	
1995		v dry		v dry	X	X	short	short	X	X	X	dry	X		dry	dry				dry	dry	dry	
1996			wet		X	v high	long	long	X	X	X		X										
1997					X	X	long	v long	X	X	X		X	wet						v dry	dry		
1998					X	high		short	X	X	X			wet									

1999		wet		wet		v high	v long	long	X	X	X	wet				wet						
2000		wet		wet	high	v high		long	X	X	X	wet	wet									
2001					low	v high				long	X						dry					
2002						v low			dry		X			dry			dry	dry				
2003	v dry		dry			v low	v short	v short	dry		dry			dry				v dry			v wet	
2004						low	v short	short	wet											X		
2005						v low														X		
2006					v high		v long	v long			wet		wet			wet				X	v wet	wet
2007			X	X	high	low			wet		wet									X		
2008	wet		X	X	v high				wet		dry									X		
2009	dry		X	X		v low	short			short			dry	X	dry	dry		v dry		X	X	
2010			X	X			short	short	dry		wet		dry	X	dry	dry				X	X	
2011			X	X							dry			X				X	X	X	X	
2012	dry		X	X			v short		dry	short	dry			X				X	X	X	X	dry
2013		v wet	X	X		v high						wet		X			wet	X	X	X	X	
2014	v wet		X	X			v long		X	X	X	wet		X	X		wet	X	X	X	X	wet
2015			X	X	X	X			X	X	X		X	X	X	X	X	X	X	X	X	dry

* Viste *et al.* (2013) present only droughts, not wet periods.

8.3.14 Comparison between Dangila and Bahir Dar drought analyses

A similar drought analysis was conducted for Bahir Dar, details of which are provided in Appendix E. The analysis indicated that Bahir Dar generally experienced the same drought and wet periods as Dangila, that there are particularly dry and wet periods that are not represented in the available Dangila time series, and that reanalysis does not pick up the early-80s droughts, misrepresenting those years as being particularly wet.

8.4 Generation of synthetic meteorological time series

8.4.1 Purpose

The SHETRAN models presented in Chapter 7 were run for as long as possible according to the length of the river flow or groundwater level calibration time series or the length of the daily rainfall and PET time series, whichever was shorter. To fully assess the potential effects of climate variability on the shallow groundwater and surface water resources, it was necessary to run the SHETRAN models for longer periods than as presented in Chapter 7. Very dry years have been identified from the drought analysis but because the time series simulated in the models were quite short, extreme years rarely occur consecutively. Whereas, a longer time series is more likely to contain extended droughts and different dry/wet year sequences. Therefore, a long time series of daily rainfall and PET needs to be generated. Unfortunately, the pre-1994 Dangila rainfall data, from the NMA or from GHCN, are monthly totals, which are inappropriate for the daily simulation required in this study. However, a longer time series of daily rainfall data is available for Bahir Dar and drought analysis showed that the climate is similar. A long time series could be generated for incorporation into SHETRAN, combining Dangila and Bahir Dar daily meteorological data if the datasets are comparable.

8.4.2 Comparison between Dangila and Bahir Dar rainfall

Bahir Dar lies 70 km northeast of Dangila, at 300 m lower altitude and adjacent to Lake Tana, therefore has a slightly different climate. For that reason, it was necessary to test whether the Bahir Dar data could be used to inform the longer period climate at Dangila, i.e. are the coincident portions of the datasets sufficiently similar. Details of the statistical analyses are provided in Appendix E. Essentially, satisfactory correlation testing of rainfall totals and wet days justified the use of Bahir Dar rainfall years in the Dangila time series used for the climate variability future scenario SHETRAN simulations. Further statistical comparisons indicated that climatic extremes, both wet and dry, were not captured within the 22-year Dangila rainfall dataset used in the SHETRAN modelling; confirming what was discovered during the drought analysis. Notably, the Bahir Dar dataset includes the infamous Ethiopian droughts of the early-80s and the very wet early-70s.

8.4.3 Methodology

One option for generating a synthetic daily rainfall time series is the use of a Markov chain model or other weather generator. The models generate new time series using the persistence and periodicity of observed historical data to estimate transitional probabilities between dry and wet conditions (Haan *et al.*, 1976). Unfortunately, the available Dangila daily rainfall time series is short and, we now know from the Bahir Dar analysis, does not include the climatic extremes that would lead to a satisfactory probability distribution function for generating the full range of likely climate variability. What's more, long periods of zero rainfall (at Dangila that is typically from mid-November to early March) limit the applicability and effectiveness of rainfall generators (Kilsby *et al.*, 2007).

Therefore, the existing years of Dangila daily rainfall would be randomly arranged into a longer sequence for simulation with SHETRAN. However, the previous section and the drought analyses confirmed that additional extreme years should be added to the 22-year Dangila dataset to simulate the full range of climate variability experienced in Dangila but not represented in its meteorological record. Scaling the existing Dangila data according to the rainfall range identified at Bahir Dar would be subjective as rules would have to be generated governing the scaling factor for rainfall above and below certain thresholds and whether to create or eliminate zero rainfall days. Instead, the extreme years from the Bahir Dar time series were simply added unchanged to the sequence of Dangila daily rainfall years.

To decide which additional years to add, the analysed years were approximately ranked according to drought severity. Only 25 years at Dangila had sufficient datasets to enable confident ranking. The 25 ranked years were divided into three eight-year periods to represent the dry, normal (nine years) and wet conditions. The highest and lowest eight years in the drought ranking are presented in Table 8-2 along with the eight driest and wettest years from Bahir Dar. The ranking is approximate because rarely were enough data available to apply more than a few of the possible analysis methods per year. Any years in either column of Table 8-2 not represented in the Dangila time series were incorporated, i.e. 1964, 1965, 1971, 1973, 1974, 1980 and 1982 (note that only monthly rainfall records for 1964 and 1965 are available at Dangila thus the daily Bahir Dar records were added).

Table 8-2. Approximate ranking of available years according to drought severity, showing the eight worst (driest) and eight wettest years and the corresponding annual rainfall total.

Extreme drought			Extreme wet		
Year	**Dangila (mm/a)**	**Bahir Dar (mm/a)**	**Year**	**Dangila (mm/a)**	**Bahir Dar (mm/a)**
1982	?	890	1973	?	2035
1980	?	1114	1974	?	1966
1995	1186	1182	2014	2005	1712
2003	1375	?	1999	1965	1460
2009	1451	?	2006	1867	1652
2012	1640	?	1971	?	1859
2002	1351	?	2000	1889	?
1965*	1639	1089	1964*	1420	1783

* Selected primarily due to the Bahir Dar annual rainfall total.

PET time series for the additional rainfall years were not available. However, they may be of questionable applicability at Dangila with its higher altitude and lower average temperature. Therefore, existing years of Dangila PET time series were selected and matched to rainfall total to coincide with the added rainfall years. Such practice was robust as Figure 8-12 and analysis in Chapter 7 revealed the small interannual variability in PET with a very low coefficient of variation (3.4-6.8%) between interannual monthly totals.

The meteorological time series were randomly arranged using a Python script into a 200-year sequence based on the 29 existing years (22 from Dangila and 7 from Bahir Dar). A 200-year sequence was considered long enough to allow generation of multi-year drought and wet periods while not being too computationally time-consuming.

8.5 SHETRAN modelling

8.5.1 Initial/preceding conditions

Given that river discharge reduces to almost zero and groundwater drops to similar levels at the end of each dry season, and that groundwater levels reach the surface in many areas at the peak of the wet season, it was expected that there would be little "memory" in the hydrological system and only a single year run-in period would be necessary. To test this hypothesis, the subsurface water storage (including the saturated and unsaturated zones) outputs from the SHETRAN models were divided by hydrological year and analysed. The correlations in Table 8-3 show that the conditions of the previous year have no statistically significant influence on the conditions of the following year, with the exception of the correlation between the mean subsurface water storage and the previous year's minimum. Importantly, the minimum subsurface water storage, which controls the abstractable quantity of groundwater during the dry season, is independent of whether the previous year was wet or dry. Table 8-4 shows that subsurface water storage varies little year on year with very small standard deviation, coefficient of variation, and absolute range. Therefore, rainfall is sufficient during the wet season for the shallow aquifer to essentially fill up every year. This is evident from observational and anecdotal evidence, as well as from SHETRAN outputs, of the large expanses of inundated floodplain during the wet season. The small range in absolute subsurface water storage shows that there is little interannual variation and that the system is storage-controlled rather than recharge-controlled regarding groundwater availability. This is a significant conclusion in itself though understanding the spatial distribution of groundwater availability and how it varies necessitated the more detailed modelling.

Table 8-3. Correlations between subsurface water storage from one year to the next for the Amen and Kilti-Durbete catchments for 1998 to 2014 as computed by SHETRAN. SSW = subsurface water storage.

	SSW min and previous year's:			**SSW max and previous year's:**			**SSW mean and previous year's:**		
	mean	**min.**	**max.**	**mean**	**min.**	**max.**	**mean**	**min.**	**max.**
Amen									
Pearson	0.40	0.09	0.40	-0.10	0.56	0.34	0.38	0.82	0.52
P-value	0.13	0.73	0.13	0.71	0.02	0.19	0.15	0	0.04
Kilti-Durbete									
Pearson	0.34	0.02	0.43	0.01	0.64	0.40	0.36	0.81	0.55
P-value	0.20	0.93	0.10	0.96	0.01	0.13	0.17	0	0.03

Table 8-4. Statistics of annual subsurface water storage in Amen and Kilti-Durbete catchments for 1998 to 2014 as computed by SHETRAN. SSW = subsurface water storage (spatially averaged mm), CV = coefficient of variation.

	Amen			**Kilti-Durbete**		
	SSW mean	**SSW min.**	**SSW max.**	**SSW mean**	**SSW min.**	**SSW max.**
Mean	3042	2805	3237	3212	2959	3417
St. deviation	26.1	37.2	12.0	35.1	40.6	11.6
CV	0.9%	1.3%	0.4%	1.1%	1.4%	0.3%
Minimum	3006	2750	3207	3165	2895	3386
10^{th} percentile	3011	2758	3224	3173	2906	3402
Median	3040	2803	3238	3215	2950	3419
90^{th} percentile	3075	2862	3251	3241	3018	3428
Maximum	3087	2869	3252	3310	3029	3429

This analysis confirmed that a single year spin up period was sufficient. The models were run for 201 years and the first year was discarded. The first year spin up period added was 2011 because this year falls in the centre of the drought analysis ranking; 2011 is ranked 15 of 29 and has close to mean and median annual total rainfall.

8.5.2 Modelled catchments

The potential future scenario simulations were run on the higher resolution (100 m) Amen and Brante catchment SHETRAN models described in Chapter 7. The Kilti-Durbete model was excluded as the groundwater potential mapping exercise suggested that the 500 m resolution was insufficient to capture groundwater level subtleties to enable community-scale resource assessment. The Kilti-Dangesheta model was also excluded from future scenario simulation, partly due to its lower (200 m) resolution and partly due to computational restraints (Amen and Brante 201-year simulations were run on eight powerful and fast Dell Blade servers and still took 4-7 days to run).

8.6 Measuring potential impacts

8.6.1 Additional irrigated growing seasons

Cultivation in Dangila *woreda* is predominantly rainfed. The aim of using shallow groundwater for irrigation would be to enable a second growing season after the main rainfed growing season. Therefore, increasing food security, employment and wealth, as well as having a host of additional benefits described elsewhere such as improved nutrition and gender equality. The most likely onset of a second growing season would be straight after harvest of the main rainfed crop, taking advantage of residual soil moisture and shallow water tables following the wet season. Harvest currently takes place in October, which could be immediately followed by land preparation then seed sowing. A potential second growing season is therefore simplified to begin on 1st November, and be of 3-month duration. Traditional short-cycle crops in Ethiopia are wheat (104-170 day cropping cycle), barley (91-174 days) and *teff* (78-123 days) (Meze-Hausken, 2004; Reynolds, 2008) (cropping cycle lengths from FAO (2017)). However, research has shown that small-scale farmers prefer to grow high-value vegetables and cash crops when irrigated agriculture becomes an option (Kloos, 1991; Rockström *et al.*, 2002; Emana *et al.*, 2015). Therefore, more likely, and more suitable for the prescribed growing season length of 3-months, short-cycle crops include: okra (75-90 days), chilli peppers (82-97 days), chickpea (78-135 days) and tomato (75-130 days). These crops have all been observed locally under backyard irrigation and are grown under rudimentary irrigation elsewhere in Ethiopia (Wiersinga and de Jager, 2009); tomatoes being preferably grown outside of the rainy season in the Lake Tana Basin otherwise they are vulnerable to pests and disease (Abera, 2017).

8.6.2 Groundwater availability

Whether or not a second irrigated growing season is possible depends on groundwater availability throughout that growing season. The length of groundwater availability will vary by location and for each location it will vary interannually. To assess this variability of shallow groundwater availability, the SHETRAN output of spatiotemporal distribution of water table depth was processed using Python. The most useful measure of impact on the shallow groundwater resource from the potential future scenarios would be a measure of how much the proportion of the catchment where a second growing season is possible varies spatially and interannually. The processing and analysis methodology was as follows:

1. The groundwater level accessibility threshold was assigned as per Chapter 7: Groundwater is considered accessible when the level is >0.5 m above the base of the regolith, i.e. the water table is not in the basal basalt layer below the base of wells and a sufficient water column is present to allow pumping by mechanical or motorised means.
2. For each cell, the days from 1st November onwards when groundwater level was above threshold were counted and the cell was assigned a category:

- Failure: groundwater is partially or unavailable for the 3-month period, therefore, a second growing season after the main rainfed growing season using shallow groundwater for irrigation is impossible.
- Success: groundwater is available for the whole 3-month period, therefore, a second growing season is possible.
- High success: groundwater is available year-round, therefore, a second, and possibly a third, growing season are possible.

3. The proportional spatial coverage of "Failure", "Success" and "High success" was determined for each simulated hydrological year and plotted.
4. In addition to assessing how climate variability affects the proportional areas, the initial run was considered the baseline against which the land use and abstraction scenarios were compared.
5. For quantitative comparison of the potential future scenarios, cumulative frequency curves were plotted of the proportional coverage of "High success" for each land use and abstraction scenario. These plots show the degree to which groundwater availability is affected by the different scenarios.

An example of a success/failure plot is given in Figure 8-14 based on the historic Amen catchment time series rather than a new 201-year simulation. The format of this plot was developed with consideration of the paper by Forni *et al.* (2016) that discusses visualisations to condense model results into meaningful formats for decision makers. The aim was to combine spatiotemporal, multivariate, multi-scenario information into an easily explainable and understandable format for local stakeholders.

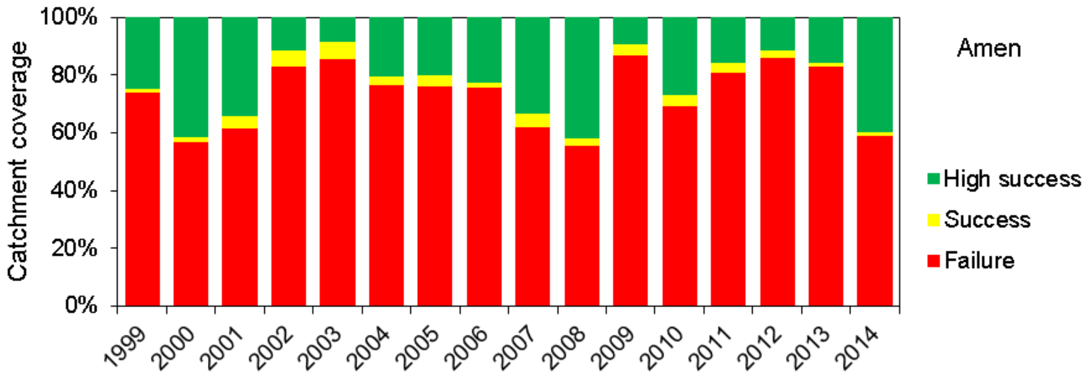


Figure 8-14. Example plot of proportional coverage of failure (only rainfed agriculture possible), success (second growing season possible) and high success (second and third growing season possible; shallow groundwater available year-round) per year for the Amen catchment historic time series.

Apparent from Figure 8-14 is that a substantial proportion of the catchment always achieves "High success" whereas "Success" is always a small proportion and the majority of the arable land has potential for only rainfed agriculture. This realisation led to the cumulative frequency curves being plotted for proportional coverage of "High success" as described above. Also apparent by the high proportion of failure are the drought years of 2002-2003, 2009 and 2012 as revealed in the Drought Analysis section.

8.6.3 Surface water availability

The impact on surface water resources were also considered in terms of availability. The processing and analysis methodology was as follows:

- A low flow threshold of 1 l/s was set as the lower limit of productive flow.
- The SHETRAN outputs of daily discharge were assessed by counting the number of days per year with flow <1 l/s.

As with groundwater availability, for quantitative comparison of the potential future scenarios, cumulative frequency curves were plotted of the percentage of each year that the low flow threshold was exceeded (flow <1 l/s). These plots show the degree to which surface water availability is affected by the different scenarios. It should be noted that SHETRAN provides this information on groundwater and surface water availability for conversion into spatial plots if required.

8.7 Climate variability

The 200-year simulations applying the synthetic rainfall and PET time series indicated that interannual variability in shallow groundwater availability would be high. This can be seen visually in Figure 8-15 and Figure 8-16 and is confirmed by the statistics in Table 8-5. On average, a little over 30% of the catchments could be cultivated under irrigation all year. The average proportional coverage of high success is almost identical for both catchments, though with greater interannual variability in the Amen catchment as shown by the high coefficient of variation of ~36%. However, even in the worst drought years, 7 and 10% of the Amen and Brante catchments have groundwater available for year-round irrigation. The worst cluster of drought years can be seen during a four-year period from years 6-9 in Figure 8-15 and Figure 8-16, although, the proportion of the arable land that could sustain a second and third growing season only once drops below 20% during this period for the Amen catchment and only twice drops below 25% for the Brante. The coverage of success is lower for the Brante catchment though is generally very low for both. This is significant and indicates that either year-round irrigation is feasible or only rainfed agriculture is possible for most areas. Therefore, irrigated cultivation need not be restricted to short-cycle crops, but the main long-cycle crops usually grown in the wet season may be grown under irrigation.

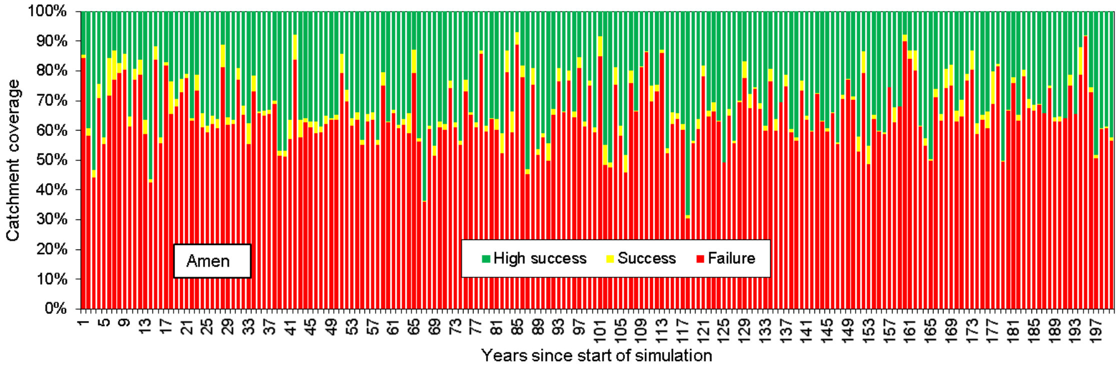


Figure 8-15. Amen catchment baseline plot of proportional coverage of failure (only rainfed agriculture possible), success (second growing season possible) and high success (second and third growing season possible; shallow groundwater available year-round) per year for the 200-year simulation showing the potential impact of climate variability on groundwater availability.

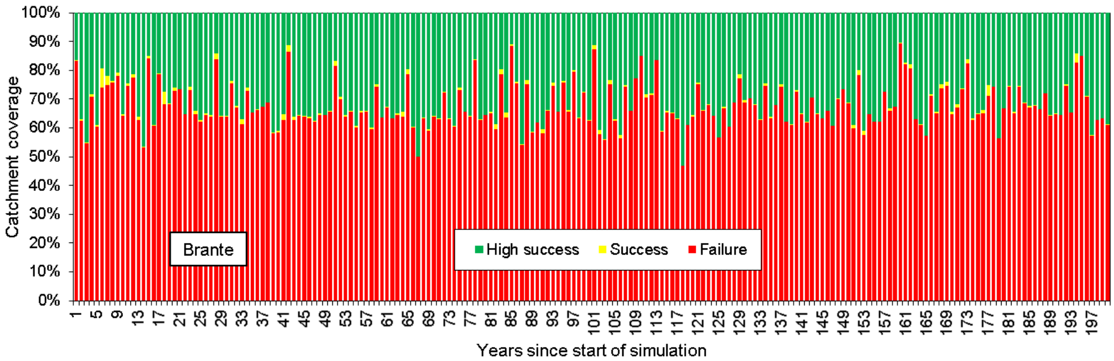


Figure 8-16. Brante catchment baseline plot of proportional coverage of failure (only rainfed agriculture possible), success (second growing season possible) and high success (second and third growing season possible; shallow groundwater available year-round) per year for the 200-year simulation showing the potential impact of climate variability on groundwater availability.

Table 8-5. Statistics of proportional coverage of high success, success, and failure from Amen and Brante baseline 200-year simulations. CV = coefficient of variation, c10 = 10th percentile, c90 = 90th percentile.

	Amen			Brante		
	High success	**Success**	**Failure**	**High success**	**Success**	**Failure**
Mean	31.4%	2.8%	65.8%	31.7%	0.6%	67.6%
St.dev	11.2%	2.4%	10.5%	7.9%	0.8%	7.6%
CV	35.9%	84.3%	15.9%	24.9%	126.4%	11.3%
Min.	6.9%	0%	30.4%	10.3%	0%	46.8%
c10	14.5%	0.3%	52.7%	19.9%	0%	59.7%
Median	33.9%	2.1%	63.8%	34.2%	0.4%	65.5%
c90	43.6%	6.4%	79.4%	39.6%	1.5%	78.4%
Max.	68.4%	12.8%	91.5%	53.0%	6.6%	89.3%

The simulations presented here formed the baseline for comparison when applying the potential future LULC and abstraction scenarios.

8.8 Land use land cover (LULC) change

8.8.1 Simulated LULC scenarios

The LULC change scenarios were selected based on observations and on literature review of changes occurring in the region as described earlier caused by a growing population. Essentially, a sensitivity analysis approach was used since detailed LULC spatial information was not available, e.g. from processed satellite images. LULC change simulations involved adjusting the proportional coverage of LULC classes. The coverage of a particular class was increased by 10, 20, 50 and 100% over another class:

1. Pasture was progressively converted to arable land to simulate encroachment of cultivation onto floodplain or other grasslands.
2. Highland areas were progressively converted to arable land to simulate increasing cultivation on areas currently considered marginal due to slope or naturally vegetated areas that are being cleared.
3. Highland areas were progressively converted to bareground to simulate excessive firewood collection and overgrazing.
4. Arable areas were progressively converted to Eucalyptus to simulate expansion of plantations.

The full range of LULC scenarios simulated is shown in Table 8-6.

Table 8-6. The potential future climate variability, LULC and abstraction scenarios simulated with SHETRAN.

	LULC scenario	**LULC change**	**Abstraction rate**	**Abstraction period**	**Abstraction area**
Baseline	Existing	-	-	-	-
1 – 4	Pasture converted to arable	10% 20% 50% 100%	-	-	-
5 – 8	Highlands converted to arable	10% 20% 50% 100%	-	-	-
9 – 12	Highlands converted to bareground	10% 20% 50% 100%	-	-	-
13 – 20	Arable land converted to Eucalyptus (two variations)	10% 20% 50% 100%	-	-	-
21 – 23	Existing	-	1 l/s/ha	3 months	10% of arable area 50% of arable area 100% of arable area

The particular cells that had their LULC converted were randomly selected within their land class with a Python script. The two additional LULC classes that were not run in the historical models discussed in Chapter 7 were bareground and Eucalyptus. Bareground was simulated with a higher Strickler coefficient of 2.0 $m^{-1/3}/s$, a low AET/PET ratio and proportional vegetation coverage reduced to zero. Eucalyptus was simulated in two ways:

1. With a low Strickler coefficient of 0.5 $m^{-1/3}/s$, high AET/PET ratios, increased rooting depth and root density at depth, high leaf area index (4.0) and increased canopy storage capacity; the parameter values were based on numerous studies including some that reported field investigations from the Lake Tana Basin, e.g. Moroni *et al.* (2003); White *et al.* (2010); Chanie *et al.* (2013).
2. With parameters as for variation 1 and with increased PET for the cells containing Eucalyptus. The PET time series was calculated using the FAO56 Penman-

Monteith method although in trees PET is higher because of the lower aerodynamic resistance compared to the reference crop short grass. A multiplier of 1.5 was applied to the PET time series for areas of Eucalyptus to simulate the additional expected evapotranspirative loss. This multiplier is applied with some uncertainty as published studies on the topic include: Enku *et al.* (2017a) who measured evapotranspiration of Eucalyptus to be double the reference PET in the Lake Tana Basin; Sharma (1984) measured Eucalyptus evapotranspiration up to three times reference PET in the wet season of Australia though it was generally equal in the dry season; Roohi and Webb (2016) quote a value for Eucalyptus of 15-20% greater than PET, and; Hutley *et al.* (2000) measured evapotranspiration of Eucalyptus of around a third of PET (the latter two studies are also from Australia). The average variation in additional evapotranspiration of Eucalyptus above PET measured in these studies led to the selection of the 1.5x PET multiplier.

8.8.2 Results for simulated LULC scenarios

Firstly, considering the conversion of pasture to arable land, Figure 8-17 and Figure 8-18 show that the impacts on surface and groundwater availability are negative and, though quite small for the Amen catchment, are significant for the Brante catchment. The negative impact is due to the greater evapotranspiration losses of the simulated crops over grasses. The reason for the discrepancy between catchments is the higher proportion of pasture in the Brante catchment, 47% compared to 34% of the Amen, which when converted has a correspondingly greater impact on the overall catchment water balance.

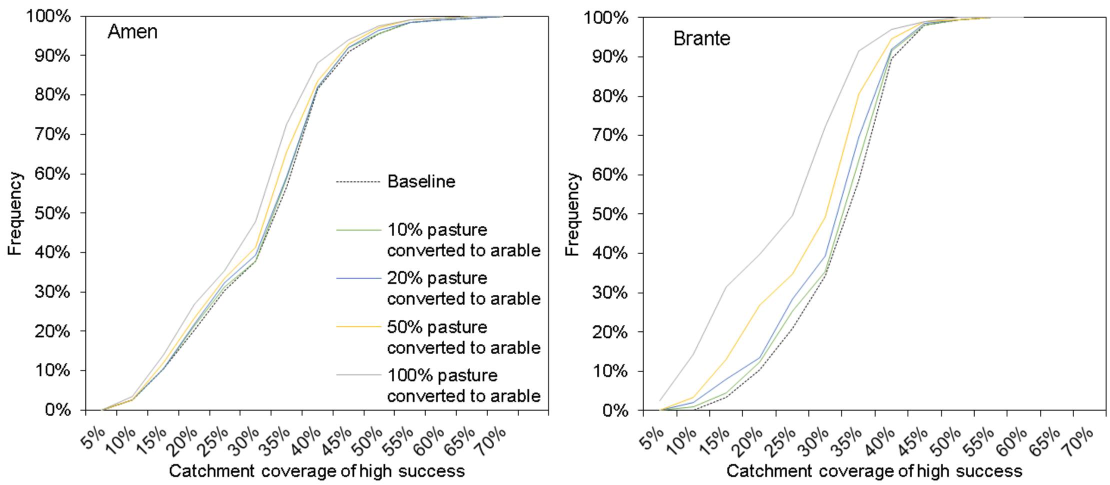


Figure 8-17. Cumulative frequency curves showing the impact of converting pasture to arable land on shallow groundwater availability (the proportional coverage of high success).

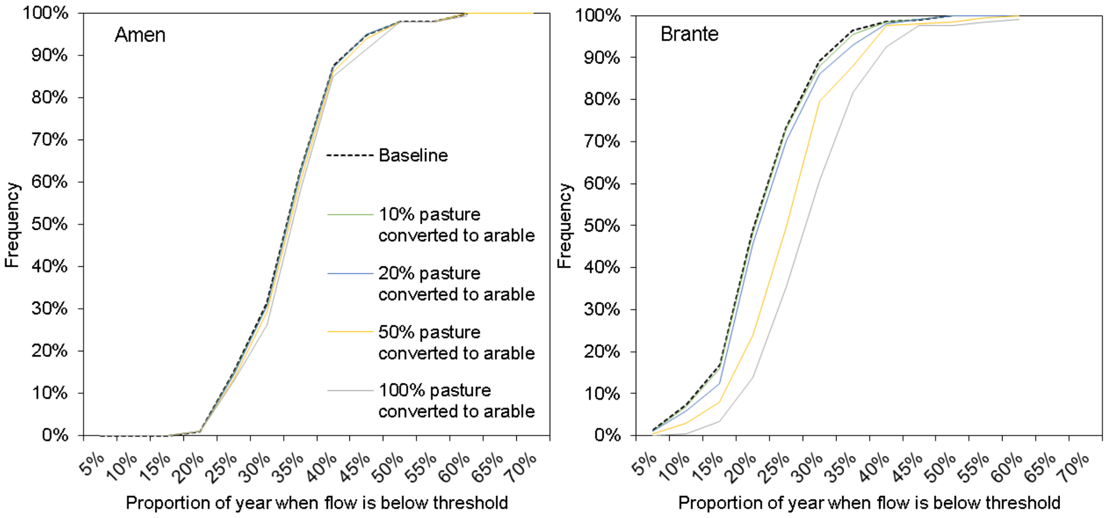


Figure 8-18. Cumulative frequency curves showing the impact of converting pasture to arable land on surface water availability (the proportional of the year when flow is <1 l/s).

Secondly, considering the conversion of highlands to arable land, almost no impacts are seen on surface and groundwater availability in either catchment (Figure 8-19 and Figure 8-20). The principal reason is the small proportional coverage of the highland LULC category, 17% for the Amen and 5% for the Brante catchments. In addition, the water demand of the scrub-like vegetation is only slightly greater than the common tall crops such as maize and sugarcane, hence little difference in the overall water balance, and therefore only slight positive impacts on surface and groundwater availability were expected and seen.

Potentially significant for the scenarios converting pasture or highlands to arable land, though not specifically simulated in the models, is the impact of tillage on infiltration. While there is research that shows that the roughness resulting from ploughing required by some crops increases infiltration (e.g. Lipiec *et al.* (2006); de Almeida *et al.* (2018)) other research suggests tillage decreases infiltration (e.g. Abid and Lal (2009); Tuzzin de Moraes *et al.* (2016)).

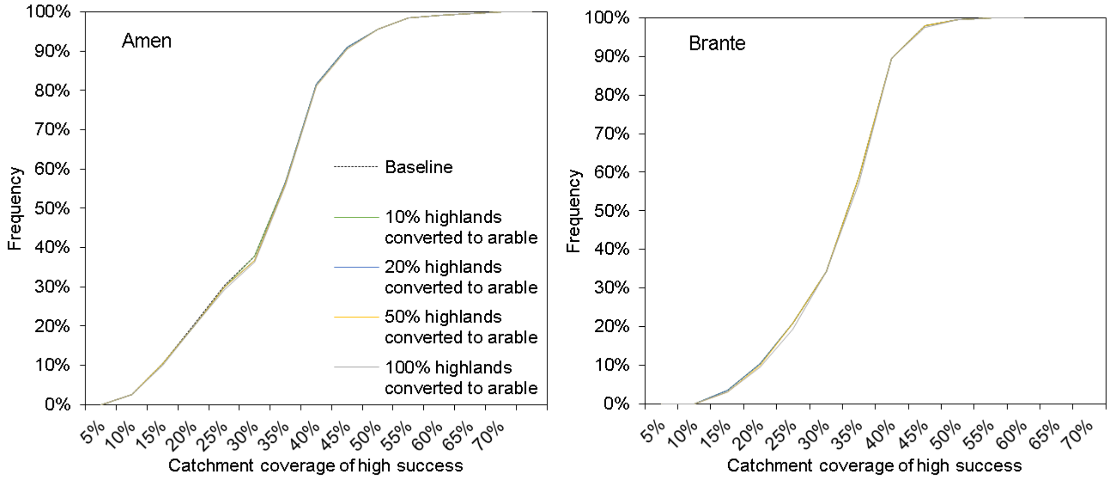


Figure 8-19. Cumulative frequency curves showing the impact of converting highlands to arable land on shallow groundwater availability (the proportional coverage of high success).

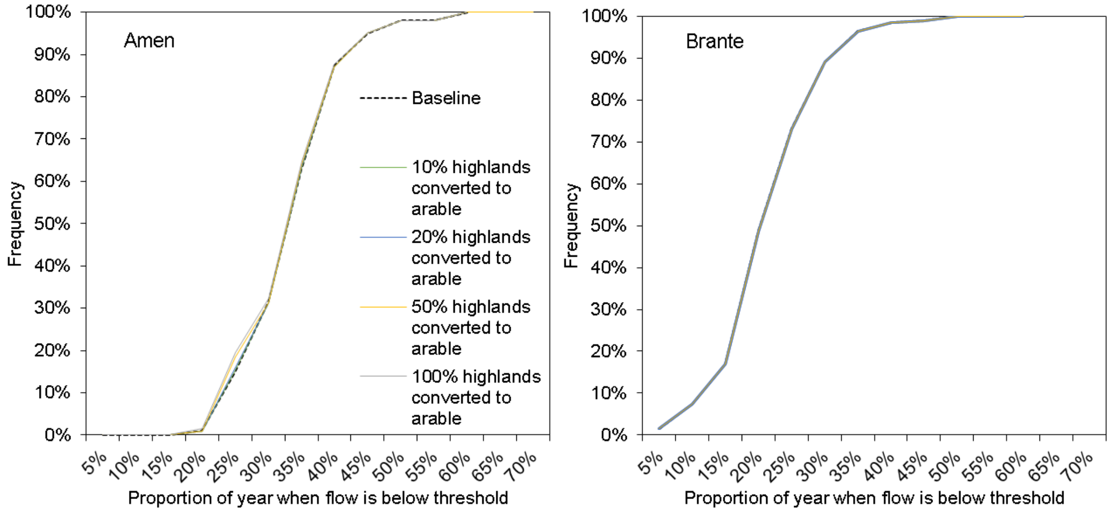


Figure 8-20. Cumulative frequency curves showing the impact of converting highlands to arable land on surface water availability (the proportional of the year when flow is <1 l/s).

Thirdly, regarding the degradation of highlands to bareground, significant positive impacts are seen on surface and groundwater availability in both catchments (Figure 8-21 and Figure 8-22). There is an increase in flashiness of the river levels but more significant is the reduction in evapotranspirative losses causing an increase in recharge maintaining groundwater levels and surface water flows for longer into the dry season. However, importantly, the modelling does not simulate hillslope erosion commonly observed elsewhere in Ethiopia. The positive hydrological impacts may be temporary until gully formation and soil erosion lower water tables.

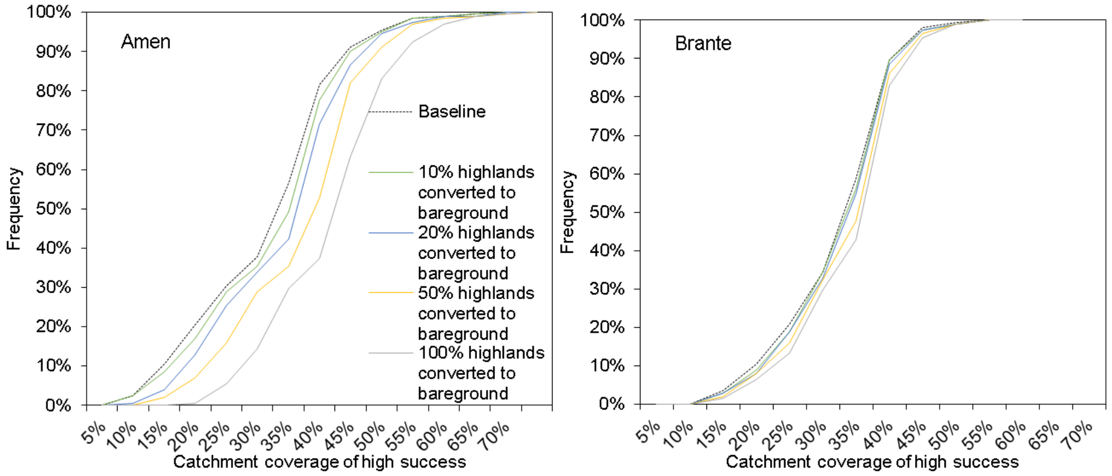


Figure 8-21. Cumulative frequency curves showing the impact of degrading highlands to bareground on shallow groundwater availability (the proportional coverage of high success).

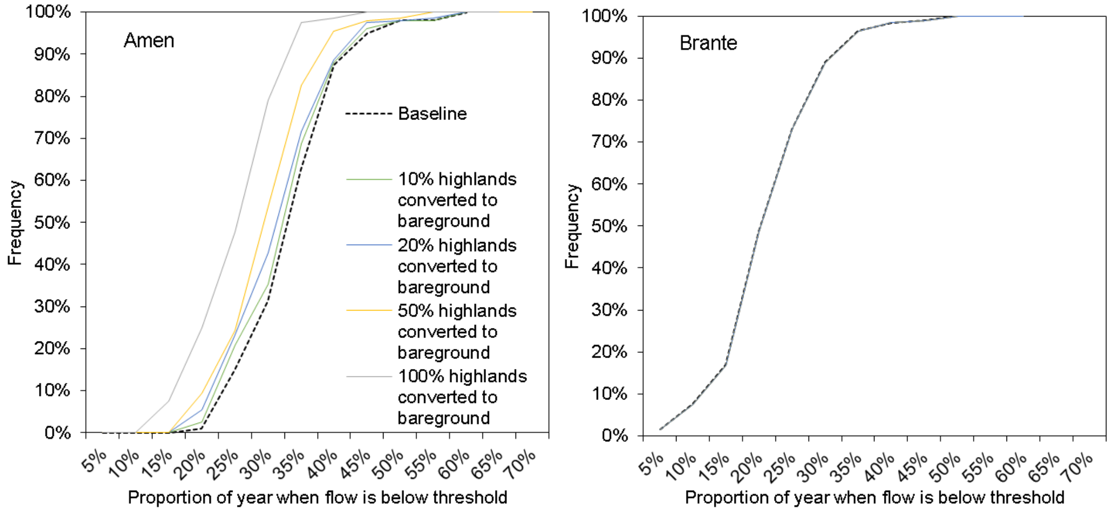


Figure 8-22. Cumulative frequency curves showing the impact of degrading highlands to bareground on surface water availability (the proportional of the year when flow is <1 l/s).

Finally, Figure 8-23 and Figure 8-24 show that the expansion of Eucalyptus plantations on arable land had the greatest impacts of all the LULC scenarios. The increase in evapotranspirative losses significantly reduces surface and groundwater availability. The negative impacts are greater for the Amen catchment even though the proportional coverage of arable land is similar for both catchments, 50% (Amen) and 48% (Brante). The second variation in Eucalyptus parameterisation shows greater impacts, explained by the increased PET time series applied to Eucalyptus cells. The uncertainty over the correct simulation of the increased evapotranspiration from Eucalyptus means the most likely hydrological impacts are somewhere between the results of the two alternative methods.

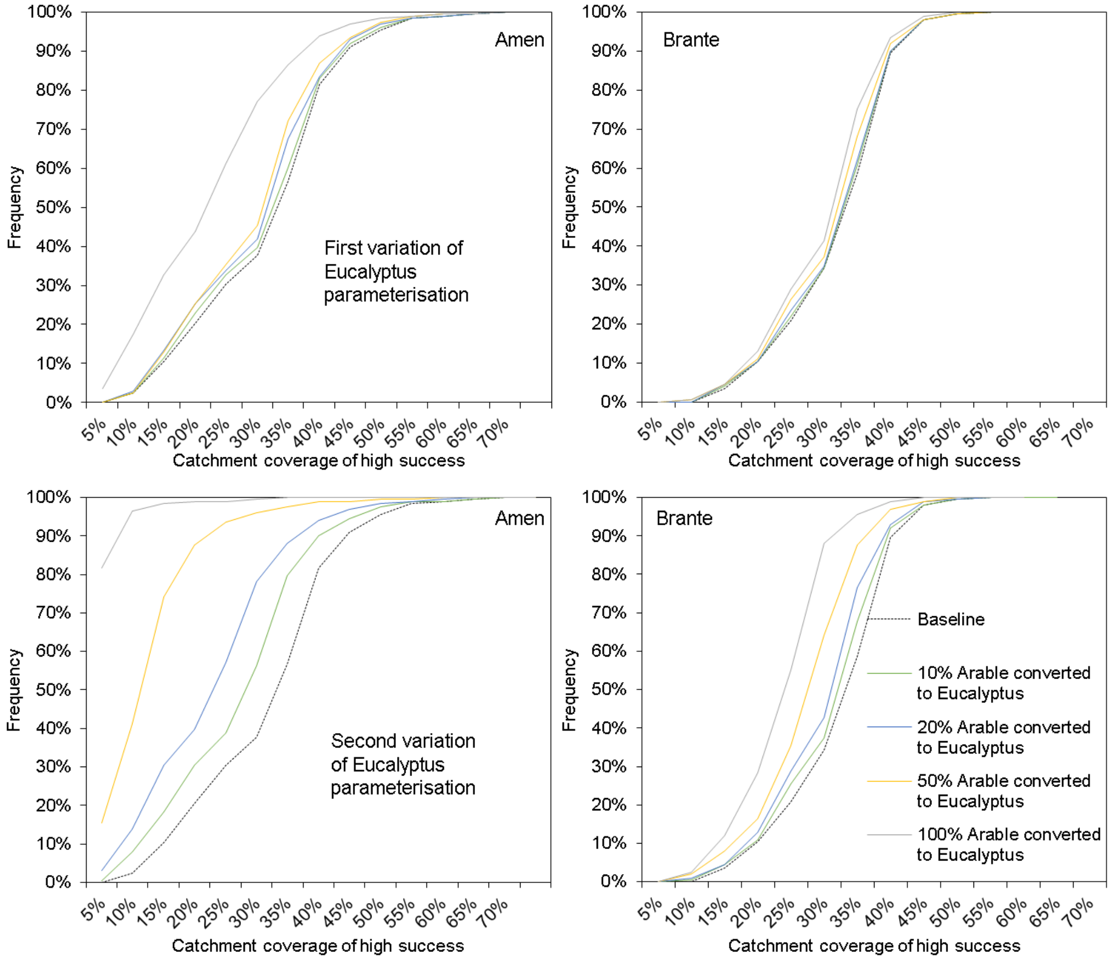


Figure 8-23. Cumulative frequency curves showing the impact of expanding Eucalyptus plantations on arable land on shallow groundwater availability (the proportional coverage of high success). The two variations refer to alternative methods of parameterising the Eucalyptus LULC category.

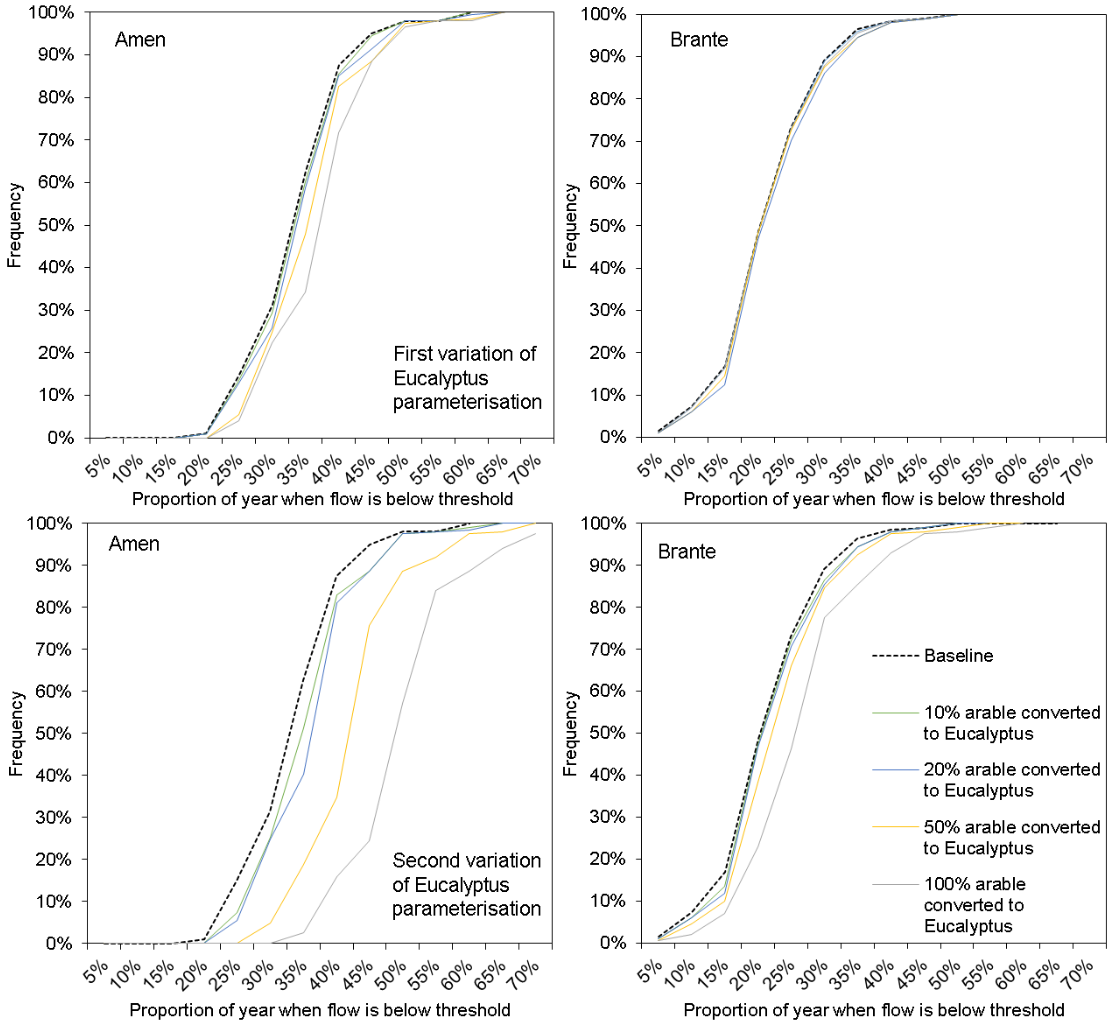


Figure 8-24. Cumulative frequency curves showing the impact of expanding Eucalyptus plantations on arable land on surface water availability (the proportional of the year when flow is <1 l/s). The two variations refer to alternative methods of parameterising Eucalyptus LULC category.

8.9 Increased groundwater abstraction

8.9.1 Simulated abstraction scenarios

The future abstraction scenarios are based on literature review of the "Green Revolution" in South and East Asia where cheap pumps and energy subsidies kick-started the explosion in small-scale irrigation. Therefore, this future scenario carries the assumption that pumps, fuel and irrigation infrastructure are going to become available at low cost and/or a government ministry, NGO or private investor provides, directly or via credit, the necessary equipment. As defined previously, the most likely future abstraction rate is 1 l/s/ha and the most likely pumping period would be a second growing season immediately after harvest of the main rainfed crop for 3 months (1st November to 31st January). The most likely short-cycle crop types, as discussed in Section 8.6.1, would be high-value vegetables and cash crops such as okra, chilli peppers and tomatoes. The areas subjected to abstraction and irrigation were 10%, 50% and 100% of the area of arable land cover; this translated as 177, 887 and 1773 cells for the Amen model and 300, 1500 and 3000 cells for the Brante model. This arbitrary distribution of abstraction and irrigation was specified based on the Asia examples where small-scale irrigation expanded autonomously. The resolution of the models meant that one cell was one hectare in size, therefore, to simulate a well abstracting at 1 l/s/ha, an abstraction of 1 l/s was applied to the selected cells. Irrigation occurred in the same cell as the groundwater was abstracted and at the same time, i.e. there was no storage for later irrigation. Irrigation was simulated as additional rainfall input specifically onto cells with abstracting wells. Wells were simulated, as observed, to be of the same depth as the regolith shallow aquifer. The range of abstraction scenarios is listed in Table 8-6. It is noted that the baseline case involves no abstraction as current levels of abstraction from the shallow aquifer are for domestic use and as such are low and sparsely distributed.

8.9.2 Results for simulated abstraction scenarios

The results from the abstraction simulations showed little impact on surface and shallow groundwater resources from abstracting and irrigating (Figure 8-25 and Figure 8-26). Shallow groundwater availability reduced as the area under abstraction and irrigation increased. However, surface water availability increased (at the expense of groundwater availability) as some excess irrigation water not evapotranspired by crops augmented dry season low flows. Return flow of irrigation water to river channels is well documented, often constituting a large proportion of flow (Blodgett *et al.*, 1992; Smakhtin, 2001). What’s more, the simulations abstracted and irrigated at a constant rate regardless of occasional dry season rainfall, which would also contribute to return flows. The Amen and Brante catchments showed similar responses with the 10% arable area under irrigation simulation giving results very similar to the baseline, especially concerning shallow groundwater availability. The slight positive impact on surface water availability and negative impact on shallow groundwater availability showed that flow paths from fields to rivers must be rapid and are likely via surface runoff and unsaturated zone flow. It should be noted that the increase in surface water availability is measured at the outlet. It is possible that certain reaches may see slight decreases in surface water availability, though, this would be less significant given the method of abstraction (from hand-dug wells) compared to stream diversions for irrigation.

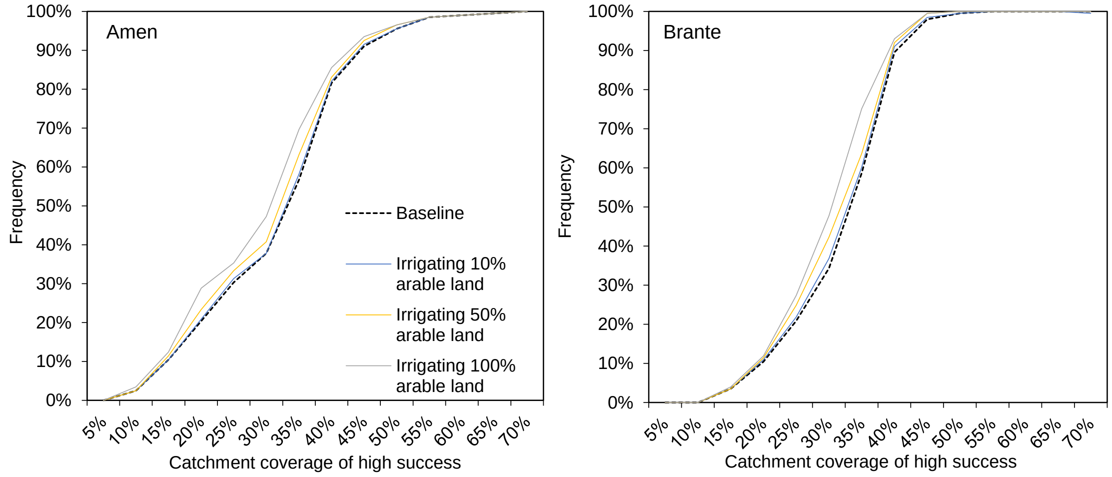


Figure 8-25. Cumulative frequency curves showing the impact of increasing abstraction and irrigation on shallow groundwater availability (the proportional coverage of high success).

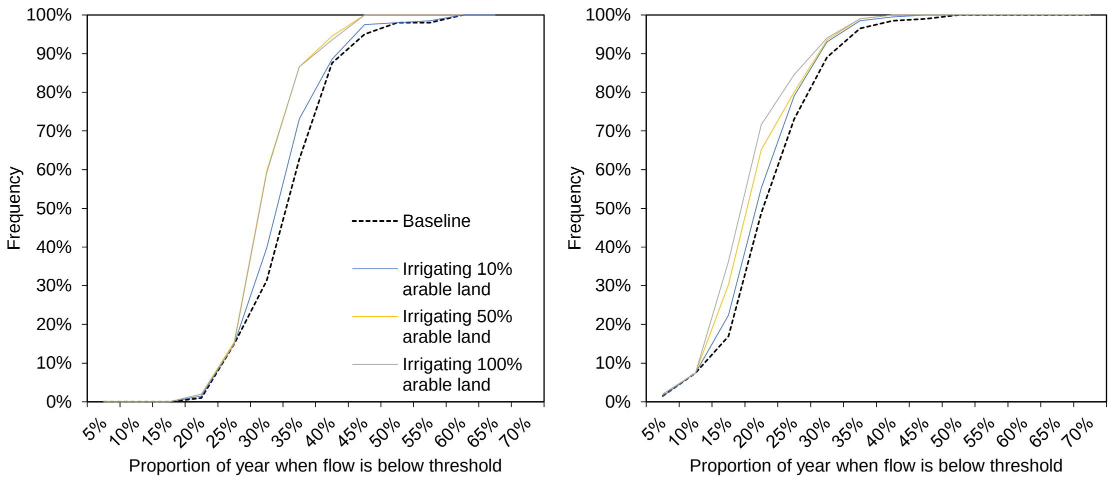


Figure 8-26. Cumulative frequency curves showing the impact of increasing abstraction and irrigation on surface water availability (the proportional of the year when flow is <1 l/s).

8.10 Discussion and conclusions

Even though rainfall, and therefore recharge, has high interannual variability, the shallow aquifer geometry means that availability of shallow groundwater is mostly storage- rather than recharge-controlled. This means that even in drought years, recharge is sufficient to substantially refill the thin regolith aquifer.

Climate variability will strongly affect surface and groundwater availability with high interannual variation in proportional coverage of areas able to have an additional growing season after the main rainfed season. However, even during the most extreme and prolonged droughts, a substantial proportion of the catchment will still have available and accessible shallow groundwater for a second and possibly a third growing season. Examples of shallow groundwater resilience to climate variability include northern Ghana where shallow groundwater irrigation has led to poverty alleviation (Laube *et al.*, 2008). A particularly bad drought in 2006 led to many farmers losing crops due to water shortages, though many others simply dug their wells deeper and still found groundwater at <8 m.

Increased abstraction for irrigation resulted in small impacts on surface and groundwater availability. This finding is significant and positive for farmers who gain access to pumps, to the local community who use groundwater for domestic supply, to downstream water users, and to ecosystems reliant on the same water resources. The finding somewhat contradicts the traditional view that considers excessive withdrawal followed by aquifer and surface water depletion to be a constraint on the use of shallow groundwater for small-scale irrigation (e.g. Adams (1993); Giordano and Villholth (2007); Ngigi and Denning (2009)). Abric *et al.* (2011) extol the benefits of small-scale irrigation in West Africa then go on to describe how overdrafting of groundwater leads to continuous lowering of the water table and increased exploitation costs. However, their studied region of West Africa (Niger, Burkina Faso, Mali and Nigeria) receives much less rainfall and recharge than the Dangila study site and the shallow groundwater exploitation examples are somewhat large-scale, e.g. the Fadama Development Project in Nigeria (Inocencio *et al.*, 2007). Similarly, the Haromaya watershed in eastern Ethiopia is an oft-cited example of excessive abstraction causing surface water bodies to dry up (e.g. Alemayehu *et al.* (2007); Werner *et al.* (2013)). However, this region of Ethiopia is also semi-arid, low transmissivity constrains excessive abstraction from the shallow aquifer (Tadesse *et al.*, 2010a) and reductions in lake volumes are most likely due to LULC change and land degradation (Gebere *et al.*, 2016). The slight decreases in shallow groundwater availability simulated for the Dangila study site mean some local management of groundwater use may be required to negate conflicts between adjacent (upgradient-downgradient) water users. However, the slight increases in surface water availability due to irrigation return flows mean wetlands and downstream surface water users would not be negatively impacted by small-scale irrigation.

LULC change could have the greatest impact on water resources. However, it is noted that the 100% change scenario would be extremely unlikely; it was simulated mainly to see the direction the impacts on surface and groundwater resources could take. Wet season flooding prevents significant agriculture, of the type currently practised, on most of the floodplain pasture, high slope gradients would prevent all of the highland areas from being cultivated and the basic human need for food crops surely limits the land allocation that can be made to Eucalyptus planting thus preventing it from taking over completely. In addition, the World Bank funded Sustainable Land Management Project is active in Ethiopia with a large budget and wide geographical reach aimed at preventing and restoring degraded land (World Bank, 2017a), therefore, it is hoped a 100% conversion of highlands to bareground would be avoided. The 50% change scenarios are less far-fetched though they may require a change to farming practices such as terracing of hillslopes and retreat cultivation of floodplains as seen on the edges of Lake Tana. The most likely and most impactful change is the increased planting of Eucalyptus. While there is uncertainty over which variation most accurately simulates its impact, if the first variation is considered the lower end of the impact range, then the negative effects on surface and groundwater availability are still pronounced. This finding is in agreement with the many observational studies in the literature that report decreased river flows and reduced groundwater levels following Eucalyptus planting, e.g. Van Lill *et al.* (1980); Sikka *et al.* (2003); Rodriguez Suarez *et al.* (2014) due to greater wet season interception and greater dry season evapotranspiration. The additional impact only briefly mentioned is the yield losses from crops grown in proximity to Eucalyptus plantations, which would obviously be more pronounced if the number of plantations increases.

It has been shown that the shallow groundwater resource at Dangila *woreda* is resilient to climate variability, LULC change and increasing abstraction. There exists the potential for a sustainable intensification in irrigated agriculture. Whereas the maps presented in Chapter 7 showed the areas that, on average, have greatest potential for small-scale irrigation, the model outputs from this chapter reveal how the potential areas spatially vary under different climatic conditions and with future variations to land use and abstraction. This more detailed analysis enables greater targeting of areas for development of small-scale irrigation and provides more confidence that such development is sustainable.

Chapter 9. Conclusions, including recommendations, transferability, and future work

9.0 Chapter overview

Chapter 8 showed, through simulation of potential future scenarios with SHETRAN, that the shallow groundwater resource is resilient to climate variability, land use change, and increasing abstraction. This chapter will draw together findings from all the previous chapters presenting the conclusions with reference to the aim and research questions in Chapter 1. Recommendations are provided for stakeholders, and the transferability of the results and of the methodology is discussed. The limitations of the study are described before the final section gives suggestions for future work.

9.1 Conclusions

To conclude this thesis, we will revisit the aims and research questions presented in Chapter 1. The overall aims of this PhD research were:

> Firstly, to determine the potential for small-scale irrigation and the resilience of shallow groundwater resources used by rural communities at a representative study site in Ethiopia.

The research demonstrated that shallow groundwater resources do have the potential for exploitation for small-scale irrigation and the most suitable areas were identified. The research also showed the resilience of the resource in the face of likely climate variability, and only the most extreme land use changes had severe negative impacts on the resource. Critically, the resource is resilient to small-scale abstraction for irrigation.

> Secondly, to develop transferable methodologies for assessment of shallow groundwater resources throughout SSA.

The research demonstrated that citizen science for the collection of hydrometeorological time series is an effective measure in areas of data scarcity, benefitting both researchers and local stakeholders. Field hydrogeological investigative techniques were developed and local partners, such as Bahir Dar University students, were trained in their implementation for shallow groundwater assessment. The extensive recharge assessment revealed which methods are most appropriate for recharge estimation of shallow aquifers with wet, though seasonal, climates. The modelling indicated areas with highest potential for shallow groundwater exploitation and suggested simpler means for identification of such areas without requiring costly and complex modelling, i.e. through field hydrogeological and geomorphological assessment and through local community discussions.

The specific research questions in Chapter 1 were:

1. Do shallow aquifers have the requisite properties, in terms of hydraulic conductivity, potential well yield, specific yield, aquifer geometry and hydrochemistry, for productive groundwater use?

The field investigations conducted in Dangila *woreda* described in Chapter 4 showed that while hydraulic conductivity and consequently well yield, and specific yield of this shallow aquifer are quite low, they are not too low for small-scale irrigation; especially, if abstraction commenced at the immediate cessation of the wet season when well yield is high. Specifically, dry season average K was 1.6 m/d while the wet season average was 6.5 m/d; the greater saturated thickness led to interception of higher K layers thus increasing average K. These results gave dry season average yield of 0.2 l/s and wet season average of 1.7 l/s, while the median specific yield was 0.09. Multiple wells and/or wells of larger diameter would likely have to be excavated to increase well bore storage, as described in the recommendations section of this chapter. The aquifer is also quite thin in many areas (<5 m), which restricts the shallow groundwater volumes that can be stored. However, the modelling in Chapter 7 revealed areas where shallow groundwater is available year-round and when abstraction was modelled in Chapter 8, the resource was not depleted. Hydrochemistry analysis described in Chapter 4 indicated that the shallow groundwater is suitable for irrigation. What's more, contrasting major ion and stable isotope hydrochemistry of the shallow and deep groundwaters suggest that there is little to no connection between the shallow regolith aquifer and the deep fractured aquifer. Radon-222 measurements support this conclusion, as shallow aquifer leakage was not identified. The stable isotope analysis also enabled development of a conceptual model where shallow groundwater flow does not necessarily match surface water flow directions from the small sub-catchment "dambos". In summary, the research showed that shallow aquifers could have the requisite properties for productive use.

2. Due to the scarcity of time-series data, are community-based hydrometeorological monitoring programmes able to produce useful, high quality data comparable to formal data sources?

As explained in Chapter 5, the satisfactory application of accepted quality control procedures and statistical comparisons with formal data sources indicated that the community-monitored hydrometeorological data from Dangila is of high quality. Furthermore, the community data often outperforms some formal and remote sensing or reanalysis data; especially concerning groundwater where there is no formal equivalent. The research showed that such citizen science data can infill the gaps in sparse and deteriorating formal monitoring networks. This hydrometeorological data was invaluable for the initial understanding of the hydrological system and the development of the conceptual model. The data were then used in the recharge assessments to assess if a renewable shallow groundwater resource was present. Finally, the time series data enabled modelling of the shallow groundwater as simulated river flows and groundwater levels were calibrated against the observed data.

3. Can shallow groundwater be considered a renewable resource, and; which recharge assessment methods provide the highest confidence in the calculated recharge amounts when applied to these types of aquifers?

Chapter 6 reported that recharge to the shallow aquifer was sufficient for small-scale irrigation to consider the shallow aquifer a renewable resource, i.e. groundwater would not be “mined”: The methods computing actual recharge gave a catchment-wide recharge estimation of 280-430 mm/a. A simplistic calculation can be run with this recharge estimate, albeit ignoring other factors relevant to irrigable area: If we specify a nominal irrigation demand of 1000 mm and take the median recharge value from the actual recharge range, a little over a third of the study site could be irrigated without exceeding the recharge rate. The recharge assessment also revealed the range of results that can be computed for a single site, from 45 to 814 mm/a, when multiple recharge estimation methods are applied. The discrepancy in recharge results can provide insights on the hydrogeological system allowing update of the conceptual model and informing the type of recharge computed by the different methods. Concerning recharge method selection, it is crucial to be sure of the spatiotemporal scale of the method, to use high quality input data, to have developed but be willing to further develop the conceptual model, and to know what type of recharge is being computed. In this study, the conceptual model meant streamflow hydrograph and soil moisture balance methods were computing minimum and potential recharge, respectively, rather than actual. If these methods are to be applied to shallow aquifers elsewhere, consideration of the conceptual model and application of additional methods is recommended. For identifying areas of shallow aquifers that may be the most productive for irrigation, water table fluctuation methods that actually calculate change in aquifer storage can reveal areas of highest potential; certain wells analysed in this study showed “recharge” of over 1600 mm (incorporating lateral groundwater flow).

4. Are there easily identifiable zones that show the greatest potential for sustainable intensification of agriculture through shallow groundwater irrigation?

The modelling described in Chapter 7 showed that the base of hillslopes and narrow valleys, corresponding to approximately 17% of the study area, have the greatest potential for small-scale irrigation as the shallow groundwater resource remains available for the longest period in these areas. Areas with the least potential, where shallow groundwater was available for short periods, were high on steeper hills especially near ridges. Additionally, low potential areas were those where the aquifer is thinnest and easily drained such as the large flat floodplains. At shallow aquifers elsewhere, these locations should be easily identifiable from topographic maps and DEMs though well surveys would still be required for appreciation of aquifer thickness variations.

5. How will climate variability, land use change and increased abstraction impact shallow groundwater resources and surface water?

Chapter 8 revealed that, on average, around 35% of the modelled catchments’ arable land had available shallow groundwater year-round (Figure 9-1), allowing cultivation with irrigation, additional to the main rainfed growing season. Modelling of climate variability indicated that even during prolonged droughts, significant proportions of the catchments would still have the potential for a second crop planted immediately following the main rainfed crop harvest; Figure 9-1 shows that in years in the driest 5th percentile, around 15% of the arable area has shallow groundwater available all year.

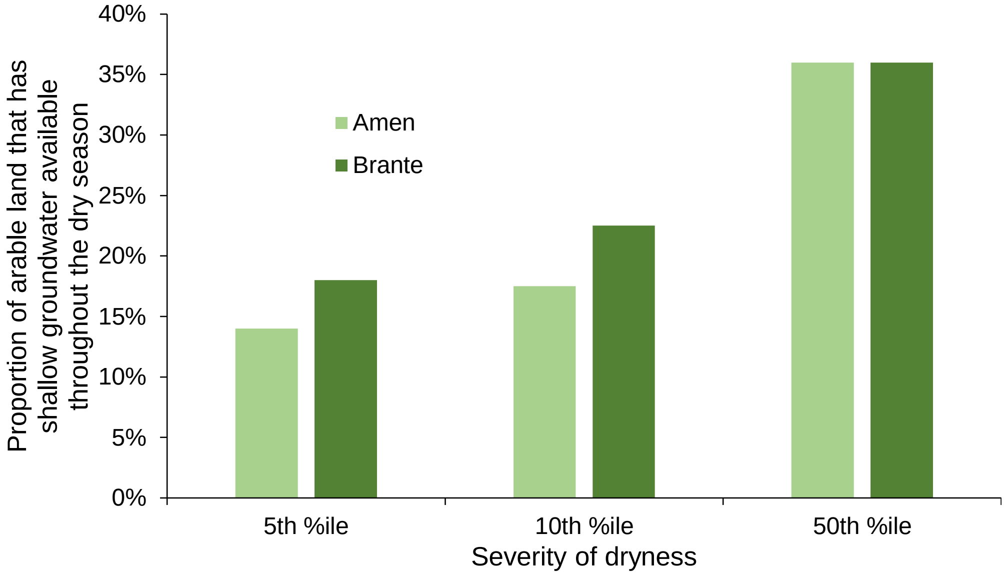


Figure 9-1. Output of climate variability model simulations showing the proportion of arable land that has shallow groundwater available in a particular year according to that year's severity of dryness.

Simulating progressive land use change had varying effects on shallow groundwater and surface water resources. Conversion of pasture (the floodplain grasslands) to arable land had a slight negative impact on shallow groundwater availability but very little effect on surface water. Converting highlands to cultivation had almost no impact on water resources whereas highlands degrading to bareground had a positive impact due to decreased evapotranspiration. Though it is noted that the likely related impacts of soil erosion and gully formation were not simulated and these would increase flashiness of the streams and probably decrease shallow groundwater availability through decreased infiltration and recharge. The land use change scenario that had the greatest (negative) impact was increasing the area of eucalyptus plantations.

Increasing abstraction and irrigation at likely smallholder levels (rate of 1 l/s/ha) had small impacts on shallow groundwater and surface water availability. Simulation of a 3-month irrigated growing season immediately following the main rainfed growing season led to slight reductions in shallow groundwater availability. However, rapid return flows of excess irrigation water led to slight increases in surface water availability.

9.2 Recommendations

9.2.1 Potential for the productive use of shallow groundwater

This research indicated that there is available shallow groundwater for an expansion of small-scale irrigated agriculture at the study site (Chapter 7). What's more, the shallow groundwater resource can be considered renewable (Chapter 6) and is resilient to climate variability, land use change and increasing abstraction based on the simulated future scenarios (Chapter 8).

The recommendation is for a second growing season to commence immediately after the main growing season, taking advantage of residual soil moisture and shallow water tables following the wet season. This would require immediate land preparation and planting following harvest of the main rainfed crop. This is of course with the assumption that pumps and irrigation infrastructure will become available. Cooperation between farmers regarding mobilisation and sharing of the infrastructure should not be problematic as land is currently cultivated cooperatively. There is some risk to planting a second long-cycle crop (e.g. grain), even in areas classed as "high potential", as the modelling in Chapter 8 showed that in the worst drought years, shallow groundwater available year-round is restricted to around 15% of the arable area of the catchments (Figure 9-1). Planting of a short-cycle crop carries less risk of insufficient irrigation water and is the more likely eventuality as research shows that small-scale farmers prefer to grow high-value vegetables and cash crops when irrigated agriculture becomes an option (Kloos, 1991; Rockström *et al.*, 2002; Emana *et al.*, 2015). While it has traditionally been feared that groundwater use for irrigation will have unacceptable impacts on domestic water supply, wetlands and other groundwater-dependent ecosystems (Adams, 1993; Giordano and Villholth, 2007; MacDonald *et al.*, 2009), this research showed that the impacts from small-scale irrigation on surface and groundwater resources would be minor (Chapter 8).

9.2.2 Abstraction strategy

Pumping tests showed that potential well yields might not achieve the desired 1 l/s for irrigation of a hectare (Chapter 4). However, wells are not difficult to excavate, as reported by the local community and indicated by the small (<0.25 ha) backyard plots that commonly have multiple wells. Therefore, to expand irrigation onto the fields currently only utilised for rainfed agriculture, a high density of wells may have to be excavated. Therefore, pumping equipment will have to be mobile, or many pumps will be required, in order to switch to abstracting from a different well as each is depleted. In the meantime and overnight, the non-abstracting wells will refill naturally. The recommendation is for electric submersible pumps. Solar power would be preferable, though, the local community have spoken of the desire for small generators that could also be used at home: During workshops, the local community questioned having generators in fields to power pumps when they do not have light in their houses. The generally shallow water table means simple and low cost motorised vacuum or centrifugal pumps would be sufficient, however, the altitude of ~2000 m means suction lift is restricted to around 2 m. Therefore, for such pumps to be practicable, shelves would need to be excavated at depths in the wells for pump placement, as described by Carter and Alkali (1996).

9.2.3 Well design

Large diameter wells would be required if shelves for pumping infrastructure were to be excavated, and larger diameter is also a recommendation from a point of view of storage. The reason for the multiple well recommendation is that the low transmissivity would lead to a well being pumped dry before it could naturally refill. Larger diameter wells would increase the well bore storage meaning less wells would be required and the pumping equipment could be moved less frequently. This is not a new idea to Ethiopia as large diameter wells are utilised for these same reasons in Tigray, where they are often stone-lined to prevent collapse (Woldearegay and Van Steenbergen, 2015).

9.2.4 Floodplain cultivation

Modelling the future land use change of conversion from pasture to cultivation indicated that this scenario would not have a significantly negative impact on surface and groundwater resources (Chapter 8). Therefore, could this scenario be encouraged? The generally flat and seasonally inundated floodplains are almost exclusively used as pasture for cows, sheep and goats, typically tended by local children. Other infrequently observed floodplain activities are harvesting of wetland vegetation for animal fodder and small plant nurseries found beside perennial reaches of streams during the dry season. While the floodplain marginal areas are sought after for cropping to take advantage of residual moisture and shallow water tables, cropping is largely non-existent within Dangila *woreda* on the floodplains themselves. Elsewhere in the Amhara Region, wetlands have been put to use for rice growing. A study by Tefera (2017) from Fogera Plain adjacent to Lake Tana reported that participation in the rice industry increased from 30 households in two *kebeles* with an area coverage of 6 ha in 1993/94 to 34,249 households in 24 *kebeles* with an area of 20,230 ha by 2014/15. Fogera district now produces 60% of Ethiopia's rice. Surveys and interviews revealed that ~55% of producers rely on rain and ~45% supplement rainfall with irrigation water from rivers and springs. Multiple cropping cycles per year are practiced utilising residual moisture in seasonally waterlogged areas. In addition to local consumption or market sale, the grain straw was used for house construction, animal feed, as a fuel source, and as a raw material for some manufacturing processes. Floods and related water-borne diseases were serious problems on the plains around Lake Tana (Sewmehon, 2012), however, with the introduction of rice as a crop, these water-rich ecosystems have developed from an environmental problem to an economic and lifestyle opportunity (Tefera, 2017). Rice production has had such a positive impact that the crop is known locally as “white gold” (MoWIE, 2015; AgroBIG, 2016). Tefera (2017) states that there was initial resistance to rice production due to a perception that the grain causes infertility in humans. This was apparently resolved through collaborative and “aggressive” promotion by the local agricultural research centre. It seems feasible for such a transformation of wetlands to occur in Dangila *woreda*. As in Fogera, the local population generally speak of the problems caused by the seasonally inundated floodplains, in particular the extended journey times as the wetlands can often not be crossed during the wet season, however, in Fogera the seasonal inundation is now considered a blessing rather than a curse (Tefera, 2017). Similar complaints, including of flooded or waterlogged fields, were recorded in the wider Gilgel Abay catchment by Abera (2017). Whereas Fogera plain occupies an expansive lakeshore position, an area of over 500 km^2, there are many examples of much smaller scale agricultural exploitation of seasonally flooded land. A well-developed system of rice cultivation exists in small seasonal valley bottom swamps in Sierra Leone, which are also cultivated with such crops as wheat, tomatoes and onions during the dry season to take advantage of the better soil fertility compared to upland soils (Richards, 1985; Dries, 1991). Small-scale ‘garden’ cultivation of rice with dry season crops at the margins, based on indigenous water management techniques, takes place in dambos of Zimbabwe, Zambia and Malawi (Dixon, 2003) that are geomorphologically similar to the features seen in Dangila. As long ago as 1998, Rwanda already had 165,000 hectares of wetlands, 50% of which are cultivated, and the Tanzania Ministry of Agriculture were developing policies for utilisation of its ~850,000 ha of wetlands (Inocencio *et al.*, 2003). However, before promoting agricultural development of Dangila’s wetlands, it must be stated that there is currently little awareness of the status of Ethiopia’s wetlands ecosystems (Abebe and Geheb, 2003). These ecosystems support both aquatic and terrestrial biodiversity, e.g. around 25% of Ethiopia’s bird species are wetland-dependent (Wondefrash, 2003) and some wetland plants are used locally for medicinal purposes (Hailu, 2003). In addition, the hydrological controls of the floodplains in terms of groundwater recharge and flood control is uncertain (Abebe and Geheb, 2003). Both Dugan (1988) and Roggeri (2013), however, argue that the conversion of wetlands to a different ecosystem should be considered where a cost benefit analysis proves that conversion is the most effective means of contributing to the social and economic needs of the human population. The current use of the floodplains is likely in relative harmony with the ecosystem: Fynn *et al.* (2015) discuss how even overgrazing does not impact such ecosystems because they are so waterlogged in the peak wet season that animals can only access the periphery allowing vegetation to fully recover.

9.2.5 Conversion from Eucalyptus to Pine

The impact on surface and groundwater availability caused by increased Eucalyptus planting was the greatest of all proposed land use change scenarios modelled (Chapter 8). Eucalyptus planting is reported to be on the increase in the Lake Tana Basin even though farmers are aware of its negative impacts on groundwater levels, springs and streamflow, and on adjacent crop yield (Chanie *et al.*, 2013; Alebachew *et al.*, 2015; Jaleta *et al.*, 2016). The demand (locally, nationally to Tigray, and internationally to Sudan) for wood for house-building and charcoal production is unlikely to diminish in the short-term due to the high population growth rate and loss of native forest that could otherwise provide timber and firewood (Abiyu *et al.*, 2016). Pine could be an alternative cash crop that is not as water intensive. Eucalyptus is popular because it is so highly productive with growth rates of >35 m^3/ha/a and because of its short rotation length of 6-8 years (Albaugh *et al.*, 2013). However, in many parts of the world, pine is favoured, even though the growth rate is less at 25-27 m^3/ha/a and the rotation period is longer at 15-25 years, as it is known to be less water intensive (Maier *et al.*, 2017). Paired catchment studies are abundant in the literature comparing the effects of pine with that of Eucalyptus. Scott and Smith (1997) working at several sites in South Africa recorded streams drying up eight years after Eucalyptus afforestation of a catchment whereas in afforested pine catchments streams took 12 years to cease flowing. Lima *et al.* (1990) measured more than 200 mm greater evapotranspirative losses from Eucalyptus than pine and significant reductions in soil moisture at a site in Brazil. A global analysis of 26 catchment data sets with 504 observations, including annual runoff and low flow by Farley *et al.* (2005) showed that Eucalyptus afforestation has the greatest impact on water yield reducing runoff by 75% (±10%), compared with a 40% (±3%) average decrease with pines and similar decreases of low flows. Research by Calder *et al.* (1993) at multiple sites in India showed how soil erosion was greater in Eucalyptus plantations compared to pine and soil moisture was greatly depleted, the latter conclusion also reported by many other studies, e.g. Lima *et al.* (1990); Zavala *et al.* (2009); Santos *et al.* (2016). *Pinus canariensis*, the Canary Island pine, may be a specific alternative for Ethiopia as the species is tolerant to climate variability, especially drought (Dr Juan Suarez, Forest Research, Roslin, personal communication, 18 December 2017 and Wieser *et al.* (2016)). The species has the lowest canopy storage capacity of conifers (though it is still slightly greater than Eucalyptus) meaning more water is transferred to the soil surface (McPherson *et al.*, 2017), and has been successfully forested for decades in South Africa (Richardson and Higgins, 2000). If the shallow groundwater resource is increasingly exploited, planting should consider the optimum tree cover that results in greatest recharge; above this the trees use too much water and below this there is increased overland flow (Ilstedt *et al.,* 2016).

9.3 Transferability of results

9.3.1 Transferability within Ethiopia

The transferability of this PhD research to other areas of Ethiopia can be identified from the map in Figure 9-2 of the main aquifer types within Ethiopia and their distribution. Aquifers termed “shallow” and “very shallow” have a wide distribution, approximately 50% of the country (Kebede, 2013). What’s more, it is likely that the deeper volcanic aquifers have superficial geology very similar to Dangila *woreda*. Considering Ethiopia’s climate, all but the east and north has similarly high rainfall and seasonality to Dangila. Fieldwork elsewhere in Ethiopia, and travelling to those field sites, showed similarities in geomorphology with Dangila, i.e. expansive floodplain wetlands and low hills.

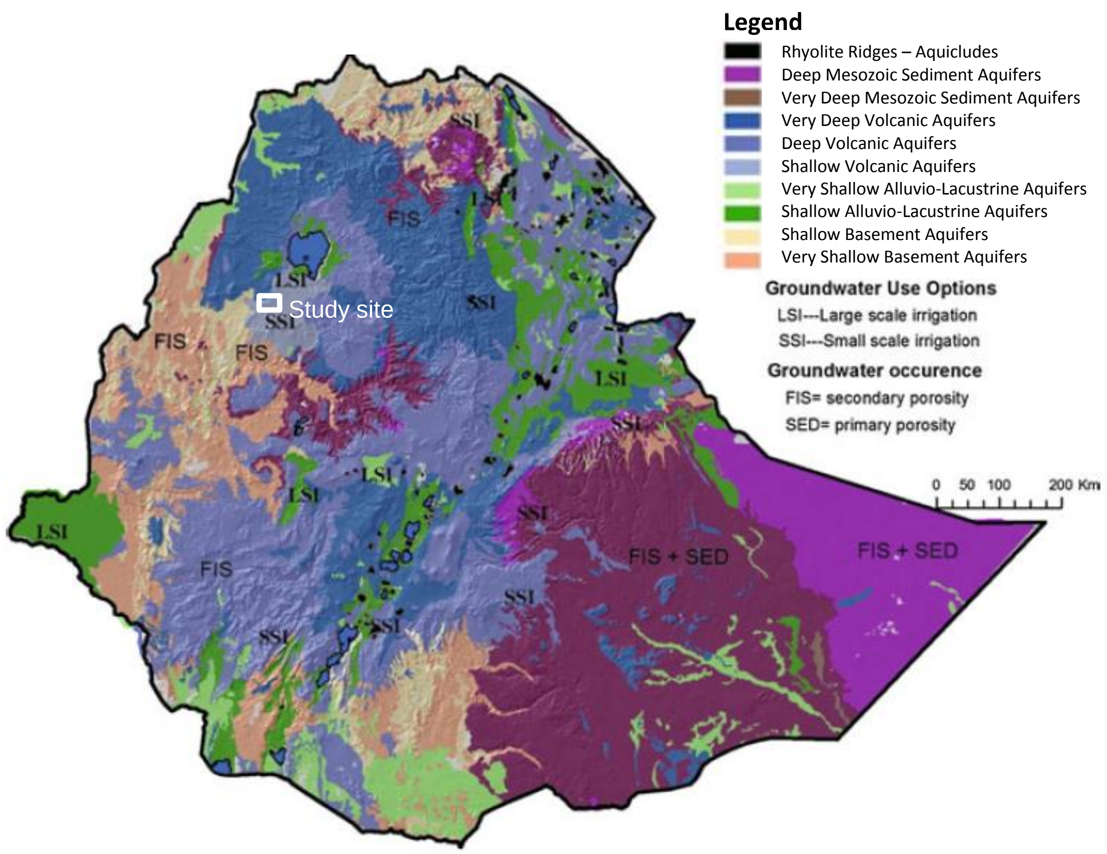


Figure 9-2. Map of Ethiopia showing distribution of main aquifer types (from Kebede (2013)).

9.3.2 *Wider transferability within sub-Saharan Africa*

The field site was selected to be representative of shallow aquifers at a broader scale than northwest Ethiopia. It would be expected that the findings from this research in terms of areas of high and low potential and the resilience of the resource would be applicable in areas of similar climate, geology and geomorphology. The map in Figure 9-3 shows areas of shallow (<25 m) water tables abound in SSA. Considering rainfall, a large swathe of the African continent between 10^{o} North and 20^{o} South receives rainfall of 800-3200 mm/a (Figure 2-4) with a similar seasonality to Dangila (Guiraud, 1988; Frenken, 1997). Within that rainfall zone and within the shallow water tables zone, young (Cenozoic to Quaternary) volcanic rocks are present all along the East African Rift from Eritrea to Malawi and in unconnected areas such as western Cameroon/eastern Nigeria and southwest Sudan (MacDonald *et al.*, 2011). In addition, key texts on regolith state that hydrogeological properties are similar independent of parent rock age and mineralogy (Jones, 1985). The abundance of crystalline rock in Africa (Figure 2-2) suggests shallow weathered regolith aquifers overlying very low to zero permeability bedrock, as at the study site, may be common, though the transferability to these areas requires further research. Similar geomorphology to Dangila may be expected in the previously mentioned regions due to the similar climate and geology (Grove, 1986; Burke and Gunnell, 2008).

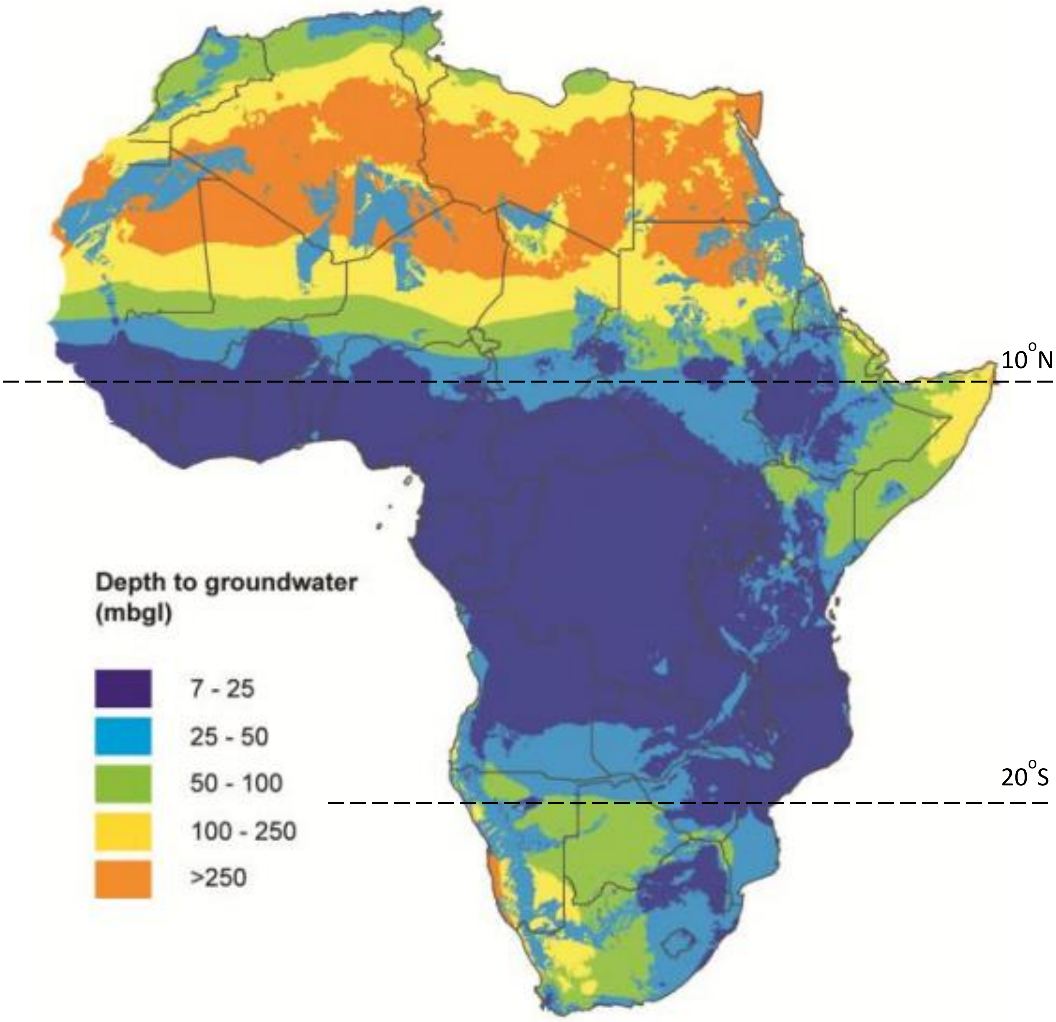


Figure 9-3. map of Africa with estimated depth to groundwater (from Bonsor and MacDonald (2011))

9.4 Transferability of methodology

The methodology of this research is confidently transferable. While a thorough review of background information and previous work is always recommended (Chapter 3), not all the field investigations applied here (Chapter 4) would have to be carried out during a shallow groundwater resource assessment. Surveys of wells (measuring the depth, groundwater level and determining the seasonality) are invaluable for assessment of aquifer geometry, groundwater recession rates and areas of highest/lowest potential for increased abstraction. Such surveys, including questioning local stakeholders, enable qualitative determination of aquifer properties. If modelling is required, or accurate estimation of potential well yield, pumping tests must be applied to quantitatively determine aquifer properties, even though with hand-dug wells and manual water-lifting the method is quite rough-and-ready. Hydrochemistry and stable isotope analysis are useful in revealing aquifer connectivity and recharge mechanisms enabling development of the conceptual model.

Citizen science for the gathering of hydrometeorological time series (Chapter 5) is being successfully applied as part of a REACH accelerated project, "Water security risk science: local knowledge for participatory resource management", (REACH, 2018) in Boloso Bombe *woreda*, SNNPR, based on, and improving, the Dangila programme. Other successful citizen science programmes with which potential collaborations have been discussed include Sierra Leone where community-based monitoring continued throughout the 2014-2016 Ebola virus epidemic when formal monitoring halted (Prof. Richard Carter and Peter Dumble, personal communication, 13 September 2016) and Burkina Faso where market gardeners plot groundwater levels in order to decide which crops to grow that season, or which alternative activities to pursue in the case of low levels, based on groundwater availability (Djibril Barry, WaterAid, personal communication, 8 December 2016). The latter example shows that, ultimately, communities conducting the monitoring can independently utilise the data for resource management with no external influence.

The techniques applied during the recharge assessment (Chapter 6) are all transferable, though again, not all must be applied in shallow groundwater assessment studies. It is recommended, however, to apply as many methods as the available quality data allows as then more can be learnt about the hydrogeological system from the discrepancies in the results and greater confidence can be had over the final *actual* recharge range.

The degree of parameterisation and time taken for calibration and simulation means SHETRAN modelling would not be feasible for shallow groundwater resource assessment at every study site (Chapter 7). However, as shown here, if time and data permit, SHETRAN can be used to show areas of greatest potential for productive groundwater use and determine the resilience of the resource in the face of various future scenarios (Chapter 8). The modelling results indicate that areas of groundwater potential could feasibly be identified from topographic and geological mapping

9.5 Limitations of the study

This discussion will consider the chapters separately. The limitation of the methodology being applied at a single study site is the subject of the discussion in the transferability section of this chapter. It should be noted that many of the limitations presented below may be considered opportunities for future work.

Limitations revealed by the literature review presented in Chapter 2

Literature review revealed that the widespread use of groundwater for irrigation in South and East Asia suggested such growth could occur in SSA. However, as stated by MacDonald *et al.* (2009), the rapid expansion in groundwater use experienced in parts of Asia was only made possible through provision of cheap energy, credit and market integration, which catalysed private investment in productive aquifers, such as the deep sedimentary aquifer in Gujarat and the extensive basaltic aquifers of the Deccan (Kulkarni *et al.*, 2000). Policies in Asia in the 1960s supported intensification of small-scale agriculture through massive public investment and price guarantees to raise smallholders' incomes (Birner and Resnick, 2010). African governments today are dealing with greater conditionality structures from structural adjustment policies set up in the 1980-90s and African smallholders must deal with lower and more volatile prices (Dorward *et al.*, 2004). Additional factors compound the situation: Africa has traditionally seen a greater diversity in crops, i.e. the green revolution in Asia was dominated by just two crops, rice and wheat, and in Mexico by just maize and wheat (Mellor, 2014); SSA is more vulnerable to climate change (Collier *et al.*, 2008), and; physical infrastructure is far inferior to Asia, leading to high input prices, notably fertiliser, and low output prices (Rashid *et al.*, 2013; Mellor, 2014).

At local-scale, there are numerous examples from SSA where the impact of smallholder irrigation has not lived up to expectations. Comas *et al.* (2012) report a situation in Mauritania where farmers resorted back to traditional rainfed and flood recession (beside the Senegal River) cropping because the returns were exceeded by start-up loan repayments and running costs. Considering drip irrigation systems introduced by NGOs, Friedlander *et al.* (2013) conducted surveys in Ethiopia, Malawi, Senegal and Zambia and found that 36% of farmers had abandoned the systems. The authors admit there is bias in their sampling technique towards successful adoption and present findings by Kulecho and Weatherhead (2005) from Kenya where 78% of farmers had abandoned drip irrigation systems within two years and by Belder *et al.* (2007) from Zimbabwe where 68% of farmers had abandoned the systems within 1-2 years. Reasons for abandonment included water shortage, effort of dismantling, storing and reassembling the system according to season, and lack of funds for replacements following damage due to vandalism and by animals (particularly common with subsistence farmers). The final negative example comes from Fogera, east of Lake Tana in Ethiopia and approximately 110 km northeast of the Dangila study site, where pumps can be rented cheaply and used autonomously, unlike river diversions and dams that are controlled by water user committees (WUCs). Dessalegn and Merrey (2015) report that, seeing as there is no driver for cooperation, over-abstraction has led to water shortages with some rivers running dry in the dry season and a necessary shift from water intensive crops such as onions to grain.

It is clear from these few examples that uptake of small-scale groundwater irrigation alone will not solve all problems of food insecurity and poverty. The important issues of availability of credit, ensuring equality for women and other disadvantaged groups, strong governance, and fluctuating crop prices are beyond the scope of this study. However, the fundamental issues of shallow groundwater availability and resilience were investigated and proved optimistic. The final example from Fogera in the previous paragraph bears out the requirement for such investigations.

Chapter 4. Field investigations and development of conceptual model

The field investigations described in Chapter 4 that led to development of the conceptual model were limited by the lack of exposures of the underlying geology. Basalt bedrock was frequently visible in streambeds (Figure 4-5) though exposures of the weathered regolith that constitutes the shallow aquifer were uncommon. Riverbank sections were present but the floodplains where these sections existed may have a different composition to regolith elsewhere. Borehole logs are unavailable, therefore, characterisation of the regolith relied on inspections of the few wells under construction with adjacent as-dug materials (Figure 4-4), community discussions recalling well excavations, and the pumping tests conducted on hand-dug wells. Record keeping of well excavations with simple logging (ease of excavation, colour and texture of material, depth of excavation) would greatly aid future hydrogeological investigations.

In addition to this limitation of thorough understanding of aquifer properties, understanding of aquifer geometry also had limitations. Estimates of aquifer thickness were gained through extensive well depth and riverbank depth measurements. Such measurements were applicable where wells were excavated to basalt bedrock and the river had incised to basalt bedrock. In the case of wells, communities revealed that wells were typically excavated until further excavation became impossible, i.e. the materials were too strong to excavate, which was inferred as the base of the regolith aquifer. However, logic and experience elsewhere suggest that wells excavated in areas with perennial water supply would have been excavated to a point below the water table when water inflow made further excavation problematic, dangerous, and unnecessary. This may or may not coincide with the base of the aquifer. Local communities also spoke of wells being dry though when dug less than 10 m away they hit water. As shown in Figure 4-6, this may be due to residual basalt boulders within the regolith though it is likely to also be due to a heterogenous surface of the basalt/regolith boundary, which would be more of a zone than a boundary. Therefore, well depth measurements may not be ideal for estimating aquifer thickness, however, it was the only available option. Geophysical investigations could better estimate aquifer thickness. Two-, or ideally three-, dimensional electrical resistivity tomography (ERT) surveys should differentiate the low resistance saturated clay-rich regolith and the high resistance basalt bedrock. Although, resistivity results obtained from GSE for surveys conducted in the Dangila area prior to commencement of this PhD were inconclusive. GSE, partners in the AMGRAF catalyst project, could not be persuaded to provide the raw geophysical data nor conduct further surveys.

Chapter 5. Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme

The limitation of the community-based monitoring described in Chapter 5 concerns the groundwater level measurements and their consideration in conceptual and numerical model development. Only five wells were monitored, and they were within a few 100 m of each other. Ideally, for more confident extrapolation of water table response, many more wells could be monitored across the catchment representing different topographical and geological locations.

Chapter 6. Insights from a multi-method recharge estimation comparison study

A conclusion of Chapter 6 is that there is sufficient renewable shallow groundwater for a sustainable intensification of small-scale irrigation. However, the study did not consider potential future climate impacts on recharge. While studies applying GCMs and RCMs generally predict increased rainfall totals for Ethiopia (e.g. Mitchell *et al.* (2004); IPCC (2007)), this may not necessarily lead to increased recharge for two reasons: Firstly, these same studies generally predict increasing rainfall intensity that could reduce recharge due to enhanced runoff; secondly, the studies generally project rainfall increasing in the dry season and lessening in the wet season (notwithstanding the increases in wet season rainfall intensity) and a higher proportion of dry season rainfall would likely be lost to evapotranspiration (Carter and Parker, 2009). This limitation of Chapter 6 is not considered significant due to the relatively high recharge totals computed, i.e. the shallow aquifer is not a marginally sustainable resource where lack of consideration of climate change impacts would be a serious limitation.

Chapter 7. Modelling the shallow aquifer

The limitations of the modelling presented in Chapter 7 begin with the previously discussed limitations on thorough understanding of aquifer properties and geometry. Three hydrogeological categories were applied with particular properties and layer thicknesses. This categorisation was selected for simplicity due to a lack of data for assigning more categories. It is likely that the aquifer has some heterogeneity in properties and in thickness that was not represented in the models. A similar limitation is the assignment of the three LULC categories. Existing LULC mapping was not identified at sufficiently high resolution for incorporation into the models (e.g. Setegn *et al.* (2011); ADSWE (2015)) and other maps shared by local partner IWMI of uncertain origin). Generating new LULC maps based on remote sensing was beyond the scope of this PhD. The assignment of LULC categories based on field observations and slope analysis was validated with comparisons with Google.Earth, however, there are areas within the catchments that are not correctly represented, i.e. cultivated though flat areas and sloping floodplains comprising pasture. Utilisation of MODIS or Sentinel imagery could provide improved LULC mapping, though, as shown in Figures 8-1 and 8-2, LULC is dynamic at the study site and a static map may not be representative for long. In addition to the assignment of LULC categories, the vegetation properties applied within SHETRAN were necessarily averaged for each category. The "Arable land" category comprises vegetation with a range of properties (e.g. from onions to Eucalyptus), especially in areas close to settlements where plots may be <0.1 ha and are often intercropped. Even high resolution remote sensing imagery with extensive ground truthing may struggle to provide LULC mapping across the catchments for which realistic vegetation properties could be confidently assigned.

Concerning the time series inputs to the models described in Chapter 7, the scarcity of rainfall and PET time series within the modelled catchments meant extrapolating rainfall and PET measurements from a single point. This was not a significant limitation for the smaller and more homogenous high resolution Brante and Amen models that were used for the subsequent future scenarios analysis. However, the larger two Kilti models have greater ranges of elevation and topography meaning the blanket rainfall and PET inputs may have less accuracy in some areas of the catchments. Additionally, the aforementioned localised groundwater level measurements used for calibration were a limitation of the modelling; ideally, groundwater level time series spread across the catchments would have been utilised.

A limitation on the conclusions of Chapter 7, that is the maps showing the potential for an increase of small-scale irrigation, is the non-consideration of land ownership, governance and the finance for and availability of irrigation equipment. These issues must be addressed alongside issues of water resource availability to render the maps practicable.

Chapter 8. Resilience of shallow groundwater resources

The fact that the future scenarios described in Chapter 8 do not consider climate change may be considered a limitation. Even though it was shown that observed climate variability was much greater than climate change projections, this variability could be expected to become more extreme but by how much is not known (Smerdon, 2017).

The quite short daily rainfall time series available for Dangila and Bahir Dar were a limitation as they meant that a synthetic long period time series had to be developed for future scenario simulation. If longer time series would have been available, then the return period of agricultural and hydrological droughts could have been estimated.

It is likely that the LULC change scenarios will occur in tandem though this was not simulated. However, this is considered only a minor limitation as the combined effects of LULC changes can be estimated from the results, i.e. conversion of pasture to cultivated land combined with increased Eucalyptus planting would significantly negatively affect water resources. Similarly, the non-simulation of simultaneous LULC change and increased abstraction is not considered a limitation due to the lack of significant impacts from the abstraction scenarios. Detailed analysis of historic aerial or satellite imagery could be used to estimate the rate of different LULC changes and the Asia example could be further analysed to assess the rate of irrigation uptake. However, simulation of these combined changes would still be uncertain going forward as the rates and type of LULC change and irrigation uptake will vary according to various factors such as crop and fuel prices, government policy, climate, population growth, etc.

A further limitation in the future scenarios modelling was exposed by the uncertainty over accurate simulation of the cropping cycle, i.e. different crop growth stages are not represented. This could be reduced with the implementation of a crop model within the SHETRAN program that would provide greater confidence in the conclusion that small-scale abstraction and irrigation will not negatively impact shallow groundwater and surface water resources.

Summary of limitations

It should be noted that most of these limitations are omnipresent with hydrogeological and hydrological modelling: aquifer properties and dimensions are never certain, vegetation properties are always variable, time series data for model set up and calibration are always fewer than desirable, climate change effects are uncertain, and socioeconomic factors typically complicate conclusions. Some of these limitations could be reduced with further work that was beyond the scope or financial means of this PhD. Other limitations would be difficult to resolve and must be considered when making recommendations based on this study.

9.6 Future work

Future work would involve testing the research findings at other field sites in Ethiopia and elsewhere. The topographic criteria identified in Dangila for areas of high potential for abstracting groundwater and the criteria for low potential areas could be tested thoroughly with a modelling assessment as carried out during this research though it may be enough to conduct water point surveys during a field hydrogeological assessment and query local stakeholders. In addition to testing the findings in areas of similar young volcanic geology, it would be enlightening to conduct comparative research in areas of similar climate but crystalline bedrock to determine if regolith hydrogeology really is independent of bedrock age and type. If this is the case, then the transferability of this PhD research widens substantially. To further target the research gap concerning shallow aquifers, in addition to research of regolith aquifers above crystalline basement, other common shallow aquifer types could be targeted for research such as unconsolidated coastal and river valley aquifers, and coastal limestone aquifers. These studies should be conducted at community scale; the scale at which understanding the potential and resilience of the groundwater resource could have a direct benefit to poor rural communities.

As climate varies, land use changes and abstraction increases, the community hydrometeorological monitoring data can confirm or otherwise the resilience of the shallow groundwater and surface water resources, validating the modelling. It is important to continue this monitoring with regular feedback of results to the local community. Research in East Africa by Comte *et al.* (2016) indicates that local stakeholders are critical of researchers who commonly do not share project findings. The study also found that communities want to be actively involved in water resource management. Therefore, the hope is that the Dangesheta community become independent with the monitoring and utilisation of the monitoring data as occurred in the Burkina Faso example described in the transferability section of this chapter.

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Appendix A: Properties of shallow thin regolith aquifers in sub-Saharan Africa: a case study from northwest Ethiopia

The following section is taken from a peer-reviewed conference paper submitted to and orally presented at the 7th RWSN Forum "Water for Everyone" in Abidjan, Côte d'Ivoire, in November/December 2016.

Citation: Walker, D. (2016) 'Properties of shallow thin regolith aquifers in sub-Saharan Africa: a case study from northwest Ethiopia', *7th RWSN Forum "Water for Everyone"*. Abidjan, Côte d'Ivoire, Nov-Dec 2016. Available at: https://rwsnforum7.files.wordpress.com/2016/12/full_paper_0061_submitter_0166_walker_david-rev1.pdf Retrieved 14 March 2017.

Note that the references, as with all the appendices, are included within the main references list.

A-1 Introduction

It is well discussed that the hydrogeology of sub-Saharan Africa is poorly understood, particularly regarding shallow groundwater resources (Robins *et al.*, 2006; Calow *et al.*, 2009b; MacDonald *et al.*, 2009), even though such resources sustain the majority of the continent's population (Lapworth *et al.*, 2013). A knowledge of aquifer properties allows for calculations and models to assess groundwater recharge, abstraction potential, contamination risk, impacts of future climate variability, and management strategies. However, few data are available on shallow aquifer properties for this region (Bonsor *et al.*, 2014).

The most useful shallow aquifer properties are; hydraulic conductivity (K) – the ease by which water moves through an aquifer, specific yield (S_y) – the volume of water that drains from the aquifer per unit surface area of aquifer per unit decline of the water table (the drainable porosity), and well yield – the rate at which water can be abstracted from a well.

As part of an ongoing project assessing the vulnerability of shallow aquifers in sub-Saharan Africa, pumping tests were first conducted during a field visit to Ethiopia in March/April 2015, timed to coincide with the end of the dry season and period of greatest water scarcity. Further testing was undertaken during a second field visit in

October/November 2015 at the end of the wet season. In order to estimate hydraulic conductivity, specific yield and well yield, tests were conducted on hand-dug wells in two locations within the Amhara region (Figure A-1). Both drawdown (the drop in water level within the well caused by pumping) and recovery (the increase in water level back to pre-test level following cessation of pumping) were monitored then analysed using alternative methods.

A-2 Testing Locations

Seven wells were tested within Dangila *woreda* (Figure A-1), benefiting from and enhancing relationships established by a community-based monitoring programme which has been ongoing since March 2014 (Walker *et al.*, 2016). A further well was tested in Robit-Bata *kebele*, 80 km northeast of Dangila *woreda*, close to the city of Bahir Dar.

All of the wells tested were located within weathered basalt regolith above variously massive, vesicular and/or fractured basalt. Tested wells ranged in depth from 3.55 to 10.09 metres below ground level (mbgl) with (often irregular) diameters of around a metre (±0.2 m). Wells are excavated by hand with picks and shovels until the solid geology is hit. Therefore, water column height is considered the saturated thickness of the aquifer and in the tested wells ranges from 0.54 to 3.85 m in the dry season and 1.99 to 6.34 m in the wet season. These ranges of well geometries and water depths are typical of hand-dug wells in the areas. Wells were selected to cover a range of topographies from floodplains, to valley slopes, to higher elevations, in an area of moderate relief within the Ethiopian Highlands.

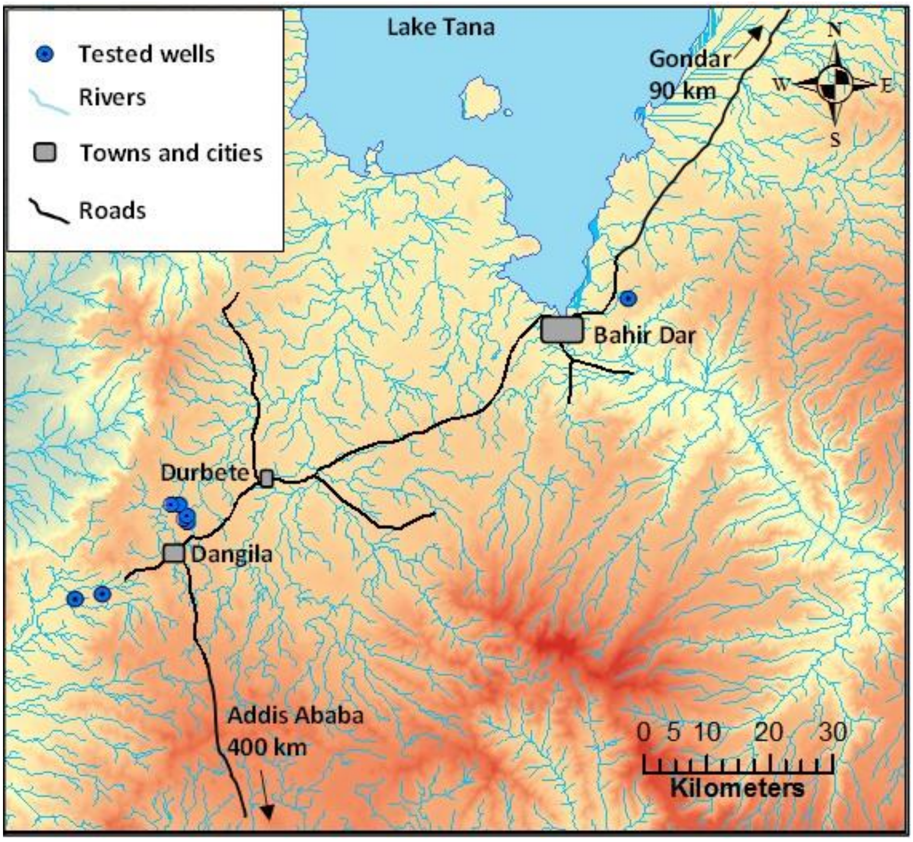


Figure A-1. Geographical distribution of testing locations.

A-3 Methodology

Motor pumps were not available, therefore, water was removed from wells using manual methods. Water-lifting incorporated a rope and bucket; the bucket being a modified HDPE water container. At least two people were involved in water-lifting (Figure A-2) which helped to maintain a largely constant discharge rate.

A pressure transducer measuring every two seconds was placed in the well prior to starting a test and water levels were also manually measured using a dip-meter. The volume of the emptying water container was measured in addition to well diameter and depth. The number of buckets abstracted per minute was monitored to calculate the pumping rate. The pumping rate varied between wells from 2 litres/minute to 15 litres/minute (with one exception) dependent on the size of the container and the depth to the water table; the smallest container and deepest water table giving the slowest pumping rate. The test in Robit-Bata *kebele* had a pumping rate of 30 litres/minute being the only tested well with a pulley and double bucket system, which leads to much more efficient water lifting.

Water was abstracted until the well water column was reduced by at least 10%. The necessary time to remove the entire well volume or to reach steady-state conditions with the equipment available would have been excessive and extremely labour-intensive. More importantly, given that the first field visit took place during the period of greatest water scarcity, it would have been unethical to attempt to reduce the water level in the wells to near empty. In order not to waste water, all containers that each household possessed were filled during pumping tests and further water was used for backyard irrigation and for watering livestock. The recovery of the water level was monitored with no additional abstraction.


Figure A-2. Photographs of pumping tests.

A-4 Analysis

Selecting analysis methods was not straightforward. The shallow aquifer here may be unconfined, however, a low-permeability though leaky clay-rich layer is commonly observed in weathered igneous regolith profiles above more permeable material which hosts the aquifer (Taylor and Eggleton, 2001; Sharp, 2014). In addition, it is suspected that fractures in the underlying solid geology are influential. There is further uncertainty over whether the wells are fully-penetrating; wells are generally excavated until solid geology is hit though they may be partially penetrating if a boulder was struck (such boulders are commonly observed in regolith stream bank sections) or where water tables are shallow (i.e. on floodplains).

The Moench (1985) method was selected because it considers leaky aquifers and large-diameter wells, i.e. well bore storage is included, and is straightforward to use on AquiferWin32 software. The method requires: well geometry, aquifer thickness, pumping rate, and a time-series of drawdown. Given that the period of pumping was quite short and did not reach steady state, only a small portion of curve was available for matching to provide values for hydraulic conductivity and specific yield. Therefore, there is a potential error on the results though it is likely to be less than the natural variation of the aquifer material. However, the specific yield values resulting from this method were often considered impossibly low ($< \sim 1 \times 10^{-6}$), as they are computed from early time data which is considered in pumping test analysis to be the least reliable, and have not been included when calculating averages (Table A-1).

Recovery data was analysed using nomograms presented by Barker and Herbert (1989) to facilitate application of the solution of Papadopulos and Cooper (1967) to recovery tests on large-diameter wells. The method requires: well geometry, pumping rate and period, drawdown at the end of pumping, and time taken for 25%, 50% or 75% recovery, and provides values for transmissivity (T) (the rate at which water flows horizontally through an aquifer; T = K multiplied by aquifer saturated thickness) and specific yield. Values for hydraulic conductivity were derived by dividing the transmissivity by the measured saturated thickness.

Potential well yield is considered the maximum continuous abstraction, i.e. pumped to steady-state, that a well could be subjected to without drying out. In this case, “drying out” is considered to be a water depth of 0.3 m which is the minimum depth from which water could be abstracted using bucket and rope methods or without excessive sediment intake in a motor pump. Well yield (Q) was calculated with the application of the Thiem (1906) equation:

$$\boldsymbol{Q} = \frac{\boldsymbol{K}(\boldsymbol{H}^2 - \boldsymbol{h}^2)}{\boldsymbol{C}\log(\boldsymbol{R}/\boldsymbol{r})} \qquad \text{(A-1)}$$

Hydraulic conductivity (K) was taken from the pumping test analyses, saturated thickness (H) and well radius (r) were as measured prior to testing, water depth (h) was fixed at 0.3 m, C is a constant equal to 0.733, and the radius of the cone of depression (R) was varied from 5-20 m.

A quick yield calculation was also conducted simply by dividing the recovered well volume by the time taken for recovery and multiplying by the abstractable saturated thickness.

A-5 Results

Given the uncertainties over well and aquifer geometry, hydraulic conductivity and specific yield results are sufficiently similar from the drawdown and recovery analyses to indicate suitability of methods (Table A-1). The largest differences in properties between testing methods are within the natural variation of the aquifer materials.

Table A-1. Aquifer properties determined by pumping tests; K = hydraulic conductivity and S_y = specific yield. The S_y results in italics are considered unreliable (see text) and were not used to calculate averages. Note the quick yield estimate is calculated during recovery, as described in the text. NR = no result. The test labelled “unable to analyse” (Well dw32) resulted in a drawdown time series that could not be explained or analysed (see plot in Sub-Appendix A-1). Note that an uppercase well ID, e.g. DW73, denotes a well originally surveyed by Demis Alamirew whereas lower case, e.g. dw6, indicates a well surveyed only by David Walker.

					Well yield (l/s)	
	Well ID	**Test length (mins)**	**K (m/d)**	**S_y**	**quick**	**Thiem**
End of the dry season						
Dangila						
Drawdown	DW73 (MW2)	16	1.3	0.12		0.02
	dw6	21	3.1	0.08		0.02
	DW77 (MW4)	32	0.7	0.03		0.12
	DW61	32	5.3	0.11		0.01
	dw7	48	1.4	NR		0.01
Recovery	DW73 (MW2)	76	6.4	0.32	0.10	0.11
	dw6	61	3.6	0.13	0.09	0.03
	DW77 (MW4)	133	1.5	*1×10^{-5}*	0.22	0.26
	DW61	56	2.0	NR	0.05	0.01
	dw7	114	0.2	0.06	0.05	0.001
Robit-Bata						
Drawdown	RB	13	1.8	0.03		0.20
Recovery	RB	138	0.4	NR	0.26	0.04
End of the wet season						
Dangila						
Drawdown	DW73 (MW2)	27	3.7	*3.6×10^{-6}*		0.29
	dw6	18	6.1	*3.2×10^{-6}*		0.27
	DW77 (MW4)	14	2.8	*7.8×10^{-7}*		1.5
	dw32	29	Unable to analyse			
	dw33	12	6.8	*2.4×10^{-6}*		0.80
Recovery	DW73 (MW2)	41	22.3	0.05	1.0	1.8
	dw6	65	19.0	0.1	0.31	0.76
	DW77 (MW4)	30	6.2	0.07	2.5	2.8
	dw32	46	Unable to analyse			
	dw33	82	10.3	0.1	0.50	1.2

Significantly, the result from Robit-Bata is consistent with those from Dangila confirming field observations of the similarity of the regolith of both areas. This outcome suggests that conclusions reached on the hydrogeology may be transferrable to other shallow aquifers above basalt bedrock throughout Ethiopia. Continuing research is required to determine if findings on the shallow aquifer in this region are potentially transferrable across a wider area as studies have shown that regolith has hydrogeologically similar characteristics across a variety of rock types (Jones, 1985).

The mean dry season hydraulic conductivity values derived from all wells using analysis of both drawdown and recovery data is 2.3 m/d with a median of 1.6 m/d, a range of 0.2 to 6.4 m/d and a standard deviation of 1.95. The mean wet season hydraulic conductivity is 9.7 m/d with a median of 6.5 m/d, a range of 2.8 to 22.3 m/d and a standard deviation of 7.19. This disparity between seasons is not only of transmissivity but hydraulic conductivity, therefore, is not explained by greater saturated thickness. Layers of higher hydraulic conductivity must exist within the higher water column during the wet season. The implication of this finding is significant; not only would wells excavated more deeply below the water table have higher well bore storage, but they are more likely to intercept more transmissive (water-bearing) layers providing greater yield, unless such layers only exist at shallower depths. Estimates of well yield are generally >1 l/s in the wet season when the water column is high though this may drop an order of magnitude during the dry season.

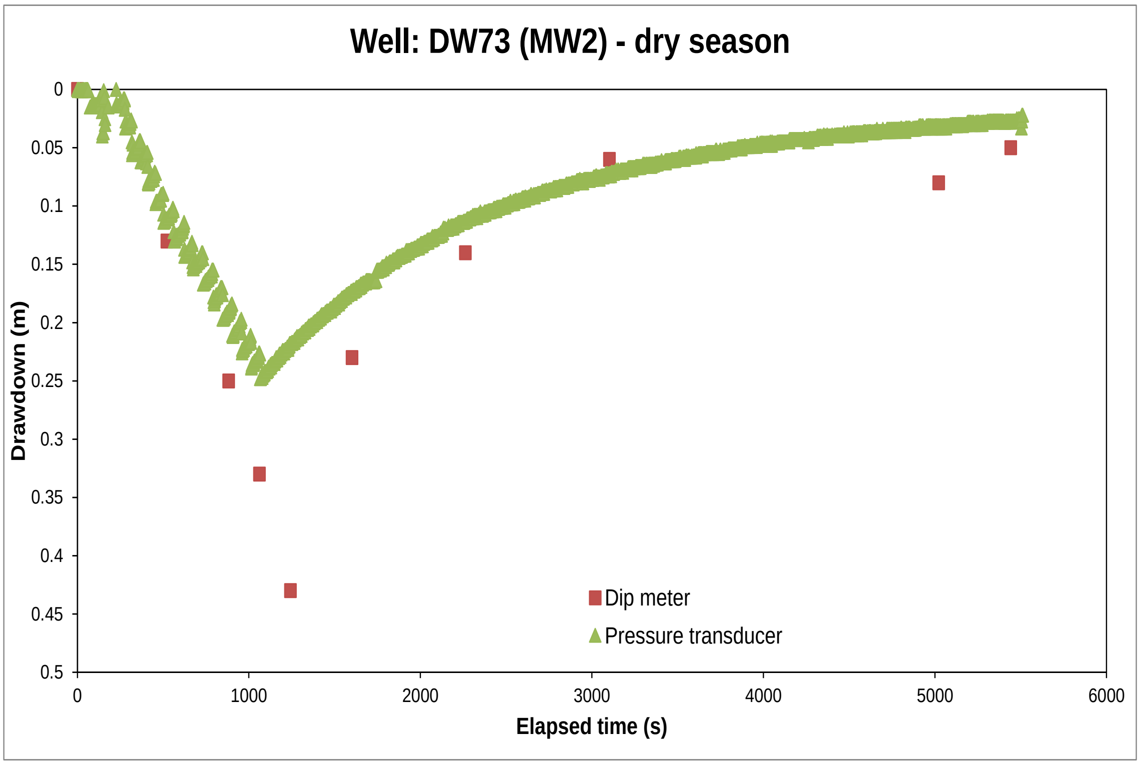
The hydraulic conductivity results are comparable to studies of regolith elsewhere in Africa: Olaniyan *et al.* (2010) report a range of 0.30 to 9.36 m/d (average: 2.13 m/d) from a study in Nigeria, Taylor and Howard (1998) report a range of 0.3 to 3.0 m/d in Uganda, while 0.05 to 1.5 m/d is reported by Chilton and Smith-Carington (1984) in Malawi. A textbook range for weathered igneous regolith presented by Taylor and Eggleton (2001) is 0.09 to 1.7 m/d.

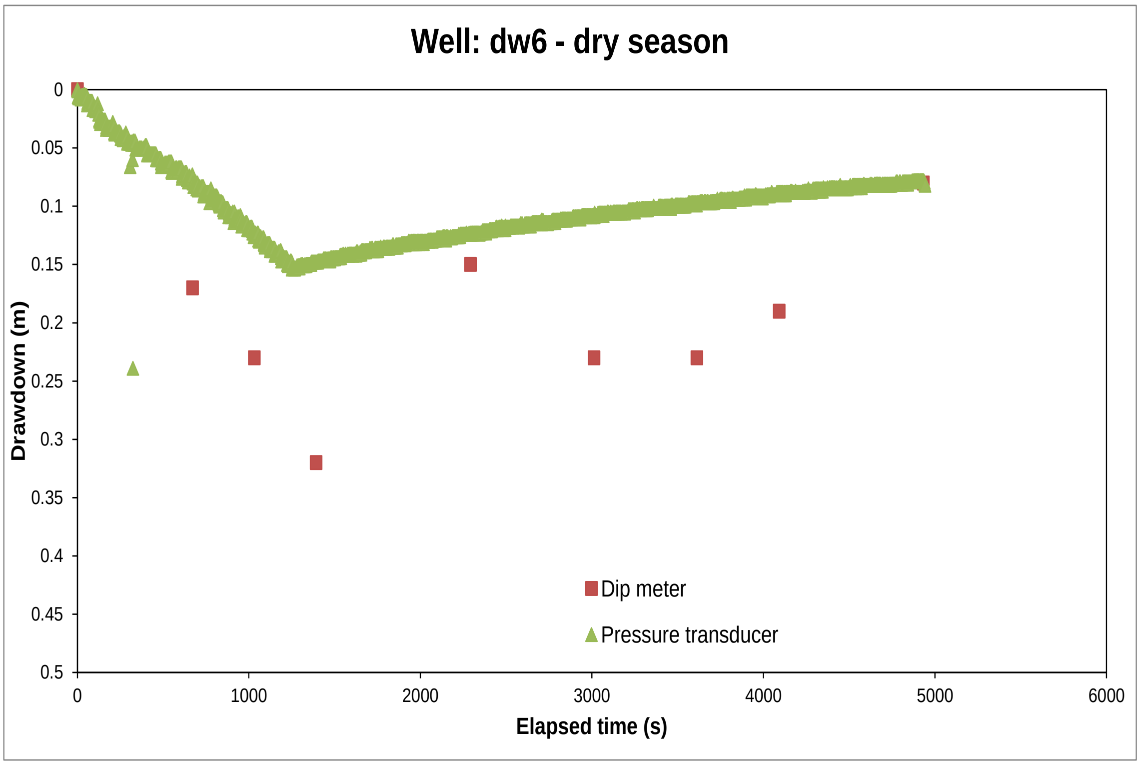
It is well reported that there are few data on specific yield of regolith, or indeed any, aquifers in Africa (MacDonald *et al.*, 2012a). From all seasons and locations the specific yield range of 0.00001 to 0.32 and mean of 0.09 (median of 0.08 and standard deviation of 0.079) is similar to the wide range quoted by Jones (1985) of 0.00001 to 0.1 for Central Africa and higher than the 0.003 reported by Taylor *et al.* (2010). Bahir Dar University laboratory assessment of density, porosity and field capacity of five bulk samples enabled estimation of a specific yield range of 0.052 to 0.219 for weathered basalt regolith from Robit-Bata *kebele* (D. L. Yilak, personal communication, March 2015). A textbook range for specific yield of regolith presented by Fetter (2001) is 0.15 to 0.3.

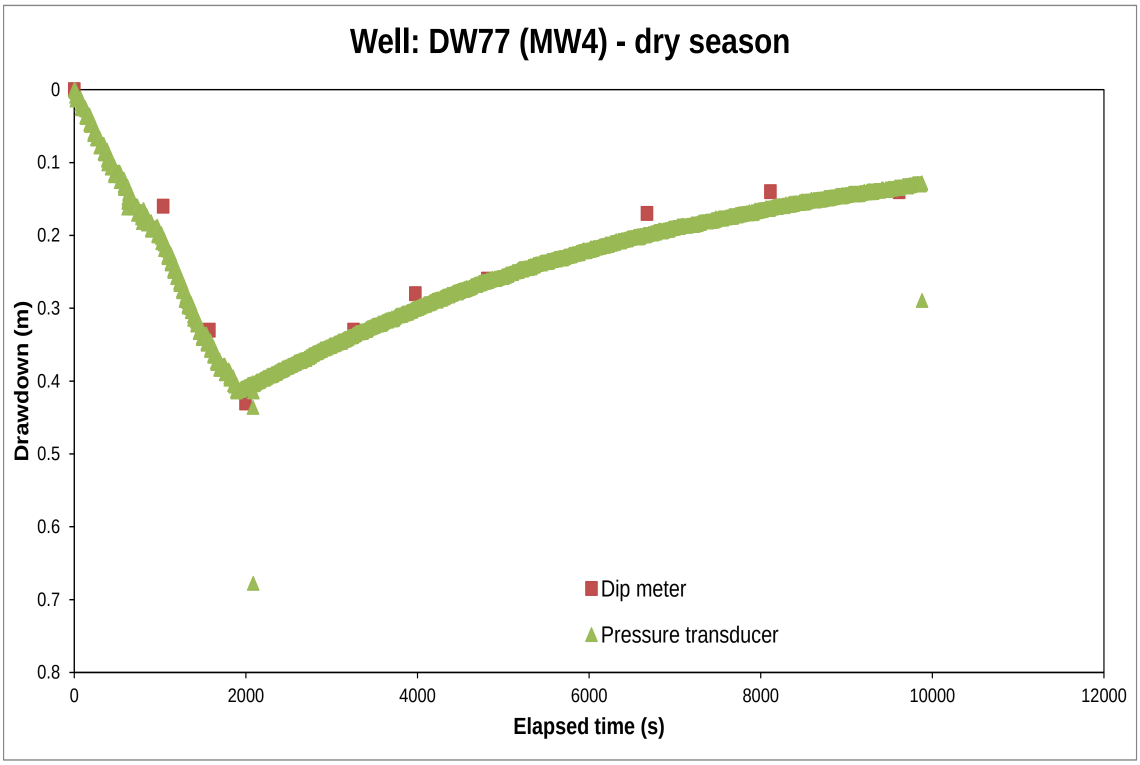
A-6 Conclusions

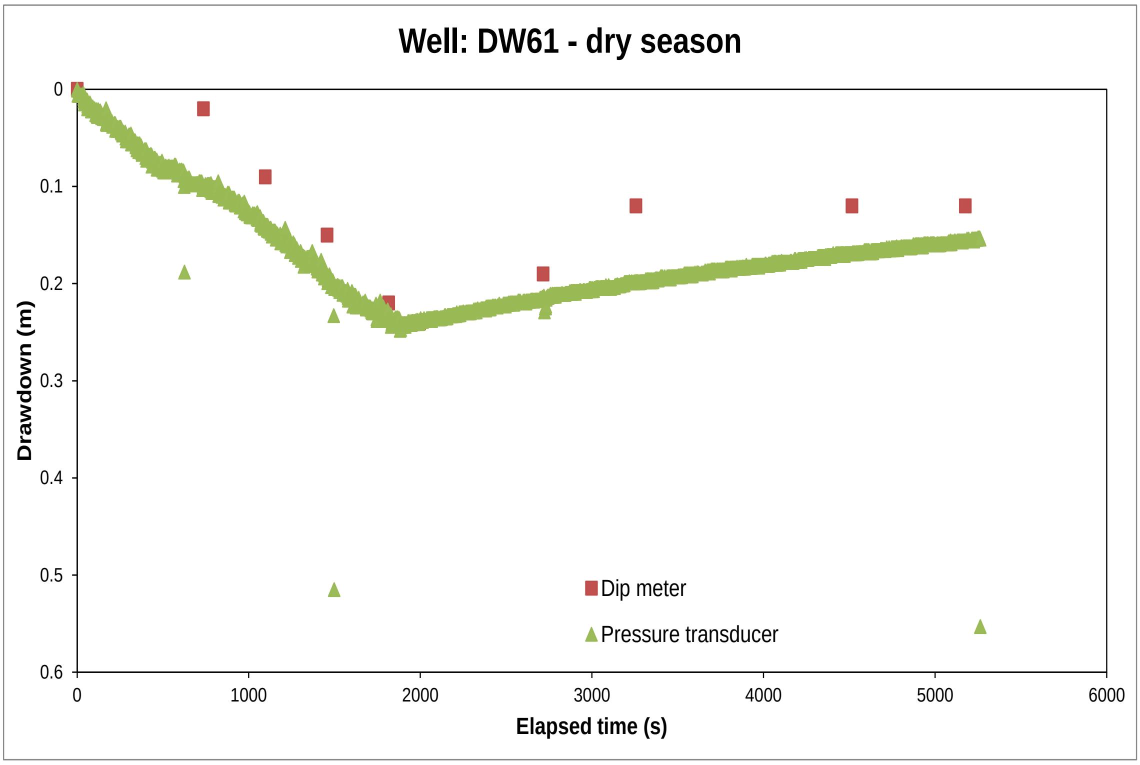
Pumping tests conducted on hand-dug wells in northwest Ethiopia provide mean hydraulic conductivity values of 2.3 m/d in the dry season and 9.7 m/d in the wet season (median = 1.6 and 6.5 m/d), and a mean specific yield value of 0.09 (median = 0.08). These values contribute to the extremely sparse data available in published literature for shallow regolith aquifers in sub-Saharan Africa. Calculations of well yield (average = 0.5 l/s) indicate that penetrating a substantial saturated thickness of aquifer (>3 m below water table) to maximise water column height is as important for achieving desirable yield as locating areas of high hydraulic conductivity. A well or borehole fitted with a handpump must be able to sustain a supply of >0.1 l/s (preferably 0.3 l/s) to supply a community (MacDonald *et al.*, 2012a). Irrigation demand depends on crop type and local environmental conditions, though these are less significant when considering general feasibility. For the range of crops and conditions likely to be encountered at the study site, daily water use can be calculated as approximately 1 l/s/ha (Brouwer *et al.*, 1992). Given this calculated irrigation requirement, the well yield estimations give some optimism that small scale irrigation, in addition to the existing community supply, is achievable from hand-dug wells in shallow regolith aquifers. Further research is required to determine the transferability of findings, though similarities in results from wells some distance apart and with published results suggest the findings may be transferable to other areas of shallow weathered regolith aquifers across sub-Saharan Africa and certainly to shallow weathered basalt regolith aquifers within Ethiopia. Knowledge of aquifer parameters is vital in constructing models for simulation of climate change impacts and in developing management strategies for sustainable development of shallow groundwater resources.

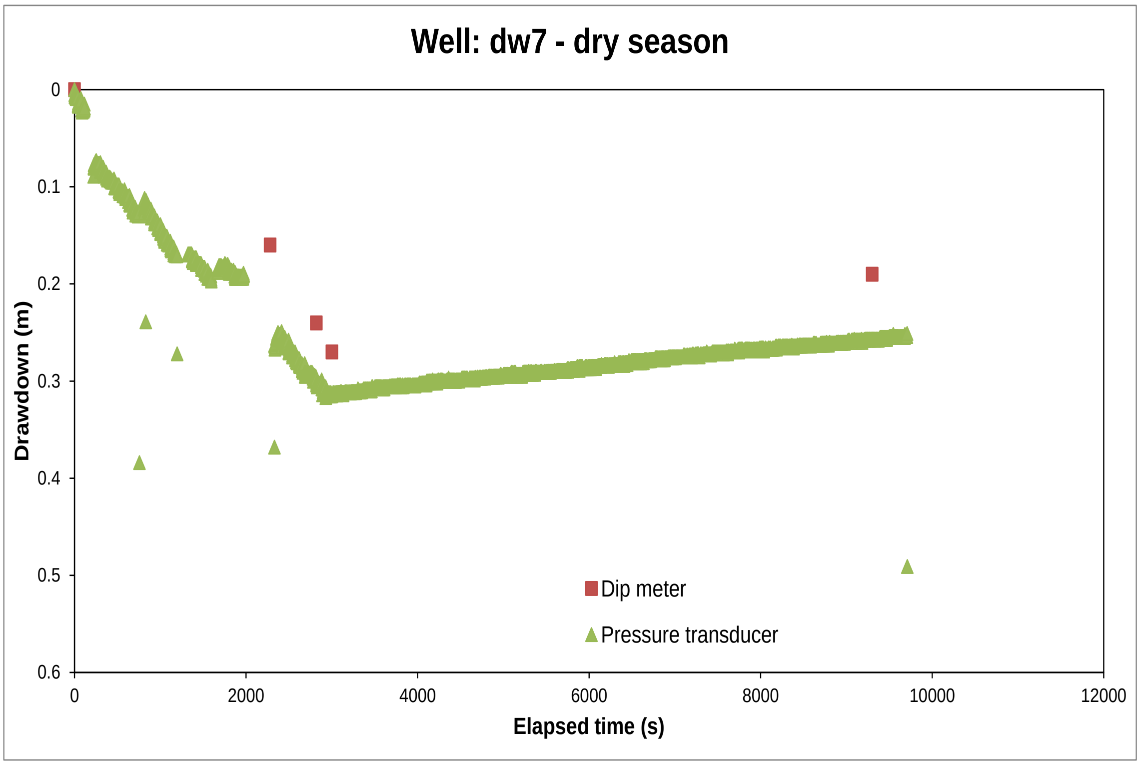
Sub-Appendix A1 – Plotted pumping test data

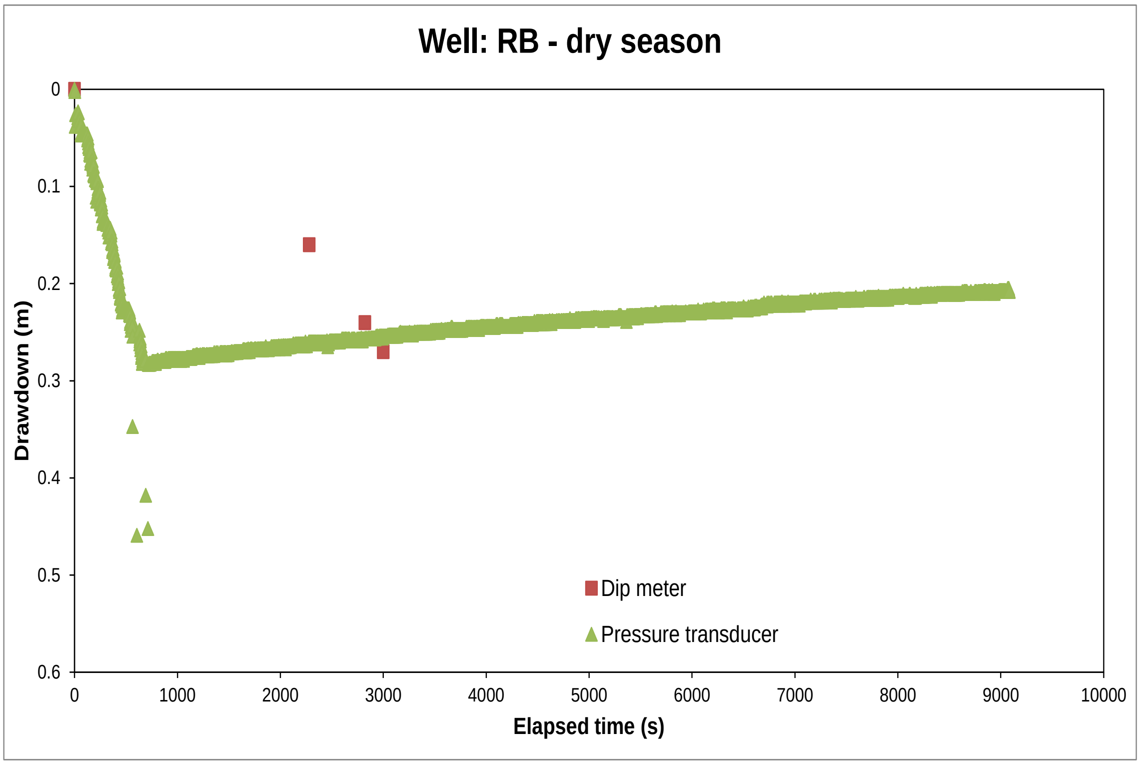


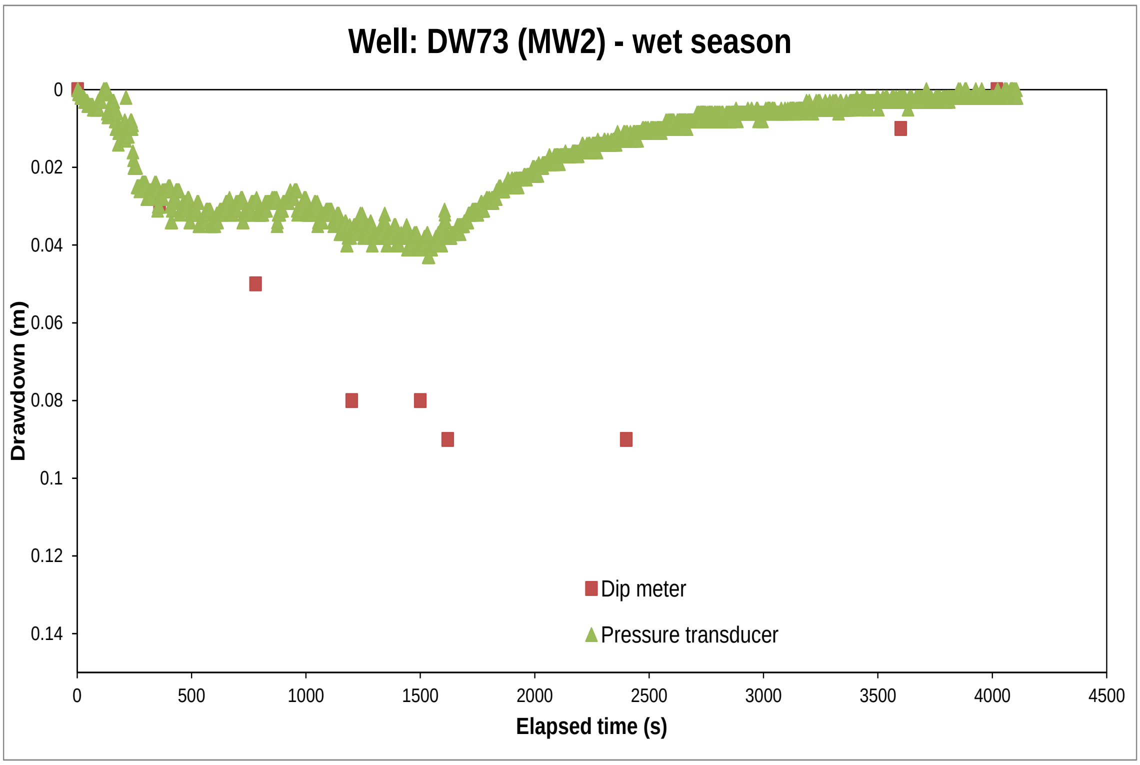


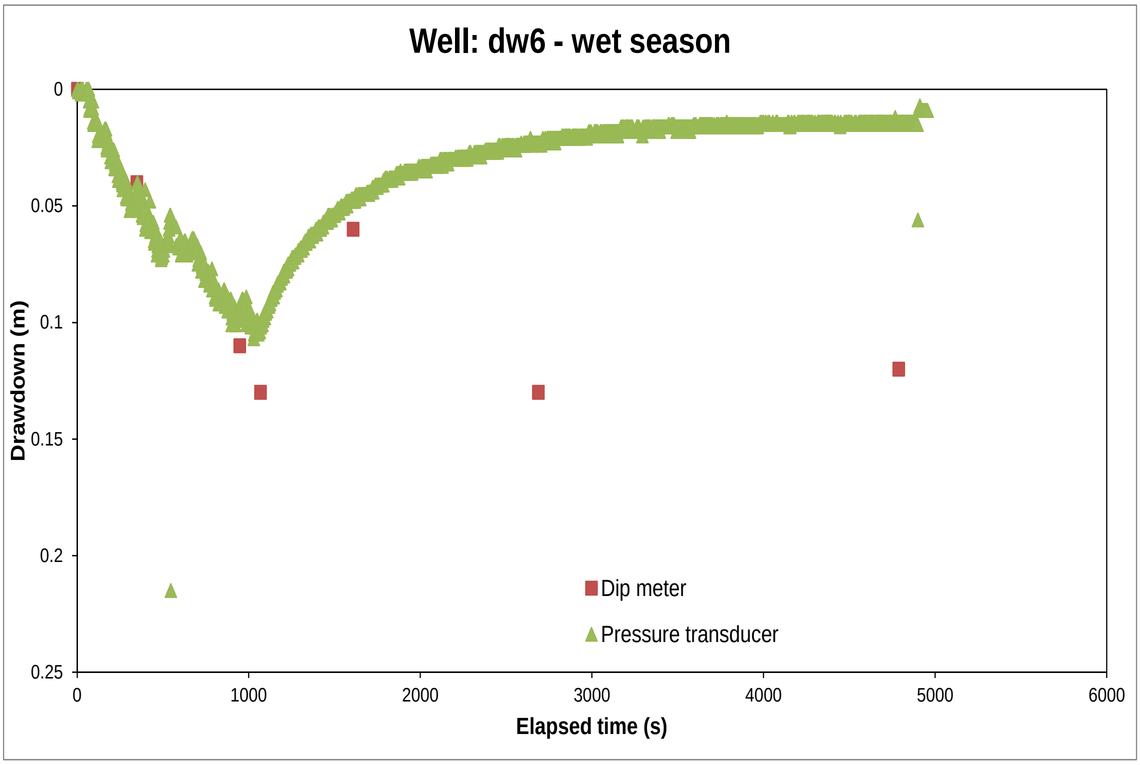

Well: DW77 (MW4) - dry season
Drawdown (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2000
4000
6000
8000
10000
12000
Elapsed time (s)
Dip meter
Pressure transducer

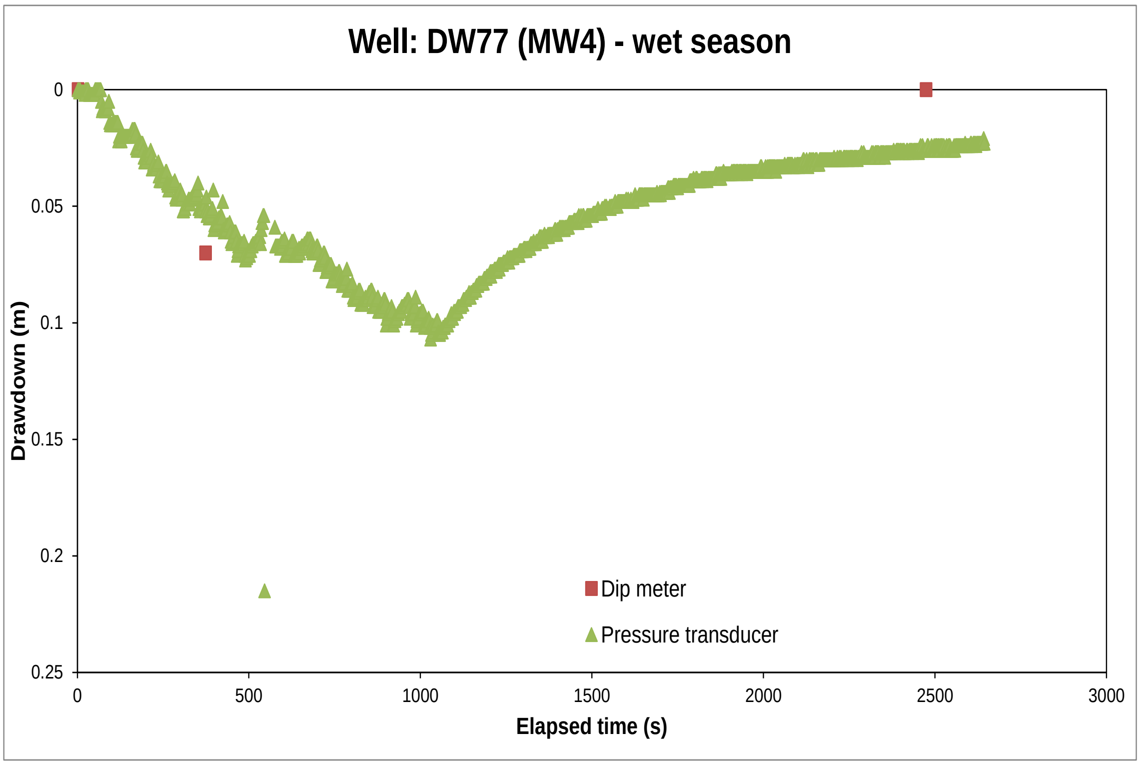

Well: DW61 - dry season
Drawdown (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
1000
2000
3000
4000
5000
6000
Elapsed time (s)
Dip meter
Pressure transducer

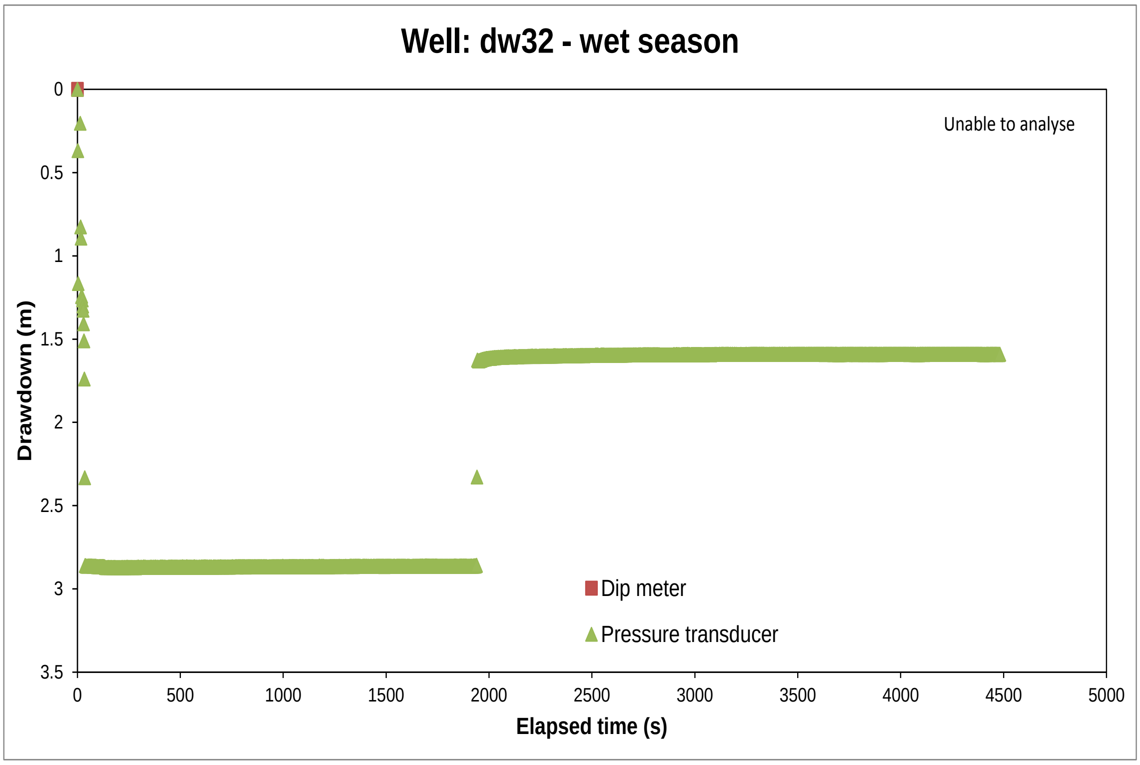

Well: dw7 - dry season
Drawdown (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
2000
4000
6000
8000
10000
12000
Elapsed time (s)
Dip meter
Pressure transducer

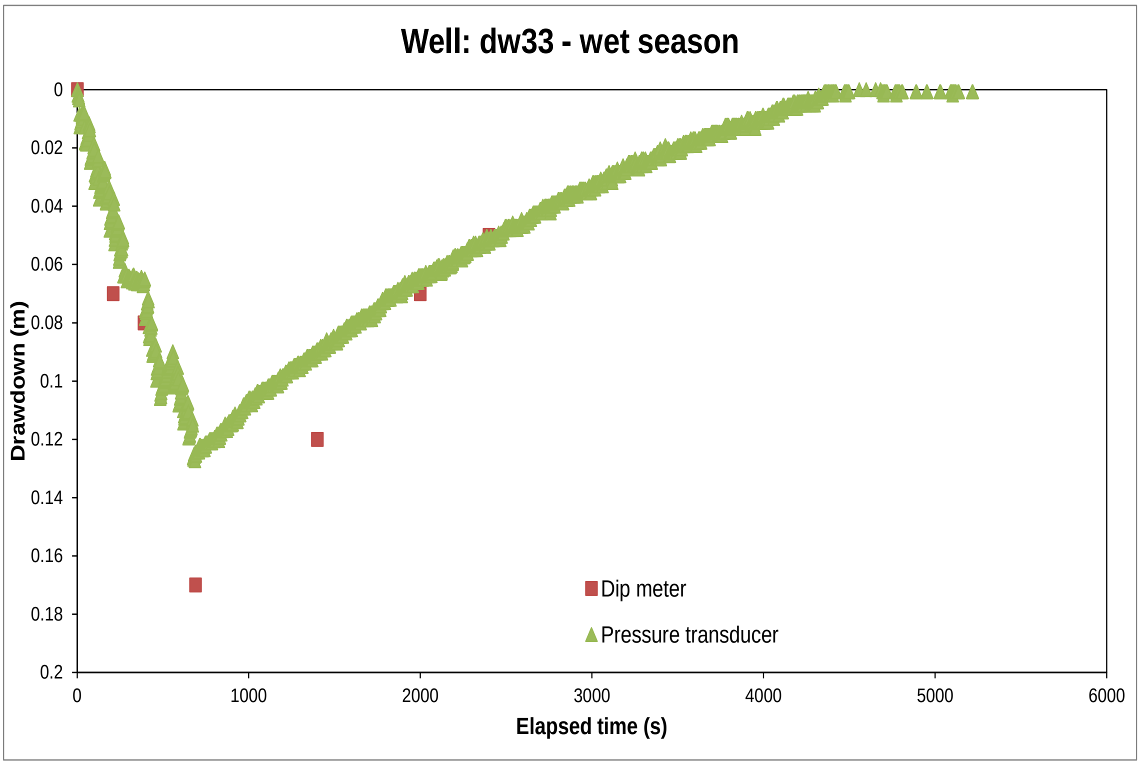

Well: RB - dry season
Drawdown (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Elapsed time (s)
Dip meter
Pressure transducer


Well: DW73 (MW2) - wet season
Drawdown (m)
Elapsed time (s)
Dip meter
Pressure transducer
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0
500
1000
1500
2000
2500
3000
3500
4000
4500


Well: dw6 - wet season
Drawdown (m)
Elapsed time (s)
Dip meter
Pressure transducer
0
0.05
0.1
0.15
0.2
0.25
0
1000
2000
3000
4000
5000
6000


Well: DW77 (MW4) - wet season
Drawdown (m)
0
0.05
0.1
0.15
0.2
0.25
0
500
1000
1500
2000
2500
3000
Elapsed time (s)
Dip meter
Pressure transducer


Well: dw32 - wet season
Unable to analyse
Drawdown (m)
0
0.5
1
1.5
2
2.5
3
3.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Elapsed time (s)
Dip meter
Pressure transducer


Well: dw33 - wet season
Drawdown (m)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0
1000
2000
3000
4000
5000
6000
Elapsed time (s)
Dip meter
Pressure transducer

Appendix B. Hydrochemistry field investigations at Dangila *woreda*

B-1 Introduction

Groundwater sampling and in-situ testing was initially undertaken during the first field visit in March/April 2015 at the end of the dry season. All samples and tests were taken from traditional hand-dug wells (HDWs) or springs. Samples were analysed principally at laboratories in Ethiopia with some samples tested in the UK to assess consistency and accuracy of the results. Laboratory analysis consisted of major ion and stable isotope testing. In-situ testing consisted of measurement of field pH, temperature and electrical conductivity.

Much of the sampling and testing was repeated during the second field visit in October/November 2015 at the end of the wet season. In addition, the sampling and testing regime included deep boreholes, surface water, rainwater, and radon-222 measurements.

B-2 Purpose of sampling and in-situ testing

The aims of the sampling and in-situ testing programme were:

- Identification of water types: (i) higher yielding wells may have a particular chemical signature; (ii) there may be areas where groundwater is chemically unsuitable for certain uses.
- Assessment of aquifer connectivity: (i) if nearby wells and springs have contrasting hydrochemistry then it may indicate low connectivity, (ii) similar hydrochemistry at distant locations may indicate preferential groundwater flow paths.
- Groundwater aging: (i) very low ionic concentrations would indicate recently recharged groundwater; (ii) it may be possible to estimate groundwater residence times to indicate areas of greatest storage and therefore the least vulnerability to climate variability.
- Recharge mechanism: (i) estimations on the degree of evaporation prior to recharge could indicate if recharge occurs during intense storm events or is more diffuse, (ii) the role of floodplains to act as recharge basins could be evaluated, (iii) it would suggest whether recharge occurs locally or ubiquitously.

- Consistency of groundwater: (i) comparisons with testing results from previous studies will suggest whether the samples are representative, (ii) such comparisons will also show whether the groundwater is changing over time.
- Identification of losing and gaining reaches of surface water to aid conceptual model development.

B-3 Sampling locations

Sampling locations were identified prior to the field visit utilising data collected by Demis Alamirew of GSE during fieldwork in February/March 2014 as part of the AMGRAF catalyst period. Sampling locations were selected to give a distribution of groundwater analyses from various catchments, topographic positions, altitudes, *kebele*s, positions in the catchment; e.g. close to the watershed or close to rivers, geologies; e.g. from fractured or vesicular basalt with or without regolith or alluvium, seasonal and perennial sources, springs and wells, shallow and deeper water tables, zones of various groundwater potential indicated by SHETRAN modelling of low-flows by Dr Geoff Parkin during the AMGRAF catalyst period, and zones of various groundwater potential indicated by Demis Alamirew according to geological formation and field investigations.

It was not possible to keep entirely to the sampling location plan during the field visit due to occasional springs or wells being dry and a number of pumps being broken. Furthermore, the selection of sampling points according to geology, particularly regarding bedrock, was generally unfeasible due to outcrops being restricted to riverbeds and banks. Superficial geology was occasionally easier to identify from well excavation arisings or by peering into the well shaft. However, the generally ubiquitous weathered basalt regolith or clayey sandy floodplain materials above variously massive, vesicular and/or fractured basalt meant sampling according to precise geology was overly-ambitious.

The geographical distribution of the sampling locations is presented in Figure B-1. During the second field visit, ten locations were resampled; more resamples were proposed but non-functioning wells made this impossible. New sampling sites included transects of surface and groundwater to test hypotheses from the conceptual model development. The ease of in-situ testing meant that measurements were taken at many other sites in addition to the sampling locations; wherever it was thought results could provide useful information.

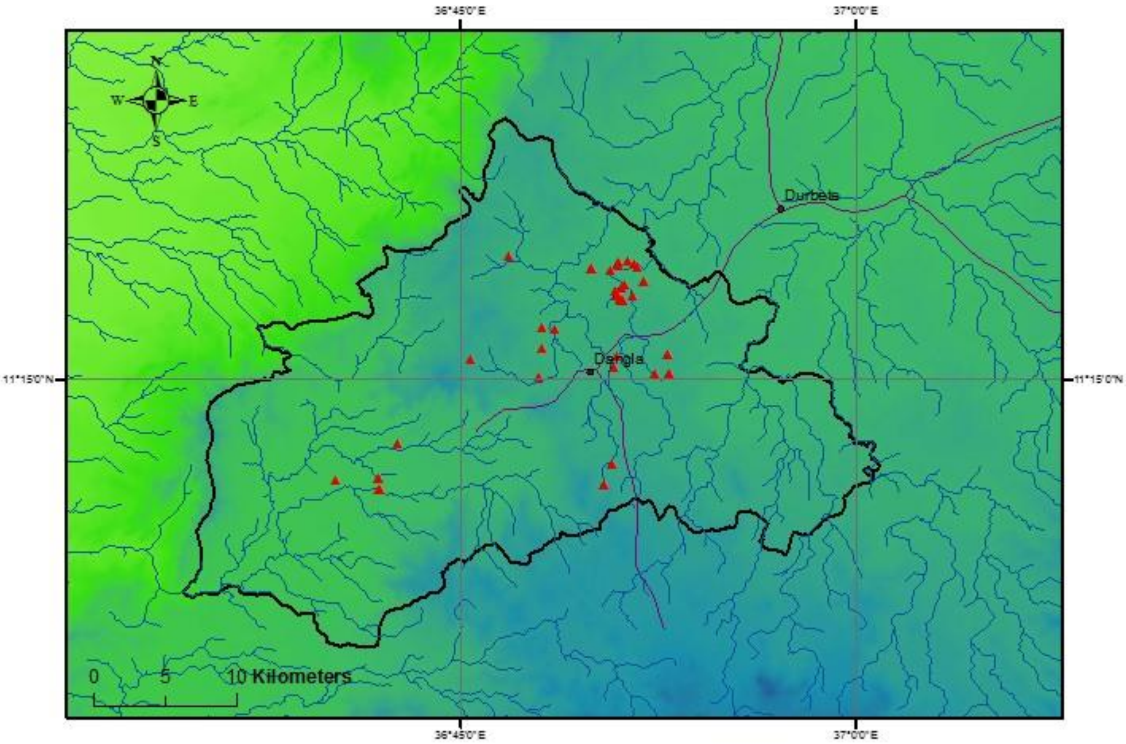


Figure B-1. Geographical distribution of sampling locations (red triangles) across Dangila *woreda* (black outline). The background is a DEM with green being the lowest elevation and blue the highest elevation.

B-4 Sampling methodology

Sampling was conducted in accordance with accepted international standards and guidelines (Gov. WA, 2009; CCME, 2011; IAEA, -). A polypropylene syringe was rinsed several times in sample water prior to filling for sample collection. Sample water was collected directly from the hand pump or rope-and-washer pump outlet, from a collection bucket on a rope (typically a doctored 10-litre HDPE jerry can) or the point of emergence of a spring (Figure B-2). New nalgene bottles were used for sampling, which were brought from the UK. Major ion samples were filtered through 0.2 μm Supor® Membrane into 125 ml bottles. Two 125 ml samples were collected and filtered at each sampling location, one for cation analysis and one for anions; the sample for cation analysis having the addition of three to four drops of nitric acid preservative. Stable isotope samples were collected in 60 ml bottles with no filtration or preservative. Care was taken to keep the bottles clean and avoid contamination during sampling. In addition to tightly capping, samples had their caps sealed further with electrical insulation tape to restrict the possibility of evaporation from the bottles.

Figure B-2. Receiving local assistance sampling and in-situ testing from a developed spring (left) and a rope and washer pump.

Wells were not purged to commonly proposed standards prior to sampling. Pumping tests showed that the hydraulic conductivity of the shallow aquifer is quite low and water level recovery in the wells was slow following abstraction. Given that the first field visit took place during the period of highest water scarcity it would have been unethical to attempt to purge several (typically three) well volumes prior to sampling. What’s more, HDWs in the area have diameters of around a metre and consequently well bore storage is high. The necessary time to remove several well volumes with the equipment available would have been excessive and extremely labour-intensive. However, sampling preferentially took place from wells that experienced heavy use and/or following use in order for the collection of water by the local community to mimic controlled purging. In addition, sampling preferentially took place from sealed sources, which were not open to evaporation, such as hand pumps, rope-and-washer pumps, and springs at the point of emergence. To restrict the sampling of groundwater that had potentially undergone evaporation, samples from open wells were collected following abstraction of water during pumping tests, which in effect was a low volume purge of the well.

On each sample bottle the sample number, site name, sampling date and required analysis was marked with indelible marker. For each sample location the following information was recorded: sample number, *woreda*, *kebele*, site name, GPS coordinates, GPS altitude, sampling date, geology, field pH, temperature, electrical conductivity, well depth, depth to water, pump or cover type, flow estimate (if a spring), adjacent land use, immediate topography, wider topography, mode of emergence (if a spring), use (e.g. domestic, irrigation, etc.), seasonality, and any other information that could be pertinent, such as the history of the feature, either observational or through conversation with local users.

Samples were stored in a cool dark place until transportation to the laboratory; the average storage period being eleven days for the first field visit and three days for the second.

B-5 Major ion hydrochemistry

B-5-1 Analysis

Major ion analysis took place at ADSWE (Amhara Design & Supervision Works Enterprise) Laboratory in Bahir Dar, Ethiopia. ADSWE is a modern and professional soils and water testing laboratory currently working towards international accreditation. Anion analysis was undertaken by a Palintest 2700 photometer utilising Dionex ion chromatography, with the exception of bicarbonate and carbonate that was analysed by titration. A Nova 300 Series utilising atomic absorption spectroscopy undertook cation analysis. Analysis equipment was calibrated in accordance with manufacturer's instructions.

Major ion analysis consisted of testing for Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO_3^{-}. In addition, some samples were analysed for CO_3^{2-}, F^{-} and Fe^{2+}. Analysis for Fe^{2+} was deemed pertinent due to common red staining of filters during sampling. Samples were analysed for F^{-} because Ethiopia is known for having problems with fluorosis caused by groundwater, though excess F^{-} in groundwater is generally found in the Rift Valley and from deep wells (Kloos and Haimanot, 1999; Tekle-Haimanot *et al.*, 2006; Kebede, 2013).

B-5-2 Quality assurance

A sample was collected in triplicate with one sample submitted blind to the laboratory and the third brought to the UK for analysis at Newcastle University. The average difference between measured concentrations of the samples tested by ADSWE was 16.6%. The average difference between measured concentrations of ADSWE vs Newcastle University tested samples was 26.2% for anions and 71.1% for cations. The discrepancies between the triplicate samples appear high; particularly in the case of cations tested at Newcastle University, which gave significantly higher concentrations than for all samples analysed in Ethiopia. This sample also showed a high positive ionic balance error of 15.9%. The cause of the discrepancies was investigated and several possibilities can be ruled out:

- Contact with the laboratories indicated that all equipment had been recently calibrated.

- A review of manufacturers' datasheets and discussion with equipment operators revealed that the discrepancies are in excess of the tolerance of the analysis equipment.
- Following discussion with operators of such equipment at Newcastle University, the natural variations in hydrochemistry within a sample could not account for such discrepancies.
- The sample that appeared to contain excessive cations was retested at Newcastle University to determine if an erroneous result had been obtained. Almost identical concentrations were measured.

It is therefore suggested that the sample with excessive cations had become contaminated. It is worth noting that, given the very low concentrations of all major ions, reduction of just 5 mg/l of calcium, magnesium and potassium would bring the ionic balance error within ±5%. However, the cation concentrations would still be significantly higher than those measured in Ethiopia. A sample collected in duplicate during the second field visit and analysed at ADSWE and at Newcastle University showed an average difference between measured concentrations of just 1.3% further suggesting that the triplicate sample from the first visit had become contaminated.

Regarding the first field visit, ionic balance calculations in only 35% of the samples were within ±5% and 82% of samples were within ±10% with an average ionic balance error of 6.6%. From the second field visit, just 12.5% of samples were within ±5% while only 43.8% of samples were within ±10% and the average ionic balance error is 12.9%. Three possibilities are identified which could (singularly or together) be causing the high ionic balance errors:

1) Major ion concentrations within the groundwater samples are low, often at trace level. Therefore, trace elements, which are usually unimportant in calculating electroneutrality, are having an impact. For the first field visit, 73% of the ionic balance errors greater than ±5% are in the negative suggesting there are unanalysed cations affecting the ionic balance. To substantiate this claim, it was intended that subsequent testing regimes would include trace metal analysis such as aluminium and silica (considering the mineralogy of the shallow aquifer). Unfortunately, when the samples from the second visit were delivered to the ADSWE laboratory they informed us that such analysis could not be undertaken at that time due to a shortage of necessary equipment consumables. However, samples from the second visit in all but one case show high positive ionic

imbalances and therefore an excess of cations perhaps indicating the presence of unanalysed anions. This suggestion of unanalysed ions influencing electroneutrality is supported by the higher TDS of samples with greatest ionic balance error though analysed concentrations are not significantly different.

2) Because the major ion concentrations are low, small errors in concentration measurement (due to the equipment, the operator, or minor contamination) would be amplified when calculating percentage errors.
3) There is of course the third possibility that the major ion analysis is unreliable and significant conclusions should not be drawn from the groundwater chemistry analysis.

B-5-3 Results

The results of the major ion analysis are presented in Tbale B-1 and Table B-2. Considering the first field visit, there was not great variation among the shallow groundwater analyses. In trying to assign water types there are three samples with very low EC and dissolved ion concentrations (TDS all <25 mg/l) that could be considered the youngest, i.e. most recently recharged, groundwater. However, perhaps unexpectedly given the proposed short groundwater residence time, SI/A/C 1 and 3 are from sources with very good perennial supply. An older water type could be assigned to the groundwater with higher concentrations of HCO_3^- and Ca^{2+} and highest EC (TDS all <150 mg/l). Such groundwater (SI/A/C 7, 8, 9, 11 and 18) has a longer residence time though again, similar to the youngest water type, the sampling locations have few similarities. There are not significant enough differences to assign water types or identify a hydrochemical signature of the highest yielding sources. Although there is the possibility that all of the samples represent the water type for good perennial water sources because the seasonal wells were dry in March/April and couldn't be sampled.

Considering the second field visit, there is not great variation among and between the shallow groundwater and surface water analyses though the deep groundwater has a different signature. The deep groundwater has low calcium and high sodium suggesting ion exchange. pH is high at 8.8 (possibly due to release of CO_2 from the water). The groundwater is likely to be old – as would be expected from boreholes >100 m deep – as it has high EC (>300 µS/cm), high bicarbonate and has taken time for Ca-Na exchange. Nitrate and sulphate are both low due to little human input and reducing waters. It may have been expected to see bicarbonate to sulphate exchange and this may have occurred followed by sulphate reduction, though there is no evidence of sulphide (not analysed but no smell). However, sulphide could have precipitated out as FeS_2, which is why iron concentration is lower than may be expected in a (suspected) low to zero dissolved oxygen water, though this sulphate reduction would have reduced the pH. Generally, the EC and ionic concentrations are lower than the first field visit, which indicates that at the end of the wet season the analysed groundwater had been recently recharged. However, repeat tests show very similar chemistries suggesting a longer (months rather than days/weeks) residence time. Surface water samples show similar chemistries to shallow groundwater samples though with EC at the lower end (around 100 µS/cm) and pH at the upper end (around pH 6.5).

Table B-1. Results of in-situ testing and laboratory analysis from first field visit in March/April 2015. All the samples are shallow groundwater.

Sample number	Location ID	In-situ field measurement			Calculated from EC	Laboratory analysis (mg/l)											Ionic balance error	Laboratory analysis (‰ VSMOW)	
		Temp. (°C)	pH*	EC (µS)	TDS (mg/l)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Fe^{2+}	Cl^{-}	F^{-}	SO_4^{2-}	NO_3^{-}	HCO_3^{-}	CO_3^{2-}		$\delta^{18}O$	$\delta^{2}H$
SI/A/C 1	DW43	20.9	5.19	50.62	25	8.83	1.07	0.08	2.65	0.1	1.5	0.31	2.8	2.7	25.8	0	1.70%	-2.14	-0.17
SI/A/C 2	dw4	20.8	5.84	99.7	50	10.8	1.44	2.4	7.5	2.93	3.2	0.5	8.2	1.54	35.4	0	8.52%	-1.81	0.23
SI/A/C 3	CS42	22.1	5.31	48.67	24	14.1	2.42	0.08	5.13	0.01	0.8	0.8	2.4	2.34	50.2	0	3.11%	-1.56	-0.58
SI/A/C 4	DW56	22.9	5.53	171.9	87	12.5	2.28	0.08	0.15	0.01	2.6	0.21	1.5	4.85	48.8	0	-9.63%	-1.24	3.64
SI/A/C 5	DW73	20.3	5.83	130.7	66	14.6	2.37	1.73	0.42	0.2	0.5	0.22	1.1	4.37	52.0	0	2.26%	-1.55	1.98
SI/A/C 6	dw6	22.3	5.57	144.2	73	15.5	2.23	0.08	0.83	0.03	4.9	0.3	1.2	1.98	40.2	0	6.10%	-2.54	-3.58
SI/A/C 7	DW79	25.2	6.88	334.9	172	19.4	3.4	0.08	1.74	0.01	3.7	0.31	1.1	2.9	85.2	0	-10.08%	-1.91	no result
SI/A/C 8	DW79	25.2	6.88	334.9	172	17.5	3.07	0.08	3.43	0.01	4.1	0.41	2.3	3.05	80.3	0	-12.03%	-1.36	1.67
SI/A/C 9	DW79	25.2	6.88	334.9	172	41.9	16.7	9.0	0.99	0.002	5.597	0.116	1.167	2.822			15.89%	no sample	
SI/A/C 10	CS12	22	5.98	217.6	111	21.7	4.24	5.03	0.04	0.01	1.2	0.35	1.5	4.95	95.1	0	-2.08%	-1.48	0.27
SI/A/C 11	DW18	25.9	6.66	481.9	249	19.8	3.61	17.55	3.21	0.01	2.1	0.43	2.1	1.99	152.2	0	-10.90%	no result	0.59
SI/A/C 12	DW2	21.9	5.76	200.4	102	18.4	3.44	0.08	2.13	0.01	1.3	0.32	0.84	3.2	90.4	0	-12.03%	-1.83	-2.12
SI/A/C 13	dw10	22.1	5.69	44.29	22	10.1	1.78	2.87	1.03	0.01	1.4	0.33	0.92	2.65	38.5	0	3.37%	-1.95	-2.74
SI/A/C 14	DW21	24.7	6.17	174.0	88	17.4	2.81	4.6	1.54	0.01	1.3	0.4	6.2	1.48	60.2	0	5.60%	-1.85	0.76
SI/A/C 15	DW22	24	6.31	264.4	135	18.8	2.94	2.54	2.29	1.65	0.7	0.56	1.6	1.22	97.3	0	-9.30%	-2.86	-5.04
SI/A/C 16	dw15	23.4	5.69	196.8	100	18.7	3.12	0.1	1.14	4.3	1.7	0.28	1.4	2.37	86.1	0	-5.63%	no result	no result
SI/A/C 17	cs6	22.2	6.09	189.6	97	23.3	3.87	0.8	1.24	0.01	1.2	0.37	1.1	2.5	91.2	0	-2.00%	-1.97	-1.45
SI/A/C 18	dw30	21.9	5.99	309.4	159	27.1	3.18	0.19	9.06	0.7	2.7	0.25	1.2	4.12	125.4	0	-8.67%	-2.16	-0.02

* The field pH meter was suspected to have been reading 0.25-0.5 pH too low (see text).

Triplicate samples highlighted grey (SI/A/C7, 8 and 9) with the sample tested at Newcastle University highlighted darkest.

Table B-2. Results of in-situ testing and laboratory analysis from second field visit in October/November 2015.

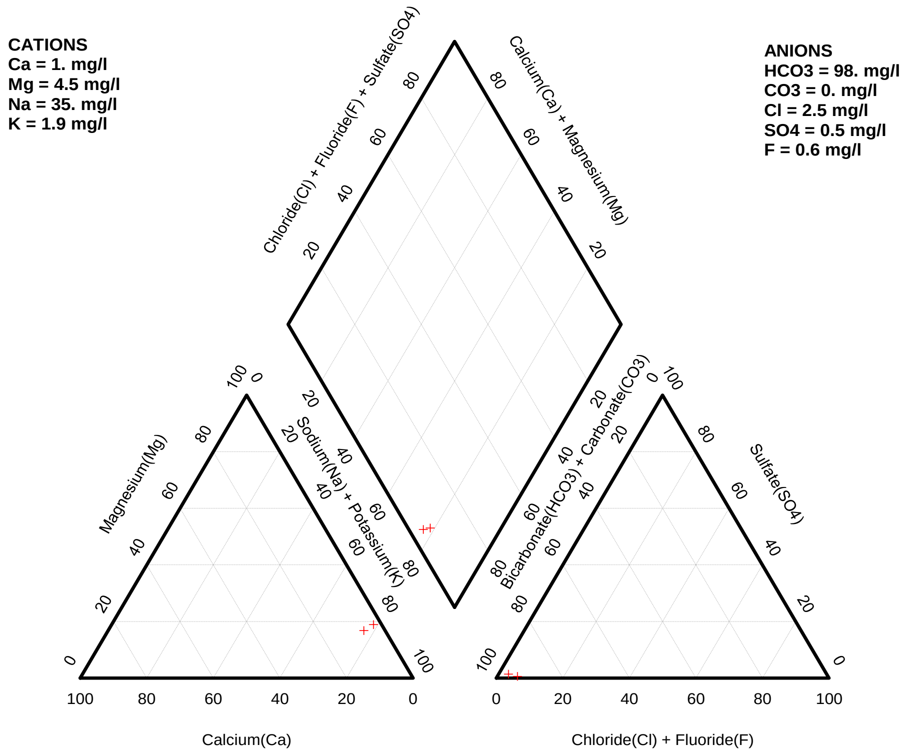
Sample number	Location ID	Sample type	In-situ field measurement			Calculated from EC	Laboratory analysis (mg/l)										Ionic balance error	Laboratory analysis (‰ VSMOW)	
			Temp. (°C)	pH*	EC (μS)	TDS (mg/l)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Fe^{2+}	Cl^{-}	F^{-}	SO_4^{2-}	NO_3^{-}	HCO_3^{-}		$\delta^{18}O$	$\delta^{2}H$
2SI/A/C1	DW56	Groundwater	22.9	5.61	167.7	107	15.88	6.5	8.65	1.91		2.70		1.10	10.50	51.85	22.09%	5.74	-0.47
2SI/A/C2	dw21	Groundwater	30.9	6.71	403.5	258	45.67	5.5	16.21	4.71		2.60		3.20	0.96	140.30	18.34%	-0.45	-0.41
2SI/A/C3	cs6	Groundwater	22.9	6	188.70	121	19.85	5.5	13.1	0.85		2.70		5.20	3.76	54.90	27.99%	3.46	-0.01
2SI/A/C4	DTW3	Deep Groundwater	22.9	8.77	315	202	2.55	4.05	34.1	1.84	0.01	0.90	0.47	1.10	0.98	97.60	8.23%	-3.98	-1.63
2SI/A/C5	dw31	Groundwater	21.8	5.55	136.4	87	14.73	5.01	10.4	1.24		2.20		8.10	3.70	51.85	17.72%	10.59	0.41
2SI/A/C6	D3	Deep Groundwater	21.8	8.81	335	214	0.97	4.51	34.5	1.86	0.01	2.50	0.64	0.50	1.44	97.60	6.23%	-1.02	-1.61
2SI/A/C7	RFL39	Rain										0.380		1.912	0.799			16.96	1.58
2SI/A/C8	DW43	Groundwater	20.5	4.77	46.26	27	4.89	6.02	5.33	1.34		1.20		8.30	4.20	24.40	19.71%	9.57	0.21
2SI/A/C9	CS42	Groundwater	22.2	4.77	58.44	37	6.25	4.03	3.01	1.08		1.20		7.20	4.50	27.45	6.35%	1.46	-0.29
2SI/A/C10	DW22	Groundwater	21.7	5.46	133.3	85	18.07	7.03	5.51	2.25		1.60		2.01	6.20	24.85	49.89%	11.39	0.72
2SI/A/C11	DW21	Groundwater	22.1	5.19	167.1	107	18.55	5.02	5.37	1.05		11.5		7.04	1.16	46.15	12.41%	8.79	0.59
2SI/A/C12	DW73	Groundwater	20.9	5.3	110.9	71	8.87	7.01	1.97	1.68		0.3		8.12	10.5	42.6	4.70%	4.19	0.33
2SI/A/C13	dw6	Groundwater	22.2	5.41	133.8	86	12.48	5.02	1.73	0.57		4.8		7.05	4.2	24.85	19.57%	4.81	0.30
2SI/A/C14	dw18	Groundwater																1.75	-0.04
2SI/A/C15	DW77	Groundwater	22.3	5.24	146.6	94												4.23	0.31
2SI/A/C16	dw2	Groundwater	22.5	6.43	289	185												6.37	0.11
2SI/A/C17	RFL46	Wetland stream	21.8	6.83	99.35	64												10.98	1.59
2SI/A/C18	CS12	Groundwater	22.8	5.98	217.6	139	17.56	5.05	6.27	2.01		1.2		6.1	11.5	60.35	9.50%	6.99	1.03
2SI/A/C19	CS12	Groundwater	22.8	5.98	217.6	139	15.85	6.71	3.92	3.86		2.67		8.22	9.41	60.26	7.55%	6.37	0.96
2SI/A/C20	RFL48	River	23.1	6.39	106.6	68												13.49	0.92
2SI/A/C21	RFL49	Wetland	30.9	6.71	256.1	164												16.42	1.85
2SI/A/C22	RFL50	Rain										0.541		1.225	0.935			51.30	5.90
2SI/A/C23	RFL39	Rain										1.122		1.063	1.102				
2SI/A/C24	RFL51	Wetland stream	20.3	6.84	83.26	53												23.14	0.35
2SI/A/C25	RFL52	Wetland stream	26.6	6.04	70.28	45	9.41	7.08	2.64	4.33		1.3		14	2.06	53.25	1.73%	23.44	0.92
2SI/A/C26	RFL53	River	23.1	6.18	91.1	58												21.97	0.64
2SI/A/C27	RFL55	River	22.3	6.27	93.45	60												23.13	1.29
2SI/A/C28	DW79	Groundwater	24.7	6.59	231.3	148	33.0	8.72	4.5	<1	0.001	2.119		1.146	6.485		86.43%	3.31	0.91
2SI/A/C29	cs9	Groundwater	23.2	5.75	124.8	79.8												2.65	0.50
2SI/A/C30	cs10	Groundwater	23.5	6.11	171.7	110												5.39	0.34
2SI/A/C31	RFL61	River	22.9	6.29	104.8	67	9.66	6.12	1.34	1.83		2.8		25.1	2.1	74.55	-26.00%	8.29	1.16

* The field pH meter is no longer thought to have been reading low (see text).

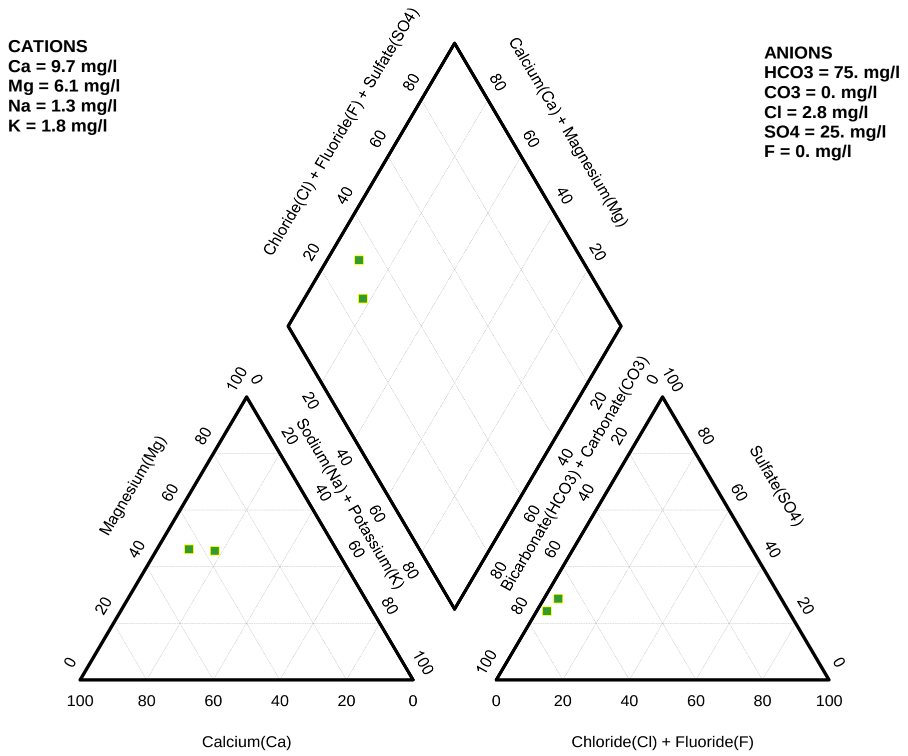
Duplicate samples highlighted grey (2SI/A/C18 and 19) with the samples tested at Newcastle University highlighted darkest.

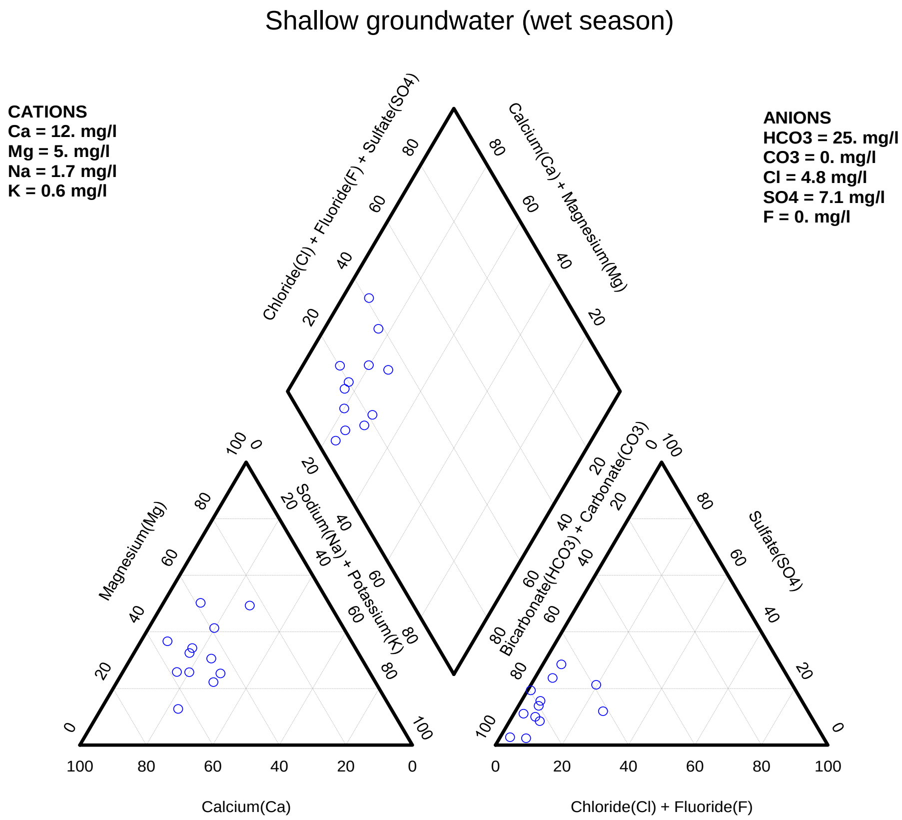
The piper diagrams in Figure B-3 show that the surface water and shallow groundwater belong to the “bicarbonate calcium” type typical of recent recharge. The deep groundwater is of “bicarbonate sodium” type indicative of higher mineralisation due to longer residence time and greater distance of flow. The shallow groundwater samples from the wet season plot more closely to the surface water samples indicating a high degree of interconnectivity between the surface and shallow groundwater. This was expected in the wet season from the observed very shallow water table.

Deep groundwater (wet season)



Surface water (wet season)





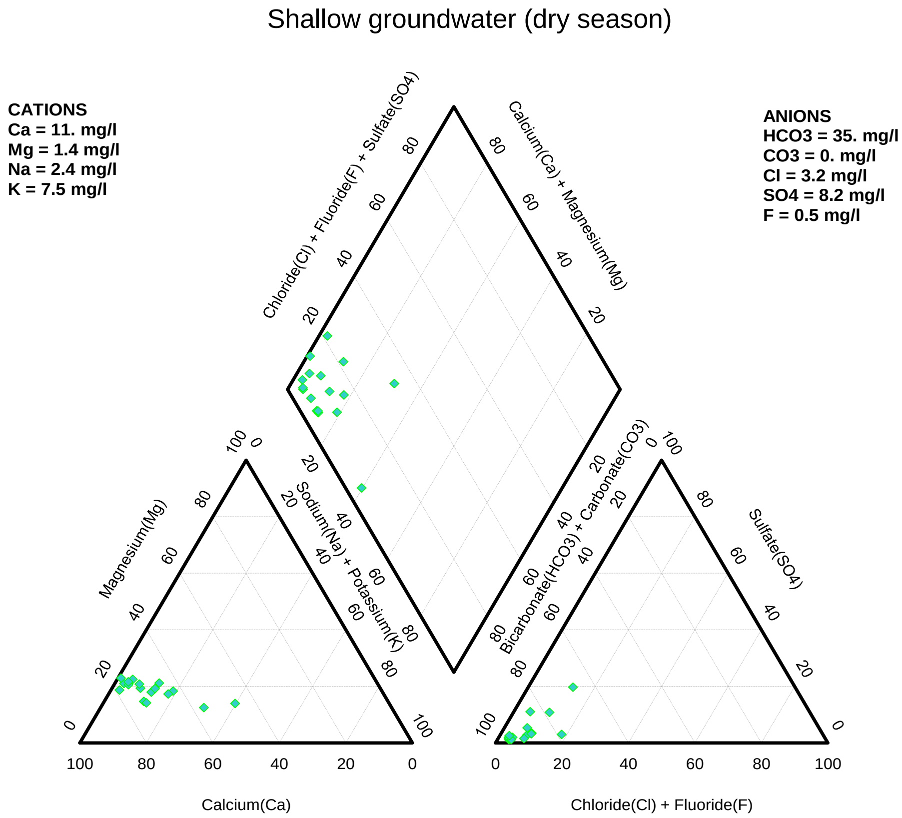


Figure B-3. Piper diagrams for different sources of water analysed within Dangila *woreda*. Average cation and anion concentrations are also given on the plots.

Fluorine levels within all samples, including those from the deep aquifer, were below the WHO recommended maximum of 1.5 mg/l (WHO, 2011); the maximum measured was

0.8 mg/l. Pit latrines, occasionally in close proximity to wells, could elevate nitrate levels in shallow groundwater though all samples recorded well below WHO guidelines; the maximum measured was 11.5 mg/l. WHO does not give a guideline value for iron concentration in drinking water though four samples were above the 0.3 mg/l at which water discolours and staining can occur. The sodium adsorption ratios (SAR) were extremely low: ~3.0 for the deep groundwater samples and <1.0 for all other samples. SAR >3.0 is generally thought potentially problematic for irrigation water (Olson, 2012). Considering only hydrochemistry and not microbial content, the analyses indicate that all the groundwater tested is suitable for both irrigation and potable use.

B-6 Stable isotope

B-6-1 Analysis

Dr Seifu Kebede, a renowned isotope hydrogeologist, at the School of Earth Science, Addis Ababa University, Ethiopia, conducted stable isotope analysis. Analysis was undertaken by a LGR DLT-100 utilising laser spectroscopy. Analysis equipment was calibrated in accordance with manufacturer's instructions. Stable isotope analysis consisted of testing for $\delta^{18}O$ and $\delta^{2}H$.

B-6-2 Quality assurance

A sample was collected in duplicate with one sample submitted blind to the laboratory. A result was not obtained for $\delta^{2}H$ for one of the samples whereas for $\delta^{18}O$ the results differed by 28.8%. This percentage difference seems high though it is a percentage of a low result, which actually equates to only 0.55‰ VSMOW. Both results would plot in a very similar position on Figure B-4Figure B-4. Plot of all stable isotope results. Units are ‰ VSMOW. The dotted line equates to the Addis Ababa local meteoric water line derived from data presented by Rozanski *et al.* (1996) and the dashed line is the derived local evaporation line.. The blind submitted during the second field visit varies by 8.9% ($\delta^{18}O$) and 6.8% ($\delta^{2}H$) with small absolute differences.

B-6-3 Results

Unfortunately, analysis could not be completed on all of the samples. "No Result" on Table B-1, according to the laboratory, "means we haven't gotten good results for those analysis and we have discarded them". Each sample is analysed a number of times due to the sensitivity of the equipment and if the standard deviation of the results is above a certain threshold the result is rejected. The stable isotope results are presented in Figure B-4.

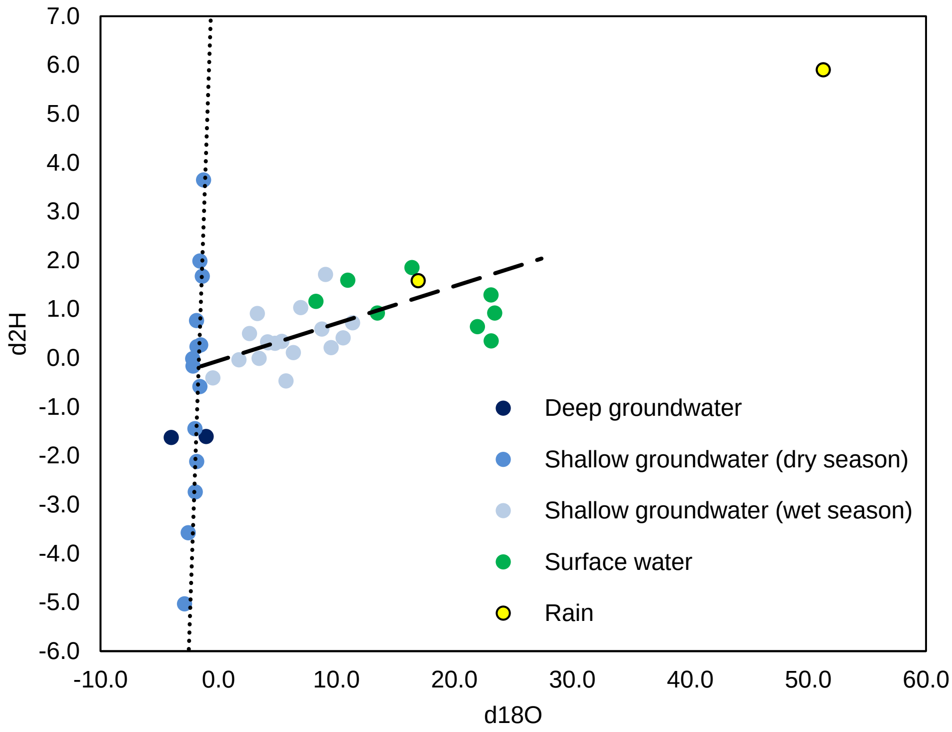


Figure B-4. Plot of all stable isotope results. Units are ‰ VSMOW. The dotted line equates to the Addis Ababa local meteoric water line derived from data presented by Rozanski *et al.* (1996) and the dashed line is the derived local evaporation line.

Figure B-4 shows clear differences between water sources and notably between shallow groundwater sampled in the dry season and from the wet season. A local evaporation line can be drawn through the wet season shallow groundwater and surface water results at odds with the dry season shallow groundwater results, which plot close to the local meteoric water line. The surface water samples are indicative of evaporation causing enrichment, which would be expected as rainfall collects in dambo wetlands before accumulating to form streams and rivers. The wet season shallow groundwater results are also enriched and similar to the surface water results indicating recently recharged water that infiltrated from wetlands. The slightly lower enrichment of the shallow groundwater than the surface water suggests mixing with diffusely recharged and thus less evaporated and enriched water. The dry season shallow groundwater results plot close to the local meteoric water line suggesting diffuse recharge. This would be predicted, as the wetlands are dry outside of the wet season, therefore, there is less opportunity for evaporation at the time of infiltration in the dry season despite the higher temperatures and lower relative humidity. The deep groundwater was sampled during the wet season and plots well away from other wet season groundwater samples indicating little interconnectivity. The deep samples show the highest depletion meaning recharge could have occurred at a distant high mountain area. The rainwater samples show very high enrichment. The cause of this enrichment is uncertain. Sampling was directly from falling rain during intense storms and at night so there was no opportunity for evaporation.

B-7 In-situ testing

B-7-1 Methodology

A handheld Myron L Company Ultrameter II was used for in-situ water testing, calibrated immediately prior to the field visits. Testing was conducted in accordance with accepted international standards and guidelines (Gov. WA, 2009; IAEA, -). Testing comprised measurement of water temperature, pH and electrical conductivity. The sensor was thoroughly rinsed with sample water and the reading allowed to stabilise prior to a measurement being recorded.

B-7-2 Results

The results of in-situ testing from the locations where samples were collected are presented with the laboratory results in Table B-1 and Table B-2. Results from locations that had been tested a year previously during fieldwork by GSE are presented in Table B-3; there are eleven locations where testing was repeated. A total of 28 locations were subjected to testing in March/April 2015 following the 198 in February/March 2014 and a further 40 in October/November 2015.

Table B-3. Comparison of in-situ testing results from February/March 2014, March/April 2015 and October/November 2015.

Location code	Sample number	Oct/Nov 2015 pH *	Mar/Apr 2015 pH *	Feb/Mar 2014 pH	Oct/Nov 2015 EC (µS)	Mar/Apr 2015 EC (µS)	Feb/Mar 2014 EC (µS)	Oct/Nov2015 Temp. (^oC)	Mar/Apr 2015 Temp. (oC)	Feb/Mar 2014 Temp. (^oC)
DW73	SI/A/C 5 & 2SI/A/C 12	5.3	5.83	6.22	110.9	130.7	132.6	20.9	20.3	21.5
DW77	2SI 15	5.24	5.28	6.04	146.6	90.74	104	22.3	22.2	26.4
DW43	SI/A/C 1 & 2SI/A/C 8	4.77	5.19	5.82	46.26	50.62	56.8	20.9	20.9	18.9
DW56	SI/A/C 4 & 2SI/A/C 1	5.61	5.53	6.04	167.7	171.9	182.2	22.9	22.9	25.4
DW61			5.95	6.33		216.6	217		22.1	22.5
DW79	SI/A/C 7 8 9 & 2SI/A/C 28	6.59	6.88	7.35	231.3	334.9	320	24.7	25.2	26.7
DW18	SI/A/C 11		6.66	7.2		481.9	502		25.9	24.2
DW2	SI/A/C 12		5.76	6.32		200.4	203		21.9	23.3
DW21	SI/A/C 14 & 2SI/A/C 11	5.19	6.17	6.54	167.1	174	142	22.1	24.7	21.7
DW22	SI/A/C 15 & 2SI/A/C 10	5.46	6.31	6.69	264.4	264.4	200	24	24	26.4
dw6	2SI/A/C 13	5.41	5.57		133.8	144.2		22.2	22.3	
CS42	SI/A/C 3 & 2SI/A/C 9	4.77	5.31	6	58.44	48.67	49.7	22.2	22.1	23.5
cs6	2SI/A/C 3	6	6.09		188.7	189.6		22.9	22.2	
CS12	2SI/A/C 18 19	5.98	5.98		225.3	217.6	220	22.8	22.0	22.9
cs1		5.36	5.22		66.35	61.93		20.3	22.8	

* The field pH meter was suspected to have been reading 0.25-0.5 pH too low after the first field visit but now it is thought the 2014 readings were too high (see text).

Considering the first field visit, it was suspected that the handheld meter was falling out of calibration with regard to pH. The field pH results were consistently lower than tested previously whereas electrical conductivity results were almost identical 12-13 months after first being recorded and water temperature measurements are similar. However, pH results from the second field visit are similar to that of the first suggesting the anomalous readings may be those taken by GSE in 2014.

In-situ testing indicates that shallow groundwater in the area generally has pH around 6 and EC 50-300 µS. These values are typical of young groundwater in igneous terrain. The field tests gave remarkably similar EC measurements on both field visits, and to the previous period of testing 12-13 months earlier. The consistency of results indicates that the groundwater has consistent properties and, therefore, the samples are representative of shallow groundwater from this location.

B-8 In-situ radon-222 testing

B-8-1 Methodology

Radon-222 is one of the radioactive decay products of uranium-238, a radioactive element that naturally occurs in the minerals of most rocks. As an inert gas, ^{222}Rn readily migrates, through advection and diffusion, into and with groundwater. Groundwater ^{222}Rn concentration reaches steady state and declines rapidly upon discharge due to the short half-life of 3.8 days. Analysis of the spatial distribution of ^{222}Rn concentrations in surface and groundwater was used to assess infiltration from surface water to aquifers by Hoehn and Von Gunten (1989) in Switzerland and by Bertin and Bourg (1994) in southern France, to measure rates of groundwater discharge into a river in the Northern Territory of Australia by Cook *et al.* (2003) and into small lakes in Florida, USA, by (Dimova *et al.*, 2013), and in Central Chile by Oyarzún *et al.* (2014) to assess groundwater-surface water connectivity. No previous studies were identified from Africa.

A DURRIDGE RAD7 with the “Big Bottle System” was used for in-situ measurement of radon-222 concentration in water. The equipment was borrowed from Dr Seifu Kebede at the University of Addis Ababa. Radon-222 testing was conducted in accordance with the Durridge Company Inc. manuals, comprising:

1. Equipment set up.
2. Purging of the equipment for at least 10 minutes and until a maximum internal relative humidity of 10% was achieved.
3. Careful sampling of water directly into the “big bottle” avoiding turbulent flow and degassing.
4. Running the test for at least 45 minutes with monitoring of radon-222 concentration, internal relative humidity and water temperature.

5. Removal of sample and minimum of 8-minute post-test purge before equipment disassembly.

The initial test was unsuccessful; purging took several hours to reduce the relative humidity to the correct level and following over an hour of testing the radon-222 concentrations were approaching zero. Considering the sample came from one of Dangila town's deep supply boreholes a concentration of several thousand Bq/m^3 would be expected. Later investigation revealed that a one-way valve, in place to prevent water from entering the RAD7 instrument, had been installed the wrong way round. Once the valve had been reinstalled correctly, the equipment operated satisfactorily.

Sites for testing were selected along surface and groundwater flow reaches to attempt to identify areas that were losing to groundwater and areas where groundwater discharged to surface water. Photographs of the equipment set up and testing in progress are shown in Figure B-5.

Figure B-5. Photographs showing radon-222 testing. The in-situ EC, pH, and temperature meter is also visible.

B-8-2 Results

The first phase of testing concentrated on Dangesheta *kebele* and took place over three days; the locations and results of the testing can be seen in Figure B-6. The highest radon-222 concentrations were obtained high on the elevated floodplain close to monitoring well MW2. The samples were very recently discharged groundwater and the high values are as expected. The radon-222 concentrations decrease along the surface water flow path through the wetland towards the Brante River. This decrease is caused by dilution of spring-fed surface waters (high ^{222}Rn) with rain-fed runoff (zero to very low ^{222}Rn) through the wetland. The main Brante River always shows lower concentrations than the wetlands due to dilution of recent groundwater input. The pattern shown by the testing along the Brante River is higher radon-222 concentrations along reaches through floodplains with alluvium beds and lower concentrations in narrow valleys with basalt bedrock riverbeds. Radon-222 concentrations increase along the length of floodplains. The results indicate that groundwater discharge occurs in the floodplains from the regolith aquifer and not from basalt bedrock along narrow valley reaches. However, it should be noted that the faster, more turbulent flow through rocky reaches would have a degassing effect on the river water thus reducing radon-222 concentrations (Cook *et al.*, 2003).

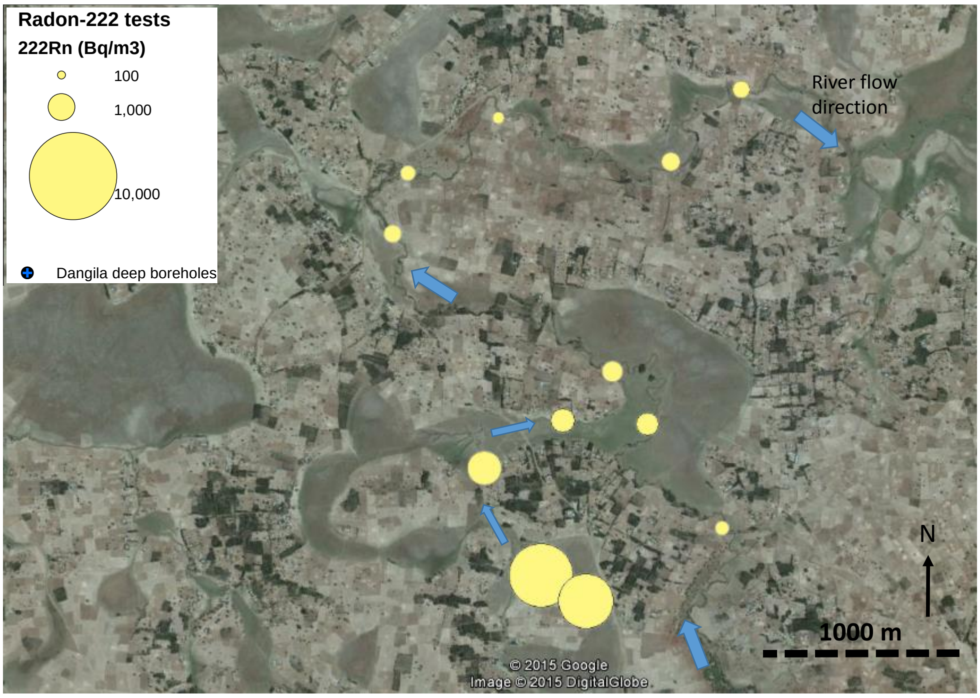


Figure B-6. Map of radon-222 testing results in Dangesheta within the Brante catchment.

The second phase of testing took place to the northwest of Dangila town; the locations and results of the testing can be seen in Figure B-7. Quick water balance estimates had suggested that there might be groundwater loss from the shallow to the deep aquifer. In addition, an official at the Dangila town water supply office spoke of farmers complaining that wells close to the town's deep abstracting boreholes were suffering declining water levels. If the deep boreholes were drawing water from the shallow aquifer this should show up in radon-222 concentrations in the vicinity of the boreholes. The three deep boreholes were drilled in 2009 to depths of 150-192 m in Berayta *kebele* and provide Dangila town's water supply. The boreholes are open hole with electric submersible pumps at 60 m depth. The deep abstracting boreholes aim to tap groundwater in fractures and scoriaceous layers. At the time of the second visit, only two boreholes were abstracting, at 20 l/s and 32 l/s respectively, for 10 h/d. Testing was conducted on samples from the Amen and Kilti rivers close to the abstraction boreholes and also at a distance beyond their influence. The testing results were inconclusive concerning the impact of the deep boreholes. The highest radon-222 concentration measured was actually at the closest point to the northernmost borehole and though the value for a sample from beside the centre borehole was much lower, a sample from upstream away from the borehole's influence was lower still. The results do match the findings from the Dangesheta testing programme in that radon-222 concentrations increase as a river progresses through a floodplain, again indicating that groundwater is discharging into the rivers predominantly at floodplains.

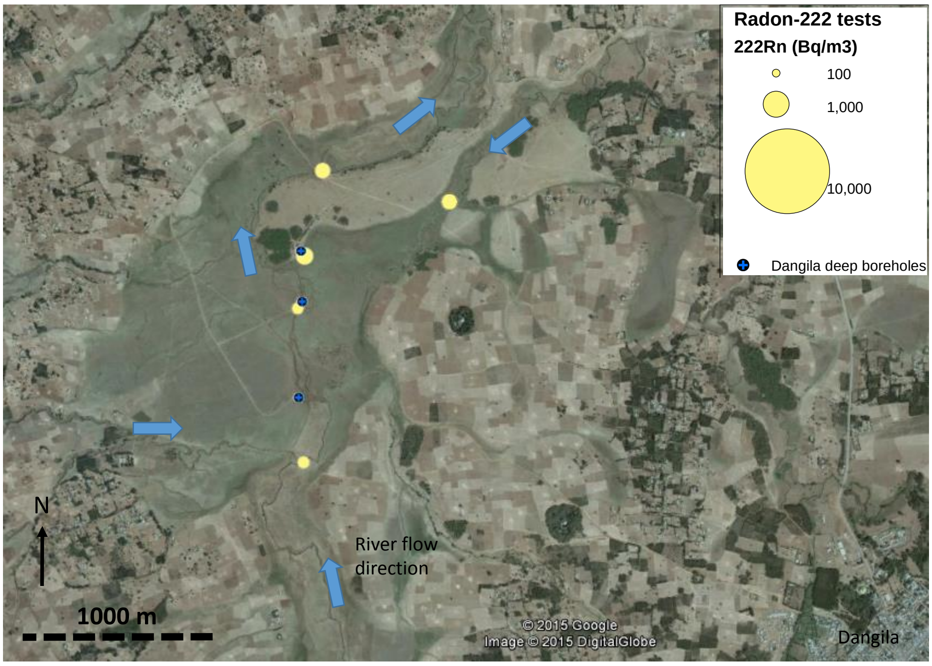


Figure B-7. Map of radon-222 testing results near deep boreholes at Kilti and Amen confluence. Note the southernmost borehole was not abstracting at the time of the second field visit.

B-9 Summary

The shallow groundwater is consistent in chemistry both spatially and temporally. Residence time is low, indicated by low EC and ionic concentrations, suggesting that the resource could be vulnerable to drought.

There is no hydrochemistry evidence to suggest mixing between the shallow and deep groundwaters though there is evidence to suggest mixing between shallow groundwater and surface water. Furthermore, radon-222 measurements showed the opposite of what would be expected if surface water and shallow groundwater were being drawndown by abstraction from the deep boreholes. However, the investigation was not exhaustive and groundwater levels in shallow wells near the deep abstracting boreholes should be monitored in order to observe any long-term changes in groundwater level.

Large floodplains in river valleys are areas of groundwater discharge, as shown by radon-222 testing.

Other interesting findings resulted from comparing individual samples collected during the same visit. Wells reported by the community to have a good year-round supply often showed greater stable isotope enrichment and higher ionic concentrations than would be expected from their topographic position close to a flow divide (see samples SI/A/C 4 and 5 in Table B-1). Often, across the flow divide, there was a dambo. The higher enrichment (through evaporation when inundated) and higher concentrations (due to the longer residence time) may indicate the sampled water originated in the dambo, which provides continuous groundwater supply through the dry season with groundwater flow paths contradicting surface water flow paths.

Appendix C. Filling the observational void: scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme – Supplementary material

C-1 AMGRAF research project

As stated on www.upgro.org: "Unlocking the Potential of Groundwater for the Poor (UPGro), is a seven-year international research programme (2013-2020) which is jointly funded by UK's Department for International Development (DFID), Natural Environment Research Council (NERC) and the Economic and Social Research Council (ESRC). Over 130 of the world's best researchers from 43 organisations across Africa and Europe are focused on improving the evidence base around groundwater availability and management in Sub-Saharan Africa. The goal is to ensure that the hidden wealth of Africa's aquifers benefit all citizens and the poorest in particular. UPGro projects are interdisciplinary, linking the social and natural sciences to address this challenge." AMGRAF was one of 15 UPGro catalyst projects.

Dangesheta *kebele* was selected as a focus community within Dangila *woreda* to assess the potential of the shallow groundwater resource to support increased irrigation use. A *kebele* is the smallest administrative unit in Ethiopia; equivalent to a parish or ward. Dangesheta is one of 27 rural *kebele*s within Dangila *woreda*, a *woreda* being similar to a district. The selection of Dangesheta *kebele* for hydrogeological study followed collaboration with IWMI, GSE and a field visit in September/October 2013: The rural *kebele*s of the *woreda* were ranked for intervention, according to: (i) access to market, i.e. proximity to an all-weather road and distance to market: necessary for the adoption of groundwater irrigation, (ii) experience in small-scale irrigation, and (iii) potential of shallow groundwater, i.e. evidence of existing shallow groundwater use. Shallow groundwater is here defined as <25 m; that which is accessible to the poor rural communities using manual excavation methods.

Further information on the background of the AMGRAF project and the work completed to date can be found in (Gowing *et al.*, 2016). A key aspect of the research, which is being conducted as part of a PhD project, is to evaluate the vulnerability of the shallow groundwater resource. A greater understanding of the shallow groundwater system is being achieved through fieldwork, water chemistry, stable-isotope and radon-222 analysis, recharge assessments and physically-based modelling. The latter two elements rely on hydrometeorological data though formal rainfall and river flow data is sparse and groundwater data is non-existent. Recharge must be quantified in order to assess the sustainability of irrigative agriculture and such quantification can be conducted (alongside other less direct techniques) with water-table fluctuation and cumulative rainfall departure (CRD) methods (Xu and van Tonder, 2001) only with time series of rainfall and groundwater level. Physically-based modelling of the shallow groundwater system will allow the simulation of potential changes and variations in climate, land use and abstraction to assess the impacts on the groundwater resource, on surface water and on downstream users. Time series of river flows and groundwater levels at various locations within the catchments allow thorough calibration and construction of representative transient models. The limited available formal data mean it has been necessary to implement a new hydrometeorological monitoring scheme.

C-2 Dangesheta community-based monitoring network

A workshop was held with the local community in February 2014 and the monitoring equipment was presented prior to installation. The community were encouraged to handle and use the equipment, including measuring water level in a nearby well. Following installation of the equipment (rain and river gauges) the community were shown the equipment in-situ and took part in surveying the rivers at the gauge locations, measuring flow velocity with an electrical current-meter, and were tested in their ability to take measurements.

The community member selected to monitor the wells and host the rain gauge is a known and respected member of the community due to his occupation in the Dangesheta Service Cooperative where the local population deliver agricultural produce to be weighed and transported to market in Dangila. Having such a person involved in the community-monitoring programme was deemed to be crucial to gaining the acceptance and continuing support of the local community. The community members who would monitor the river gauges were chosen because they lived very close to the river gauges and again were known in the local community. The Irrigation and Water Manager of the Dangila *woreda*, who was instrumental in organising community workshops and site selection, provides support and receives measurement data from the monitors then types up the data onto an Excel spreadsheet before forwarding it on to IWMI in Addis Ababa.

The rating curve for converting river stage to flow was developed from flow gauging measurements. Flow gauging was conducted by IWMI and Newcastle University staff during the AMGRAF catalyst project (prior to commencement of the PhD), by David Walker during each field visit, and by Bahir Dar PhD and master's students at other times following training by David Walker. The flow gauging always involved local community assistance. A current velocity meter was utilised and the velocity-area method was applied to calculate discharge. Flow gauging was conducted at various seasons to incorporate variations in river stage. The rating curves for the Brante and Kilti Rivers are presented in Figure C-1.

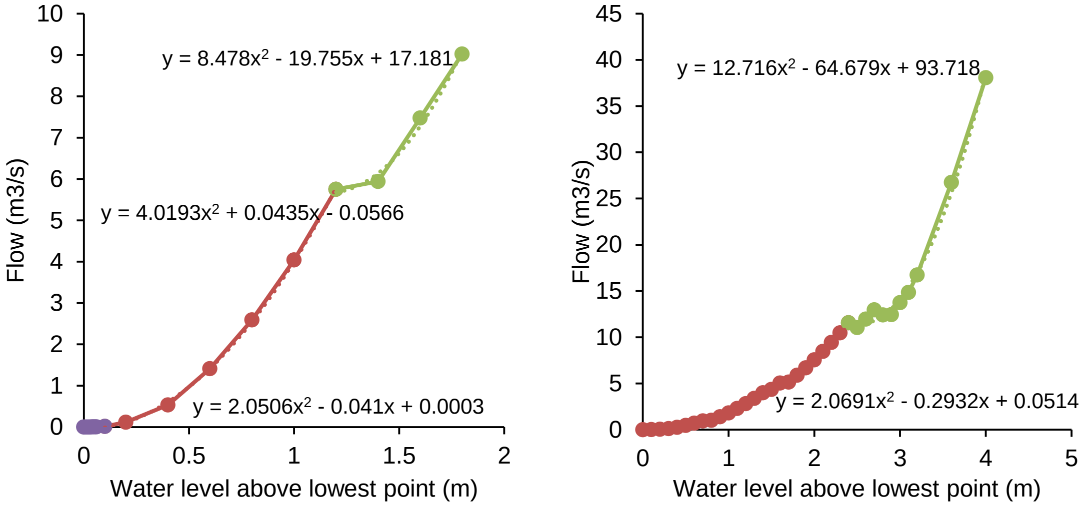


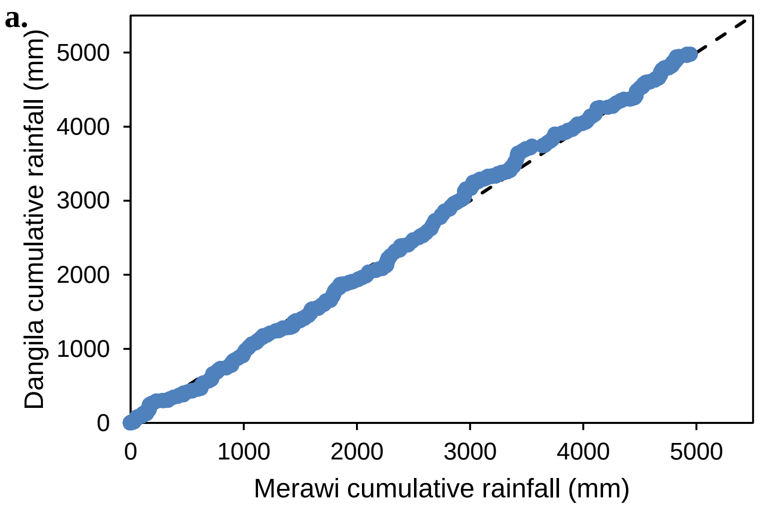
Figure C-1. Rating curves for the Brante (left) and Kilti Rivers at the locations of the community-monitored river gauges. Note that the kinks in the rating curves relate to when flow becomes out of bank.

The community-monitoring programme was explicitly designed to be low cost. Previous such programmes by IWMI, detailed in Zemadim *et al.* (2014), confirmed that low cost community monitoring programmes are the most sustainable. The number of wells, rivers and rain gauges to be monitored was considered the minimum possible in order to obtain sufficient initial data from this pilot study to allow planning of a longer-term community-monitoring programme. In addition to utilising minimal low cost equipment, payment of members of the community involved in the monitoring was designed to be a small financial incentive rather than a wage. The decision to provide remuneration for observational duties was made in order to get the project up and running with a longer-term aim of continuing the monitoring with no payment once the benefit to the community was seen.

C-3 Formal ground observations – rainfall

The NMA rain gauges in the region of Dangila *woreda* vary from tipping bucket type housed within professionally manned meteorological stations, to electronic weather stations within small fenced compounds, to traditional graduated cylinder rain gauges monitored by local part-time observers. Data quality checks were conducted and, as may be expected, higher quality data was identified from the professionally manned meteorological stations of which Dangila is one:

Double mass checks were conducted for the nine NMA rain gauges in the vicinity of Dangila *woreda*. The checks indicate that the Dangila rainfall record is the most reliable. Several of the NMA rainfall records showed breaks of slope when the double mass checks were conducted. These rain gauges were visited, the person responsible for taking measurements was interviewed and the regional NMA office in Bahir Dar was visited and consulted in an attempt to determine the causes of the breaks of slope. The precise reasons could not always be ascertained though suggestions were proffered, for example; the breaks of slope seen in the Meshenti rainfall record (Figure C-2) occur approximately when the data collector changed from father to daughter to sister each of whom perhaps had a slightly different measurement routine.



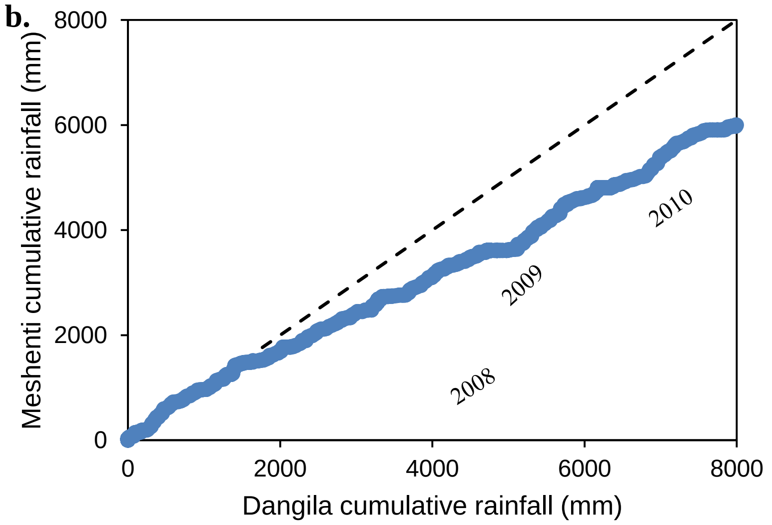


Figure C-2. Double mass checks of rainfall for Dangila and Merawi NMA (a) showing good linear relationships indicating reliable records. Compare to graph (b) of Dangila and Meshenti NMA rainfall records showing breaks of slope in early 2008, early 2009 and early 2010.

C-4 Gridded datasets – rainfall

The gridded remote sensing and reanalysis rainfall datasets that have been considered are TRMM, ERA-Interim, NASA MERRA, JRA-55 and NCEP:

TRMM (Tropical Rainfall Measuring Mission) was a joint research mission between NASA and JAXA measuring rainfall in the tropics. The satellite was launched in 1997 and re-entered Earth's atmosphere in 2015 providing a 17-year rainfall dataset at a grid resolution of 0.25^o x 0.25^o. The instruments on board the TRMM satellite included a precipitation radar, a microwave imager, a visible and infrared scanner, a cloud and Earth radiant energy sensor, and a lightning imaging sensor (Adler *et al.*, 2007).

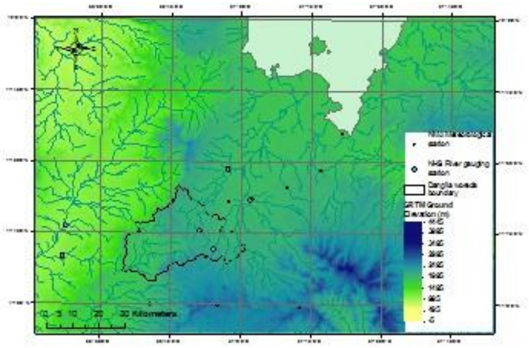
ERA-Interim is the third generation ECMWF data assimilation reanalysis product produced using a four-dimensional variational analysis. The rainfall dataset is available from 1979 to present on a 0.75^o x 0.75^o grid. Details of the data assimilation method, the forecast model and the input datasets can be found in Dee *et al.* (2011).

NASA-MERRA (Modern-Era Retrospective analysis for Research and Applications) was generated with version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS). The rainfall dataset is available from 1979 to present at a grid resolution of 0.666667^o x 0.5^o. Details of the DAS and the processing strategy can be found in Rienecker *et al.* (2011).

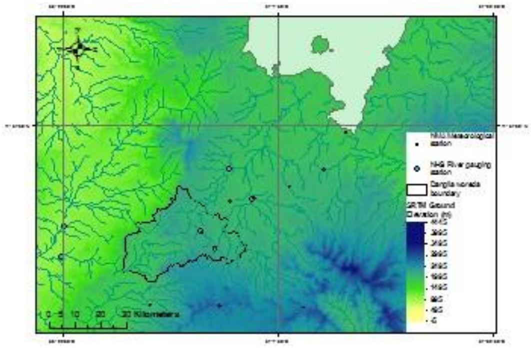
JRA-55 is a third generation reanalysis product and was the first to apply four-dimensional variational analysis. The rainfall dataset is available from 1958 to present on a 1.25^o x 1.25^o grid. Details of the observational datasets and data assimilation can be found in Kobayashi *et al.* (2014).

NCEP (the NCEP/DOE AMEP-II Reanalysis) is a first generation reanalysis product. The rainfall dataset is available from 1979 to present at a grid resolution of 0.5^o x 0.5^o. For more details on this product see Kanamitsu *et al.* (2002).

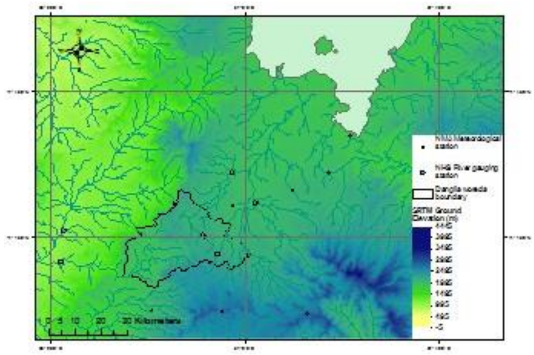
The spatial resolution of these gridded datasets can be seen in Figure C-3 relative to the study area. Each grid square evidently comprises quite an altitudinal range and where multiple NMA rain gauges are present within a grid square the observed variations in rainfall totals can be very high.



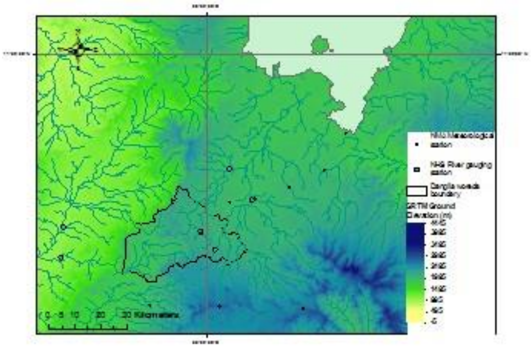
TRMM grid size: 0.25º x 0.25º



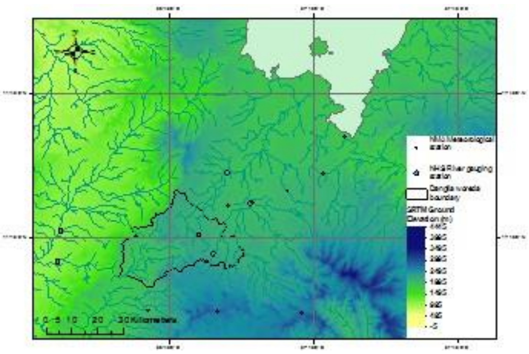
ERA-Interim grid size: 0.75º x 0.75º



NASA-MERRA grid size: 0.666667º x 0.5º



JRA-55 grid size: 1.25º x 1.25º



NCEP grid size: 0.5º x 0.5º

Figure C-3. Remote sensing and reanalysis dataset grids overlain on area around Dangila *woreda*.

C-5 River flow

A double mass check of monthly flow totals from the formal gauges; "Kilti Nr Durbete" and "Amen @ Dangila" shows two significant breaks of slope; in August 2001 and April 2014 (Figure C-4a). It has been proposed by MoWIE that the more recent break of slope could be due to the rating-curve becoming unreliable and efforts are ongoing to remedy this (S. Mamo, personal communication, 10 December 2015).

A double mass check was conducted for the two community monitored rivers (Figure C-4b) and a significant step in the data can be seen beginning in January 2015. The explanation for this feature is because the Brante River almost dries up from January to March 2015 (as it usually does during the dry season) whereas the larger Kilti River has perennial flow.

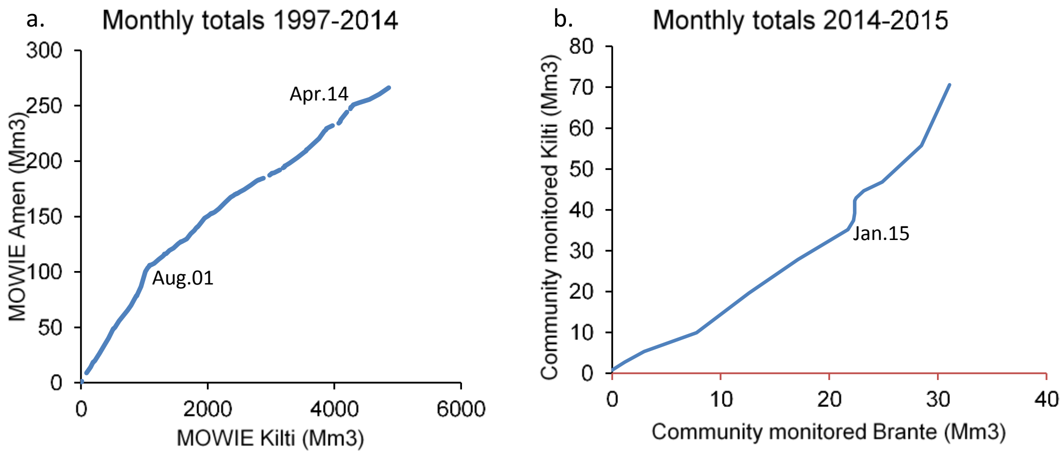


Figure C-4. Double mass checks of river flow

C-6 Formal observations – groundwater

According to the Amhara Regional State Bureau of Water Resources Development, there are fifteen known boreholes within Dangila *woreda* of which three are 25-75 m in depth and twelve are 100-200 m deep. Only four are abstracting for domestic supply, the rest having been abandoned, typically due to decreased yield. Borehole yield data are available for some of the boreholes at the time of drilling and sporadically since. Data on the shallow aquifer is limited to the quantity of hand-dug wells within the *woreda*; estimated at 2281 in September 2013 (Gebregziabher and Haile, 2013), though the lack of regulation on hand-dug wells means this figure is difficult to keep updated.

Appendix D. Insights from a multi-method recharge estimation comparison study – Supporting Information

D-1 Non-selection of certain recharge estimation methods

Recharge estimation methods can be subdivided to the three hydrological zones, namely surface water, the unsaturated zone and the saturated zone (Scanlon et al. 2002) with a further category for methods that consider all zones (Table D-1).

Table D-1. Methods of recharge estimation grouped by hydrological zone. Methods applied in this study are marked with *.

All zones	Surface water	Unsaturated zone	Saturated zone
*Basin water balance	Channel water budget	*Soil moisture balance (SMB)	*Water table fluctuation (WTF)
*Numerical modelling	*Streamflow hydrograph methods	Lysimeters	*Rainfall infiltration breakthrough model (RIB)
*Empirical methods, e.g. rainfall-recharge relationship	Seepage meters	Zero flux plane	Darcy's law
Remote sensing, e.g. GRACE, InSAR	Heat tracers	Infiltration models	Groundwater dating, e.g. tritium or CFCs
*Large-scale mapping	Isotopic tracers	Applied tracers, e.g. bromide or coloured dye	*Environmental tracers, e.g. chloride mass balance (CMB)
	[a] Numerical modelling	Historical tracers, e.g. tritium or ^{36}Cl	[a] Numerical modelling
		Environmental tracers, e.g. chloride	
		[a] Numerical modelling	
		Empirical methods, e.g. infiltration coefficients	

[a] SHETRAN modelling used in this study couples surface and subsurface (both unsaturated and saturated zones) flows.

All the techniques presented in Table D-1 were explored and several were rejected for this study for the following reasons:

- Insufficient stream gauge locations were available for the channel water budget method.
- There are no surface water bodies available for seepage meter and thermocouple (for the heat tracer method) installation with the exception of highly seasonal

rivers in which installed equipment would not be secure during wet season floods.

- Stable isotopes are very useful for providing information on recharge sources but not for quantitative recharge estimation (Healy, 2010).
- Lysimeters and zero flux plane equipment were excluded due to their high cost and maintenance requirements.
- Insufficient soil properties data were collected for use in infiltration models or to estimate infiltration coefficients.
- Applied tracers were not used due to the potential cultural conflicts that could arise from application of (albeit, harmless) chemicals into groundwater that is used domestically.
- The high rainfall and shallow thin aquifer leads to low groundwater residence times, therefore bomb-pulse tritium and ^{36}Cl are unlikely to still be present.
- There is insufficient spatial groundwater level and hydraulic conductivity data to determine hydraulic gradient for application of Darcy's law.
- Sampling groundwater for CFCs requires zero atmospheric contact (Gooddy *et al.*, 2012), which is impossible to achieve from open wells.
- Satellite based remote sensing is increasingly used to evaluate changes in groundwater storage, in particular with the Gravity Recovery and Climate Experiment (GRACE) satellite mission (Tapley *et al.*, 2004), and Interferometric Synthetic Aperture Radar (InSAR) (Galloway *et al.*, 1998). InSAR was not considered for this study, as its application is most suited to arid and semi-arid areas (Galloway and Hoffmann, 2007). GRACE measures temporal variations in the Earth's gravity field, which are used to estimate changes in terrestrial water storage. It has a spatial resolution of ~300 km and a monthly temporal resolution (NASA, 2016), both of which were considered too coarse for this study.

It can be seen in Table D-3 that none of the methods rejected by this study was used in other Ethiopia recharge studies, with the exception of tritium analysis, though this was used for source assessments and timing rather than quantification (e.g. Demlie *et al.* (2007); Girmay *et al.* (2015)). However, there may be some bias as many of the studies share authors, or supervisors in the case of university theses.

D-2 Recharge estimates for the study site from large-scale mapping and modelling

There have been several attempts to produce global scale groundwater recharge maps beginning with L′vovich (1979), whose map was based on the estimation of the baseflow component of observed river discharge. More recently, Döll and Flörke (2005) introduced recharge into their WaterGAP Global Hydrological Model (WGHM). The authors state a shortfall of the model in that it is calibrated against measured river discharge only, due to the unavailability of direct recharge measurements. The scarcity of independent recharge estimates meant the model was tuned in arid and semi-arid areas against just twenty-five recharge assessments (nine of which were in sub-Saharan Africa) using chloride and isotope profiles. The WGHM was updated by Döll and Fiedler (2007) and incorporated into the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP, 2016) by BGR (the German Federal Institute for Geosciences and Natural Resources) and UNESCO. MacDonald *et al.* (2012a) used WHYMAP to produce the recharge map in their "Quantitative maps of groundwater resources in Africa". The recharge estimates for the study site from WHYMAP and the other large-scale studies are shown in Table D-2. The Africa-wide recharge map presented by Altchenko and Villholth (2015) utilised data from the PCR-GLOBWB global hydrological model (van Beek *et al.*, 2011), which is calibrated against river discharge and reanalysis evapotranspiration data. At national scale, Ayenew *et al.* (2008b) produced a hydrogeological framework of Ethiopia based on analysis of pertinent information from governmental and non-governmental organisations and academic institutions, as well as over a decade of field study comprising conventional hydrogeological mapping, well drilling, geophysics, hydrochemical and environmental isotope analysis and remote sensing techniques.

Table D-2. Comparison of recharge estimates from large-scale mapping/modelling studies.

Source	Scale	Resolution	Recharge
WHYMAP (2016)	Global	0.5º	20-100 mm/a
Altchenko and Villholth (2015)	Africa	0.5º	100-300 mm/a
Ayenew et al. (2008)	Ethiopia	~40 km*	250-400 mm/a

* Estimated from the map zonation.

The large-scale mapping and modelling methods share two characteristics that lessen confidence in those recharge results: 1) a necessarily low spatial resolution, and 2) the scarcity of recharge studies in the sub-Saharan Africa region that would aid calibration. Concerning the first point, at the resolution of 0.5º for WHYMAP and the continental recharge map, it is unsurprising that the recharge estimates are dissimilar to those utilising catchment and local-scale methods. This region of Ethiopia has high variation in elevation, topography and climate, from 1100 m and hot dry plains immediately to west of Dangila, to cold wet mountains over 3000 m to the east (Figure 6-1 of Chapter 6). These environments often appear in the same grid square at these scales. The particular usefulness of the maps in data scarce regions coincides with a higher uncertainty in those regions as products frequently cannot be validated. This point is valid not just for recharge but remote sensing and reanalysis weather data products (Walker et al. 2016). The global-scale WHYMAP clearly underestimates recharge and was rejected from this study.

D-3 Field data not described in the main text [of Chapter 6] that was used to develop the conceptual model and to parameterise models

Geological surveys, water point surveys and workshops with the local community

The soils and aquifer properties for input into SHETRAN relied on field investigations as soil and geological mapping of the area is not available at sufficiently high resolution. The observed variation in well depths, differences in monitored well responses, variation in well pumping/recovery test results, geological and soil observations, and discussions with local communities led to the definition of hydrogeological zones.

Outcrops are visible in riverbeds, occasionally on steeper slopes and in a few man-made excavations. The basalts are variously massive, fractured and vesicular with variations occurring in short distances. Above the solid geology lies weathered basalt regolith, itself overlain by red clayey loam soils. Local communities report that there are rarely problems with well sidewall collapse. Often the solid geology is reached abruptly and well excavation is halted. Depth to the top of the solid geology is variable. Wells are typically excavated until further excavation becomes impossible, therefore, the location of rockhead can be inferred from well depth. Over the three field visits, 80 wells were measured for estimation of regolith thickness; more wells were visited but access for measurement, such as in the case of wells fitted with handpumps, was not always possible. Rockhead was generally found to be deeper in more steeply sloping areas and shallower in floodplains. Rivers have often incised to the level of the rockhead where solid basalt forms the riverbed with banks of only 1 to 3 m in height.

In addition to season, topography appears to govern shallow groundwater availability. The variations in geology are sufficiently subtle, particularly concerning the regolith, which forms the shallow groundwater aquifer, to be less of a control on the hydrogeology than geomorphology. Near the end of the dry season in March/April within the floodplains where the solid geology is at a depth of around 4 m, the water table lies at 2-4 mbgl. The water table can often be seen as a seepage face at this depth within riverbank sections in floodplain sediments. However, on the larger and steeper slopes where rockhead is around 15 m deep the water table is at a depth of 12-15 m. Thus, the shallow aquifer is thicker on slopes giving deeper water tables and generally greater saturated aquifer thickness.

It is noted that farmers often talk of a well excavation striking rock at a shallow depth and being dry, then when the well is relocated a short distance away (~10 m) rock is struck at greater depth and the well fills with water. Such a situation is commonly ascribed to heterogeneous rockhead, however, the unsuccessful wells are perhaps more likely to be due to the presence of large and massive basalt boulders lying higher in the weathered profile as are often visible in riverbank sections.

Over 200 hand-dug wells were surveyed during field visits; the surveys included GPS location, depth and water level measurements, description of geology, topography, land use, pump/lifting device and cover, in-situ measurement of water temperature, pH and electrical conductivity, and discussions with local community over the well's use, seasonality and history. Water point surveys also included assessment of springs, many of which are used by the local community, whether developed or not, to collect water for domestic and potable use. Where springs and seepages emerge from gullies they commonly occur at contacts between regolith and bedrock or gravelly regolith and more solid regolith. Springs and seepages are also very common around the edges of floodplains where the water table from the surrounding slopes intercepts the ground surface.

Hydrochemistry and stable isotope sampling, radon-222 measurements

The conceptual model was developed with the aid of hydrochemistry investigations. Samples of shallow and deep groundwater, surface water and rainwater were analysed in the laboratory for major ions, some trace elements, and stable isotopes oxygen-18 and deuterium ($\delta^{18}O$ and $\delta^{2}H$). In-situ testing involved measurement of pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, and radon-222 concentration.

The shallow groundwater is consistent in chemistry both spatially and temporally. Residence time is low, indicated by low EC and ionic concentrations, suggesting that the resource could be vulnerable to drought. Surface water and shallow groundwater belong to the “bicarbonate calcium” type typical of recent recharge. The deep groundwater is of “bicarbonate sodium” type indicative of higher mineralisation due to longer residence time and greater distance of flow. The shallow groundwater samples from the wet season are very similar in chemistry to surface water samples indicating a high degree of and rapid interconnectivity. This was expected in the wet season from the observed very shallow water table. There is no hydrochemical evidence to suggest mixing between the shallow and deep groundwaters; they belong to clearly different water types. What’s more, Radon-222 measurements showed the opposite of what would be expected if surface water and shallow groundwater were being drawndown by abstraction from the deep boreholes: ^{222}Rn concentrations would be lower in the vicinity of the abstracting boreholes as groundwater discharge would be prevented but the reverse was measured. Radon-222 measurements did suggest that the large floodplains in river valleys are areas of groundwater discharge from the shallow regolith aquifer, whereas the narrower valleys with basalt riverbeds are not discharge areas.

Vegetation properties

Categorisation of vegetation was required for the SHETRAN models. The three categories were:

- Grassland – floodplains that are almost always and entirely utilised as pasture.
- Arable – where the majority of land is devoted to rainfed agriculture. The crops planted are 87% cereals (39% maize, 35% *teff* and 13% millet), with the rest being pulses, oilseeds, sugarcane, potatoes, vegetables, fruits, onions, garlic, and tomatoes (Belay and Bewket, 2013), the latter few generally occupying backyard plots.
- Shrub – areas of higher gradients with characteristic scrub-like vegetation.

How SHETRAN converts the potential evapotranspiration time series into actual evapotranspiration is specific for each of these categories. Each category within SHETRAN differs in rooting depth and root density at different depths, ground coverage at maximum seasonal extent, canopy storage capacity, leaf area index, and AET/PET at particular soil moisture tensions. These parameter values were estimated from ground observations in order to generalise vegetation and crop types followed by consultation of the key instructional texts for calculating water demand; FAO24 (Doorenbos and Pruitt, 1975) and FAO56 (Allen *et al.*, 1998), and other published studies providing detail of particular vegetation types, particularly, Canadell *et al.* (1996); Dardanelli *et al.* (1997); Cain (1998) and; Fan *et al.* (2016).

D-4 Empirical method

There are numerous published examples of the development of a rainfall-recharge relationship, often utilising secondary literature sources e.g. Bonsor and MacDonald (2010), Crosbie *et al.* (2010), Zhang *et al.* (1999). A series of Boolean searches were undertaken in February 2017 on Google Scholar and repeated on Web of Science in order to identify quantitative recharge studies from Ethiopia. The common Google search engine was also utilised to identify reports and other documents that may be outside of the usual scientific literature. The initial search terms were "groundwater AND recharge AND Ethiopia", which produced 1000s of documents. Despite including the search term "Ethiopia", many of the "hits" were from other countries and could be discarded immediately. Many other studies that did take place in Ethiopia had mention of recharge but had no recharge estimate and were also discarded. The first 150 hits were reviewed for inclusion in the analysis before the searches became more specific by adding a recharge estimation method in an attempt to exclude the non-quantitative recharge studies. Specific searches involved adding a fourth term to the search described above. The added search terms were (independently): "baseflow", "chloride", "balance", "fluctuation", "wtf", "tritium", "lysimeter", "zero flux plane", "channel water budget", "seepage meter", "heat tracer", "Darcy's law", "infiltration model", "bromide", "applied tracer", "isotropic tracer", "infiltration coefficient" and "CFC". The first 100 documents were reviewed for each search, or all the documents if there were fewer than 100 hits. In an attempt to fill in the gaps when the study site locations were plotted on a map of Ethiopia (Figure D-1), further searches were conducted with a geographic location replacing the third search term (the first two still being "groundwater AND recharge"). The geographic search terms used were the regions of Ethiopia that were under or not represented on the map of study sites, namely: "Gambella", "Benishangul Gumuz", "Afar", "Somali AND Ethiopia" and "SNNPR". The first 50 documents were reviewed, seeing as, by this stage of the search, the majority of hits had been reviewed previously. Table D-3 presents information on all of the studies identified in addition to the reference. Several studies are included that were found during other literature searches undertaken for other aspects of the wider AMGRAF (Adaptive Management of shallow GRoundwater for small-scale irrigation and poverty alleviation in sub-Saharan AFrica) project. Where a study was cited within another study, an attempt was made to locate the cited study for review. Occasionally, a cited study could not be found though sufficient detail was provided for its inclusion in this project (listed in Table D-3 as "… cited in…"). Several times a cited study with or without sufficient detail was not listed in the citing study's reference list and as such, after a failed attempt at location, it was not included in this project. Attempts were made within Ethiopia to access often-cited but seldom seen reports via university and other organisations' libraries with limited success. Forty-nine quantitative studies were located comprising 22 peer-reviewed articles, the rest being grey literature (predominantly MSc theses). Where a study used multiple methods or multiple catchments, recharge results were considered independently. Therefore, 102 annual recharge estimates could be plotted against annual rainfall. Various trendlines were fitted through the data, excluding points with rainfall below certain thresholds (in an Africa-wide study, Bonsor and MacDonald (2010) recognised a linear relationship between recharge and rainfall above 500 mm/a). A quadratic trendline, reflecting an increase in recharge disproportionate to increasing precipitation, achieved the best R^2 and standard error.

Table D-3. Details of the recharge estimation studies used to develop a new empirical recharge method for Ethiopia based on the rainfall-recharge relationship. Note that multiple recharge results from the same study relate to different recharge estimation methods applied and/or to different catchments or areas of the study site. *CMB* = chloride mass balance method, *SMB* = soil moisture balance method, *SNNPR* = Southern Nations, Nationalities and Peoples' Region, *WTF* = water table fluctuation method.

Location	Area (km^2)	Recharge estimation method	Annual rainfall (mm) [a]	Annual recharge (mm) [a]	Publication	Reference
Raya Valley Basin	2579	Water balance CMB	813	50 52	Addis Ababa University master's thesis	Abdella (2011)
Kobo Valley Basin, Tigray	1351	Water balance CMB	813	63 53		
Gilgel Abay Catchment	4178	SWAT model	2141	753	Landscape Dynamics, Soils and Hydrological Processes in Varied Climates	Abiy *et al.* (2016)
Gumera Catchment	1418		1424	438		
Ribb Catchment	2132		1407	453		
Megech Catchment, Lake Tana Basin, NW Ethiopia	661		1251	407		
Lower Awash Sub-Basin	41887	CMB	553	29	Addis Ababa University master's thesis	Addisu (2012)
Aysha Basin, Afar	4092		553	58		

Geba Basin, Tigray	5150	WetSpass model	550	22	KU Leuven (Belgium), master's thesis	Alene (2006) cited in Tesfagiorgis *et al.* (2011)
Negelle Borena, south Ethiopia	?	?	647	31	GSA (Geological Society of America) Annual Meeting presentation	Ali Jr (2006)
Teji Catchment, central Ethiopia	700	Streamflow hydrograph Water balance incorporating SMB and streamflow hydrograph	1104	109 325	Addis Ababa University master's thesis	Andualem (2008)
Gilgel Abay, Koga and Kilti Catchments	1664	Streamflow hydrograph	1376	70	ITC (Netherlands), master's thesis	Asmerom (2008)
Megech Catchment	514	BASF rainfall-runoff model	959-1212	50-77		
Lake Tana Basin, NW Ethiopia	6316	CMB	1094-1730	45-155		
Weybo Catchment, SNNPR	574	Water balance incorporating SMB Streamflow hydrograph (baseflow separation) Streamflow hydrograph (Meyboom method) CMB	1341	88 63 75 124	Addis Ababa University master's thesis	Aychluhim (2006)
Lake Tana Basin, NW Ethiopia	15339	"CMB, baseflow separation, etc." [b]	1094-1730	70-120	Addis Ababa University master's thesis	Ayalew (2010)
Meki Basin, central Ethiopia	3051	Streamflow hydrograph WATBAL water balance model	762-1138	80 63	SINET: Ethiopian Journal of Science	Ayenew (2008)
Lake Awassa Basin, central Ethiopia	1455	MODFLOW model	1030	47	Lakes and Reservoirs: Research and Management	Ayenew and Tilahun (2008)

Raya Valley Basin, Tigray	2480	WATBAL water balance model	813	86	Water International	Ayenew *et al.* (2013)
Guder Sub-Basin	7088	SMB CMB	1424	258 210	Journal of African Earth Sciences	Azagegn *et al.* (2015)
Muger Sub-Basin	8263	SMB CMB	1201	150 163		
Jema Sub-Basin	6760	SMB CMB	992	164 120		
Upper Awash Sub-Basin, central Ethiopia	16000	SMB CMB	1112	232 133		
Southern Lake Tana Basin, NW Ethiopia	1664 [c]	Streamflow hydrograph	1541 [c]	308	Technical report for the Ministry of Water Resources (MoWR)	BCEOM (1998) cited in Ayalew (2010)
Kulubi area, Dire Dawa	?	Water balance using assumed runoff coefficients	626 [c]	150	Technical report for the Ministry of Water Resources (MoWR)	BCEOM (2005) cited in Tilahun and Merkel (2009)
Dengego area, Dire Dawa	?		626 [c]	50		
Between Melko Jebdu and Hurso, Dire Dawa, NE Ethiopia	260	Spring-area relationship	721	43		
Lake Beseka Basin, central Ethiopia	505	WTF EARTH modelling CMB	534	42 47 1.2	University of Bonn (Germany) PhD thesis	Belay (2009)
Upper Awash Sub-Basin	6735	Water balance CMB Streamflow hydrograph	1077	131 135 91	Journal of Geoscience and Environmental Protection	Berehanu *et al.* (2017)
Muger Sub-Basin	1770	Infiltration model Water balance CMB Streamflow hydrograph	1077	157 125 148 158		
Jema Sub-Basin, central Ethiopia	304	Infiltration model Water balance CMB Streamflow hydrograph Infiltration model	1077	239 130 122 86 239		
Akaki Catchment, central Ethiopia	1500	CMB	1254	265 [d]	Hydrological processes	Demlie *et al.* (2007)

Akaki Catchment, central Ethiopia	1464	SMB CMB	1254	105 273	Environmental Earth Sciences	Demlie (2015)
Fogera Plain, Lake Tana Basin, NW Ethiopia	500	Soil moisture profiles and groundwater level/evaporation relationship	1360	850-1000 [e]	Land Degradation & Development	Enku *et al.* (2017b)
Adama-Wonji Basin, central Ethiopia	1760	MODFLOW model	860	123	Environmental Earth Sciences	Furi *et al.* (2011)
Werii, Tekeze Basin, Tigray	1797	WetSpa WetSpass	717	30 [b]	Haramaya University (Ethiopia) master's thesis	Gebremeskel (2015)
Geba Basin, Tigray	5260	WetSpass model	400-950	41	Journal of Hydrology	Gebreyohannes *et al.* (2013)
Dire Jara and Hurso, Dire Dawa, NE Ethiopia	85-90	?	626 [c]	31	Technical report for the Ministry of Water Resources (MoWR)	Gibb and Seureca (1996) cited in Tilahun and Merkel (2009)
Dire Dawa, NE Ethiopia	?	?	626 [c]	40	Hebrew University, Jerusalem, PhD thesis	Greitzer (1970) cited in Tilahun and Merkel (2009)
Upper Wabe Sub-Basin, central Ethiopia	4489	SMB Water balance Streamflow hydrograph	924	21 23 155	Addis Ababa University master's thesis	Habtamu (2009)
Raya Valley Basin, Tigray	1085	CMB MODFLOW model	724	116 114	ITC (Netherlands), master's thesis	Hagos (2010)
Berga Catchment, central Ethiopia	303	Water balance incorporating SMB and streamflow hydrograph	1119	83	Addis Ababa University master's thesis	Hussen (2006)
Aynalem Wellfield, Mekelle, Tigray	104	CMB MODFLOW model	670	30-40 42	ITC (Netherlands), master's thesis	Kahsay (2008)
Gedeb Catchment, central Ethiopia	290	SWAT model	1392	467	Proceedings of 2012 international congress on	Koch *et al.* (2012)

					environmental modeling and software managing resources of a limited planet, sixth biennial meeting, Leipzig, Germany	
Gidabo Basin, south Ethiopia	3302	SWAT model	800 1600	25 410	Journal of Hydrology: Regional Studies	Mechal *et al.* (2015)
Koraro Area, Tigray	59	Water balance incorporating SMB	549	57	Momona Ethiopian Journal of Science	Nedaw (2010)
Meki Basin, central Ethiopia	1669	Water balance incorporating SMB	992	117	Addis Ababa University master's thesis	Netsanet (2007)
Becho	1552	Water balance incorporating SMB	1131	320	Addis Ababa University master's thesis	Nuramo (2016)
		Streamflow hydrograph		81		
Koka, Upper Awash, central Ethiopia	1461	Water balance incorporating SMB	879	50		
		Streamflow hydrograph		104		
Koka Becho, Upper Awash, central Ethiopia	1461 1552	Water balance incorporating SMB and streamflow hydrograph	900 1026	27 227	Addis Ababa University master's thesis	Reys (2016)
Shaya Watershed, SE Ethiopia	504	SWAT model	1071	174	HESS	Shawul *et al.* (2013)
Bulbul Basin, SW Ethiopia	508	Water balance incorporating SMB and streamflow hydrograph	1520	350	Asian Journal of Applied Science and Engineering	Shimelis *et al.* (2014)
		Streamflow hydrograph		395		
Upper Bilate Catchment, SNNPR	2075	Streamflow hydrograph	1232	129	Addis Ababa University master's thesis	Sintayehu (2009)
		Water balance incorporating SMB and streamflow hydrograph		96		

May Nugus Catchment, Tigray	15	Water balance incorporating SMB	738	19	International Journal of Earth Sciences and Engineering	Tadesse *et al.* (2010b)
Illala Catchment, Tigray	340	WetSpass model	550	66	Momona Ethiopian Journal of Science	Teklebirhan *et al.* (2012)
Bilate Catchment, SNNPR	5625	Water balance incorporating SMB and streamflow hydrograph Streamflow hydrograph	1146	116 201	Addis Ababa University master's thesis	Tesfaye (2010)
Dire Dawa, NE Ethiopia	920	WetSpass model	626	28	Hydrogeology Journal	Tilahun and Merkel (2009)
Zenako-Argaka Catchment, Tigray	4	MODFLOW model	724	167	Hydrogeology Journal	Vandecasteele *et al.* (2011)
Zenako-Argaka Catchment, Tigray	2	Runoff model SMB model MODFLOW model	"525-900 (average = 687)"	110-334 [b]	Hydrological Sciences	Walraevens *et al.* (2009)
Mendae Plain, Tigray	5	CMB SMB model	512	18 [b]	Land Degradation and Development	Walraevens *et al.* (2015)
Aba'ala *woreda*, Afar	254	Hydrochemistry	340-480	43	Research and development experience on dryland husbandry in Ethiopia	Woldearegay (2004)
Aynalem and Illala Catchments, Tigray	?	?	576	53	Addis Ababa University master's thesis	Yihdego (2003) cited in Teklebirhan *et al.* (2012)
Aynalem Catchment, Tigray	?	MODFLOW model	550 [c]	61	Mekelle University master's thesis	Zeru (2008) cited in Teklebirhan *et al.* (2012)
Gilgel Abay Catchment Gumera Catchment Megech Catchment Ribb Catchment	1640 1394 492 1592	Streamflow hydrograph	1614 1292 1081 1263	379 158 62 77	Addis Ababa University master's thesis	Zewdie (2010)

Koga Catchment	302	1410	234
Kilti Catchment, Lake Tana Basin, NW Ethiopia	698	1322	57

[a] Where a range is given, the mean rainfall or recharge was used for the plot.

[b] It is uncertain which technique gave which result.

[c] Unclear from the study; therefore, the value is taken from a study in the same area.

[d] For uncertain reasons, this value is stated to be an overestimate.

[e] Not included in the analysis as the study-specific conceptual model renders the recharge value inapplicable.

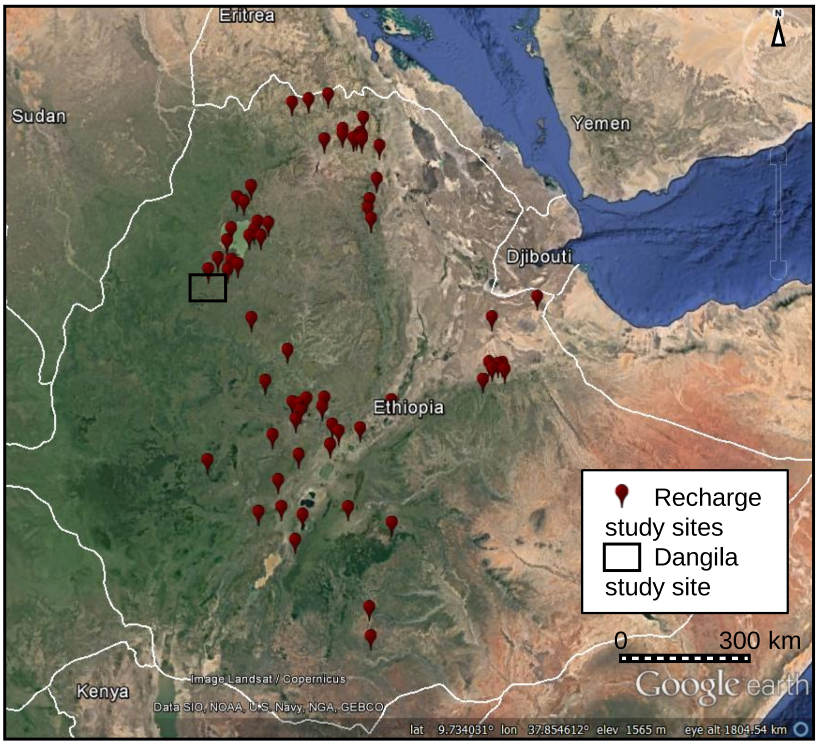


Figure D-1. Location map of the study area with other *recharge study sites* identified in the literature review shown on the right (image source: Google.Earth; Imagery ©2017 DigitalGlobe).

D-5 Streamflow hydrograph methods

Recharge estimation using streamflow hydrograph methods typically involves separating the baseflow component (Figure D-2) and approximating this to groundwater recharge. In humid regions, according to Döll and Fiedler (2007), who required recharge assessments for the entire globe for calibration of their WaterGap Global Hydrology Model, streamflow hydrograph methods are the most commonly applied recharge estimation method and numerous examples are available in the literature. The methods are idealised in assuming that groundwater storage remains constant interannually, or is in balance over longer time periods, and that precipitation entering the aquifer as recharge must be balanced by groundwater discharge into rivers that forms baseflow.

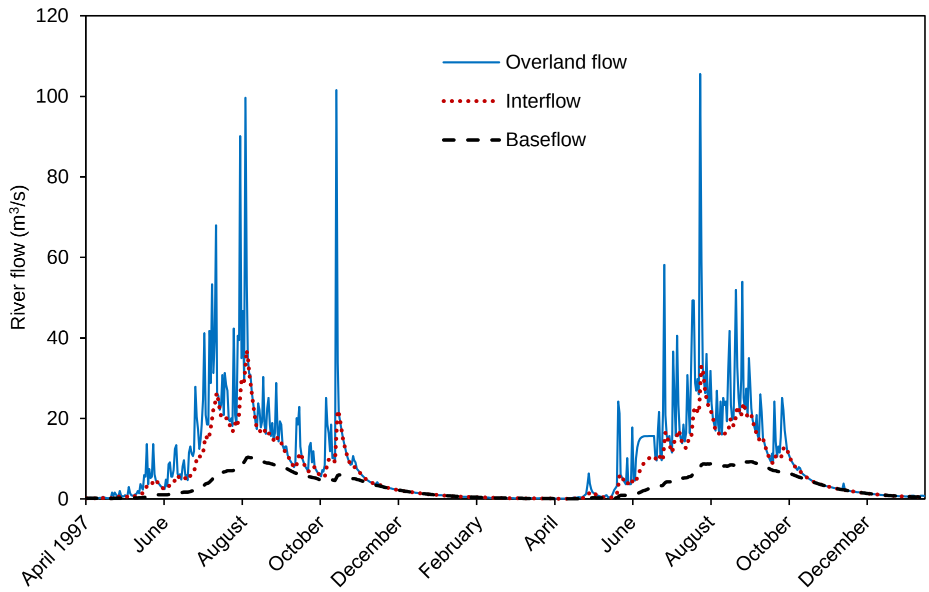


Figure D-2. The components of a streamflow hydrograph. Total flow is the sum of the three components, or the entire area below the *Overland flow* curve. The plot is a snapshot of the WETSPRO analysis of Kilti river flow.

Three streamflow hydrograph methods were used in this study, the baseflow recession method presented by Meyboom (1961), and two digital recursive filter tools, the Web GIS based Hydrograph Analysis Tool (WHAT) (Lim *et al.*, 2005) and WETSPRO (Willems, 2009). For both Meyboom and WHAT, the interflow is part of the quick flow component whereas for WETSPRO the interflow is separated in a two-step digital filter method after baseflow filtering. There are many very similar digital filter programs available for baseflow separation and two were chosen to assess whether they would give significant differences in recharge result. More in-depth comparison studies of baseflow separation methods are available, e.g. Chapman (1999), Eckhardt (2008).

The Meyboom method uses analysis of baseflow recession from at least two consecutive years to estimate recharge. The stream hydrograph is plotted on semi-logarithmic paper creating a straight-line recession curve. The start and end times of the recession "curve" are noted manually. According to Meyboom (1961), the total potential groundwater discharge can be estimated from

$$V_{tp} = \frac{Q_0 t_1}{2.3} \qquad \text{(D-1)}$$

where V_{tp} is the total potential groundwater discharge, Q_0 is the baseflow at the start of the recession, and t_1 is the time that it takes the baseflow to drop from Q_0 to 0.1 Q_0. The amount of potential baseflow, V_t, remaining at some time, t, after the initiation of baseflow may be estimated by:

$$V_t = \frac{V_{tp}}{10^{(t/t_1)}} \quad \text{(D-2)}$$

The difference between the remaining potential groundwater discharge at the end of a given baseflow recession and the total potential groundwater discharge at the beginning of the next recession represents the recharge that takes place between these two recessions, i.e.

$$V_{tp} - V_t = R \quad \text{(D-3)}$$

where R is the total quantity of recharge which is divided by the basin area to give a value in mm/a.

The Meyboom method is well-used, e.g. Mau and Winter (1997), Kumai and Mitamura (2004), Berhail *et al.* (2015), though seems inappropriate for this study site. The recharge quantities calculated using the Meyboom method are the lowest of all methods. Uncertainty of manually choosing start times of baseflow recessions could lead to recharge underestimation when early times of interflow recession have been incorrectly identified as baseflow recession (Figure D-3). Furthermore, when plotted on semi-log graph paper, baseflow recessions of the three rivers did not always form a straight-line meaning the Meyboom method is rejected for this study site.

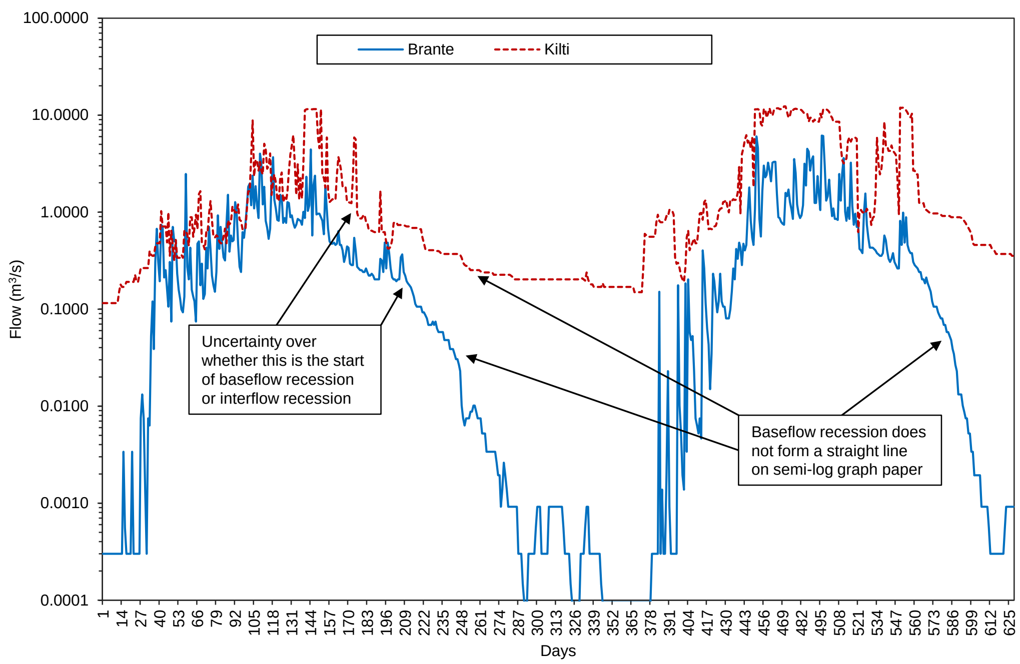


Figure D-3. Snapshot of the Brante and Kilti hydrographs showing uncertainties encountered with the Meyboom method.

The WHAT method requires a filter parameter *a* (the recession constant) and a BFI_{max}, which is the maximum value of long-term ratio of baseflow to total streamflow. The developers of WHAT recommend using representative BFI_{max} values proposed by Eckhardt (2005): 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with porous aquifers, and 0.25 for perennial streams with hard rock aquifers. The local hydrological system meant a BFI_{max} of 0.50 was most appropriate for this study, which was confirmed by a calculated BFI_{max} 0.57 (average of the three catchments). The WETSPRO method uses two main parameters to filter out the baseflow and interflow respectively. For each of the two components a recession constant *k*, which relates to the WHAT filter parameter as $a = \exp(-1/k)$, and the portion contributing directly to runoff *w* are defined. Both parameters are dependent on catchment size and characteristics.

D-6 Soil moisture balance (SMB)

The SMB method has the advantage over other unsaturated zone methods that it is not point based, rather it is at the scale that the precipitation, potential evapotranspiration (PET) and soil property inputs remain applicable. Rainfall totals were utilised in addition to the required meteorological time series to enable PET computation using the Penman-Monteith FAO-56 method (Allen *et al.*, 1998). The Thornthwaite-Mather (1955, 1957) (T-M) method additionally requires a value for soil moisture retention (*MC*), which is dependent upon vegetation and soil type. *MC*, or 'root zone storage', equals field capacity multiplied by depth of root zone. *MC* values were assigned to each LULC class and recharge was calculated individually for each class (Tables D-4 and D-5). The SMB method calculates total monthly actual evapotranspiration (AET) and soil moisture surplus with this surplus contributing to recharge. The direct runoff component is dealt with in two ways:

(a) It can be subtracted from the precipitation input by applying a runoff factor that could be taken from literature (e.g. Bakundukize *et al.* (2011)), derived from streamflow hydrograph analysis (e.g. Demlie (2015)), or modelled (e.g. Walraevens *et al.* (2009)).

(b) A portion of the soil moisture surplus is subtracted; Thornthwaite and Mather (1957) recommend subtracting 50% (e.g. Chishugi and Alemaw (2009), Azagegn *et al.* (2015).

Both methods were applied in this study; the runoff factor based on a simple flow separation (IOH, 1980) conducted on the longer time series river flow records (Kilti and Amen).

Calculation of groundwater recharge using a SMB involved the application of the Thornthwaite and Mather (1955, 1957) method and equating soil moisture surplus to recharge. The SMB calculations are shown in Table D-4 with a description of the parameters below.

Table D-4a. Calculation of actual evapotranspiration (*AET*), soil moisture deficit and soil moisture surplus (from which 50% forms recharge) using the Thornthwaite-Mather (1955, 1957) method. The year 2000 has been selected and grassland LULC category (*MC* = 200 mm) as an example. All values are in mm.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual total**
P	0	7.1	7.5	77.0	135.3	344.1	313.0	436.1	237.8	265.3	70.0	2.5	1895.7
PET	98.7	105.1	117.4	119.1	114.5	86.3	81.3	84.6	90.1	93.4	92.4	90.0	1172.7
P-PET	-98.7	-98.0	-109.9	-42.1	20.8	257.8	231.7	351.5	147.7	172.0	-22.4	-87.5	
APWL	-208.6	-306.6	-416.5	-458.5	0	0	0	0	0	0	-22.4	-109.9	
SM	70.5	43.2	24.9	20.2	41.0	200.0	200.0	200.0	200.0	200.0	178.8	115.5	
ΔSM	-45.0	-27.3	-18.3	-4.7	20.8	159.0	0	0	0	0	-21.2	-63.4	
AET	45.0	34.4	25.8	81.7	114.5	86.3	81.3	84.6	90.1	93.4	91.2	65.9	894.0
SMD	53.7	70.7	91.6	37.3	0	0	0	0	0	0	1.2	24.1	
SUR	0	0	0	0	0	98.8	231.7	351.5	147.7	172.0	0	0	1001.7
Rech.	0	0	0	0	0	49.4	115.9	175.8	73.9	86.0	0	0	500.9

Table D-4b. Calculation of actual evapotranspiration (*AET*) with the application of a runoff factor, soil moisture deficit and soil moisture surplus (which is equated to recharge) using the Thornthwaite-Mather (1955, 1957) method. The year 2000 has been selected and grassland LULC category (*MC* = 200 mm) as an example. All values are in mm.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual total**
P_{eff}	0	0.2	10.5	26.9	131.3	230.8	290.4	316.5	208.4	83.4	17.1	1.3	1316.7
PET	98.7	105.1	117.4	119.1	114.5	86.3	81.3	84.6	90.1	93.4	92.4	90.0	1172.7
P-PET	-98.7	-104.9	-106.9	-92.2	16.7	144.5	209.1	231.9	118.3	-9.9	-75.3	-88.7	
APWL	-262.7	-367.6	-474.5	-566.7	0	0	0	0	0	0	-75.3	-164.0	
SM	53.8	31.8	18.6	11.8	28.5	173.0	200.0	200.0	200.0	200.0	137.3	88.1	
ΔSM	-34.3	-21.9	-13.2	-6.9	16.7	144.5	27.0	0	0	0	-62.7	-49.2	
AET	34.3	22.1	23.7	33.8	114.5	86.3	81.3	84.6	90.1	93.4	79.8	50.5	794.3
SMD	64.4	83.0	93.7	85.3	0	0	0	0	0	0	12.5	39.5	
SUR	0	0	0	0	0	0	182.1	231.9	118.3	0	0	0	532.3
Rech.	0	0	0	0	0	0	182.1	231.9	118.3	0	0	0	532.3

Where

P = monthly rainfall total as measured by the NMA (National Meteorological Agency of Ethiopia) at the meteorological station in Dangila town, in the above examples for the year 2000.

P_{eff} = monthly effective rainfall, which is the monthly rainfall total minus the direct runoff computed by a simple flow separation (IOH, 1980) applied to river flow data; $P_{eff} = P.(1-RF)$ where *RF* is the runoff factor calculated to be 0.145.

PET = potential evapotranspiration calculated using the Penman-Monteith FAO-56 method (Allen *et al.*, 1998) with input parameters measured by the NMA at Dangila, in the above examples for the year 2000.

APWL = accumulated potential water loss; the summation begins with November, the first month of the dry season, until end April.

MC = moisture capacity; also known as soil moisture retention and equals field capacity multiplied by depth of root zone. It is dependent upon vegetation and soil type and, in the above examples, is specified as 200 mm for the grassland land use/land cover (LULC) category (see further explanation below).

SM = soil moisture; the soil moisture during dry months is obtained using accumulated potential water loss by the following formula: $SM = MC.\exp(APWL/MC)$. For the wet months, the soil moisture is calculated by adding the excess rainfall of the current month to the soil moisture of the previous month; where this exceeds the moisture capacity, the excess is booked as moisture surplus.

ΔSM = change in soil moisture from the previous month.

AET = actual evapotranspiration; for the wet months *AET* = *PET* as it is assumed that all rainfall is available for plants. During dry months, *AET* = *P* + moisture loss from the soil (i.e. negative ΔSM).

SMD = soil moisture deficit; the difference between *PET* and *AET*.

SUR = surplus moisture available for infiltration. According to Thornthwaite and Mather (1955, 1957) and shown in Table D-4a, 50% of *SUR* = recharge (*Rech*). Alternatively, where a runoff factor is applied, shown in Table D-4b, 100% of surplus moisture forms recharge (*SUR* = *Rech*).

Rech. = recharge

MC values were assigned to each LULC class and the recharge was calculated for each. The recharge values were then multiplied by the proportional area of each LULC class and summed to give the recharge for Dangila district. The LULC information was taken from ADSWE (2015) and the *MC* values were based on field identification of soil and vegetation types then assigned according to published values (see FAO-UNESCO world soils database and mapping; Batjes (1997) and Nachtergaele et al. (2010)) (Table D-5).

Table D-5. Representative *MC* values and proportional coverage of LULC classes for Dangila *woreda*.

LULC class	Coverage (%)	MC (mm)
Built up	8.72	10 [a]
Cultivated	71.7	150
Forest	11.0	300
Grassland	7.9	200
Shrub and bush	0.5	250

[a] The built up areas have some patches of vegetation; therefore, a nominal *MC* was applied.

D-7 Basin water balance

The water balance, or water budget, was the most commonly used method identified during the literature review of Ethiopian recharge studies (see Table D-3 for examples). AET is not straightforward to estimate and was calculated with three methods for comparison: (1) The T-M method mentioned in the previous section (Table D-4); (2) Application of Turc's formula (Turc 1954), see below for a full description, and; (3) A value estimated by Allam *et al.* (2016) for this region of the Tana Basin by combining remote sensing and river flow records. The average AET values were 789, 831 and 931 mm/a, respectively. Annual average runoff values were obtained using a simple and standard flow separation method (IOH 1980); the separated baseflow was subtracted from total flow to give the direct runoff component. The basin water balance can be increased in complexity by computing at a daily time step and utilising high-resolution soil and vegetation mapping with which to calculate AET; such data were not available for this study. Accurate quantification of all the fluxes is always troublesome though is required in order to leave an accurate residual that is equated to *actual* recharge (Scanlon et al. 2002). There persists the potential for unaccounted groundwater depletion as described in the streamflow hydrograph section.

Turc's formula requires only annual precipitation and temperature and was established empirically based on 254 watersheds, globally distributed (including 10 in Ethiopia) in different climatic zones (Turc, 1954). Actual evaporation from a catchment, *AET*, is defined as

$$\boldsymbol{AET = P/((0.9 + (P^2/L^2))^{-0.5})} \quad \text{(D-4)}$$

Where *P* is average annual precipitation in mm and

$$\boldsymbol{L = 300 + 25T + 0.05T^3} \quad \text{(D-5)}$$

Where *T* is average annual air temperature in ^{o}C.

D-8 Chloride mass balance (CMB)

The CMB method requires: P_{eff} – the average annual effective precipitation (rainfall minus direct runoff), Cl_{wap} – the weight-average chloride concentration in precipitation including dry deposition, and Cl_{gw} – the average chloride concentration in groundwater. Direct runoff was calculated using a simple flow separation (IOH 1980) for the two longer time series streamflow records, the Kilti and Amen. Dry deposition at this distance from the coast is considered negligible (Keywood *et al.*, 1997) and is typically neglected. Cl_{gw} from the 31 shallow groundwater samples was 2.10 mg/l with a standard deviation of 1.33 mg/l. Cl_{wap} was 0.68 mg/l (standard deviation = 0.32 mg/l); this is the most uncertain parameter of Eqn. 6-3 in Chapter 6 given the limited amount of samples as, ideally, samples from throughout the wet season should be obtained. However, the $\mathrm{Cl_{wap}}$ value compares well with other studies (Table D-6) giving confidence that the value used is representative of rainfall chloride concentrations in this region. The use of few rainfall samples and corroboration with other studies is not uncommon, e.g. Bazuhair and Wood (1996), Subyani (2004), and in South Africa $\mathrm{Cl_{wap}}$ is often unmeasured and simply approximated to 1 mg/l (Dennis, 2017), e.g. Butler and Verhagen (2001), and many theses available online.

Table D-6. Comparison of rainfall chloride concentrations with other studies.

Cl_{wap} (mg/l)	Source	Region	Altitude (m asl)	Distance to coast (km)	Rainfall (mm/a)
0.68	This study	Dangila, NW Ethiopia	~2000	~600	1541
0.50	Kebede *et al.* (2005)	Tana Basin, NW Ethiopia	~2000	~600	~1500
0.86	Asmerom (2008)	Tana Basin, NW Ethiopia	~2000	~600	~1500
0.70	Demlie *et al.* (2007)	Addis Ababa, Central Ethiopia	~2300	~550	1254
0.71±0.18	Vallet-Coulomb *et al.* (2001)	Lake Ziway, Central Ethiopia	~1650	~600	~900

D-9 Water table fluctuation (WTF) and rainfall infiltration breakthrough (RIB)

The locations of the hand-dug wells used in the water table fluctuation (WTF) and rainfall infiltration breakthrough (RIB) analyses are presented in Figure D-4. Details of the five monitoring wells initially set up as part of the AMGRAF project and the community-based monitoring programme can be found in Walker *et al.* (2016). The depth to groundwater was measured every two days by a community-nominated observer using a dip meter at 6am (prior to well use). The ILSSI project (Innovation Lab for Small-Scale Irrigation funded by USAID) community-based monitoring programme operated in a similar fashion. Two local community members using dip-meters at 6am monitored groundwater level in twenty-five hand-dug wells. Measurements were made weekly in the dry season and daily through the wet season.

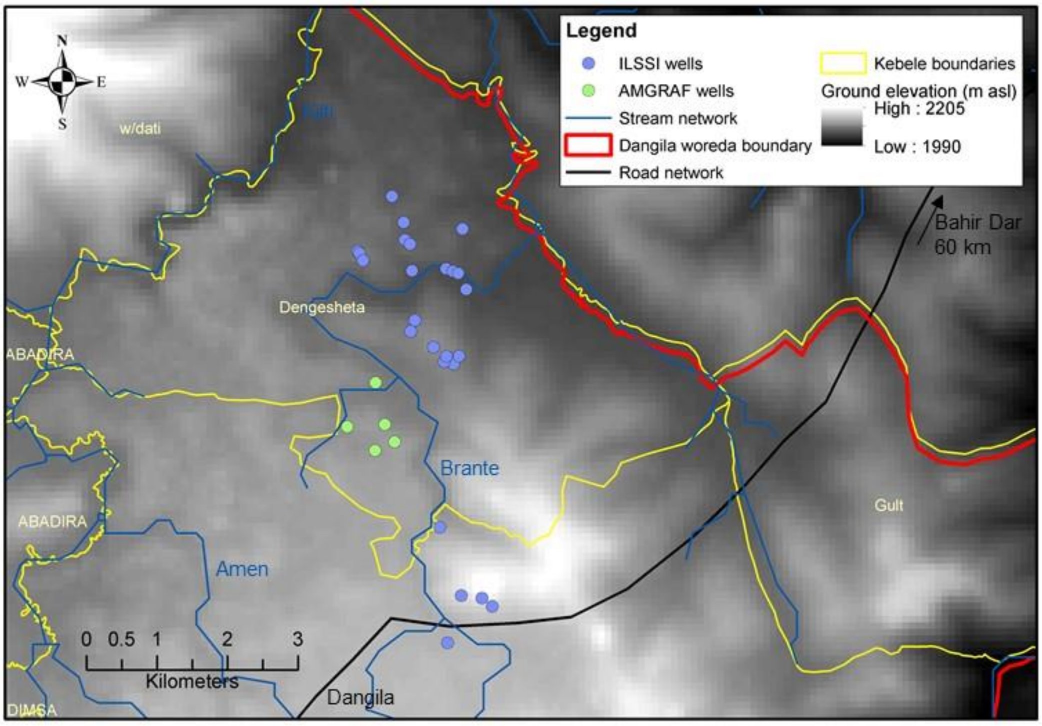


Figure D-4. Location map of the AMGRAF and ILSSI monitoring wells.

The WTF method has the key assumption that, because recharge rates vary substantially within a catchment due to differences in elevation, geology, slope, vegetation, and other factors, monitoring wells should be sited so the water levels are representative of the entire catchment (Healy and Cook 2002). Identifying a "representative" location is problematic, therefore, the possibility of recording groundwater level change due to lateral groundwater flow is considerable.

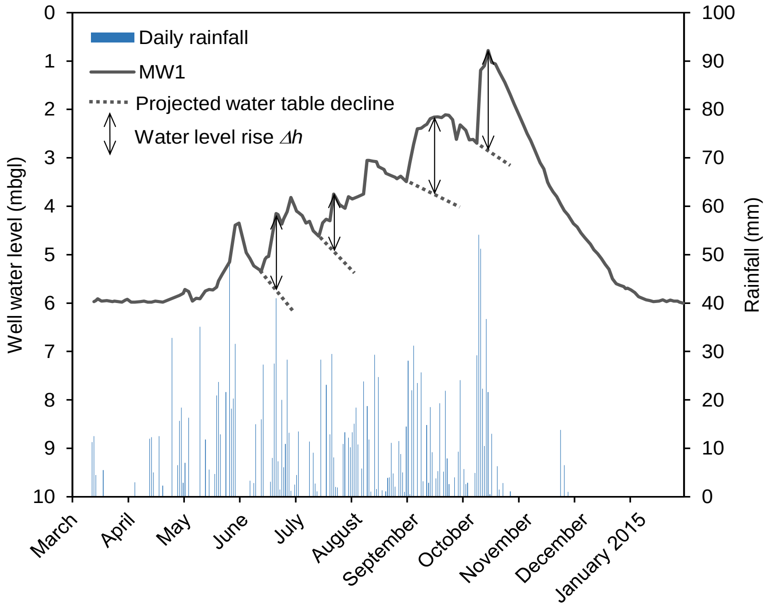


Figure D-5. Groundwater hydrograph through the wet season and determination of water table rise for the WTF method. *MW1* refers to the groundwater level in monitoring well 1 from where this snapshot is taken. (*mbgl* = metres below ground level).

Two RIB method parameters, "*lag days*" and "*length days*", were calibrated within the model. "Lag days" indicates the time it takes percolating rainwater to reach the water table. It was assigned as 1 day (pre and post-calibration) because the shallow water table leads to a short time lag between rainfall and groundwater level peak. "Length days" refers to the length of related rainfall events and is adjusted to gain the best fit between simulated and observed groundwater levels (Figure D-6). Lateral groundwater inflows and outflows can be specified in the model though the difficulty in quantifying these means they are typically set at zero under the assumption that they are in balance. As with the WTF method, this generates the possibility of accounting for groundwater level rise from lateral flows in recharge estimation.

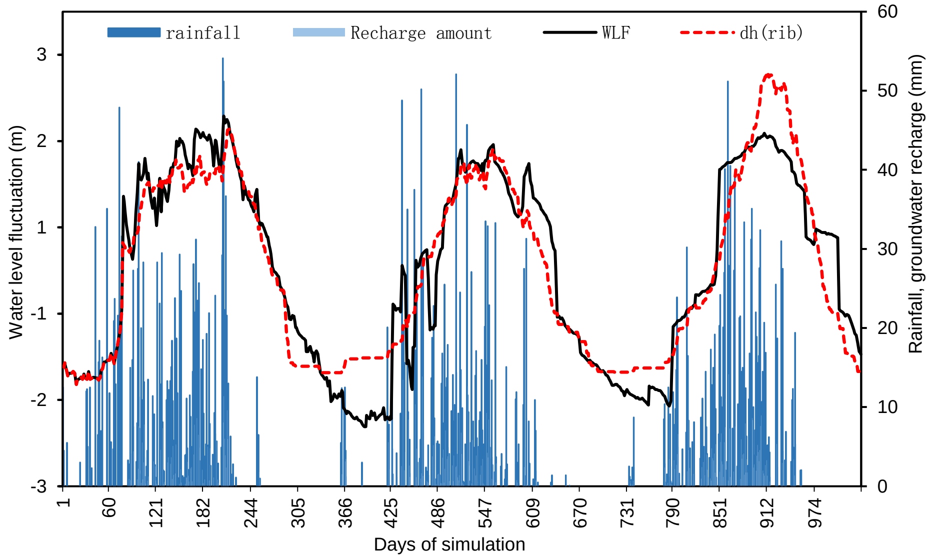


Figure D-6. Graphical output of the RIB model showing observed rainfall, observed groundwater level fluctuation (*WLF*), simulated groundwater level fluctuation (*dh (rib)*) and computed recharge. This plot shows the simulation of monitoring well MW3.

D-10 SHETRAN modelling

The main advantages of SHETRAN over alternative physically based spatially distributed river basin modelling systems are its comprehensive nature and capabilities for modelling subsurface flow and transport. The subsurface is treated as a variably saturated heterogeneous porous medium, and fully three-dimensional flow and transport can be simulated for combinations of confined, unconfined, and perched systems. The ''unsaturated zone'' is modelled as an integral part of the subsurface, and subsurface flow and transport are coupled directly to surface flow and transport (Ewen *et al.*, 2000). SHETRAN is well established in the literature, having been applied to a variety of situations such as predicting climate and land use change impacts on a Mediterranean catchment (Parkin *et al.*, 1996), modelling landslide sediment yield in Scotland (Burton and Bathurst, 1998), coupling flow and nitrogen transport in Sweden (Birkinshaw and Ewen, 2000b), and modelling forest impact on floods caused by extreme rainfall and snowmelt in Latin America (Bathurst *et al.*, 2011a).

Both saturated and unsaturated zones of the subsurface are represented by a single equation:

$$\eta\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial x}[K_x k_r\frac{\partial\psi}{\partial x}] + \frac{\partial}{\partial y}[K_y k_r\frac{\partial\psi}{\partial y}] + \frac{\partial}{\partial z}[K_z k_r\frac{\partial\psi}{\partial z}] + \frac{\partial(k_r K_z)}{\partial z} - q \qquad \text{(D-6)}$$

where

$$\eta = \frac{\theta S_s}{n} + \frac{d\theta}{d\psi} \qquad \text{(D-7)}$$

and

k_r = relative hydraulic conductivity (-)

(K_x,K_y,K_z) = principal components of saturated hydraulic conductivity (m/s)

n = porosity (-)

q = specific volumetric flow rate out of the porous medium (general source/sink term) (1/s)

S_s = specific storage (1/m)

t = time (s)

(x,y,z) = ordinates of the position vector (m)

θ = volumetric soil water content (-)

η = storage coefficient (1/m)

ψ = pressure potential (m)

As this equation is continuous across saturated-unsaturated boundaries, fluxes across the boundary are implicit in the solution, unlike groundwater models such as MODFLOW where the control volume is the saturated zone defined by the time-varying water table as its upper boundary, and recharge is defined separately as a boundary input. In SHETRAN, therefore, recharge is a derived variable, which includes both the flux (vertical flow per unit area) through the moving water table, and the rate of capture (or loss) of water in the saturated zone as the water table position moves. There is also no explicit use of a variable equivalent to specific yield, so an approximation of this concept is defined here as the amount of water available due to drainage of pore water space above the water table, derived from the shape of the unsaturated zone characteristic functions. Recharge is therefore calculated as:

$$\boldsymbol{Q_{rch} = -Q_v + S_y \, {dH}/{dt}} \tag{D-8}$$

where

H = phreatic surface (i.e. water table) level (m)

Q_{rch} = recharge rate (m/s)

Q_v = vertical velocity (m/s), +ve upwards

dH = change in phreatic surface level (m), approximated as change in pressure potential ($\Delta\psi$) over the timestep in the highest saturated cell at the end of the timestep

S_y = specific yield (-), approximated as change in water content ($\Delta\theta$) in the cell above the water table over the timestep, implemented as $\eta * \Delta\psi$

dt = timestep (s)

SHETRAN was manually calibrated using an iterative approach with the adjustment of geological layer thicknesses, aquifer properties, channel characteristics, Strickler overland flow roughness coefficient, and evapotranspiration characteristics. The range of values used for the input parameters was determined from field investigations and literature review of models set up for similar climates. Calibration aimed to minimise the error between observed and simulated time series. Calibration and validation periods were selected to give "typical" ranges of hydrological conditions and ran from the end of a wet season recession to the same point one, two or three years later. In addition to visual comparison of plotted observed and simulated data, the following performance indicators were utilised: Nash-Sutcliffe Efficiency (NSE) coefficient (Nash and Sutcliffe, 1970), where a value greater than 0.5 is considered acceptable (Moriasi *et al.*, 2007), and root mean square error (RMSE), with units matching the compared data thus the value should be as low as possible. NSE is very sensitive to peak flows (Krause *et al.*, 2005), therefore, given the flashy nature of the rivers with short-lived and relatively extremely high peaks, NSE (and RMSE) was calculated on low flows following hydrograph separation. For the

Brante model, NSE and RMSE were calculated on groundwater levels in the five monitoring wells selected at the onset of the AMGRAF project. The Brante model was principally calibrated against monitored groundwater levels (with consideration of river flow) combined with a semi-quantitative calibration to other areas of the catchment where simulations were compared against occasional observations and anecdotal evidence of frequent flooding or wells prone to drying up. The Amen and Kilti models were chiefly calibrated against river flow, though again with consideration of groundwater level information from around the catchments. A validation period was run to confirm that the calibrated parameters still produced a satisfactory simulation for independent input datasets. Table D-7 shows that the calibration statistics are acceptable for both the calibration and validation periods for all catchment models.

Table D-7. Details and statistics of the calibration and validation periods for the SHETRAN catchment models.

Catchment	**Calibration period**	**No. of days**	**NSE**	**RMSE**
Amen	5 Apr 1999 to 4 Apr 2001 (years 2-3)	731	0.79	0.19 m^3/s
Kilti	16 Apr 1998 to 15 Apr 2000 (years 2-3)	731	0.78	1.47 m^3/s
Brante	12 Mar 2014 to 11 Mar 2015 (year 1)	365	0.69	2.01 m
Catchment	**Validation period**	**No. of days**	**NSE**	**RMSE**
Amen	12 Mar 2010 to 11 Mar 2013 (years 13-15)	1096	0.75	0.13 m^3/s
Kilti	2 Apr 2004 to 2 Apr 2007 (years 8-10)	1096	0.67	2.30 m^3/s
Brante	12 Mar 2015 to 11 Mar 2016 (year 2)	365	0.53	2.08 m

D-11 Comparison of recharge results from the three nested catchments

In this case, catchment scale means 37-632 km^2 for the three catchments in this study. Despite being nested, the catchments have slightly different characteristics, in terms of proportional land cover and topography, therefore, differences in recharge result would be expected. Additionally, it is useful to evaluate if the different spatial and temporal scales contribute to the discrepancies in recharge results between catchments. The Amen and Kilti analyses utilise 17+ years of input data, the Brante only three, with little overlap. What's more, those three years include 2014; the wettest year on record with annual rainfall of 2005 mm, and 2015 with annual rainfall only in the 20^{th} percentile (1390 mm). Figure D-7 shows the recharge results plotted for each catchment. While no spatial scale dependence can be seen, temporally, the shorter and alternative data periods of the Brante catchment are contributing to the reduced recharge estimate of the streamflow hydrograph methods. For each year from 2014-2017, the streamflow hydrograph methods give much lower recharge estimates than for the longer period analyses of the Amen and Kilti. However, the Brante catchment is flatter with the greatest proportion of floodplain wetlands and shallow water tables; therefore, direct groundwater evaporation would be elevated causing the low *minimum* recharge computations.

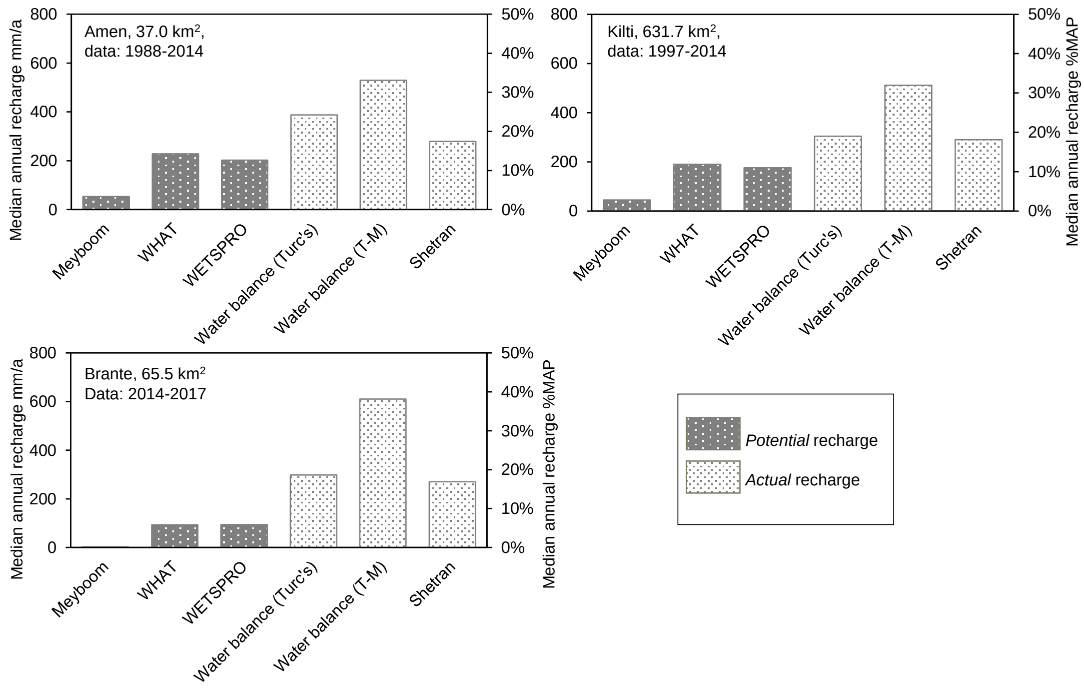


Figure D-7. Graphical comparison of annual recharge estimates from the catchment-scale techniques separated into catchments. *T-M* = Thornthwaite-Mather method of AET estimation.

D-12 Insights gained on the conceptual model in other recharge studies

Other studies exist where fewer methods were applied and useful insights were gained. These insights are specific to the conceptual model of the study site. King *et al.* (2017) applied four recharge estimation methods to an alluvial aquifer in Queensland, Australia. Low CMB recharge results indicated that inherent assumptions were invalidated and channel leakage and overland flow were significant at the site. The WTF method gave the highest recharge results, especially in proximity to a river, which was considered, since the timing coincided with high stream levels, to be due to temporary influxes of water (bank storage). While a water balance gave a useful approximation of recharge for the catchment, only by applying and comparing the additional methods could the conceptual model be updated and understood. Takounjou *et al.* (2011) compared a hybrid

WTF/water balance method with the CMB method for a humid region of Cameroon. The discrepancy in results led the authors to suggest the CMB method was overestimating due to preferential shallow groundwater flow paths; ultimately, they considered the CMB method to be unsuitable for a humid forested environment). Huang *et al.* (2017), by comparing results from a CMB method with groundwater aging and stable isotope analysis, were able to update the conceptual model for a site in northwest China revealing that no recharge had occurred for >2,500 years, and, as such, potential abstraction of the paleaowater would be unsustainable. Misstear *et al.* (2009) compared SMB, WTF, numerical groundwater modelling and water balance recharge estimation methods for an aquifer in Ireland. The variations in WTF recharge estimates at particular locations, in comparison with more consistent results from other methods, indicated S_y variations within the aquifer.

D-13 Annual recharge time series

The interannual variation between recharge estimates and between methods is shown in Table D-8.

Table D-8. Annual recharge time series calculated by the methods that do not apply temporally averaged input data. Meyboom results not shown as they were rejected from the study. All results in mm.

YEAR	WHAT			WETSPRO			SHETRAN			WTF		RIB
	Brante	Kilti	Amen	Brante	Kilti	Amen	Brante	Kilti	Amen	Graph.	Simp.	
1988			321			288						
1989			235			224						
1990			202			186						
1991			237			219						
1992			159			170						
1993												
1994												
1995			440			483						
1996			321			350						
1997		180			146							
1998		171	297		145	259		280	289			
1999		225	347		176	325		300	297			
2000		243	346		201	318		288	280			
2001		148	259		116	298		289	266			
2002		169	129		131	111		294	274			
2003		162	131		142	119		287	265			
2004		184	163		144	144		288	276			
2005		153	155		127	133		267	252			
2006		303	230		225	203		302	297			
2007		277	172		207	145		301	279			
2008		306	188		267	201		276	271			
2009		190	138		169	121		313	286			
2010		191	181		194	162		282	267			
2011		213	228		184	219		290	277			
2012		257	188		224	165		327	306			
2013		182	315		280	286		296	292			
2014	135			139			256	314	310	1077	893	288
2015	70			65			293			915	806	620
2016	93			94			270			871	763	636

Appendix E. Bahir Dar drought analysis and rainfall comparison

E-1 Bahir Dar drought analysis

A drought analysis was conducted for Bahir Dar with assessment of SPI and SPEI for both spring and summer, growing season length using both Segele and Lamb (2005) and Stern *et al.* (2006) criteria, annual rainfall totals from NMA ground observations, remote sensing (TRMM) and reanalysis products (NCEP, JRA-55, ERA-Interim and NASA-MERRA), and comparison with other studies using SPI and SRA. SPI indicates extreme droughts were spring 2003 and summer 1982 (Figure E-1), likewise SPEI indicates extreme drought in summer 1982 (Figure E-2), and both indicate very wet conditions in the early-70s. Assessment of growing season length and SRA from other studies support the findings from the SPI and SPEI. Table E-1 shows the results from all analysis methods for all years.

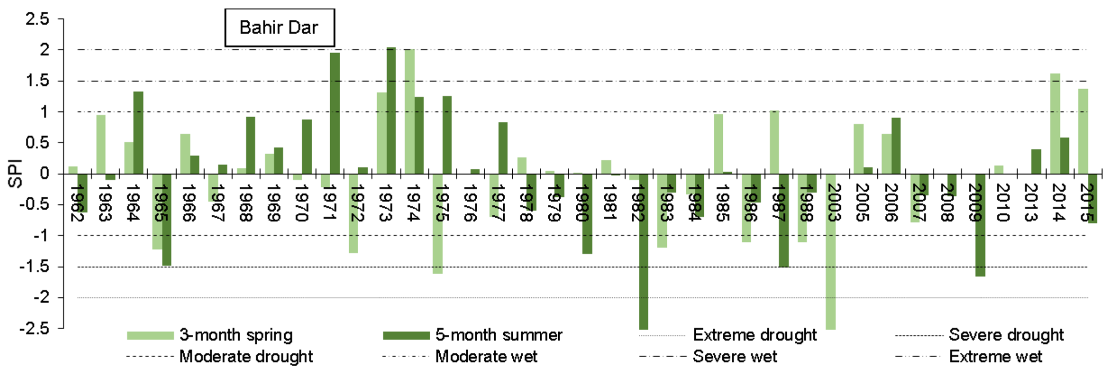


Figure E-1. SPI calculated for Bahir Dar for spring (3-month, March-May) and summer (5-month, June-October). Note the non-continuous year sequence, which is different to that of Dangila.

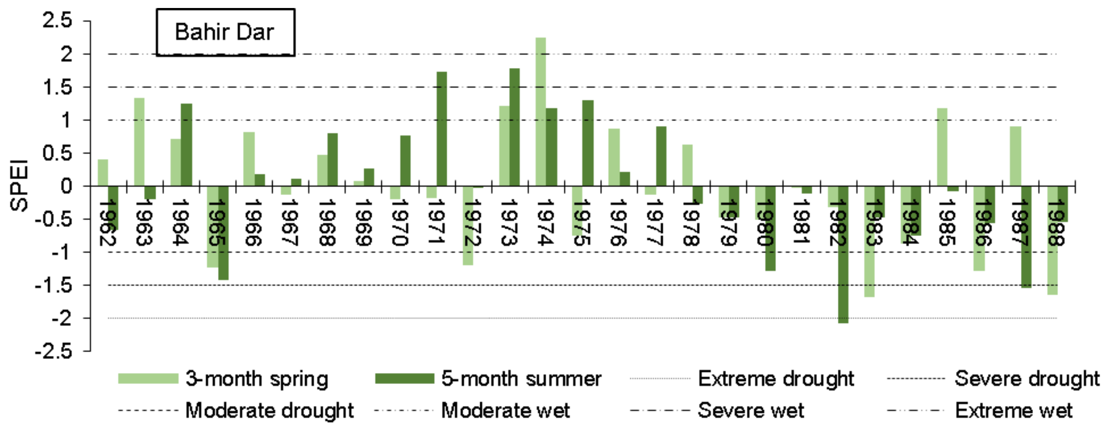


Figure E-2. SPEI calculated for Bahir Dar for spring (3-month, March-May) and summer (5-month, June-October). Note the non-continuous year sequence, which is different to SPI and that of Dangila.

Table E-1. Identification of drought/wet years and comparison of drought analysis methods for Bahir Dar. X = insufficient data for analysis. v = very. For SPI, SPEI and SPI/SRA from other studies: v dry and v wet are <-2 and >2 respectively, dry and wet are <-1.5 and >1.5 respectively. For growing season length: v long and v short are >±20% difference from mean length in days, long and short are >±10% difference from mean length in days. Annual rainfall: dry is rainfall total <10%ile, wet is >90%ile.

Year	SPI		SPEI		Growing season length		Annual rainfall						Viste *et al.* (2013) NW Highlands*		Bewket and Conway (2007) Bahir Dar SRA	Ayalew *et al.* (2012) Bahir Dar SRA
	spring	summer	spring	summer	Segele and Lamb (2005)	Stern *et al.* (2006)	ground obs.	TRMM	NCEP	JRA-55	ERA-Interim	NASA-MERRA	spring SPI	summer SPI		
1962								X	X	X	X	X	X	X		X
1963					v short			X	X	X	X	X	X	X		X
1964					long		wet	X	X	X	X	X	X	X	wet	X
1965							dry	X	X	X	X	X	X	X	dry	X
1966					v long	long		X	X	X	X	X	X	X		X
1967					v short	long		X	X	X	X	X	X	X		X
1968								X	X	X	X	X	X	X		X
1969						v short		X	X	X	X	X	X	X		X
1970								X	X	X	X	X	X	X		X
1971		wet		wet	long		wet	X	X	X	X	X	X	X	wet	X
1972					long			X	X	X	X	X	dry			X
1973		v wet		wet	v long		wet	X	X	X	X	X			v wet	X
1974	v wet		v wet				wet	X	X	X	X	X			v wet	X
1975	dry				long	long	wet	X	X	X	X	X	dry			X
1976					short			X	X	X	X	X				X
1977					long			X	X	X	X	X				X
1978					short			X	X	X	X	X				X
1979						long		X	wet	wet		wet				
1980					short	short	dry	X			wet				dry	dry
1981						short		X	wet			wet				
1982		v dry		v dry	short	short	dry	X			wet	wet		v dry	v dry	v dry
1983				dry				X	wet	wet	wet	wet				
1984						v short		X		wet				dry		dry
1985								X		wet	wet	wet		dry		
1986								X	wet	wet			v dry			
1987		dry		dry	long			X		wet				v dry	dry	
1988			dry		long			X		wet						
1989	X	X	X	X	X	X		X		wet						wet
1990	X	X	X	X	X	X		X	dry				dry			
1991	X	X	X	X	X	X	X	X				dry	dry			
1992	X	X	X	X	X	X		X						v dry		
1993	X	X	X	X	X	X		X			dry					wet
1994	X	X	X	X	X	X	dry	X			dry				dry	dry
1995	X	X	X	X	X	X	dry	X		dry	dry			dry	dry	dry
1996	X	X	X	X	X	X		X	wet							
1997	X	X	X	X	X	X		X						v dry	dry	
1998	X	X	X	X	X	X	X	wet	wet		wet					
1999	X	X	X	X	X	X					wet					
2000	X	X	X	X	X	X	X									
2001	X	X	X	X	X	X	X	wet			wet	dry				
2002	X	X	X	X	X	X	X		dry			dry	dry			
2003	v dry		X	X	X	X	X						v dry			v wet
2004			X	X	X	X	X								X	
2005			X	X	X	X									X	
2006			X	X	X	X	wet		wet			wet			X	v wet
2007			X	X	long										X	
2008			X	X			X	dry	dry			wet			X	
2009		dry	X	X			X	dry	X	dry			v dry		X	X
2010			X	X			X		X	dry					X	X
2011			X	X	X	X	X		X			wet	X	X	X	X
2012			X	X	X	X	X		X				X	X	X	X
2013			X	X			X		X				X	X	X	X
2014	wet		X	X	short		wet		X	X			X	X	X	X

E-2 Comparison between Dangila and Bahir Dar rainfall

It was necessary to test whether the Bahir Dar rainfall data could be used to inform the longer period climate at Dangila, i.e. are the coincident portions of the datasets sufficiently similar. The correlation testing results shown in Table E-2 indicate a high correlation between monthly rainfall totals. The poorer daily rainfall correlation is simply due to timing as weather systems proceed slowly with the generally low winds (Kebede *et al.*, 2006; Setegn *et al.*, 2010). Annual rainfall totals correlate well though with lower significance due to few matching complete years.

Table E-2. Comparison between NMA Dangila and Bahir Dar rainfall for all coincident periods.

Period compared	Resolution	Missing data	Pearson	P-value	Spearman	P-value
1 Jan 2007 - 31 Oct 2015	Daily	915 out of 3226 days (28%)	0.403	0.000	0.703	0.000
Jan 1922 - Apr 1924, Feb 1961 - Jun 1969, and Jan 1987 - Oct 2015	Monthly	101 out of 475 months (21%)	0.890	0.000	0.915	0.000
1922-1923, 1962-1967, and 1989-2014	Annual	16 out of 34 years (47%)	0.592	0.010	0.610	0.007

The histogram in Figure E-3 shows that the distribution of the daily rainfall data is very similar for both sites with an almost identical standard deviation and an offset in the Bahir Dar data of approximately 1 mm/day less than Dangila.

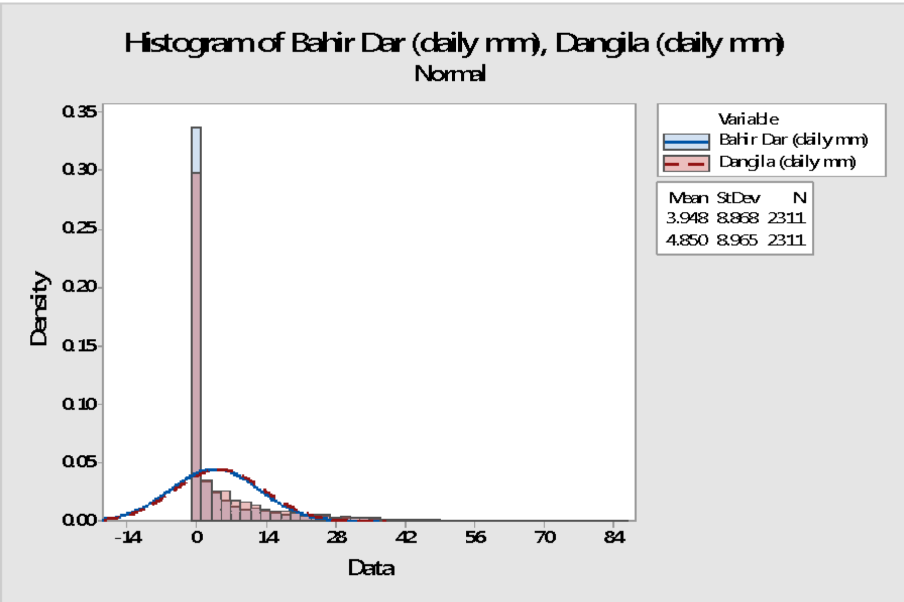


Figure E-3. Histogram of daily rainfall from Dangila and Bahir Dar for 1 Jan 2007 to 31 Oct 2015 (excluding non-matching days).

A further correlation was conducted between the wet days per month, here defined as days with greater than 5 mm of rainfall (i.e. productive rainfall), for the overlapping period of the daily datasets (Jan 2007 to Oct 2015). Bahir Dar and Dangila correlate very well with a Pearson correlation coefficient of 0.938 (P-value = 0.000) and Spearman Rho of 0.929 (P-value = 0.000). This justifies the use of Bahir Dar rainfall years in the Dangila time series to be used for the climate variability future scenario SHETRAN simulations.

Tables E-3 and E-4 show that the percentile range is greater for the Bahir Dar dataset, indicating that climatic extremes, both wet and dry, were not captured within the 22-year Dangila rainfall dataset used in the SHETRAN modelling; confirming what was discovered during the drought analysis. This can be seen in the histogram in Figure E-4 where Bahir Dar, allowing for its lower annual total offset, has a greater spread. Notably, the Bahir Dar dataset includes the infamous Ethiopian droughts of the early-80s and the very wet early-70s. The actual range of annual rainfall totals for Bahir Dar is 890 mm (1982) to 2035 mm (1973) – two particular years that are not present in the Dangila record – compared to the Dangila range of 1118 mm (1930) to 2005 mm (2014).

Table E-3. Long-term averages of NMA Dangila rainfall (Jan 1922 – Feb 1934, Aug 1955 – Jun 1969, and Jan 1987 – Oct 2015). Note that the *Total* column relates to annual totals rather than the presented monthly values.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Total**
Mean	3.3	3.6	24.6	43.4	126.4	245.6	346.6	348.2	230.6	104.2	40.0	7.4	1533.2
StDev	7.6	5.0	28.6	38.6	74.6	55.8	68.6	71.9	63.5	64.5	38.8	12.3	218.9
Min	0.0	0.0	0.0	0.0	0.0	140.6	220.8	165.0	102.0	12.0	0.0	0.0	1118.0
c10	0.0	0.0	0.0	2.0	45.3	169.2	274.0	262.2	151.6	37.6	3.5	0.0	1245.1
c25	0.0	0.0	2.4	10.9	61.8	197.0	305.5	299.0	184.0	58.0	7.5	0.0	1389.2
Median	0.0	1.0	12.1	33.9	125.4	251.0	339.0	351.7	229.0	80.0	28.8	1.9	1517.8
c75	3.0	6.0	35.3	66.1	169.1	283.0	369.2	384.4	268.1	133.1	58.8	9.4	1652.5
c90	7.0	9.8	69.8	92.8	242.2	320.8	440.2	435.5	320.4	194.4	97.2	23.5	1858.7
Max	40.1	21.0	97.4	153.0	302.9	354.4	570.2	531.0	391.7	270.1	163.0	62.0	2004.7

Table E-4. Long-term averages of NMA Bahir Dar rainfall (Aug 1920 – Apr 1924, Jun 1938 – Aug 1939, and Feb 1961 – Oct 2015). Note that the *Total* column relates to annual totals rather than the presented monthly values.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Mean	2.6	1.4	11.8	23.4	84.9	178.0	427.4	372.1	204.0	94.1	19.3	2.8	1429.4
StDev	4.7	4.4	21.8	27.4	70.0	70.7	100.4	105.6	55.7	52.5	25.8	6.1	233.5
Min	0.0	0.0	0.0	0.0	1.6	60.0	208.0	150.8	106.2	0.0	0.0	0.0	894.8
c10	0.0	0.0	0.0	0.0	11.3	86.1	305.6	243.2	138.9	23.2	0.0	0.0	1186.5
c25	0.0	0.0	0.0	1.3	34.3	124.2	350.4	293.4	163.3	55.6	2.1	0.0	1258.5
Median	0.0	0.0	4.0	11.0	76.0	178.2	417.9	368.1	200.9	100.5	8.9	0.0	1422.1
c75	3.1	0.3	13.6	33.5	112.3	216.3	481.9	447.7	240.6	123.2	24.6	2.6	1558.2
c90	9.1	4.1	27.4	66.3	153.7	261.5	557.2	504.1	262.9	168.2	52.4	9.8	1703.6
Max	20.3	26.9	118.5	111.0	363.0	404.9	643.9	648.2	378.5	206.6	107.2	34.8	2035.3

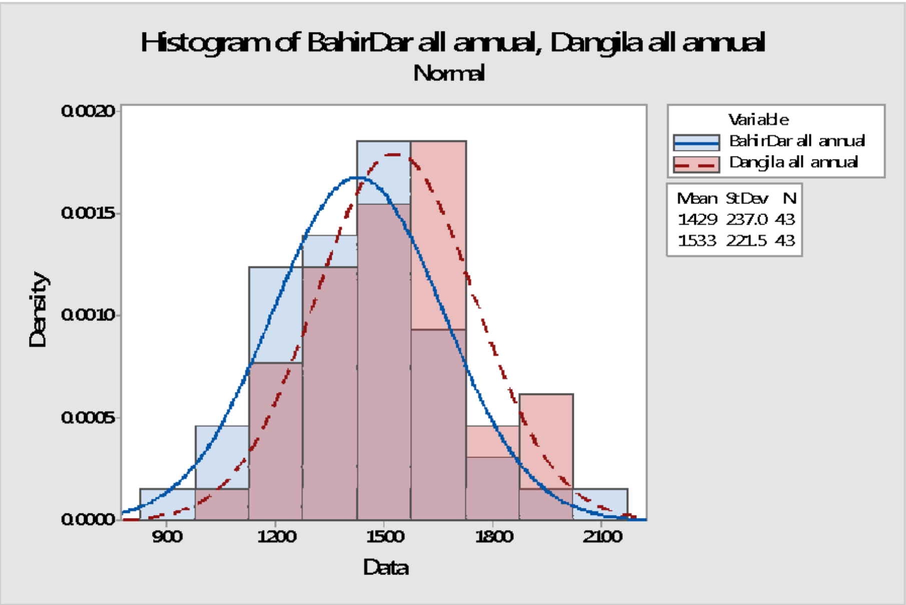


Figure E-4. Histogram of annual rainfall from Dangila and Bahir Dar for all complete years.

Appendix F. Water point surveys

The information in Tables F-1, F-2, F-3 and F-4 is from surveys conducted by Demis Alamirew of GSE as part of the AMGRAF catalyst project in February and March 2014. Longitude and latitude are in the UTM37N coordinate system, taken from a handheld GPS along with elevation. SWL = static water level.

Table F-1. Hand-dug wells.

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation m asl	Geology	Date of visit	Field pH	EC µS/cm	Temp °C	Depth m	SWL mbgl	Water strike mbgl	Pump/cover
DW1	Guangu/Chagni	Tigiri	Metekel ber	243236	1226624	1887	Weathered basalt + soil	03/02/2014	5.79	59.8	22.8	19		16?	hand pump
DW2	Dangila	Washa	Kulkul (lay Medhanialem)	254911	1245762	2205	soil and weathered basalt	04/02/2014	6.32	203	23.3	6		4	hand pump
DW3	Dangila	Washa and Kabilita	Washa & Kabilita school well/Robit	252972	1246806	2163	basalt with hematite and laterite stains	04/02/2014	7.34	344	26.5	32		27	hand pump
DW4	Dangila	Wondayita	Woranti gote)	259028	1244564	2119	weathered basalt and red soil	04/02/2014	6.14	86.5	25.3	13.5		about 4m	hand pump
DW5	Dangila	Dimsa	Emadadi/lay Dimsa	256321	1243793	2225	weathered andesitic basalt/red soil	05/02/2014				0			hand pump
DW6	Dangila	Washa Medhanialem	Tach Yihun gote	254887	1244238	2199	weathered basalt	05/02/2014				12.5		4m, 5m	hand pump
DW7	Dangila	Warkit kebele	Dekit	265130	1254942	2038	soil and fractured/weathered basalt	06/02/2014				10		7.5	hand pump
DW8	Dangila	Warkit kebele	Dekit/ Ato Yeshalem Zegey	265323	1255195	2043	weathered basalt and grey soil	06/02/2014	6.78	318	24.4	7	6.7		Metal sheet
DW9	Dangila	Dengela Georgis	Addis Alem	263753	1255546	2055	weathered basalt with varigated colours	06/02/2014				12.5		8	hand pump
DW10	Dangila	Dengela Georgis	addis Alem(Masresha Atalele's well	263940	1255494	2053	Soil and andesitic basalt	06/02/2014	6.84	301	24.8	4.5	3.6	3	pot cover
DW11	Dangila	Warkit kebele	Ato Hayimanot Wonde's well (Deki gote)	264930	1254845	2046	soil and weathered basalt	06/02/2014	6.37	197.6	21.8	11	7.2	9	Metal sheet
DW12	Dangila	Warkit kebele	Ato Fekadie Berku's well(Dekit gote)	265044	1254813	2045	soil and varigated colour weathered basalt	06/02/2014	7.11	307	24.8	10	8.2		Metal sheet
DW13	Dangila	Warkit kebele	Mokel	265561	1253511	2057	soil and weathered basalt	06/02/2014	6.27	151.3	27.1	11	6.89		hand pump
DW14	Dangila	Warkit kebele	Legasta	266550	1254196	2044	soil and weathered basalt	06/02/2014	6.29	124.5	26.4	5			hand pump
DW15	Dangila	Warkit kebele	Nana Minch/Legasta gote	266344	1253350	2047	soil and weathered basalt	06/02/2014		166.3	27	8		6	hand pump
DW16	Dangila	Warkit kebele	Nana minch(Ato Wubante Eyasu's well)	266327	1253334	2054	red soil (2m) and weathered basalt	06/02/2014				5.5	4.53	4.5	pot cover
DW17	Dangila	Manguda	Jabi gote	266925	1253133	2048	weathered basalt	07/02/2014	6.68	339	27.7	8.5			hand pump
DW18	Dangila	Badani	Delelti	249874	1239907	1922	boulder type basalt and black soil	07/02/2014	7.2	502	24.2	4		2	hand pump
DW19	Dangila	Badani	Akuacha	250264	1241521	1921	alluvium and weathered basalt	07/02/2014	6.52	680	27.9	7.5		6	hand pump
DW20	Dangila	Badani	Ambo/Guji	250363	1241161	1917	black loamy clay soil	07/02/2014				10			hand pump
DW21A	Dangila	Kuandisha	Gezewetie	264708	1238299	2190	soil and fractured/weathered basalt	08/02/2014	6.79	162	19.8	9.5		6	hand pump
DW21	Dangila	Kuandisha	Gezewetie	264965	1237972	2203	loamy-silty soil and weathered basalt	08/02/2014	6.54	142	21.7	11		6	hand pump
DW22	Dangila	Abla Mariam	Mariam Wuha/Addis Alem gote	264115	1236875	2230	red clay top, silty loam dark soil bottom	08/02/2014	6.69	200	26.4	11		4.5	hand pump
Dw23	Dangila	Abla Mariam	Abla Mariam school well	264676	1237084	2229	fractured vesicular basalt and soil	08/02/2014	6.28	129.3	24.9	6			hand pump
DW23B	Dangila	Gayita	Tach Gayita	270288	1237497	2159	red soil and regolith	08/02/2014				0			hand pump
DW24	Fagita Lekuma	Ashewa Fera	Cambo	267140	1231866	2362	silty clay soil and basalt from bottom	10/02/2014	6.89	93.2	23.7	6			hand pump
DW25	Fagita Lekuma	Makia Teklehaymanot	Makia	268237	1232047	2332	weathered basalt	10/02/2014				0			hand pump
DW26	Fagita Lekuma	Abla Mariam	Meskelti	265301	1231556	2401	silty loamy clay soil above vesicular basalt	10/02/2014	6.39	126.1	25.1	10			hand pump
DW27	Fagita Lekuma	Meskelti	Wondie Yenesew's well	265278	1231230	2388	weathered basalt	10/02/2014	6.18	113.3	22.3	6	4.8	5	pot cover
DW28	Fagita Lekuma	Shangani	Kesisi	263863	1230061	2394	red soil and boulder type basalt	10/02/2014	6.32	123	25.1	14			hand pump
DW29	Fagita Lekuma	Gula Azmach	Tankuari	269703	1228230	2411	red soil and basalt	11/02/2014	6.52	116.8	18.4	0			hand pump
DW30	Fagita Lekuma	Tafoch Damburi	Akuta	270339	1231449	2339	weathered basalt with pink tint	11/02/2014	7.73	150.2	19.8	24.5			hand pump
DW31	Fagita Lekuma	Tafoch Damburi	Dambul Elementry school compound	270147	1232224	2313	Deeply weathered basalt	11/02/2014				20			hand pump
DW32	Fagita Lekuma	Tafoch Damburi	Wonjela/Adurja	270441	1232461	2296	weathered basalt	11/02/2014	6.68	156.9	23.2	21		9	hand pump
DW33	Fagita Lekuma	Giraita and Zembel	Mariam Wuha gote	273870	1228651	2358	fractured and weathered basalt	11/02/2014	6.61	119.9	25.5	0			hand pump
DW34	Fagita Lekuma	Segila Bambildawna	Besena	280373	1224286	2476	weathered basalt	11/02/2014	7.11	131.8	22.4	27		12	hand pump
DW35	Fagita Lekuma	Awsa Fenzit	Fenzit school	276697	1228065	2347	weathered basalt	11/02/2014				9			hand pump
DW36	Dangila	Afessa/Segino Gebeya	Segino Gebeya	278706	1237135	2129	aquifer is boulder type basalt	12/02/2014	6.14	107.5	18.5	26		23.5	hand pump
DW37	Dangila	Afessa	Kes Adugna Fantahun/Arbit Gebreal	277399	1234214	2181	weathered vesicular basalt	12/02/2014	5.89	60.7	23.7	10	8.55		Metal sheet
DW38	Dangila	Afessa	Arbit Gebreal new	277384	1234070	2182	weathered basalt	12/02/2014	6.56	117	23.3	9.5	7.55		hand pump
DW39	Dangila	Ligaba	Setto	278169	1242126	2054	weathered basalt above massive basalt	12/02/2014	5.92	46.7	28.2?	16		9	hand pump
DW40	Dangila	Ligaba	Ligaba	277205	1243337	2034	soil + basalt?	12/02/2014				11			hand pump

ID	Topography	Land use	Use	Perennial	Remark
DW1	flat land	near small town	domestic/town supply	good supply	A lot of users/Jericans in line
DW2	sloping area	farm land	domestic/rural supply	good supply	saturated water depth in the stream cut below well is 2m
DW3	top land	near school compound	school water supply	good supply	andesitic basalt at middle, and sandy material aquifer (oral information)
DW4	foot of gently falling area	farm land	domestic/rural supply	water scarcity may/April	Water strike depth is interpolated from spring levele downstream
DW5	gentle slope	farm land	domestic/rural supply	high water scarcity	not sampled because of poor storage
DW6	sloping area	farm land	domestic/rural supply	good supply	Pump broken on same day morning
DW7	flat land	grazing land	domestic/rural supply	not functional/pump uninstalled	the pump is uninstalled for fear of teaft
DW8	flat land	house compound	domestic,cattle	well dries in April-May	well couldn't be sunk below due to massive rock, water emerges at contact of weathered and fresh basalt
DW9	flat land	near house	domestic/rural supply		supply was good but well not working due to pump stolen
DW10	gentle slope	very near house and cattle shelter		good supply	andesitic basalt
DW11	flat land	very near house	domestic, cattle	good supply	Dug in 1997 E.C. and with 85cm diameter
DW12	flat land	house compound	domestic, cattle, and irrigation	good supply	Well EC is relatively higher than near by wells
DW13	flat land	near farm land	domestic supply	good supply but not actively used	Full of suspended material
DW14	flat land	grazing land	domestic	good supply	The swampy area near this well was wet throught the year till 1989E.C according to local people b/c of climate change
DW15	gentle slope	near grziing land	domestic supply	good supply	6m soil, 2m weathered basalt, surrounding area was wet until 1986 E.C. (equaliptus coverage highly increased and climate changed, local people)
DW16	gentle slope	near house	domestic/cattle	good supply	
DW17	flat land	3.5m from house/cattle shelter	domestic	good supply	only about 10m away from swamppy area; dug in may 2013
DW18	about 500m from ridge/gentle slope	grazing land	domestic supply	good supply	fresh boulder type jointed basalt is the main aquifer
DW19	flat land	near farm land	domestic supply		well is located few hundred meters away from ridge foot
DW20	foot of hill	grazing land	domestic supply	good supply	
DW21A	flat land	farm land	domestic supply		The well couldn't be lowered below this depth due to massive basalt; 6m soil
DW21	flat land	farm land	domestic supply	good supply	
DW22	flat land	grazing land	domestic supply	good supply	main wateris in the black soil and and night storage during digging was 1.5m
Dw23	flat land	school compound	domestic	good supply	water storage was about 1.5m in a night and flow from fractured basalt mainly (oral information)
DW23B	flat land	near farm land			Pump not functional. The well is located in higly /actively irrigated area
DW24	flat land	grazing land	domestic supply	good supply	The basalt has some regolith on top of it which stores water
DW25	gentle slope	farm land		not functional/pump uninstalled	
DW26	flat land	farm land	domestic supply	good supply	
DW27	flat land	farm land	cattle	good supply	
DW28	gentle slope	farm land	domestic supply	good supply	
DW29	depression	grazing land	domestic supply	good supply	A spring located some 800m away at down stream emerges at the contact of weathered basalt and trachyte
DW30	plateau	farm land	domestic supply	good supply	weathered basalt with red tint aquifer, a lot of commercial plants for charcol production
DW31	plateau	school compound	school water supply	good supply	not sampled
DW32	plateau	grazing land	domestic and for seedling	good supply	located in depression
DW33	flat land	near farm land	domestic supply		
DW34	flat land	school compound	domestic and school supply	good supply	
DW35	flat land	school compound	domestic supply	good supply while working	pump not functional
DW36	gentle slope	rural town supply	domestic supply	scarcity in March	soil is dry (local people, but the contact between soil and massive basalt is wet
DW37	flat land	individual well	cattle	good supply	
DW38	flat land	Rural village supply	under construction		Under construction, aquifer is weathered basalt under relatively thick red soil
DW39	plateau	Rural village supply	domestic supply	good supply	
DW40	flat land	Rural village supply	domestic	good supply	

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation m asl	Geology	Date of visit	Field pH	EC µS/cm	Temp °C	Depth m	SWL mbgl	Water strike mbgl	Pump/cover
DW41	Dangila	Ligaba	Gilgel Badma	276292	1242522	2030	massive basalt on top and weathered basalt	12/02/2014	6.41	141.7	29.1	15			hand pump
DW42	Dangila	Ligaba	Asterio	275223	1243555	2011	soil with bottom massive basalt	12/02/2014	6.57	240	25.6	6	5.4		hand pump
DW43	Dangila	Zelesa	Kilage	268713	1244603	2132	red and black loamy soil intercalation	13/02/2014	5.82	56.8	18.9	11		2	hand pump
DW44	Dangila	Enku Densi Fasiledes	Kambo gote	273025	1241891	2022	Andesitic basalt	13/02/2014				16			hand pump
DW45	Dangila	Misrak Zelesa	Sale Egziabhaire	271951	1244264	2055	alluvium and weathered basalt	13/02/2014				0			hand pump
DW46	Dangila	Misrak Zelesa	Dagnaw Tarekegn's well	271864	1244048	2064	highly weathered red basalt top, yellow bottom	13/02/2014	6.11	197.6	22.5	13	6.6	11.5	Metal sheet
DW47	Dangila	Zelesa	Wale Tilahun's well	271912	1244201	2057	red soil	13/02/2014	6.54	133.3	21.9	12.5	6.53		pot cover
DW48	Dangila	Zeguda	Lay Shewaye	270430	1246366	2084	red soil and regolith	14/02/2014	6.22	98.9	23.7	5			hand pump
DW49	Dangila	Zeguda	Weldehana	271170	1247335	2066	soil and thin regolith	14/02/2014	5.94	88.4	25.2	9		8	hand pump
DW50	Dangila	Zeguda	Abera Negash's well in Woldehana	271060	1247222	2072	weathered basalt	14/02/2014		697.6	23.1	8.5	7.25	8	Metal sheet
DW51	Dangila	Zeguda	Kuaja	269811	1248608	2064	regolith	14/02/2014	6.06	114.5	26.2	17		4.5	hand pump
DW52	Dangila	Degeshta	Kuakurti	269677	1250776	2047	weathered vesicular basalt or regolith?	14/02/2014	6.76	231	25.1	10.5		9	hand pump
DW53	Achefer	Weldafecha	Mamo Denaenqubar	269062	1251933	2046	red soil, black soil/loamy clay, weathered basalt	14/02/2014	6.86	234	22.1	10		9	hand pump
DW54	Achefer	Weldafecha	Denaenqubar	269382	1251545	2041	red soil, black soil/loamy clay, weathered basalt	14/02/2014	7.31	322	24.6	6		3	hand pump
DW55	Dangila	Zugda	Tach Kuaja/Degu Negussie	270226	1249552	2047	Loamy clay soil	14/02/2014	6.13	40.8	21.7	6	1.75		open well
DW56	Dangila	Dengesheta	Girmaw Malede/Cheba gote	265228	1252431	2057	red soil and weathered basalt	20/02/2014	6.04	182.2	25.4	10		9.5	rope and washer pump
DW57	Dangila	Dengesheta	Girmaw Malede/Cheba gote				red soil and weathered basalt	20/02/2014	6.12	212	23.6	11	10.1	10	open well
DW58	Dangila	Dengesheta	Ato Arega Wolie/Cheba gote	264608	1252655	2070	regolith, weathered trachy basalt, massive basalt	20/02/2014	6.28	172.5	23.4	5	4.75		under construction
DW59	Dangila	Dengesheta	Ato Arega Wolie/Cheba gote	264594	1252659	2069	red soil, regolith and weathered trachy basalt	20/02/2014	6.8	37.9	25.2	6.5	5.89		open well
DW60	Dangila	Dengesheta	Ato Nebretie Abebayehu/Cheba gote	264321	1252387	2067	red soil, regolith and weathered trachy basalt	20/02/2014	6.11	105.6	23.3	6	3.65	4	open well
DW61	Dangila	Dengesheta	Ato Semahagn Below/Cheba gote	264333	1252397	2075	red and weathered basalt	20/02/2014	6.33	217	22.5	5	3.2	4	open well
DW62	Dangila	Dengesheta	Ato Semahagn Below/Cheba gote				red and weathered basalt	20/02/2014				5.5	2.7		open well
DW63	Dangila	Tarra Gebreal/Dengesheta	Ato Kassa Wudu (chorka village)	263709	1252406	2075	soil and regolith	20/02/2014	6.44	169.5	26.5	4.5	3		pot cover
DW64	Dangila	Tarra Gebreal/Dengesheta	W/ro Yayesh Ayinalem	263782	1252437	2074	weathered basalt	20/02/2014	6.36	181	23.1	4.5	3.2	4	pot cover
DW65	Dangila	Tarra Gebreal/Dengesheta	Ato Abayineh Shawel (Chorka gote)	263541	1252719	2078	weathered basalt	20/02/2014	6.47	107	23.9	5	3.89		open well
DW66	Dangila	Tarra Gebreal/Dengesheta	Ato Beyene Fekadie(Chorka)	263526	1252707	2080	soil and regolith	20/02/2014	6.46	111.7	22.2	11	4.1	4	Metal sheet
DW67	Dangila	Tarra Gebreal/Dengesheta	Chorka	263565	1252721	2080	soil and weathered basalt	20/02/2014	6.48	140.4	26	7.5			hand pump
DW68	Dangila	Tarra Gebreal/Dengesheta	Ato Shibabaw Workneh (Chorka gote)	263577	1252555	2073	weathered trachy basalt	20/02/2014	6.56	124.6	21.6	7.5	3..45	7	open well
DW69	Dangila	Tarra Gebreal/Dengesheta	Ato Gedefaw Ayalew (Chorka gote)	263358	1252573	2075	regolith and weathered basalt	20/02/2014	6.61	144	23.1	5	3.25	4	pot cover
DW70	Dangila	Tarra Gebreal/Dengesheta	Ato Kasahun Worku(Abdra gote)	262992	1251801	2092	soil/regolith	20/02/2014	6.78	254	22.7	14	6		pot cover
DW71	Dangila	Tarra Gebreal/Dengesheta	Ato Necho Anagie (Abadra gote)	262987	1251752	2085	fractured basalt	20/02/2014	6.7	307	23	6.5	4.6		pot cover
DW72	Dangila	Tarra Gebreal/Dengesheta	Ato Atinkut mulu (Abadra gote)	262338	1252023	2074	weathered basalt	20/02/2014	6.11	177.1	22.7	12.5	8.18	9.5	Metal sheet
DW73	Dangila	Dengesheta	Ato Melese Worku (Mender 1-Bunteta gote, M-1)	265440	1249776	2091	regolith and weathered trachy basalt	21/02/2014	6.22	132.6	21.5	8	5.75		Metal sheet
DW74	Dangila	Dengesheta	Mender 1(Bunteta village)	265269	1249847	2087	wethered basalt, with some regolith contribution	21/02/2014	6.08	120.8	23.1	7		5	hand pump
DW75	Dangila	Dengesheta	Ato Birhanu Shibabaw, Mender 1, M-2)	265056	1250118	2082	fractured basalt with some regolith	21/02/2014	6.84	338	21.7	4.5	3.29		Metal sheet
DW76	Dangila	Dengesheta	Ato Bazezew Worku(Monitoring well 3)	265588	1250141	2093	contact of weathered basalt and massive basalt	21/02/2014	6.8	280	23.1	9.5	8		Metal sheet
DW76B	Dangila	Dengesheta	Ato Bazezew Worku				weathered vesicular basalt	21/02/2014	6.59	192.7	22.1	9.5	8		Metal sheet
DW77	Dangila	Dengesheta	Ato Getaneh Ayichew (Demekta gote, M-4)	265457	1250733	2075	red soil and weathered basalt	21/02/2014	6.04	104	26.4	11	4.56		Metal sheet
DW78	Dangila	Dengesheta	Mender 1(Demekta gote)	265360	1250728	2075	Loamy clay soil and basalt	21/02/2014	7.3	381	26.9	0			hand pump
DW79	Dangila	Dengesheta	Tara Gebreal Primary school	263346	1252081	2088	weathered basalt	21/02/2014	7.35	320	26.7	9			hand pump
DW80	Dangila	Dengesheta	Ato Tarekegn Tamiru (Abadra gote)	262754	1252201	2084	soil and regolith	21/02/2014	6.34	307	26	9	7.4	7	Metal sheet
DW81	Dangila	Dengesheta	Ato Degu Ejigu/ Abadra goote	262804	1252184	2093	soil and regolith	21/02/2014	6.21	153.3	23.2	9	7.7		Metal sheet
DW82	Dangila	Dengesheta	Ato Dessie Sewnet	262802	1252235	2090	red soil, regolith and weathered basalt	21/02/2014				0	7.5		Metal sheet
DW83	Dangila	Dengesheta	Ato Alehegn Guadie (Abadra gote)	262874	1252330	2091	red soil, weathered andesitic basalt	21/02/2014	6.46	220	24	8.5	7.63		Metal sheet
DW84	Dangila	Dengesheta	Ato Fenta Guadie	262815	1252071	2090	soil and weathered basalt	21/02/2014				7.5	7.47		Metal sheet
DW85	Dangila	Gerargie	Ato Alelgn Gebeyehu (Girarge T/Haimanot				red soil, regolith and weathered vesicular basalt	21/02/2014	6.77	277	26.5	12.5	6.65		Metal sheet
DW86	Dangila	Gerargie	Ato Atalay Gebeyehu (Gerargie)	2623306	1250311	2080	weathered vesicular basalt	21/02/2014	6.65	281	23.9	9.5	5		Metal sheet
DW87	Dangila	Abadra Tach Mender	Abadra Tach Mender	259912	1250977	2075	red soil and regolith	21/02/2014	6.32	110.4	26	7			hand pump
DW88	Dangila	Abadra/Hamusit	Abadra town	258070	1251989	2096	loamy clay soil, regolith and weathered basalt	21/02/2014	6.52	174.3	25	10		6	hand pump
DW89	Achefer	Sebte	Guchbigie	272919	1250764	2047	red soil and regolith	03/03/2014	6.05	94.6	23.3	7		5	hand pump
DW90	Achefer	Sebte	Kes Ajaw	272529	1251633	2041	weathered basalt	03/03/2014	5.92	73.5	22	12.5	6.55	10	pot cover
DW90B	Achefer	Sebte	Kes Ajaw	272550	1251627	2044	weathered basalt	03/03/2014	5.65	52.4	21.3	15	8.5	7	pot cover
DW91	Achefer	Gedema Fechito	Gedema Fechito	272840	1254285	2035	red soil, regolith and weathered basalt	03/03/2014	6.19	132.8	23.1	16		14	hand pump
DW92	Achefer	Gedema Fechito	Gedema Fechito	272173	1254395	2016	Loamy clay soil and regolith	03/03/2014	6.17	168.5	22.9	6		2	hand pump
DW93	Achefer	Gedema Fechito	Gedema Fechito	271664	1254517	2010	red soil and regolith	03/03/2014	5.65	85.4	23.6	7.5		4	hand pump
DW94	Achefer	Gedema	Dengirsi (Cheba Dure gote)	271406	1254772	2014	weathered basalt	03/03/2014	6.32	222	26.5	14		10	hand pump
DW95	Achefer	Gedema	Emahoy Zertihun Redie"s well	271539	1254776	2020	regolith and weathered basalt	03/03/2014	6.12	59.4	23.3	16.5	13.75	14	Metal sheet
DW96	Achefer	Gedema Mariam	Tajorka gote	271046	1255390	2009	regolith and weathered basalt	03/03/2014				0			
DW97	Achefer	Gedema	Tazewarka	271276	1255852	2008	weathered basalt	03/03/2014	6.93	322	25.2	10		5	hand pump
DW98	Achefer	Gedema	Ato Bazezew	271256	1256196	2021	weathered basalt	03/03/2014	6.39	165.6	23.8	0	11.45	9	pot cover
DW99	Achefer	Guta	Yetubie Senshaw (Shumbab gote)	269189	1257635	2012	red soil little regolith	03/03/2014	6.23	199.7	24.1	12	6.6	9	pot cover
DW100	Achefer	Guta	Shumbra gote near DW99	269208	1257630	2011	red soil, regolith and some weathered basalt	03/03/2014				10		8	hand pump
DW101	Achefer	Gedema	Alemneh Fentie (Tach worka gote)	272387	1256232	2015	soil and regolith	03/03/2014				0			
DW102	Achefer	Gedema	Taje Worka	272847	1256473	2012	red soil and regolith	03/03/2014	6.72	219	27	13		11.5	hand pump
DW103	Achefer	Atite Abo	Mehal Abo	272921	1266530	1942	black clay loam, regolith mainly weathered basalt	04/03/2014	6.65	232	22.2	5		4	hand pump
DW104	Achefer	Atite Abo	Ato Azene Guadie/Abalikab gote	272005	1266380	1985	soil for this well but the surrounding is basalt	04/03/2014	5.75	148	20.5	12.5	6.6	12	Metal sheet

ID	Topography	Land use	Use	Perennial	Remark
DW41	flat land	Rural village supply	domestic supply	good supply	
DW42	flat land	Rural village supply	good supply; not used: pollution	good supply	The well has been opened for measuring water level and polluted and not currently in use
DW43	flat land	near grziing land	Rural village supply	good supply	Over 5000 pots are featched every day with no scarcity
DW44	gentle slope	grazing land	Rural village supply	not functional/pump uninstalled	not functional currrently due to pump problem
DW45	sloping area	grazing land	Rural village supply		well not functional due to pump problem
DW46	sloping area	near house	cattle	moderate supply	Two dug wells close by and varying in two meters depth show some EC variation
DW47	sloping area	near house	domestic, cattle	moderate supply	located near house/mule shelter
DW48	flat land		domestic	moderate supply	Scarcity of water during dry period
DW49	flat land	near foot of gentle slope	domestic supply	good supply throughout the year	water stored in soil mainly
DW50	flat land	near house	domestic supply	moderate supply	
DW51	flat land		domestic	good supply throught	dug in 1991 E.C.
DW52	flat land	farm land, 50m from grazing land	domestic supply	good supply throught	Dug in 2000 E.C and sustainable supply all day long throught the year
DW53	gentle slope	near swamy area in farm land	domestic supply	good supply	about 3.5m red soil, about 1m black soil/loamy clay and about 5.5m weathered basalt is reported(oral info), dug in 2003 E.C.
DW54	flat land	grazing land	domestic supply	good supply	good supply but has bad smell in the rainy period due to the swampy area
DW55	flat land	grazing land	domestic, cattle	good supply	Near grazing land and sloping area before well
DW56	gentle slope	farm land	domestic and chat plantation	drops in May-April	Depth of weathering around this well is relatively deeper and some of the wells supply good water throught the year
DW57	gentle slope	irrigation land/Chat tree	irrigation only	dries in April	10m soil and one meter weathered basalt
DW58	flat land	near house	domestic	under construction	The toilet is 12.5m from the new well and old well is 133m away from new well and toilet is almost at same depth to the new well
DW59	flat land	near house	domestic and cattle	scarcity in May-April	The toilet is 12.5m from the new well and old well is 133m away from new well and toilet is almost at same depth to the new well
DW60	flat land	near house	domestic and cattle		Dug before 7 years
DW61	flat land	near house	irrigation only	scarcity in May-April	well separation is only 8m and used for irrigating chat plant
DW62	gentle slope	irrigation land/Chat tree			groundwater flow is towards east
DW63	flat land	farm land/grazing land	irrigation only	good supply	top soil is 3m thick and below this is regolith
DW64			domestic		Relatively massive basalt at bottom, (dug before 6 years)
DW65		near house	domestic		Dug in 2003 February and functional
DW66	almost flat land	near house	cloth washing and cattle	water level highly drops in May	Aquifer is regolith and water storage recovers though it falls significantly in dry period
DW67	almost flat land	grazing land	domestic supply	good supply	Main storage is in the regolith than in basalt or top soil
DW68	almost flat land	near house	cattle		dug in April 2013; top soil is 2m then 1m regolith and 3.5m trachy basalt
DW69	flat land	near house	domestic and cattle	good supply throught	Main storage is in weathered basalt
DW70	flat land	near house	domestic supply	high water scarcity	As the bottom layer is massive basalt people have difficulty to sunk wells below this depth
DW71	gentle slope	near house	domestic, cattle	supplies better than surrounding wells	The aquifer is fractured boulder type basalt and has better yield compared to other wells (1.5m soil, 1.5m regolith and weathered basalt 2.5m
DW72	sloping side	near house	domestic, cattle	good supply	good supply though water level significantly drrops (dug in 2004 E.C March)
DW73	flat land	near house	domestic and cattle	good supply	dug in May 2004E.C.(red soil 2.65m, then 2m regolith and then 2.35m trachybasalt)
DW74	flat land	grazing land	domestic supply	good but turbid in peak dry period	Black soil then regolith and then trachy basalt
DW75	flat land	4m from house	domestic, cattle	good supply	Massive basalt at a depth of 4.5m and wells can't be sunk below(loamy clay soil, regolith, weathered basalt, massive basalt layering)
DW76	flat land	near house	cooking, cattle	better supply	Main flow is under varigated colored weathered vesicular basalt at the contact with massive basalt
DW76B	flat land	near toilet	irrigation only	better supply	
DW77	flat land	near house	domestic and cattle	good potential	red soil and weathered basalt at bottom
DW78	flat land	grazing land	not used because of bad smell	good storage, but not fully functional	weathered basalt with grey weathering (aquifer), and dug in 2002EC and pump fitted in 2003 E.C., near dry creek
DW79	flat land	school compound	school water supply	better supply	The bottom layer is massive basalt and digging was stoped because of massive basalt
DW80	plateau	near house	domestic supply	high water scarcity	water well couldn't be sunk below this depth due to massive basalt
DW81	plateau	near house	domestic, cattle and irrigation	high water scarcity	well dries in may april, 1m soil 6m regolith and two meter basalt (well log, oral information)
DW82	plateau	near house	domestic, cattle	high water scarcity	water scarcity due to limited depth because of massive basalt
DW83	plateau	near house	domestic, cattle	better supply	new well (Feb. 2014) and the depth was fairly deep enough, and the aquifer is weathered andesitic basalt
DW84	flat land	inside farm land	domestic	better supply	
DW85	flat land	near house	domestic, cattle	better supply	the well has better supply and especially wells close to the swampy area
DW86	flat land	farm land	domestic supply	very good supply throught the year	the well is over 20 years old but still has great supply
DW87	gentle slope	farm land	domestic supply	better supply	
DW88	gentle slope	inside small town	domestic supply	better supply	A lot of users/Jericans in line
DW89	flat land	near swamy area	domestic supply	better supply	Located near N20W depression
DW90	gentle slope	inside irrigation farm	irrigation only	decreases in May-April	water table fluctuation is about 4.55m
DW90B	gentle slope	inside irrigation farm	irrigation only	decreases in May-April	well separation is 21m
DW91	gentle slope	grazing land	domestic supply	better supply	
DW92	flat land	near swampy area	domestic	good supply, but turbid in May	The water has bad smell during the wet period ; No massive rock at bottom
DW93	flat land	grazing land	domestic supply	good supply	very good supply since digging and good recovery during digining (2002E.C.
DW94	gentle slope	grazing land	domestic supply	very good supply throught the year	top 4m is red soil and the rest is weathered basalt since it was dug (May 2003 E.C.)
DW95	gentle slope	near house	domestic supply		very thin weathered basalt seen
DW96					abandoned due to pump problem
DW97	flat land	grazing land	domestic supply	good supply	No regolith but loamy clay soil
DW98	gentle slope	farm land	irrigation only	good supply	couldn't grow vegetable due to termites which cut the plants at any stage of growth of the plants
DW99	flat land	near house	domestic and Irrigation	good supply	Many people in the surrounding area tried to dig but couldn't sunk wells due to massive basalt at shallow depth
DW100	flat land	grazing land	domestic supply	good supply	Many people in the surrounding area tried to dig but couldn't sunk wells due to massive basalt at shallow depth
DW101					
DW102	flat land	grazing land	domestic supply	good supply	Dug in June 2003E.C
DW103	flat land	Intermountain depression	domestic supply	very good supply	there is 2msoil, thin layer of gravel and regolith at the creek cut near by
DW104	plateau	near house	domestic and cattle		Shallow water is mainly stored in weathered basalt around this place but in this well the storage is mainly in soil

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation m asl	Geology	Date of visit	Field pH	EC µS/cm	Temp ^{o}C	Depth m	SWL mbgl	Water strike mbgl	Pump/cover
DW105	Achefer	Atite Abo	Abalikab	272252	1266509	1970	fractured and weathered basalt	04/03/2014	6.67	285	20.7	7		6	hand pump
DW106	Achefer	Atite Abo	Engedaw Bezie (Abalikab gote)	272333	1266658	1968	weathered basalt	04/03/2014	6.21	125.3	21.5	7	4.8	4	Metal sheet
DW106B	Achefer	Atite Abo	Engedaw Bezie (Abalikab gote)	272303	1266670	1974	weathered basalt	04/03/2014				7.5	6.2	6	Metal sheet
DW107	Achefer	Wulsi	Tesfu Minch	274219	1265438	1936	Loamy clay soil and fractured basalt	04/03/2014	6.85	330	24.6	10		8.7	hand pump
DW108	Achefer	Wulsi	Ato Demeke Atnaw(Tesfu Minch gote)	274228	1265401	1941	loamy clay soil	04/03/2014	5.72	123	23.2	5	2.7		hand pump
DW109	Achefer	Nefasa Ashuda	Amestya Micheal	272691	1272100	1939	Trachyte	04/03/2014	6.72	259	27	8		5	hand pump
DW110	Achefer	Nefasa Ashuda	Ato Gerum Atalele (Amestya locality)	272724	1272050	1940	Trachyte	04/03/2014				6	4.05		Metal sheet
DW111	Achefer	Nefasa Ashuda	Ato Kassa Atalele	272735	1272042	1940	loamy clay soil	04/03/2014	6.2	88.5	23.3	5	3.6		pot cover
DW112	Achefer	Nefasa Ashuda	Wondi Debelo community well	269749	1270836	2044	weathered basalt	04/03/2014				0			hand pump
DW113	Achefer	Nefasa Ashuda	Wondi Debelo School supply well	269800	1270485	2063	weathered basalt	04/03/2014	6.43	174.5	22.6	9		almost 9m	hand pump
Dw114	Achefer	Lalibela Medhanialem	Eheri	273098	1272318	1941	loamy silty clay soil and regolith	04/03/2014	6.4	151.1	19.2	9		4.5	hand pump
DW115	Achefer	Azena	Amede Guma gote	276218	1269822	1900	weathered basalt	04/03/2014	7.49	350	20.3	7.5		6	hand pump
DW116	Achefer	Gergista Micheal	Gergista	276806	1249357	1986	weathered basalt	04/03/2014	6.45	244	22.4	9		7.5	hand pump
DW117	Achefer	Gergista Micheal	Kembro	276978	1249136	1991	soil and weathered basalt	04/03/2014	6.4	264	20.5	15		11	hand pump
DW118	Achefer	Gergista Micheal	Sheferaw Shiti (Kembro Gote)	276621	1249409	1987	red soil	04/03/2014	6.28	102.5	19.7	6	4.12		Metal sheet
DW119	Achefer	Sebte	Dandie mesk gote	274509	1250559	2003	weathered basalt	05/03/2014	6.7	275	24.2	13		10	hand pump
DW120	Achefer	Sebte	Ato Semachew Genetie (Tach Sebt)	274604	1250594	2003	weathered basalt	05/03/2014	6.16	132.4	22.2	13	8.85	10	Metal sheet
DW121	Achefer	Sebte	Ato Mekuanent Amare(Tach Sebt)	274659	1250615	2007	weathered basalt	05/03/2014	6	331	24	12.5	8.3	9.5	Metal sheet
DW122	Achefer	Sebte	Ato Andualem Worku(Tach Sebt)	274739	1250537	2002	weathered basalt	05/03/2014	6.18	131	23.8	10.5	6.55		Metal sheet
DW123	Achefer	Sebte	Tach Sebt	274685	1251183	2001	weathered basalt	05/03/2014	6.56	266	26	12.5		10	hand pump
DW124	Achefer	Debikan Medhanialem	Ato Degu Tayachew (Denka)	281229	1254917	1931	2m black soil +3m regolith	05/03/2014	7.19	227	25	5	4.5		Metal sheet
DW125	Achefer	Debikan Medhanialem	Bitayita	281359	1255724	1929	loamy clay and regolith	05/03/2014				12.5		11	hand pump
DW126	Achefer	Debikan Medhanialem	Ato Bekele Degarege(Bitayita gote)	281384	1255775	1932	soil and regolith	05/03/2014	7.24	189	22.3	12.5	5.8	10	Metal sheet
DW127	Dangila	Afafe Eyesus	Wawi	256420	1256428	2190	red soil and weathered basalt	06/03/2014				0			open well
DW128	Dangila	Afafe Eyesus	Tach Afafe Eyesus	256313	1255993	2135	fractured basalt	06/03/2014	6.73	273	21.5	7			open well
DW129	Dangila	Tach Wawi	Ajuri	257967	1256697	2101	alluvium and weathered basalt	06/03/2014	6.46	226	24.2	10		5	hand pump
DW130	Dangila	Afafe Eyesus	Lay Afafe eyesus	255125	1254862	2249	thin soil and weathered basalt	06/03/2014	6.57	141.8	26	12.5		10.5	hand pump
DW131	Mecha	Abro Menore	Asana	308402	1244023	2166	weathered basalt	07/03/2014	7.18	553	22.1	14		10	hand pump
DW132	Mecha	Abro Menore	Asana	308653	1243664	2184	weathered basalt	07/03/2014	7.97	302	25.8	8.5			hand pump
DW133	Mecha	Abro Menore	Abromenore school	307496	1241242	2373	weathered basalt	07/03/2014				13		12	hand pump
DW134	Mecha	Fellegehiwot	Debre Mender	306107	1248295	2143	alluvium and weathered basalt	07/03/2014	6.86	209	24	6.5		2.5	hand pump
DW135	Mecha	Fellegehiwot	Chew Duba	305262	1248163	2155	red soil	07/03/2014	6.82	266	24.5	7		5	hand pump
DW136	Mecha	Hulum Selam	Ato Yaregal Sheferaw(Gerchech town)	300494	1244287	2060	weathered basalt	07/03/2014	5.95	31.3	23	16	12.6		Metal sheet
DW137	Mecha	Hulum Selam	Ato Yenework Yayeh(Gerchech)	300492	1244320	2060	weathered basalt	07/03/2014	6.29	61	23.8	16	11.15	13.5	Metal sheet
DW138	Mecha	Hulum Selam	Ato Yaze Achenefe (Gerchech)	300476	1244381	2060	weathered basalt	07/03/2014	6.15	38	24	19	12.45		Metal sheet

ID	Topography	Land use	Use	Perennial	Remark
DW105	flat land	near creek	domestic supply	reduces in supply during May-April	Dug in 1998E.C. The local people complain water table drop due to ecualiptus tree growth
DW106	flat land	near house	currently for vegetation only		
DW106B	flat land	near house	currently for vegetation only		Top is slightly-loamy clay then fresh basalt(2.5m) and then deeply weathered basalt
DW107	flat land	about 800m away from Kilti river	domestic supply	good supply	flow at soil and rock contact but mainly through fractured basalt
DW108	flat land	near hand pump fitted well		good supply	
DW109	gentle slope		domestic supply	very low supply	There is loam clay soil, little gravel and trachyte in the area. Completely dries in May
DW110	gentle slope		domestic supply		
DW111	gentle slope		domestic supply		
DW112	gentle slope/foot of hill	grazing land	domestic supply	very low supply	The well was shallow due to massive basalt layer. There is high scarcity of water or many wells failed due to this
DW113	foot of hill/sloping area	grazing land	school supply	very low supply	Soil is upto 6m, then thin regolith and then weathered basalt, and fresh rock at a depth of 9m
Dw114	flat land	near grazing land	domestic supply	good supply	Black silty loamy clay soil seen in this flat land
DW115	depression near farm land	near farm land	domestic supply	low supply, thin saturated thickness	As the well was dug the saturated thickness was 1m and there is high scarcity of water in it
DW116	flat land	grazing land	domestic supply	good supply	there is 3.5m thick soil, then regolith and then weathered basalt
DW117	flat land	grazing land	domestic supply		there is massive fresh basalt at the depth of 15m, soil is 3m, 60cm regolith and 2.5m weathered basalt at river sections
DW118	flat land	near house	domestic supply	good supply	
DW119	flat land	grazing land	domestic supply	good supply	the flow was good at the contact of the weathered and massive basalts, (dug in 2002E.C. January to April)
DW120	flat land	near house	irrigation only	good supply	
DW121	flat land	near house			
DW122	flat land	near house	irrigation only	good supply	The basalt is deeply weathered and with brown tint
DW123	gentle slope	near stream	domestic supply	good supply	the main flow was along EW direction and along fractures (parallel to EW depression)
DW124	flat land	near house	domestic supply		Almost everyone tried to dig three to four wells but failed because of massive basalt (5 to 6m), and water fluctuation is 4m (oral information of users)
DW125	flat land	grazing land	domestic supply	good supply	not functional currrently due to pump problem
DW126	flat land	near house	domestic and for seedling	good supply	There are three wells used for seedling of plants for sale
DW127	gentle slope	farm land	not used yet		Under construction, seems to be abandoned
DW128	gentle slope	grazing land	domestic supply	under construction; good storage by night	The flow is through fractured of slightly weathered fractured basalt from 6m depth
DW129	foot of hill/sloping area	grazing land	domestic supply	good supply	Good storage throught the year, near Ajuri River
DW130	gentle slope	near farm land	domestic supply	low storage in May-April	The sloping area has highvariation of water storage depending on slope angle and depth of weathering
DW131	foot of hill/sloping area	grazing land	domestic supply		water in open well stayed for >year before pump installation, used to have bad smell, seepage at soil rock contact; main storage is in weathered basalt
DW132	sloping side	near farm land	domestic supply	good supply	There is little contribution of alluvial deposits but main storage is in weathered basalt, dug in 2005E.C.
DW133	small depression in sloping area	grazing land	domestic supply		well is not functional due to pump problem
DW134	foot of hill/sloping area	protected area	domestic supply	Scarcity in May	The buffer area for this well is the first kind in the area
DW135	depression, fault related?	protected area	domestic supply	good supply	The EC is different from shallow water hosted in soil in the surrounding area
DW136	flat land	very near to house(60cm)	domestic supply	good supply	The EC in the area is generally low but very low to this well
DW137	flat land	inside the house(kitchen)	domestic supply	good supply	
DW138	flat land	very near to house(60cm)	domestic supply	very good supply	Many people in the surrounding area fetch water from this well but the supply is good(good recovery and storage)

Table F-2. Boreholes.

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation masl	Geology	Date of visit	Field pH	EC µS/cm	Temp °C
BH1	Guangu/Chagni	Tigiri	Tigiri Health Center	243381	1226373	1891	Soil and weathered basalt	03/02/2014	7.42	205	25.3
BH2	Dangila	Gundri-Ablakena	Kuanchinta	265412	1237233	2206	weathered basalt	08/02/2014			
BH3	Dangila	Gundrie Abo	Achirta health center	266847	1237440	2213	basalt and red soil	08/02/2014			
BH4	Dangila	Gundrie	Lay Gundrie	267710	1237463	2213	vesicular basalt	08/02/2014	7.63	322	25.4
BH5	Dangila	Ligaba	Gilgel badma	277151	1243848	2021		12/02/2014	6.48	156.1	27.5
BH6	Dangila	Zeguda	Aboyita	268346	1246247	2110	alluvial soil, weathered and fractured basalt	14/02/2014	6.92	238	20.1
BH7	Debub Achefer	Sebt	Lay Sebt	272432	1251717	2038	weathered basalt	03/03/2014	6.55	254	23.5
BH8	Debub Achefer	Debre Tsion	Kechinie near Kurbani	278612	1265261	1957		04/03/2014			
BH9	Debub Achefer	Sebt	Tach Sebt	274241	1251221	2017	basalt?	05/03/2014	6.4	165	27
BH10	Debub Achefer	Debikan Mariam	Chincha	282400	1255478	1926	basalt	05/03/2014	6.91	283	
Bh11	Dangila	Abadra Medhanialem	Godguadit gote	259769	1252085	2069	alluvium and may be basalt	06/03/2014	6.28	332	26
BH12	Mecha	Rime town	Dima Gote	304790	1250896	2065	red soil and weathered basalt	07/03/2014	6.91	268	25
BH13	Mecha	Hulum Selam	Gerchech	300559	1244392	2065	basalt and weathered basalt	07/03/2014	6.71	136.8	24.1

ID	Depth m	Pump Position	Pump	Topography	Land use	Use	Perennial	Remark
BH1	40		hand pump	flat land	Health center	domestic	good discharge	No protection area
BH2	60	27	hand pump	flat land	near grazing land	domestic		new well, not functioning yet
BH3	70	35	hand pump	flat land	near health center/grazing land			new well, not functioning yet
BH4			hand pump	flat land	near stream bank	domestic	good discharge	Millitery camp and community well
BH5	51?		hand pump	flat land	near stream bank	domestic	good discharge	People are not using it due to bad smell
BH6			hand pump	flat land	near stream and probably reason not known	domestic	good discharge	Bad smell and bad test reported so people not using
BH7	78		hand pump	near Kuchbiye river	near stream and probably reason not known	domestic		
BH8			hand pump	flat land	near river	domestic		New well under construction
BH9	100?		hand pump	gentle slope	grazing land	domestic	good discharge	Data to be collected later if possible
BH10	70		hand pump	flat land	near swampy area close to Gilgel Abay			
Bh11		132?	moterized	flat land	near river and swampy area	domestic	artesian well	Not functioning due to running cost problem(fuel)
BH12			hand pump	flat land	farm land	domestic	good discharge	well data not fully found
BH13	95	16?	hand pump	flat land	center of town	town supply	good discharge	pump tested for 72hrs?(oral info), drilled in 2002EC

Table F-3. Springs.

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation masl	Geology	Date of visit	Field pH	EC µS/cm	Temp °C	Flow/yield l/s	Measuring method	Topography
CS1	Dangila	Alefa-Kacha	Barbash	238051	1230275	1793	boulder type olivine basalt and silty clay soil	03/02/2014	5.56	91.2	22.2	about 0.05	Estimation	flat land
CS2	Guangu/Chagni	Seragam Micheal	Sholal gote	240465	1228133	1821	Highly fractured and jointed basalt + red soil	03/02/2014	5.28	40	21.9	about 0.03	Estimation	flat land
CS3	Dangila	Kabita	Sihai/Deber gote	254945	1246434	2207	weathered amygdaloidal basalt	04/02/2014	6.69	300	18.9	about 0.01	Estimation	sloping area, in riverbank
CS4	Dangila	Washa	Kulkul	254940	1245733	2198	red soil (aquifer), weathered basalt in the surrounding	04/02/2014	8.16	74.5	27	about 0.01	Estimation	sloping area, in streambank
CS4	Dangila	Washa and Kabilta	Agashti	252908	1247159	2103	>4m soil thickness and moderately weathered andesitic basalt	04/02/2014	7.73	224	23.3	0.84	floating method	sloping area sliding soil mass
CS5	Dangila	Dimsa	Emadadi	256241	1243768	2213	andesitic basalt under 4m soil	05/02/2014	6.42	119.8	21.9	about 0.01	Estimation	sloping area
CS6	Dangila	Washa Medhanialem	Tach Yihun gote	254712	1244066	2214	andesitic basalt with minor iron rich basalt	05/02/2014	7.42	242	17.6	about 0.01	Estimation	sloping area
CS7	Dangila	Dimsa	Kanabari/Lamami	257249	1245757	2183	Weathered basalt, amygdaloidal basalt and soil	05/02/2014	7.83	310	18.2	0.5	floating method	sloping area
CS8	Dangila	Badani	Saguma	249425	1241057	1900	alluvial soil	07/02/2014		905	25.6	very low		flat land
CS9	Dangila	Badani	Akuacha	250368	1241676	1924	alluvial material	07/02/2014		524	23.3	about 0.01	Estimation	gentle slope
CS10	Dangila	Badani	Warkit	250903	1236661	1928	red soil (aquifer), basalt in the surrounding	07/02/2014		206	26.6	0.090909091	volumetric	flat land
CS11	Dangila	Senguri	Zerihun Minch	250799	1236196	1923	fractured basalt	07/02/2014		155.6	23.3	about 1	Estimation	riverbank
CS12	Dangila	Sehara	Iunk/Astuta gote	248488	1237421	1886	fractured basalt and regolith?	07/02/2014		220	22.9	total flow is over 30	floating method	Topographic depression
CS13	Dangila	Senguri	Dengel	247412	1237304	1868	red soil	07/02/2014		206	23.8	about 3	Estimation	Topographic depression
CS14	Dangila	Badani	Embura/Gizani gote	249831	1236850	1917	Soil and Vesicular basalt	07/02/2014		206	23.4	about 1	Estimation	flat land
CS15	Dangila	Kuandisha	Gezewtie	264708	1238299	2190	Soil and Vesicular basalt							
CS16	Dangila	Kuandisha	Bogalech Mersha/Gezewetie	265238	1237676	2207	Soil and Vesicular basalt	08/02/2014	6.35	106.2	23.2	seepage		flat land
CS17	Dangila	Gundri-Ablakena	Yaba Tegegn Minch (Guachinta)	265342	1237359	2211	weathered basalt and soil	08/02/2014	6.2	152.1	21.6	below 0.1	Estimation	flat land
CS18	Dangila	Abla Mariam	Buna Wuha	263399	1236148	2281	weathered basalt,weathered thickness is over 5m	08/02/2014	6.76	210	21.7	0.071428571	volumetric	sloping side
CS19	Dangila	Abla Mariam	Mariam Wuha	263299	1236779	2283	weathered trachybasalt	08/02/2014	7.61	164.6	18	0.75	floating method	sloping side
CS20	Dangila	Gayita Georgis	Workit Georgis Tsebel	270520	1237079	2163	boulder type vesicular basalt and top soil	08/02/2014	6.54	190.4	20.4	about 1.2	Estimation	sloping side
CS21	Dangila	Gayita Georgis	Workit Domestic spring	270541	1237061	2162	boulder type vesicular basalt and top soil	08/02/2014	6.79	200	19.7	4.3	floating method	sloping side
CS22	Dangila	Gayita Georgis	Minchit/Bambuit	271038	1237805	2149	basaltic regolith and soil	08/02/2014	6.1	113	18.1	about 2	Estimation	Topographic depression
CS23	Dangila	Lay Gayita	Dokmit	269972	1237517	2157	Soil and Vesicular basalt	08/02/2014	6.13	108	23	1	volumetric	Topographic depression
CS24	Dangila	Gayita Georgis	Yashina Micheal holy Water	270082	1236750	2172	vesicular basalt	08/02/2014	6.57	198.3	20.3	about 1.5	Estimation	Topographic depression
CS25	Dangila	Gayita Georgis	Warda Gebit/Ashola Micheal gote	268826	1235330	2253	Basaltic regolith	10/02/2014	6.33	121.8	20.1	about 0.5	Estimation	Topographic depression
CS26	Fageta Lekuma	Tafoch Dambul	Azarama(Macha)	268113	1234334	2281	silty loamy-clay soil with little regolith	10/02/2014	6.59	189.2	20.5	about 3	floating method	depression
CS27	Fageta Lekuma	Makia Teklehaymanot	Godguadit Agegnehush	268221	1232018	2336	thin regolith and weathered vesicular basalt	10/02/2014	6.13	99.7	20.8	about 0.3	Estimation	streambank depression
CS28	Fageta Lekuma	Shangani	Kechisi(Birzana Spring)	263806	1230039	2390	soil and basalt	10/02/2014						
CS29	Fageta Lekuma	Shangani	Dabula spring	263575	1230141	2393	soil and basalt	10/02/2014						
CS30	Fageta Lekuma	Gula Azmach	Kimkima	269450	1228190	2393	contact of weathered basalt and trachyte and along EW fracture	11/02/2014	5.94	60.4	17.2	0.2	Estimation	Topographic depression
CS31	Fageta Lekuma	Girayita	Mariam Wuha	274209	1228955	2336	soil	11/02/2014	6.4	105.4	20.4	below 0.1	Estimation	Topographic depression
CS32	Fageta Lekuma	Sigla Yohanes	Aba Drey. Ashebrite gote	279957	1227054	2375	boulder type basalt under soil	11/02/2014	6.92	85.6	19.7	0.25	volumetric	sloping side
CS33	Fageta Lekuma	Kuri Jegola	Besena	279941	1224254	2452	weathered basalt	11/02/2014	6.65	43.3	25	seepage		Topographic depression
CS34	Dangila	Wumbre	Yesesayitu Minch	278930	1237040	2118	thin regolith and weathered basalt	11/02/2014	6.26	104.6	19.9	about 0.7	Estimation	riverbank
CS35	Dangila	Wumbre	Yaba Semeneh Minch	279090	1236724	2121	fractured and jointed basalt	12/02/2014	6.01	81	22.6	0.21	volumetric	riverbank
CS36	Dangila	Muksi	Selamargi Mariam	277787	1239116	2085	soil and weathered basalt	12/02/2014	5.79	55	28?	2.83	volumetric	Topographic depression
CS37	Dangila	Zelesa	Kes Mender	270117	1243849	2123	regolith? Weathered basalt	13/02/2014	6.77	380	18.1	2	volumetric	Topographic depression
CS38	Dangila	Zunga	Yabagashe Minch	272876	1241213	2023	regolith? Weathered basalt	13/02/2014	6.73	194.1	21.6	0.125	volumetric	sloping side
CS39	Dangila	Zunga	Gedema	272624	1240367	2024	andesitic basalt and aphanitic olivine basalt undifferentiated	13/02/2014	6.51	183	23.7	0.31	volumetric	sloping side
CS40	Dangila	Misrak Zelesa	Sale Egziabhair	272096	1244283	2050	Scoraceous basalt under about 2m soil thickness	13/02/2014	7.51	280	27.9	about 0.01	Estimation	sloping side
CS41	Dangila	Zelesa	Karmarie	272136	1244621	2058	black cotton soil + scoraceous basalt under the soil	13/02/2014	7.44	367	25.5	0.058823529	volumetric	sloping side
CS42	Dangila	Zeguda	Thankisti/Aboyta gote	268522	1246029	2111	emerges from regolith	14/02/2014	6	49.7	23.5	0.333333333	volumetric	flat land
CS43	Dangila	Zeguda	Lay Shewaye	270493	1246381	2088	emerges from soil at riverbank	14/02/2014	5.99	110.6	24.7	about 0.1	Estimation	riverbank
CS44	Dangila	Dengesheta	Ceba gote near new metre.station	265035	1252291	2051	fractured vesicular basalt	20/02/2014	6.16	188.8	24.5	almost seepage	Estimation	riverbank
CS45	Dangila		Chereka minch/Abadra gote	262483	1252024	2063	fractured and jointed basalt	20/02/2014	6.33	128.3	21.6	seepage		depression
CS46	Achefer	Atite Abo	Aba Lika	272149	1266394	1984	loamy clay soil	04/03/2014	6.1	106.3	19	very low	Estimation	sloping side
CS47	Achefer	Sebte	Woynwuha (lay Sebte)	274071	1250601	2020	emerges from regolith and weathered basalt	05/03/2014	7.63	133	27	low flow (below 0.01)	Estimation	depression
CS48	Achefer	Abchikili Zuria	Jirfit	273763	1257658	2029	regolith	05/03/2014				low flow		depression
CS49	Dangila	Tach Afafe Eyesus	Senabo	256914	1255568	2110	foliated basalt	06/03/2014	6.29	101.6	23	low flow/about 0.001	Estimation	riverbank
CS50	Dangila	Tach Afafe Eyesus	Minchitie	257004	1256037	2132	emerges from soil rock contact	06/03/2014	6.95	139.8	22.6	about 0.2	Estimation	sloping side
CS51	Dangila	Lay Afafe Eyesus	Senabo	256112	1256369	2169	emerges from regolith but there is soil and boulder basalt around	06/03/2014	6.15	93	22.7	about 0.3	Estimation	sloping side
CS52	Mecha	Abromenore	Sosna Georgis holy water	308683	1243630	2186	alluvial material	07/03/2014	7.22	400	22.2	no flow		sloping side
CS53	Mecha	Abromenore	Ment(Genbo sub-kebele)	307420	1242491	2307	weathered and fractured trachy basalt	07/03/2014	6.52	174.2	22.4	low low		fracture spring

ID	Fractures	Land use	Mode of Emergence	Use	Perennial	Remark
CS1	EW	grazing land and vegetation	Fracture and depression/flat land	Domestic and cattle	Seasonal since the last 3y	The spring starts drying in the dry period due to deforestation and plantation of Ecualiptus tree
CS2	Ew and NS	Vegetation and grazing land	Fracture and depression/streambed	irrigation at downstream	perennial	vegetation density is good and emerges at junction of EW and NS fractures
CS3	emerges along NS fault	vegetation along streambed, farms by riverbank	Fracture and depression/streambed	cattle	perennial	dense vegetation along streambank
CS4		farm land, grazing land	topographic depression	cattle	perennial	soil thickness is over 3m and spring not developed, not protected
CS4		farm land, grazing land	topographic depression	cattle and drinking, not protected	perennial	Emerges at the contact of soil and rock, multiple eye, causes landslide
CS5	N30W and EW	near farm land	along fractures	cattle and some times domestic	perennial	emerges from fractured rock mainly along N30W and some along EW
CS6	N30W seepage and N20E fractures seen		fracture and topogrphic break	cattle, minor irrigation and domestic	perennial	
CS7	EW fracture seen	grazing land and vegetation	contact	Domestic and cattle	perennial	
CS8		grazing land and vegetation	topographic depression	Domestic and cattle	perennial	The yield reduced, or dries in April due to deforestation / population density (local ealderly people)
CS9		farm land, grazing land	contact	Domestic and cattle	perennial	The spring emergence depth has been lowered by about 30 to 40 cm away from its orgional level some years back
CS10		grazing land and near swampy area	topographic depression	Domestic and cattle	perennial	Yield increases downstream from spring eye
CS11		near farm land	contact of soil and fractured basalt	domestic supply	perennial	the water in the river is used for irrigation
CS12	N50W (main flow and N50E minor flow)	grazing land ang vegetation	fractured and contact	town supply, irrigation and cattle	perennial	It almost forms small stream
CS13		grazing land and vegetation	topographic depression	Domestic and cattle	perennial	
CS14		grazing land	topographic depression	domestic, cattle, irrigation	perennial	
CS15						
CS16		grazing land	topographic depression	domestic, cattle	perennial	possibly polluted by No3 from anaimal dung
CS17		grazing land	topographic depression	Domestic and cattle	perennial	It was dried in 2013 or 2005 E.C. Dry period
CS18		grazing land and vegetation	topographic depression	domostic, cattle	perennial	Depth of weathering is over 5 meter
CS19	N50E	church land and vegetation/forest	topographic break	irrigation, drinking, preying water	perennial	
CS20		forest	topographic break	holy water, domestic and irrigation downstream	perennial	The flow at downstream is high
CS21		forest	topographic break	domestic and irrigation	perennial	The flow at downstream is high
CS22		grazing land just at margion of irrigation land	topographic break	demestic, irrigation, cattle	perennial	Yield highly increases during rainy period
CS23		grazing land and some vegetation	topographic break	Domestic and cattle	perennial	Poor development and pipes are closed and leaks under asunery work
CS24		grazing land and vegetation	topographic break	holy water, domestic and irrigation downstream	perennial	Spring eye divided for domestic and holy water
CS25		grazing land and vegetation	topographic break	domestic and irrigation	perennial	soil thickness is 1.5m on top of regolith
CS26		grazing land	topographic break	irrigation, domostic and cattle	perennial	Yield highly increases during rainy period
CS27		streambank near farm land	topographic break	domestic, cattle	perennial	Dries around mid of March, emerges from the contact of regolith and Weathered basalt
CS28						Not measured because of its high turbidity
CS29						
CS30	EW	grazing land	topographic break	seedling and for domestic and cattle	perennial	The spring flow is along bedding joints of weathered basalt and along EW fractures at the contact
CS31		near farm land	topographic break	Domestic and cattle	perennial	reddish loamy soil with over 1.5m visible soil thickness
CS32		foot of plateau	topographic break	domestic and irrigation	perennial	Local people constructed temporary storage for irrigation
CS33		foot of plateau	topographic break	cattle	perennial	Debuki spring which was developed in 1990EC is totally dry due to water table drop/and/or development
CS34		streambank near grazing land	contact	domestic	perennial	there is seepage between soil and massive basalt but locally limmited regolith and joints have higher flow
CS35		grazing land	fracture	domestic	perennial	flow is along the vertical joint but the horizontal thinner joints are also connected with it
CS36		near river bed	topographic break	domestic, cattle and irrigation	perennial	
CS37			topographic break	domestic, cattle and irrigation	perennial	
CS38		grazing land	sloping side/topographic break	domestic, cattle	perennial	development of spring just finshed on this date
CS39		grazing land	sloping side/topographic break	domestic	perennial	development of spring just finshed on this date
CS40		grazing land	contact/ depression	domestic	perennial	yield is low as soil thickness is thin
CS41		grazing land	topographic break	domestic	perennial	development was in 2005 E.C. but with very low discharge
CS42		grazing land	topographic break	domestic, cattle	perennial	Developed and local people report emergence point shrink by about 30m and emerges from regolith.
CS43		grazing land	topographic break			
CS44		grazing land	topographic break	domestic supply	perennial	emeerges just above the relatively massive vesicular basalt
CS45	N20E, N70W, EW junction (emergence point) and N50W	grazing land	topographic break	domestic supply and cattle	perennial	emerges at junction point of fractures
CS46		near farm land	sloping side/topographic break	domestic and irrigation	perennial	turbid water and used mainly for coffee plantation
CS47		grazing land	topographic break	doemstic, cattle	perennial	flow increases downstream of the creek after small seepages along the creek
CS48		forest	Along EW depression	not used except cattle	perennial	Not measured because of its high turbidity
CS49	NS foliation,EW and NS fractures, NS is younger	riverbank	along NS foliation	domestic	perennial	The top red soil is 2.5m thick, Near Senabo stream
CS50		near farm land	topographic break	domestic	perennial	Not developed, not fenced. Multiple eye and emerges fromcontact of soil and moderately weathered basalt
CS51		near farm land	topographic break	domesic supply and little irrigation	perennial	Not developed, not fenced. Multiple eye and emerges from regolith below soil horizon
CS52		protected land, near creek	topographic break	holy water	perennial	it is kind of water hole and no low this time
CS53	EW and NS fractures, NS younger and low is along NS	farm land, sloping area	sloping side/topographic break	not intensively used	perennial	microfractures controll low and storage but yield little

Table F-4. Rivers.

ID	Woreda	Kebele	Site name	Longitude	Latitude	Elevation masl	Geology	Date of visit	Field pH	EC µS/cm	Temp °C	Flow/yield l/s	Measuring method
RW1	Dangila	Alefa-Kacha	Awsi River near Tiski fall	237656	1229863	1779	Olivine basalt slightly weathered from top	03/02/2014	8.16	234	18.3	about 130	Estimation
RW2	Gizani	Alefa-Kacha	Gizani River (Barbash gote,near Tiski fall)	237734	1229844	1778	Olivine basalt slightly weathered from top	03/02/2014	8.19	117.7	20.1	1.73m3/s	floating
RW3	Dangila	Washa and Kabilita	Fench wuha	252903	1246494	2139	weathered basalt, chonchoidal weathering	04/02/2014	8.21	290	20.3	1.3	Estimation
RW4	Dangila	Dimsa	Awsa Arka	256547	1245547	2134	amygdaloidal basalt	04/02/2014	7.75	255	23.1	about 1.5	Estimation
RW5	Dangila	Dimsa	Yaba Yenew shete(stream)	254751	1244691	2205	moderately weathered basalt	05/02/2014	7.15	265	22.3	about 1	Estimation
RW6	Dangila	Warkit	Kilti at Deki gote	264591	1255464	2029	fresh slightly fractured basalt and soil	06/02/2014	7.98	218	22.4	about 1.5 m3/s	floating
RW7	Fageta Lekuma	Girayita	Muger River	272957	1228851	2332	massive basalt with some joints and minor faults	11/02/2014	7.58	121.2	18.2	about 35	Estimation
RW8	Fageta Lekuma	Aswa Fenzit	Zuma	276908	1227475	2339	weathered trachybasalt at margin and basalt at River	11/02/2014	7.33	93	23	about 25	Estimation
RW9	Dangila	Zelesa-Ligaba	Ashare	274212	1244121	2003	basalt	13/02/2014	7.65	169.1	26.9	over 1.8m3/s	Estimation
RW10	Dangila	Diversion	Quasheni	272664	1240223	2024	Andesitic basalt	13/02/2014	8.02	195.4	21.9	about 100	Estimation
RW10 B	Dangila	Enku Densi Fasiledes	Kamo gote	273290	1242819	2007	alluvial soil	13/02/2014	7.44	300	25.1	about 40	Estimation
RW11	Dangila	Dengesheta	Branti river at New Gauge site	265107	1252291	2050	vesicular basalt	20/02/2014	8.25	256	21.5	about 5	Estimation
RW12	Debub Achefer	Dekuli	Kilty River	268938	1258318	2006	fresh fine grained massive basalt	03/03/2014	7.61	253	22.3	over 1.5m3/s	Estimation
RW13	Debub Achefer		Atibara	277039	1249117	1985	massive basalt with some joints	04/03/2014	7.54	154.6	17.6	about 4	Estimation
RW14	Debub Achefer	Sebte	Ashare river at sebte	275739	1250594	1974	massive basalt with some joints	04/03/2014	7.9	180	21.3		Estimation
RW15	Dangila	Tach Wawi	Ajuri River	257928	1256840	2099	2.5msoil,0.5m regolith, weathered basalt bottom unexposed	06/03/2014	7.21	131.6	21.9	about 35	Estimation
RW15B	Dangila	Abadra	Ajuri River	259730	1252090	2065	alluvial soil	06/03/2014	7.84	168.4	30	about 60	Estimation
RW16	Mecha	Abromenore	Koga River	309328	1243278	2171	weathered basalt, stratiied and deeply weathered	07/03/2014	8.02	205	19.3	about 180	Estimation
RW17	Mecha	Abromenore	Asanat	308004	1240354	2451	deeply weathered basalt at top, bottom is massive basalt	07/03/2014	7.48	178	20.3	about 1.5	Estimation

ID	Topography	Fractures	Land use	Bank width	Status	Use	Remark
RW1	flat land near ridge escarp	N40E and shallow joints	grazing land and vegetation	about 30m	perennial, turbid	Cattle	Depth of weathering is between 0.5 to 1.2m
RW2	flat land near ridge escarp	N40E	grazing land and vegetation	about 30m	perennial	cattle at this site	Depth of weathering varies between 2 to 12.5m
RW3	sloppy area	N60E and EW fractures	farm land	4m	perennial	cattle and rarely irrigation	depth of weathering is between 0.5 to 1m and
RW4	depression	N30W and Ew minor fractures	vegetation	15m	perennial	cattle	N60E, N30W and NS fractures seen at down stream
RW5	sloppy area	EW & NS fractures	farm land	3m	perennial	cattle, irrigation, rarely domestic	exposed weathered section is 2.3m at this spot
RW6	flat land		grazing land, farm land, vegetation	13m	perennial	cattle, irrigation, rarely domestic	few farmers are irrigating their land using motor pumps
RW7	gentle slope	EW, N50E, N30E	grazing land	about 50m	perennial	irrigation, cattle	
RW8	gentle slope		near farm land	about 30m	perennial	irrigation, cattle	
RW9	flat land		grazing land	about 35m	perennial	irrigation, cattle	it is beeing diverted by local people
RW10	flat land		grazing land	abut 35m	perennial	irrigation, cattle	The river is also diverted by local people from down stream
RW10 B	flat land		irrigation area	12m	perennial	irrigation, cattle & domestic	Local diversions are made in many places
RW11	flat land near gentle slope		grazing land	9.04m	perennial	irrigation, cattle	Slightly jointed vesicular basalt under 1.5m soil cover
RW12	flat land		grazing land	50m	perennial	irrigation, cattle, mill	riverbank is 1.4m; surrounding people complain that massive rock hinders well diging
RW13				20m	perennial	irrigation, cattle, mill	
RW14	flat land		grazing land	25m	perennial	irrigation, cattle	
RW15	depression		grazing land	8m	perennial	irrigation, cattle	exposed section depth is 3.5m
RW15B	flat land, deep erosion and landslide		grazing land	25m	perennial	irrigation, cattle	The loamy clay soil thickness is obout 4m at river bank
RW16	depression	N30W and Ew minor fractures	river valley, farm land on sides	31m	perennial	irrigation, domestic, cattle	The river is damed at down stream
RW17	sloppy area	N30W and Ew minor fractures		7m	perennial	irrigation,domestic, sanitation	Part of the river segiment is controlled by N30W vertical fracture pattern

The information in Tables F-5, F-6 and F-7 is from surveys conducted by David Walker in February and March 2014. All locations are within Dangila *woreda* unless stated. Coordinates are in the WGS84 coordinate system, taken from a handheld GPS along with elevation. Measurements in italics were received word of mouth. Note that an uppercase ID, e.g. DW73, denotes a location originally surveyed by Demis Alamirew whereas lower case, e.g. dw6, indicates a location surveyed only by David Walker.

Table F-5. Hand-dug wells and boreholes.

ID (DW = Demis ID)	Kebele	Site name	N	E	Elevation masl	Geology (*italics = Demis survey*)	Date of visit	Pumping test	Sample	222Rn test	Field pH	EC µS/cm	Temp °C	Depth m	SWL mbgl
DW76	Dangesheta	Ato Bazezew Worku (MW 5)	11°18.184'	036°51.195'	2090	*weathered basalt*	19/03/2015							8.44	5.98
dw1	Dangesheta		11°17.985'	036°51.200'	2091	quite friable fractured vesicular basalt below gravelly soil	19/03/2015							*7*	5.5
dw2	Dangesheta		11°17.986'	036°51.176'	2091	quite friable fractured vesicular basalt below gravelly soil	19/03/2015							*7*	5.5
DW73	Dangesheta	Ato Melese Worku (MW 2)	11°17.984'	036°51.120'	2091	*regolith and weathered trachyte basalt*	19/03/2015	Yes (both visits)	SI5 C5 A5		5.83	130.7	20.3	7.03	5.77
DW75	Dangesheta	Ato Birhanu Shibabaw (MW 3)	11°18.168'	036°50.907'	2086	*fractured basalt with some regolith*	19/03/2015							4.16	3.94
DW77	Dangesheta	Ato Getaneh Ayichew (MW 4)	11°18.504'	036°51.125'	2075	*red soil and weathered basalt*	19/03/2015	Yes (both visits)			5.28	90.74	22.2	9.19	5.34
dw3	Dangesheta	Ato Assaye Molla (MW 1)	11°18.051'	036°51.268'	2094		19/03/2015							6	5.95
DW43	Zelesa	Kilaje	11°15.191'	036°52.936'	2137	*red and black loamy soil intercalation*	21/03/2015		SI1 C1 A1		5.19	50.62	20.9	*17*	*2*
dw4	Zelesa	Kilaje	11°15.246'	036°52.350'	2136		21/03/2015		SI2 C2 A2		5.84	99.7	20.8	*18*	
dw5	Zeguda	Tankishti	11°16.085'	036°52.734'	2119	gravelly alluvium regolith	22/03/2015								dry
DW57	Dangesheta	Girmaw Malede/Cheba gote	11°19.435'	036°50.999'	2061	*red soil and weathered basalt*	23/03/2015							*11*	8.41
DW56	Dangesheta	Girmaw Malede/Cheba gote	11°19.424'	036°50.992'	2052	*red soil and weathered basalt*	23/03/2015		SI4 C4 A4		5.53	171.9	22.9	*10*	*9.5*
dw6	Dangesheta	Ato Birhanu Shibabaw	11°18.169'	036°50.899'	2082	regolith	24/03/2015	Yes (both visits)	SI6 C6 A6		5.57	144.2	22.3	3.55	2.71
DW61	Tara Gabriel	Ato Semahagn Abebayehu	11°19.398'	036°50.504'	2070	regolith	25/03/2015	Yes (first visit)			5.95	216.6	22.1	4.12	3.58
DW62	Tara Gabriel	Ato Semahagn Abebayehu	11°19.406'	036°50.504'	2070	regolith	25/03/2015							4.17	3.75
dw7	Tara Gabriel	Ato Getenet Birehanu	11°19.429'	036°49.755'	2089	regolith	25/03/2015	Yes (first visit)			5.97	149.9	23.6	8.75	7.91
DW79	Tara Gabriel	Tara Gabriel School	11°19.227'	036°49.959'	2081	*weathered basalt*	25/03/2015		SI7-I8 C7-9 A7-9		6.88	334.9	25.2	*10*	
dw8	Sahara	Gisa agricultural office	11°12.039'	036°40.067'	1894	black alluvium	26/03/2015							1.3	1
DW18	Badani	Delelti	11°12.568'	036°42.610'	1930	massive basalt boulders in black clayey alluvium	26/03/2015		SI11 C11 A11		6.66	481.9	25.9	*4*	*2*
dw9	Kwakurta	Chara restaurant	11°11.551'	036°45.558'	1975	regolith	26/03/2015								7.7
DW2	Washa	Amognita	11°15.763'	036°45.351'	2216	red regolith	26/03/2015		SI12 C12 A12		5.76	200.4	21.9	*6*	*4*
dw10	Wondayita	Worranty	11°15.103'	036°47.937'	2111		26/03/2015		SI13 C13 A13		5.69	44.29	22.1		8.39
DW21	Kuandisha	Gezewetie	11°11.761'	036°50.766'	2200	*loamy-silty soil and weathered basalt*	27/03/2015		SI14 C14 A14		6.17	174	24.7	*11*	*6*
dw11	Kuandisha		11°11.500'	036°50.269'	2218		27/03/2015								6.91
DW22	Abla Mariam	Avila	11°10.990'	036°50.442'	2233	red regolith	27/03/2015		SI15 C15 A15		6.31	264.4	24	*11*	*4.5*
DW130	Afafe Eyesus	Lay Afafe eyesus	11°20.705'	036°45.429'	2251	*thin soil and weathered basalt*	28/03/2015							*12.5*	*10.5*
dw12	Afafe Eyesus	Ayesheshem Chakul	11°20.595'	036°45.317'	2267	massive basalt boulders in regolith	28/03/2015				5.64	87.06	19.8	*17*	12
dw13	Afafe Eyesus	Desalign Abyu	11°20.628'	036°45.372'	2255	massive basalt boulders in regolith	28/03/2015							*16*	14
dw14	Afafe Eyesus	Asmara Sonet	11°20.437'	036°45.878'	2195		28/03/2015				5.51	136.7	20.5	*14*	11.8
DW88	Abadra	Abadra town	11°19.154'	036°47.062'	2091	*loamy clay soil, regolith and weathered basalt*	28/03/2015							*10*	*6*
dw15	Abadra	Mangudit	11°19.680'	036°46.827'	2107		28/03/2015		SI16 C16 A16		5.69	196.8	23.4	*8.5*	
dw16	Dangesheta	Girma	11°19.518'	036°51.343'	2055	regolith	30/03/2015							10.2	9.77
dw17	Dangesheta	Girma	11°19.528'	036°51.335'	2055	regolith	30/03/2015				5.59	145.5	21.9		10.39
dw18	Dangesheta	Girma	11°19.535'	036°51.342'	2055	regolith	30/03/2015				5.46	133.1	21.3		
dw19	Dangesheta	Prest Getay	11°19.424'	036°51.543'	2047		30/03/2015				5.45	166.5	22.2		
dw20	Dangesheta	Ebenew	11°19.297'	036°51.710'	2045	red regolith over friable weathered basalt	30/03/2015				5.74	215.5	21.2	3.5	2.4
dw21	Dangesheta	Asheshum	11°19.289'	036°51.721'	2043	red regolith over friable weathered basalt	30/03/2015							5	3
dw22	Dangesheta	Mobit Mulu	11°18.638'	036°51.993'	2063	alluvium and clayey regolith	30/03/2015							4.29	3.35
dw23	Dangesheta	Mobit Mulu	11°18.631'	036°51.991'	2063	alluvium and clayey regolith	30/03/2015								
dw24	Dangesheta	Wondifro Taye	11°18.638'	036°51.922'	2077	alluvium and regolith	30/03/2015							4.53	3.33
dw25	Dangesheta	Wondifro Taye	11o18.633'	036o51.921'	2077	alluvium and regolith	30/03/2015								
dw26	Dangesheta	Kindu Asmano	11°18.678'	036°51.903'	2059	regolith	30/03/2015							4.47	3.73
dw27	Dangesheta		11°18.688'	036°51.913'	2059	regolith	30/03/2015								
dw28	Dangila		11°17.074'	036°49.536'	2082		31/03/2015				6.56	231.4	21.6		
dw29	Abadra		11°16.542'	036°47.886'	2103		31/03/2015								6.49
dw30	Abadra	Berayta	11°16.174'	036°48.068'	2099		31/03/2015		SI18 C18 A18		5.99	309.4	21.9		

ID (DW = Demis ID)	Pump/Cover	Topography	Land use	Use	Perennial	Remark
DW76	pot cover	flat land on edge of floodplain	near house between crops, floodplain/pasture and eucalyptus	domestic and cattle	perennial	
dw1	open well	flat land on floodplain	floodplain pasture	will not be used		dug in March 2015, 1.5 m diameter, will not be used due to unstable sides, "easy to dig"
dw2	open well	flat land on floodplain	floodplain pasture	will be for potable supply		dug in March 2015, 1.5 m diameter, will be used for potable supply, "easy to dig", dug 10 m from previous after that one abandoned
DW73	oil drum cover	flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	
DW75	oil drum (no cover)	flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	
DW77	oil drum cover	fairly flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	
dw3	wood and branches	flat land on edge of floodplain	near house between pasture and eucalyptus plantations	"rarely used because dirty water"	seasonal	beside house of man who monitors wells - raingauge is also beside his house. Well almost dry but higher level in rainy season.
DW43	hand pump	flat land on floodplain	floodplain pasture	village potable supply	perennial	dug 19 years ago, always good supply
dw4	hand pump	flat land on floodplain	floodplain pasture	village potable supply	inconsistent	water very turbid (took about 6 filters to take samples), "sometimes no supply - it was once dry for over a year", only ~400 m from previous well in similar position
dw5	hand pump	flat land on floodplain	floodplain pasture	"contaminated so just used for irrigation"	seasonal	currently dry so locals use spring ~100 m upstream
DW57	pot cover	gentle slope above floodplain	chat and coffee	irrigation	seasonal	
DW56	rope and washer pump	gentle slope above floodplain	chat and coffee	potable and irrigation	perennial	very good supply all year. Water very clear - took no effort to push samples through filter.
dw6	pot cover	flat land on edge of floodplain	near house between crops and floodplain/pasture	irrigation	perennial	other side of house to MW3. Pump tested this one as too little water in MW3.
DW61	pot cover	flat land on edge of floodplain	in chat plantation between house and floodplain/pasture	irrigation	perennial	8 m south from next well in same plot. Adjacent to "hanging" floodplain above quite steep Brante valley. Close to catchment boundary.
DW62	wood and branches	flat land on edge of floodplain	in chat plantation between house and floodplain/pasture	irrigation	perennial	there is another well 10 m west and many more in nighbouring plots. Some become dry in April/May.
dw7	pot cover	slope on hillside	near house within crops and eucalyptus plantations	domestic and cattle	perennial	part way down long sloping valley side of Kilti river - not near any floodplain/pasture
DW79	hand pump	flat land on edge of floodplain	in school grounds between floodplain/pasture and crops	school domestic use	perennial	high, near to catchment boundary. Sampled in triplicate to send 1x to Addis lab, 1x blind to Addis lab, and 1x to UK.
dw8	open well	fairly flat land on edge of floodplain	floodplain pasture	cattle	perennial	very shallow water table, 5 m diameter open well for farmers to water cattle
DW18	hand pump	sloping floodplain at base of large steep hill	boulder-strewn floodplain pasture	village potable supply	perennial	locals don't have their own wells as sides collapse
dw9	oil drum cover	flat land	in town beside restaurant	restaurant domestic supply	perennial	
DW2	hand pump	slope on hillside	between crops and floodplain/pasture	village potable supply	perennial	high in hills, ~20 m from trickling stream
dw10	rope and washer pump	slope on hillside	crops	irrigation	perennial	cover has gaps for contamination, visibly only slightly turbid but took many filters to sample
DW21	hand pump	flat land on edge of floodplain	floodplain pasture	domestic	perennial	compound locked but locals told us it is well used. Filter discoloured red but easy to sample and not turbid.
dw11	pot cover	slight slope at base of hill	near house within crops	domestic	perennial	
DW22	hand pump	flat floodplain at base of steep hill	small pasture between nearby river and houses/crops	domestic	perennial	
DW130	broken hand pump	slope on hillside	crops	pump broken		
dw12	oil drum cover	slope on hillside	near house within crops	domestic	perennial	"very good supply" but quite near catchment boundary (crest of big cliff)
dw13	pot cover	slope on hillside	near house within crops	domestic	perennial	~100 m downslope from previous well
dw14	pot cover	slope on hillside	near house within crops	domestic	perennial	
DW88	broken hand pump	fairly flat land on edge of floodplain	near houses in small town	pump broken		well W of town near schools broken handpump, handpump in town N of river contaminated, most of town supply now from motorised pump in deep borehole E of town
dw15	hand pump	gentle slope on hillside	small pasture within crops on edge of Abadra town	domestic	perennial	pump locked with hours restricted to a few in the morning and again at end of day; "to prevent kids breaking pump"
dw16	pot cover and pulley	gentle slope	coffee, chat, mango, banana, orange, onion	irrigation	perennial	these three wells are all in same plot within 10 m of each other. Solid rock was not struck during excavation.
dw17	pot cover and pulley	gentle slope	coffee, chat, mango, banana, orange, onion	irrigation	perennial	
dw18	rope and washer pump	gentle slope	beside house and coffee, chat, mango, banana, orange, onion	irrigation and domestic	perennial	IWMI installed pump in 2014
dw19	rope and washer pump	flat land on edge of floodplain	in house plot between crops and floodplain/pasture	irrigation and domestic	perennial	IWMI installed pump in 2014
dw20	pot cover and pulley	flat land on edge of floodplain	beside house between crops and floodplain/pasture	irrigation and domestic	perennial	
dw21	open well	flat land on edge of floodplain	between crops and floodplain/pasture	under construction		~15 m from previous well at other side of house. Spoil still visible - had to chisel through basalt layer - and intend to dig a bit deeper. 1.5 m diameter.
dw22	wood and branches	flat land on edge of floodplain	between crops and floodplain/pasture	irrigation and domestic	perennial	dug two weeks ago. In same plot as next well.
dw23	rope and washer pump	flat land on edge of floodplain	between crops and floodplain/pasture	irrigation and domestic	perennial	IWMI installed pump in 2014
dw24	wood and branches, treadle pump	flat land on edge of floodplain	between crops and floodplain/pasture	irrigation	perennial	on opposite side of floodplain to previous well
dw25	rope and washer pump	flat land on edge of floodplain	beside house within crops	irrigation and domestic	perennial	IWMI installed pump in 2014. ~7 m from previous well in same plot.
dw26	open well with pulley	flat land on edge of floodplain	crops	irrigation	perennial	~20 m from next well in plot of adjacent house
dw27	rope and washer pump	flat land on edge of floodplain	beside house within crops	irrigation and domestic	perennial	IWMI installed pump in 2014
dw28	hand pump	flat land on floodplain	pasture	domestic	perennial	
dw29	hand pump half installed	gentle slope on edge of large floodplain	crops	under construction		concrete lined, all infrastructure installed except pump headworks
dw30	hand pump	gentle slope at base of large hill	crops	domestic	perennial	heavy use, bolt broken in pump so not working well, filter turned deep red but easy to sample

ID (DW = Demis ID)	Kebele	Site name	N	E	Elevation masl	Geology (*italics = Demis survey*)	Date of visit	Pumping test	Sample	222Rn test	Field pH	EC µS/cm	Temp °C	Depth m	SWL mbgl
dw3	Dangesheta	Ato Assaye Molla (MW 1)	11°18.051'	036°51.268'	2094		19/03/2015							6	3.81
DW76	Dangesheta	Ato Bazezew Worku (MW 5)	11°18.184'	036°51.195'	2090	*weathered basalt*	19/03/2015							8.44	4.91
DW56	Dangesheta	Girmaw Malede/Cheba gote	11°19.424'	036°50.992'	2052	*red soil and weathered basalt*	10/10/2015		2SI1 2C1 2A1		5.61	167.7	22.9	*9*	5.5
dw21	Dangesheta	Asheshum	11°19.289'	036°51.721'	2043	red regolith over friable weathered basalt	10/10/2015		2SI2 2C2 2A2		6.71	403.5	30.9	6	*1*
DTW3	Agaga	DTW3 deep BH	11°16.905'	036°48.558'	2076	alluvium	12/10/2015		2SI4 2C4 2A4		8.77	315.0	22.0	*150*	
DTW1	Berayta	DTW1 deep BH	11°16.762'	036°48.561'	2074	alluvium	12/10/2015							*192*	
DTW4	Berayta	DTW4 deep BH	11°16.491'	036°48.551'	2073	alluvium	12/10/2015							*150*	
dw30	Berayta	Berayta	11°16.174'	036°48.068'	2099		12/10/2015								
dw31	Agaga	Agaga	11°16.961'	036°48.115'	2082	alluvium	12/10/2015		2SI5 2C5 2A5		5.55	136.4	21.8	*?*	*?*
D3	Dangila	D3 deep BH	11°15.889'	036°50.917'	2107		12/10/2015		2SI6 2C6 2A6	Yes	8.81	335.0	21.8	*130*	
DW43	Zelesa	Kilaje	11°15.191'	036°52.936'	2137	*red and black loamy soil intercalation*	13/10/2015		2SI8 2C8 2A8		4.77	46.26	20.5	*18*	*?*
DW22	Abra Mariam	Avila	11°10.990'	036°50.442'	2233	red regolith	14/10/2015		2SI10 2C10 2A10		5.46	133.3	21.7	*18*	*?*
DW21	Kuandisha	Gezewetie	11°11.761'	036°50.766'	2200	*loamy-silty soil and weathered basalt*	14/10/2015		2SI11 2C11 2A11		5.19	167.1	22.1	*?*	*?*
dw18	Dangesheta	Girma	11°19.535'	036°51.342'	2055	regolith	15/10/2015		2SI14						
DW73	Dangesheta	Ato Melese Worku (MW 2)	11°17.984'	036°51.120'	2091	*regolith and weathered trachyte basalt*	16/10/2015	Yes (both visits)	2SI12 2C12 2A12		5.30	110.9	20.9	6.89	4.27
DW75	Dangesheta	Ato Birhanu Shibabaw (MW 3)	11°18.168'	036°50.907'	2086	*fractured basalt with some regolith*	16/10/2015							4.18	1.52
dw6	Dangesheta	Ato Birhanu Shibabaw	11°18.169'	036°50.899'	2082	regolith	16/10/2015	Yes (both visits)	2SI13 2C13 2A13		5.41	133.8	22.2	3.41	1.42
DW77	Dangesheta	Ato Getaneh Ayichew (MW 4)	11°18.504'	036°51.125'	2075	*red soil and weathered basalt*	16/10/2015	Yes (both visits)	2SI15		5.24	146.6	22.3	9.17	2.83
dw2	Dangesheta	Nr Asaye New	11°17.986'	036°51.176'	2091	friable fractured vesicular basalt below gravelly soil	17/10/2015		2SI16	Yes	6.43	289.0	22.5	7	5.5
dw32	Sehara	Little Asaye	11°11.117'	036°41.831'	1842	regolith	18/10/2015	Yes (second visit)			5.42	207.4	23.6	10.09	7.4
dw33	Kwakurta	Selam	11°11.430'	036°44.952'	1990	regolith	18/10/2015	Yes (second visit)			5.82	196.5	23.0	5.91	2.78
DW79	Dangesheta	Tara Gabriel School	11°19.227'	036°49.959'	2081	*weathered basalt*	21/10/2015		2SI28 2A28 2C28		6.59	231.3	24.7	*10*	

ID (DW = Demis ID)	Pump/Cover	Topography	Land use	Use	Perennial	Remark
dw3	wood and branches	flat land on edge of floodplain	near house between pasture and eucalyptus plantations	"rarely used because dirty water"	seasonal	
DW76	pot cover	flat land on edge of floodplain	near house between crops, floodplain/pasture and eucalyptus plan	domestic and cattle	perennial	
DW56	rope and washer pump	gentle slope above floodplain	chat and coffee	potable and irrigation	perennial	very good supply all year. Water very clear - took more effort to filter than March/April.
dw21	hand pump	flat land on edge of floodplain	between crops and floodplain/pasture	potable and domestic	perennial	was under construction when I was last here, now complete. Very shallow water table (half a pump and water flowed)
DTW3	electric submersible	very large flat floodplain	pasture (near Kilti/Amen junction)	Dangila town supply	perennial	Drilled in 2009, 150 m deep, open hole, pump at 60 m, Q = 20 l/s, operates 10h/d
DTW1	electric submersible	very large flat floodplain	pasture (near Kilti)	Dangila town supply	perennial	Drilled in 2009, 192 m deep, open hole, pump at 60 m, Q = 32 l/s, operates 10h/d
DTW4	electric submersible	very large flat floodplain	pasture (near Kilti)	Dangila town supply (not operational)	-	Drilled in 2009, 150 m deep, open hole, pump at 60 m, Q = 0 l/s, electrical problem so not operational
dw30	hand pump broken	gentle slope at base of large hill	crops	not operational	-	pump broken; could not re-sample, locals using Kilti river. Apparently school nearby also has HDW but pump is also broken
dw31	hand pump	flat land on edge of floodplain	between crops and floodplain/pasture	potable and domestic	perennial	Sampled here because it is the closest to broken Berayta HDW for re-sample (though far away), also closest to deep BHs.
D3	electric submersible	fairly flat land on edge of town	near small river (Fincha) in trees	Dangila town supply	perennial	Drilled 1985, 130 m deep, open hole, pump at 100 m, Q = 3.5 l/s, operates 10h/d. D1 and D2 close but yield decreased till they non-functional
DW43	hand pump	flat land on floodplain	floodplain pasture	village potable supply	perennial	dug 1992, always good supply
DW22	hand pump	flat floodplain at base of steep hill	small pasture between nearby river and houses/crops	domestic	perennial	"sometimes bad smell". Was very difficult to filter though not turbid - 3x filters per 125ml bottle.
DW21	hand pump	flat land on edge of floodplain	floodplain pasture	domestic	perennial	compound no longer locked
dw18	rope and washer pump	gentle slope	beside house and coffee, chat, mango, banana, orange, onion	irrigation and domestic	perennial	IWMI installed pump in 2014
DW73	oil drum cover	flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	Repeat well test now greater saturated thickness
DW75	oil drum (no cover)	flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	
dw6	pot cover	flat land on edge of floodplain	near house between crops and floodplain/pasture	irrigation	perennial	Repeat well test now greater saturated thickness
DW77	oil drum cover	fairly flat land on edge of floodplain	near house between crops and floodplain/pasture	domestic and cattle	perennial	Repeat well test now greater saturated thickness
dw2	hand pump	flat land on floodplain	floodplain pasture	potable and domestic	perennial	had just been dug in March 2015, 1.5 m diameter
dw32	plastic drum cover	flat land	beside house surrounded by crops	rarely used (cattle)	perennial	house is closest to Lunk spring which has very good water so they use that
dw33	oil drum cover	flat land	beside house surrounded by crops	domestic	perennial	near to town (Chara)
DW79	hand pump	flat land on edge of floodplain	in school grounds between floodplain/pasture and crops	school domestic use	perennial	not locked as it was during last visit

Table F-6. Springs.

ID (CS = Demis ID)	Kebele	Site name	N	E	Elevation masl	Geology	Date of visit	Sample	Field pH	EC µS/cm	Temp °C	Flow/yield	Topography
cs1		Minchinat joins Brante	11°18.174'	036°51.599'	2076	regolith	22/03/2015		5.22	61.93	22.8	0.1 l/s	slightly sloping floodplain
cs2			11°17.742'	036°51.656'	2085	gravelly alluvium regolith above massive basalt	22/03/2015						steeper sloping narrower valley with narrow floodplain
cs3			11°17.692'	036°51.681'	2084	gravelly alluvium regolith above massive basalt	22/03/2015						steeper sloping narrower valley with deep dry gullies
cs4			11°17.350'	036°52.189'	2110	regolith	22/03/2015						deep gully in floodplain high above main channel
CS42	Zeguda	Tankishti/Aboyta gote	11°15.967'	036°52.829'	2118	gravelly alluvium regolith	22/03/2015	SI3 C3 A3	5.31	48.67	22.1	1 l/s	flat floodplain
CS45		Chereka minch/Abadra gote	11°19.191'	036°49.485'	2071	fractured and jointed basalt	23/03/2015						shallow valley sloping towards Kilti gauge
CS12	Sehara	Lunk/Astuta gote	11°11.217'	036°41.861'	1896	vesicular basalt boulders in regolith	26/03/2015	SI10 C10 A10	5.98	217.6	22		gullies forming at topographic break in flat land
CS4	Washa	Kulkul	11°15.748'	036°45.283'	2222	red regolith	26/03/2015						gully in narrow sloping floodplain
CS19	Abla Mariam	Mariam Wuha	11°10.879'	036°49.925'	2275	very deep weathered basalt	27/03/2015						deep gully in hillside
cs5	Dangesheta		11°19.020'	036°51.978'	2048	alluvium	30/03/2015						flat floodplain
cs6	Dangesheta	Kote Labeles	11°18.711'	036°51.960'	2068	clayey alluvium	30/03/2015	SI17 C17 A17	6.09	189.6	22.2	0.25 l/s	flat floodplain
cs7	Dangesheta		11°18.995'	036°50.505'	2075	alluvium	02/04/2015						edge of flat floodplain
cs8	Dangesheta		11°19.432'	036°51.721'	2043	alluvium	10/10/2015		5.22	195	22.1	1 l/s	halfway down floodplain
cs6	Dangesheta	Kote Labeles	11°18.711'	036°51.960'	2068	clayey alluvium	10/10/2015	2SI3 2C3 2A3	6.0	188.7	22.9	4 l/s	flat floodplain
CS42	Zeguda	Tankishti/Aboyta gote	11°15.967'	036°52.829'	2118	gravelly alluvium regolith	13/10/2015	2SI9 2C9 2A9	4.77	58.44	22.2	high	flat floodplain
CS12	Sehara	Lunk/Astuta gote	11°11.217'	036°41.861'	1896	vesicular basalt boulders in regolith	18/10/2015	2SI18-19 2C18-19 2A18-19	5.98	225.3	22.8	very high	gullies forming at topographic break in flat land
cs1		Minchinat	11°18.174'	036°51.599'	2076	regolith	20/10/2015		5.36	66.35	20.3	0.5 l/s	slightly sloping floodplain
cs9	Workit	Workit	11°19.407'	036°51.573'	2036	alluvium above massive basalt	22/10/2015	2SI29	5.75	124.8	23.2	0.5 l/s	downstream end of large floodplain
cs10	Dangesheta	Brante SB	11°19.331'	036°50.993'	2054	alluvium over fractured basalt	22/10/2015	2SI30	6.11	171.7	23.5	0.5 l/s	small floodplain

ID (CS = Demis ID)	Land use	Mode of Emergence	Use	Perennial	Remark
cs1	pasture with cropland within 30 m of river	contact of gravelly alluvium - more solid regolith	minor use but potable	perennial	
cs2	pasture, forest on steeper sloping E bank	contact of gravelly alluvium regolith - massive basalt	none	perennial	many springs and seepages in west bank as basalt outcrops in river bed
cs3	pasture, forest on steeper sloping E bank	contact of gravelly alluvium regolith - massive basalt	none	perennial	spring ~15 m up floodplain side, between this spring and previous are many springs and seepages in W bank as basalt outcrops in river bed
cs4	cropland	topographic break	none	perennial	spring ~30 m up floodplain side where main channel cuts >10 m
CS42	pasture	water table in floodplain centre	domestic and cattle	perennial	developed with 2 of 4 pipes flowing and open concrete tank
CS45	pasture	water table at bottom of valley and fractures		seasonal	spring and gully dry and in a visibly drier area
CS12	pasture and forest	topographic break	Gisa and Chara towns' supply	perennial	several springs with high flow form quite large stream. Spring developed and piped to tanks.
CS4	pasture	water table at bottom of valley	cattle	perennial	"more flow and additional springs in wet season"
CS19	forested church land	water table at bottom of gully	domestic, cattle and irrigation	perennial	many seepages emerging from undergrowth forming trickling stream, currently low flow but higher in wet season
cs5	pasture	water table in floodplain centre	cattle	perennial	many seepages form stream that flows to Brante
cs6	pasture	water table in floodplain centre	domestic	perennial	developed with 2 of 4 pipes flowing from enclosed tank and open concrete tank. More springs and seepages ~30 m away form stream that flows to Brante
cs7	pasture	topographic break	domestic and cattle	perennial	many seepages form stream that dries up on floodplain
cs8	pasture	water table intercepts floodplain	none	seasonal	many such springs and seepages on most Dangesheta floodplains
cs6	pasture	water table in floodplain centre	domestic	perennial	developed with 2 pipes flowing from enclosed tank and open concrete tank. Many more springs and seepages all over small floodplain with high flow
CS42	pasture	water table in floodplain centre	domestic and cattle	perennial	pipes and open concrete tank submerged due to spring and stream flow
CS12	pasture and forest	topographic break	Gisa and Chara towns' supply	perennial	Very easy to filter. Several springs with very high flow form large stream. Developed; piped to tanks (overflowing into stream) then piped to elevated tanks for town supply
cs1	pasture with cropland within 30 m of river	contact of gravelly alluvium - more solid regolith	minor use but potable	perennial	numerous "eyes" all with low flow and very clear water
cs9	pasture	contact of alluvium and massive basalt	cattle	perennial	numerous seepages across fairly large area - just minor seepages in dry season
cs10	pasture	contact of alluvium and fractured basalt	cattle	seasonal	numerous seepages

Table F-7. Rivers and other features.

ID	Woreda	Kebele	Site name	N	E	Elevation masl	Geology	Date of visit	Sample	222Rn	pH	EC	Temp	Topography
RFL1	Dangila	Dangesheta	Bridge over dry stream	11°18.466'	036°50.993'	2075	dry, cracked, gravelly alluvium	19/03/2015						flat floodplain
RFL2	Dangila	Dangesheta	BDU weather station at Dangesheta Agricultural Development Office	11°18.561'	036°51.068'	2080		19/03/2015						on shallow slope up from floodplain
RFL3	Dangila	Dangesheta	Ato Assaye Molla - Community monitored rain gauge	11°18.041'	036°51.251'	2094		19/03/2015						flat land on edge of floodplain
RFL4	Dangila	Dangesheta	Dangeshta Service Cooperative	11°18.237'	036°51.142'	2111		19/03/2015						higher land between two floodplains
RFL5	Merawi		Kolga Dam	11°20.758'	037°08.530'	2028		19/03/2015						shallow valley
RFL6	Dangila	Dangesheta	East of Dangeshta Service Cooperative	11°18.403'	036°51.023'	2076		22/03/2015						bottom of slope at floodplain
RFL7	Dangila	Dangesheta	Minchinat Stream joins Brante River	11°18.174'	036°51.599'	2076	regolith	22/03/2015						sloping floodplain
RFL8	Dangila	Dangesheta	Point where Minchinat currently emerges	11°18.174'	036°51.629'	2072	regolith	22/03/2015						sloping floodplain
RFL9	Dangila			11°17.692'	036°51.681'	2084	gravelly alluvium regolith above massive basalt	22/03/2015						steep sloping narrower valley, deep dry gullies
RFL10	Dangila		Source of Brante tributary	11°17.279'	036°52.255'	2112	regolith	22/03/2015						deep gully
RFL11	Dangila			11°17.310'	036°51.955'	2118		22/03/2015						sloping valley sides
RFL12	Dangila		Brante River road bridge	11°16.572'	036°51.847'	2111	gravelly alluvium and massive basalt boulders	22/03/2015						flat floodplain
RFL13	Dangila			11°16.538'	036°52.059'	2114	fractured vesicular basalt boulder field	22/03/2015						flat floodplain
RFL14	Dangila	Zeguda	Tankishti	11°16.085'	036°52.734'	2119	gravelly alluvium regolith	22/03/2015						flat floodplain
RFL15	Dangila	Dangesheta	Brante gauge	11°19.350'	036°50.924'	2050	massive, fractured and vesicular basalt boulders	23/03/2015						gently sloping floodplain
RFL16	Dangila	Dangesheta	Kilti gauge	11°19.290'	036°49.417'	2045	massive and fractured basalt boulders	23/03/2015						quite steep valley sides
RFL17	Dangila	Dangila	Amen gauge	11°15.774'	036°50.647'	2106	clayey alluvium	23/03/2015						flat floodplain
RFL18	Dangila	Dangila	Dangila weather station	11°15.050'	036°50.749'	2105		24/03/2015						flat open field
RFL19	Dangila	Sehara	Gizani River	11°10.779'	036°41.895'	1903	massive basalt boulders	26/03/2015						flat floodplain
RFL20	Dangila	Sehara	Gisa agricultural office	11°12.039'	036°40.067'	1894	black alluvium	26/03/2015						flat wetland floodplain
RFL21	Dangila		Awsi weir	11°12.072'	036°39.998'	1858	black alluvium, massive basalt boulders in red regolith	26/03/2015						flat wetland floodplain
RFL22	Dangila		Awsi River	11°12.309'	036°42.843'	1937	massive basalt boulders in black alluvium	26/03/2015						dry flat floodplain
RFL23	Dangila		Amen River?	11°11.668'	036°50.420'	2200	regolith	27/03/2015						flat floodplain
RFL24	Dangila	Abadra	Gagie River road bridge	11°19.472'	036°46.894'	2080	black alluvium above red regolith	28/03/2015						small floodplain, quite steep valley sides in town
RFL25	Dangila	Dangesheta	Brante River	11°19.395'	036°51.574'	2047	black clayey alluvium, red regolith, vesicular jointed basalt	30/03/2015						flat floodplain
RFL26	Dangila	Dangesheta	Tributary enters Brante (currently dry)	11°19.216'	036°51.915'	2044	red regolith and massive basalt boulders	30/03/2015						flat floodplain
RFL27	Durbete		Durbete weather station	11°21.545'	036°57.376'	1990		30/03/2015						flat, on slight rise
RFL28	Dangila		Amen River road bridge	11°16.245'	036°50.100'	2084	clayey alluvium above red regolith	31/03/2015						flat floodplain
RFL29	Dangila		Tributary enters Amen (currently dry)	11°16.915'	036°48.863'	2072	alluvium	31/03/2015						very large flat floodplain
RFL30	Dangila		Tributary enters Amen (currently dry)	11°16.881'	036°48.655'	2074	alluvium	31/03/2015						very large flat floodplain
RFL31	Dangila		Amen joins Kilti River	11°16.858'	036°48.480'	2070	gravelly sandy alluvium	31/03/2015						very large flat floodplain
RFL32	Dangila		Tributary of Kilti	11°16.435'	036°47.969'	2095	clayey alluvium above red regolith, basalt cobbles in bed	31/03/2015						deep gully in slope above floodplain
RFL33	Dangila		Tributary of Kilti	11°16.346'	036°47.972'	2096	clayey alluvium	31/03/2015						deep gully in slope above floodplain
RFL34	Dangila		Kilti River	11°16.194'	036°48.447'	2083	sandy gravelly pebbly alluvium	31/03/2015						very large flat floodplain
RFL35	Dangila		Tributary of Kilti meets large floodplain	11°16.059'	036°49.024'	2091	clayey alluvium and massive basalt boulders	31/03/2015						small floodplain meets large flat floodplain
RFL36	Bahir Dar		Bahir Dar National Meteorology Office and weather station	11°35.985'	037°21.602'	1801		06/04/2015						fenced compound within flat field
RFL37	Meshenti		Meshenti rain gauge	11°28.263'	037°17.152'	1963		06/04/2015						very small fenced compound within flat field

ID	Land use	Depth m	Bank width m	Incision m	Remark
RFL1	pasture	dry	3	1	bridge over dry stream, "wetland in rainy season"
RFL2	next to cropland				weather station installed by Abdu and Debebe on 18-3-15
RFL3	between pasture and eucalyptus plantation				small tree (3-4 m high) 4 m to NW
RFL4	where crops are weighed and sold; within eucalyptus				this where Assaye Molla works
RFL5	large resevoir behind dam and irrigation canals				Koga Dam Irrigation Project on Abay River. Finished in 2011/2012, paid for by MoA and Africa Bank. 1750ha resevoir, 1730x21m dam, 9.1m3/s release for irrigation: 7000ha for 14000 people, >1m3/s released: Abay River
RFL6	limit of eucalyptus plantations before pasture				all high ground around coop office is eucalyptus
RFL7	pasture with cropland within 30 m of river	0.2	5	2	note there is a spring 10 m upstream of channel intersection (see springs tab)
RFL8	cropland and seedling nurseries immediately adjacent	dry	3	3	upstream (dry) the river is highly sinuous and cuts ~4.5 m deep
RFL9	pasture, forest on steeper sloping east bank	0.3	10	2	upstream the channel incision is 5-10 m and much deep gullying (dry) in adjacent sloping floodplain from where springs emerge in wet season
RFL10	cropland and forest	0.1	8	8	source of Brante tributary (I thought this was Brante source because most of downstream Brante flow comes from this tributary)
RFL11	cropland and eucalyptus plantations				crossroads of eucalyptus plantations on high ground to SE and cropland between here and river to west
RFL12	pasture and forest	dry	6	1.5	small pool under bridge but otherwise Brante is dry. Occasional stagnant pools upstream.
RFL13	pasture	0.05	5	1	extensive boulder field within very large floodplain. Occasional flowing sections within Brante as well as dry sections and stagnant pools.
RFL14	pasture	0.2	2	0.5	Tankishti river fed by spring (see spring tab) but doesn't reach Brante at the moment. In rainy season the whole Brante/Tankishti floodplain floods and locals must use asphalt road to reach Dangila.
RFL15	pasture then houses and cropland ~30 m from river	0.15	5	1	Brante gauge in position as originally placed and still sturdy. Measure twice daily (6am and 6pm). Wet season floods just overtop bank.
RFL16	pasture on north bank, acacia forest on south bank	0.3	15	1.5	Kilti gauge broken after being hit by a floating tree in wet season. Metal supports and upper board snapped. River stage measured twice daily (6am and 6pm) by dipping measuring stick in river.
RFL17	pasture/football pitch/builders yard	0.2	7	2	Lower part of gauge a bit bent. Upstream through town the river is very dirty and full of litter - here it's quite clear.
RFL18	fenced open field				weather station actually ~25 m NW of the coordinates. Tall eucalyptus trees ~30 m to north. Visited at 18:30 so nobody present to let me into compound or answer questions.
RFL19	pasture	0.25	20	2	Quite high flow over boulders in bed
RFL20	pasture				perennial wetland (one of several) between town of Gisa and Awsi river
RFL21	pasture	1	12	1.5	very turbid upstream of weir - probably raising water table forming wetlands. Downstream is shallower (0.25 m). Weir built in 2014. Two canals (left bank = 50 l/s) irrigate 100 ha.
RFL22	none	dry	18	2	however, further upstream east of Chara there is water in the Awsi where it is much smaller
RFL23	pasture and crops	0.05	4	2.5	I would have expected river here to be flowing south but this goes north. Where to?? Small aqueduct (currently dry) irrigates small plot. (Looking at Google Maps later: I think this is the Amen River)
RFL24	pasture, crops and forest	0.25	10	3	quite fast so substantial flow even though it's shallow. Some abstraction below bridge.
RFL25	pasture	0.2	8	1.5	cattle watered here
RFL26	pasture	dry	8	2	several tributaries such as this enter through large floodplain - most currently dry
RFL27	fenced compound within school field				weather station within Durbete Primary School, large tree ~15 m north and another tall tree ~ 15 m east
RFL28	pasture	0.1	7	2.5	almost no flow in river
RFL29	pasture	0.1	6	1.5	between here and previous location there are reaches of almost zero flow and reaches of basalt bed. In large floodplain; water table visible in bank at ~1.3 mbgl.
RFL30	pasture	0.25	3.5	1.5	between here and previous location there are dry reaches and reaches of stagnant water
RFL31	pasture	0.1	8	1	fast flow in Kilti, no flow in Amen
RFL32	pasture and crops	0.1	18	8	some flow that dries up as the channel reaches the flat floodplain
RFL33	pasture and eucalyptus	0.05	18	8	some flow (less than previous) that dries up as the channel reaches the flat floodplain
RFL34	pasture	0.2	8	2.5	flowing
RFL35	pasture and crops	0.05	3	1.5	some flow that dries up as the channel reaches the flat floodplain and dries up ~ 100 m upstream
RFL36	weather station and car park				nearby pylon and many overhead cables. Small hill ~150 m to the south.
RFL37	unused land around Kebele office and clinic				no nearby trees or other obstructions

ID	Woreda	Kebele	Site name	N	E	Elevation masl	Geology	Date of visit	Sample	222Rn test	field pH	EC μS/cm	Temp °C
RFL3	Dangila	Dangesheta	Ato Assaye Molla - Community monitored rain gauge	11°18.041'	036°51.251'	2094		10/10/2015					
RFL15	Dangila	Dangesheta	Brante gauge	11°19.350'	036°50.924'	2050	massive fractured vesicular basalt boulders	10/10/2015					
RFL38	Dangila	Dangesheta	Abdu/Debebe Brante gauge	11°19.260'	036°51.876'	2038	alluvium	10/10/2015					
RFL39	Dangila	Dangila	Hahu Hotel Roof	11°15.476'	036°50.832'	2048		12/10/2015	2SI7 2A7 2A23				
RFL40	Dangila	Dangila	Dangila Water Supply Service Office	11°15.918'	036°51.067'	2109		12/10/2015					
RFL41	Wetet Abay		Wetet Abay electronic met. station	11°22.026'	036°02.264'	1896		13/10/2015					
RFL42	Dangila	Dangesheta	Brante River road bridge and Debebe river gauge	11°16.572'	036°51.847'	2111	gravelly alluvium, massive basalt boulders	15/10/2015					
RFL43	Dangila	Dangesheta	Flow gauging location (Brante)	11°16.591'	036°51.818'	2108	gravelly alluvium, massive basalt boulders	15/10/2015					
RFL44	Dangila	Dangesheta	Flow gauging location (Brante)	11°19.338'	036°50.926'	2053	massive fractured vesicular basalt boulders	15/10/2015					
RFL45	Dangila	Dangesheta	Flow gauging location (Brante)	11°19.253'	036°51.891'	2040	sandy alluvium	15/10/2015					
RFL46	Dangila	Dangesheta	Nr Malese (Dangesheta floodplain stream)	11°18.055'	036°51.043'	2053	alluvium	17/10/2015	2SI17	Yes	6.83	99.35	21.8
RFL47	Dangila	Sehara	Gisa and Chara collection tank at Lunk	11°11.239'	036°41.813'	1893	vesicular basalt boulders in regolith	18/10/2015					
RFL48	Dangila	Sehara	Gizani River	11°10.799'	036°41.874'	1901	massive basalt boulders	18/10/2015	2SI20		6.39	106.6	23.1
RFL49	Dangila	Sehara	Dinkeresh (wetland on Gizani floodplain)	11°10.782'	036°41.910'	1906	alluvium	18/10/2015	2SI21		6.71	256.1	30.9
RFL50	Dangila	Sehara	Gisa	11°11.164'	036°40.262'	1879		18/10/2015	2SI22 2A22				
RFL51	Dangila	Dangesheta	Nr Brahanu (stream at Dangesheta floodplains' neck)	11°18.348'	036°50.895'	2063?	alluvium	20/10/2015	2SI24	Yes	6.84	83.26	20.3
RFL52	Dangila	Dangesheta	Nr Getaneh (Dangesheta floodplain stream)	11°18.478'	036°51.113'	2076?	alluvium	20/10/2015	2SI25 2A25 2C25	Yes	6.04	70.28	26.6
RFL53	Dangila	Dangesheta	Bunteta (Brante river)	11°18.613'	036°51.250'	2079?	alluvium	20/10/2015	2SI26	Yes	6.18	91.1	23.1
RFL54	Dangila	Dangesheta	Brante	11°18.468'	036°51.348'	2075?	alluvium	20/10/2015		Yes	6.22	93	23.4
RFL55	Dangila	Dangesheta	Mandar 2 (Brante river)	11°18.184'	036°51.554'	2076?	alluvium, basalt boulders	20/10/2015	2SI27	Yes	6.27	93.45	22.3
RFL16	Dangila	Dangesheta	Kilti gauge	11°19.290'	036°49.417'	2045	massive and fractured basalt boulders	21/10/2015					
RFL56	Dangila	Dangesheta	Flow gauging location (Kilti)	11°19.292'	036°49.410'	2042?	massive and fractured basalt boulders	21/10/2015					
RFL57	Dangila	Dangesheta	Bridge over large wetland stream	11°17.095'	036°51.210'	2102	alluvium	21/10/2015					
RFL58	Dangila	Workit	Workit (bridge over Brante)	11°19.390'	036°51.611'	2018?	alluvium over massive basalt	22/10/2015		Yes	6.26	109.6	21.3
RFL59	Dangila	Dangesheta		11°19.191'	036°51.413'	2045	alluvium	22/10/2015		Yes	6.25	108.8	22.7
RFL60	Dangila	Dangesheta	Brante SB	11°19.331'	036°50.993'	2054	alluvium over fractured basalt	22/10/2015		Yes	6.25	105.9	23.7
RFL61	Dangila	Dangesheta	Brante Gorge	11°19.158'	036°50.681'	2061	regolith over fractured basalt	22/10/2015	2SI31 2A31 2C31	Yes	6.29	104.8	22.9
RFL62	Dangila	Dangesheta		11°18.991'	036°50.639'	2064	alluvium and basalt boulders	22/10/2015		Yes	6.16	103.4	22.4
RFL63	Dangila	Agaga	Amen Floodplain	11°17.042'	036°48.984'	2015?	alluvium	24/10/2015		Yes	6.13	127.5	18.9
RFL64	Dangila	Agaga	Kilti Bridge	11°17.130'	036°48.620'	2067	gravelly alluvium	24/10/2015		Yes	7.03	134	19.8
RFL65	Dangila	Agaga	Amen by DTW3	11°16.889'	036°48.568'	2068	alluvium	24/10/2015		Yes	7.12	122.5	21.2
RFL66	Dangila	Berayta	Kilti by DTW1	11°16.741'	036°48.548'	2074	gravelly alluvium	24/10/2015		Yes	7.37	166.8	23.9
RFL67	Dangila	Berayta	Kilti Floodplain	11°16.307'	036°48.565'	2081	alluvium	24/10/2015		Yes	7.43	168.7	27.2

ID	Topography	Land use	Depth m	Bank width m	Incision m	Remark
RFL3	flat land on edge of floodplain	between pasture and eucalyptus plantation				No issues to report regarding rain gauge. Protective fence has gone. Small tree still 3-4 m high 4 m to NW.
RFL15	gently sloping floodplain	pasture. Houses and cropland ~30 m from river	0.3	7	1.5	No issues regarding Brante gauge. Gauge in deepest part of flow, 1m from bank, 2m from bank top and 5m from other side bank top.
RFL38	quite narrow floodplain	unused, crops 15-25 m back from bank top	0.4	8	2	Also a stage board on top of bank for floods (didn't flood in 2015)
RFL39	flat town centre	town				Rain from Hahu Hotel roof during big storm from ~midnight to ~5am morning of 12-10-15
RFL40	flat edge of town	town				Very helpful chaps at water supply office
RFL41	beside road bridge at base of quite steep slope	trees, road, river				Some trees quite close to gauge and also at base of a fairly steep bank sloping to river and road
RFL42	flat floodplain	pasture and forest	0.7	6	1.5	Debebe's gauge (monitored by a farmer) is on the parapet on the upstream left bank
RFL43	flat floodplain	pasture	0.3	12	1.5	Flow gauging location 30 m downstream of road bridge
RFL44	gently sloping floodplain	pasture. Houses and cropland ~30 m from river	0.36	5.5	1	Flow gauging location 30 m downstream of NCL/IWMI Brante gauge
RFL45	quite narrow floodplain	unused, crops 15-25 m back from bank top	0.49	6	1.5	Flow gauging location 30 m downstream of Debebe/Abdu Brante gauge
RFL46	centre of flat floodplain	pasture	0.1	2	0.4	222Rn sample/test location. Sampled surface water but very close to numerous springs/seepages.
RFL47	gullies forming at topographic break in flat land	pasture and forest				Collection tank ~80 m d/s of Lunk springs overflowing to stream. Water piped to elevated tanks closer to Gisa and Chara for towns' supply
RFL48	flat floodplain	pasture	0.5	20	1.5	High flow. Steep gradient - pool and drop.
RFL49	flat floodplain	pasture	0.04	~50	0	Wetland/floodplain sample location. Forms small stream into Gizani but no obvious springs into wetland.
RFL50	flat town centre	town				Rain from Gisa cafe roof during heavy shower at 13:30 18-10-15
RFL51	flat neck at floodplain outlet into other floodplain	trees surrounded by crops	0.2	3	3	222Rn sample/test location. Sampled surface water.
RFL52	centre flat floodplain before large Brante floodplain	pasture	0.3	1.5	1	222Rn sample/test location. Sampled surface water.
RFL53	centre of d/stream end of large Brante floodplain	pasture	0.5	4	2	222Rn sample/test location. Sampled surface water.
RFL54	centre of large Brante floodplain	pasture	0.5	5	1.25	222Rn sample/test location. Sampled surface water.
RFL55	extreme upstream end of large floodplain	pasture and crops	0.5	8	2	222Rn sample/test location. Sampled surface water.
RFL16	quite steep valley sides	crops on N bank, acacia forest on S bank	1	15	1.5	gauge broken (again) after hit by floating tree in wet season (again). Metal supports and upper board snapped. Stage measured by dipping measuring
RFL56	quite steep valley sides	crops on N bank, acacia forest on S bank	0.7	11	1.5	Flow gauging location 20 m upstream of Kilti gauge
RFL57	very very large flat floodplain/wetland	pasture/swamp	0.2	~500	0	Wetland, no flow observed, locals say no outlet, large marsh in the middle
RFL58	neck between two floodplains	crops and pasture	0.6	5	1.5	222Rn sample/test location. Sampled surface water.
RFL59	large floodplain	pasture	0.7	7	1.8	222Rn sample/test location. Sampled surface water.
RFL60	small floodplain	pasture	0.4	8	1.5	222Rn sample/test location. Sampled surface water.
RFL61	narrow valley, steep fast flow over basalt	trees, pasture, crops	0.3	9	1	222Rn sample/test location. Sampled surface water.
RFL62	floodplain u/s of where large side floodplain joins	pasture	0.4	8	1.2	222Rn sample/test location. Sampled surface water.
RFL63	huge flat floodplain	pasture	0.7	6	1.2	222Rn sample/test location. Sampled surface water.
RFL64	huge flat floodplain with braided river (3x channels)	pasture and wetland	0.5	20	0.5	222Rn sample/test location. Sampled surface water.
RFL65	huge flat floodplain	pasture	0.8	6	0.4	222Rn sample/test location. Sampled surface water.
RFL66	huge flat floodplain	pasture	0.2	4	1.2	222Rn sample/test location. Sampled surface water. There was a bridge here but it has washed away.
RFL67	huge flat floodplain	pasture and wetland	0.2	4	2.5	222Rn sample/test location. Sampled surface water.