

Monitoring and Modelling Mire Hydrology for Conservation Management

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Abstract

The functional hydrological components of the ombrotrophic mire water balance are considered in terms of their ecological relevance. It is proposed that numerical models provide a suitable framework for mire hydro-systems and their potential as quantitative tools for mire restoration and conservation management is demonstrated. Existing models previously applied to mires are reviewed. The USGS 3-D groundwater model MODFLOW is selected and a new shallow surface and groundwater model GSHAW5 is developed for application to mires. Extensive ecohydrological case studies are undertaken at two mire sites and the models are tested using data collected at the sites.

Field studies at Wedholme Flow, Cumbria, extended over four years and the data collected were combined with historical records to form a 10-year hydrological data set. Studies at Trough End Bog, Northumbria, extended over a 3-year period. Topographic, soil and vegetation surveys were carried out at both sites. Watertable fluctuation was recorded manually on a weekly basis and electronically at a 20-minute interval along with automatic meteorological records. New hydrometric techniques were developed in the Surface Water Monitoring Plot, SWaMP, constructed at Trough End to record hydrological exchanges within the hummock-hollow complex of the mire acrotelm.

The models operate on very different spatial and temporal scales. GSHAW5 is applied to reproduce ground and surface exchanges in the acrotelm. MODFLOW is used to simulate large-scale exchanges in undisturbed areas and between regenerating and active peat cutting areas. Predictive MODFLOW simulations are used to examine the impact of different peat cutting regimes on mire hydrology and potential regeneration. Both models produce simulations strongly correlated to observed hydrological exchanges.

The usefulness of numerical models as tools for mire management is considered in light of the model test results from both case studies. It is concluded that both models provide insight and quantitative estimates of hydrological exchanges not possible by other means. MODFLOW simulations reveal considerable water loss from the Wedholme Flow mire reserve to an active peat cutting area. Simulations of Trough End bog reveal hydrological acrotelm processes strongly related to vegetation assemblages. An extensified GSHAW5 acrotelm model is recommended for the simulation of intact ombrotrophic mires.

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Declaration

Chapter 1 was published in the proceedings of the British Ecological Society Mires Research Group proceedings of the conference entitled 'Patterned Mires and Mire Pools: *Origin and Development; flora and fauna*' (1998). It was co-authored with Geoff Parkin (10%).

Chapter 2 forms a sub-section of 'Theme 2.18: Monitoring Water Resources and their Quality' in 'Area 2: Water - Science and Technology Fundamentals' of the UNESCO-Encyclopedia of Life Support Systems currently in press.

A report containing a large part of the analysis presented in Chapters 3 and 4 was submitted to English Nature as part of a joint Newcastle, Nottingham-Trent and Central Lancashire Universities contract. Chapter 4 was co-authored with John Gowing (5%) and submitted in its entirety to 'Environmental Management' (August 2001) and is with the referees.

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The report contained in the main Appendix was published jointly by English Nature and EUROSITE. The author contributed 75% of the text, edited the contributions of participants and was also the workshop *reporter*.

Preface

The theme of this thesis is the application of modelling techniques to the eco-hydrological processes of ombrotrophic mires. A mire is a complex system in which ecology and hydrology are intrinsically linked, hence 'eco-hydrology'. Although this study focuses largely on the hydrological functions of mire systems, the components of each system are identified in terms of their ecological implications. Ombrotrophic mires are differentiated from other wetlands by virtue of their unique ecology, which in turn is determined by its primary hydrological component: the precipitation that sustains a mire. Positive net recharge to ombrotrophic mires is limited to this acidic, nutrient poor source, which in combination with restricted local drainage is the basic prerequisite for mire formation and the main sustaining feature of the system.

The application of modelling techniques to mires can enable better understanding of the hydrodynamics of individual mire complexes on different spatial and temporal scales. The growing recognition of the ecological value and hydrological importance of peatlands in general has generated considerable interest in their management. This has created a demand for better quantitative estimates of system exchanges and tools that can provide these. Models are used as tools every day, and in this context have already begun to build a model by conceptualising the prerequisites of mire formation. Numerical models, based on quantitative observations of mire hydrological exchanges, can potentially both improve understanding of mire hydrodynamics and predict possible outcomes of fluctuating system components.

The aim of this thesis is to demonstrate the suitability of numerical modelling techniques to increase knowledge of mire hydrological functions and to highlight the potential for the

application of validated models within mire management strategies. This is achieved by the application of two different numerical models at two field sites. The current state of understanding of mire hydrological systems is reviewed and the basis of existing models are outlined in Chapter 1. Chapter 2 is a review of hydrometric techniques available for the collection of hydrological data in mire field sites, and was compiled (on behalf of UNESCO) as a generic hydrology monitoring manual for all wetland types wetland. In order to characterise the hydrology of a site, it is essential to make accurate readings of the exchanges of defined system processes. Any assumption not based on the best available data will be essentially flawed, and this is amplified in spatially and temporally dynamic mires where many functions are transient. The hydrometric methods outlined in Chapter 2 were applied selectively at the two field sites over a four-year monitoring period. The field sites, Wedholme Flow, Cumbria, and Trough End Bog, Northumbria, are described in Chapters 3 and 5 respectively. The monitoring methodology applied at each site is outlined, the resulting data sets are discussed and where appropriate, the implications for site management are considered.

The data collected during each monitoring programme were utilised in numerical models at different scales at each field site. Chapter 4 describes the modelling process applied at Wedholme Flow, whilst Chapter 6 describes the model developed at Trough End.

At a landscape scale, the two field sites are quite different. Wedholme Flow is an entirely ombrotrophic, large (780ha) lowland raised mire, encompassing intact hummock-hollow surface features alongside degraded and disturbed mire. Wedholme is subject to the conflicting management practices of peat extraction and nature conservation, with both un-

drained surfaces, blocked drains in abandoned peat cuttings and deep arterial drains in the peat cutting area.

A review of existing models concluded that no single model available was capable of reproducing observed ground and surface water exchanges simultaneously. The USGS 3-D groundwater model MODFLOW was selected as the best available solution to reproduce subsurface flux and was applied to Wedholme in several different schemes. This project, outlined in Chapter 4, focuses on large-scale groundwater exchanges between defined regions. This form of modelling has a broad range of public and commercial applications.

Trough End Bog is a small (2ha), upland valley mire with an ombrotrophic central region containing typical hummock-hollow acrotelm features and vegetation, surrounded by a soligenous fringe. The bog is bordered by heathland and has a largely degenerate, unmanaged shallow drainage network. Limited grazing by sheep is allowed across the site. Extensive and deep peat accumulation at Wedholme, along with a 10-year history of watertable recording provide the opportunity to monitor and model mire groundwater dynamics. The accessibility and opportunity to experiment with potentially intrusive techniques make Trough End Bog an excellent site at which to investigate surface-acrotelm hydrological exchanges.

As no existing model could be found to accurately represent hydrological flux within the mire acrotelm, a model capable of reproducing processes in this region was developed. Chapter 6 outlines the numerical scheme of the integrated quasi-3-D shallow surface and groundwater model GSHAW5 (Ground and SHallow Water equation solved by FInite VolumE method). The model was parameterised using the experimental Surface Water Monitoring Plot (SWaMP) described in Chapter 5. The plot was designed for the purpose and constructed in

the ombrotrophic region of Trough End Bog. Testing of GSHAW5 using the data collected in the SWaMP (Chapter 5) is described and model outputs (groundwater heads and surface water discharge) are compared to field data (Chapter 6).

In the final Chapter the outcomes of the extensive monitoring and modelling programs at both sites are discussed and implications for further management of these and other mires sites are considered.

Excluding Chapter 3, all Chapters of this thesis have been published separately or submitted for publication (see 'Declaration'). Chapters all ready in print are presented in the form in which they were published. Those currently under review or revision at the time of thesis examination are included in the form submitted to the journals in question. Additional published work arising from this thesis is included in the final Appendix.

Chapter 1. Towards a Whole System Model for the Hydrology of Peat Mires

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TOWARDS A WHOLE SYSTEM MODEL FOR THE HYDROLOGY OF PEAT MIRES

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INTRODUCTION

Why is it that after so many years of research into the dynamics of wetland ecosystems that we still need to ask the question: *'Why be so concerned with bog hydrology?'* The answer is simply that our understanding of the hydrological behaviour of such systems, developed on organic soils, whether deep or shallow, blanket bog or raised mire, is far from comprehensive. This is in itself surprising given the level of knowledge of the ecology of such water-driven systems. What is also surprising is the willingness of many wetland managers and managing bodies, to embark on lengthy and often expensive 'rehabilitation' projects without a sound understanding of the hydrological behaviour of their site.

The current level of understanding, and the areas in which further research should be focused, seem themselves to be a matter of some disagreement. Burt *et al.* (1997) stated that 'studies of the hydrology and fluvial geomorphology of blanket peat moorland remain scarce', whilst Baird *et al.* (1997), in their paper which followed in the same proceedings, stated 'a considerable amount of work has been done on the hydrology of damaged blanket mires' and 'such work has been extremely useful in understanding the hydrology of these degraded systems'.

Our knowledge of any natural system may never be described as 'complete' but technological developments, such as computer based models and data-logging equipment, continually provide the means to improve our understanding, whilst changing environmental conditions create the necessity for further study. We intend to highlight areas in which such developments could be applied to mires, and to emphasise the need for a greater understanding of the hydro-dynamic driving forces of wetland ecosystems, if their management and conservation is to be effective. To date, the application of

hydrological theory, in the form of the principles of land drainage (Ritzema, 1994) have been applied effectively by those who wish to drain wetlands to exploit the peat resource or for agricultural purposes. However, the model with which they must be concerned is far simpler than that which is required for conservation or restoration. It excludes ecological issues, and is based simply on the height of the water table, how it is influenced by recharge, and how adequate water table drawdown for peat removal can be achieved using drainage channels.

The motivation to collaborate on a contribution to these proceedings arose from the lack of representation of hydrology at the 1998 MRG conference, despite the conference theme being *'Patterned Mires and Mire Pools. Origins and Development of Pools: Ecology of plants and animals'*. It would seem that there is still a need to stress the importance of functional hydrology in mire processes, and certainly to consider its role in the formation and ongoing development of pool networks. The need to consider the ecology of bog pools would not even arise if it were not for the presence of an excess of surface water, yet the processes which give rise to pool formation and duration were given scant attention.

In this paper we will outline the current state of understanding and research focus in mire hydrology, concentrating on the UK, and attempt to highlight those areas which we feel are critical in determining a complete mire water balance. Past work will be reviewed briefly, and then current research issues associated with components and processes of a mire water balance will be considered, including surface flow, hydraulic conductivity, and evapotranspiration. The hydrochemistry of mires is not addressed, although its importance is recognised. The need for a comprehensive model to include recharge, ground and surface water flows, and vegetation response will be discussed. Potential applications for such a model are far reaching, having implications for restoration and conservation, quantification of wetland buffer zones, and assessment of the

influence of the mire water balance on whole catchment hydrological and ecological behaviour. This paper is not a comprehensive review of all of the issues involved, nor of all published works on the subject. Rather it is an attempt to bring hydrological issues to the forefront of the wetland ecology forum, so that they may be discussed more readily and included by more practitioners in their consideration of whole mire systems. The need to conserve wetlands will be taken for granted.

CURRENT STATE OF RESEARCH AND UNDERSTANDING

In recent years the volume of research in wetland ecology and hydrology has increased steadily, resulting in several notable publications this decade, many of which have arose from the airing of research at conferences. For example, 1992 saw the publication of *Peatland Ecosystems and Man: An Impact Assessment* (Bragg *et al.*, 1992), containing papers covering both ecological and hydrological behaviour, while 1995 saw the publication of two complementary volumes, *Restoration of Temperate Wetlands* (Wheeler *et al.*, 1995), almost accompanied by *Hydrology and Hydrochemistry of British Wetlands* (Hughes and Heathwaite, 1995). Wheeler and Shaw (1995) also published an ecological 'manual' for wetland managers, *Restoration of Damaged Peatlands*, while Kevin Gilman's *Hydrology and Wetland Conservation* (1994) outlined much of the current state of understanding of wetland hydrology.

In the past, there has been a tendency to address elements of mire ecology and hydrology separately, rather than within an integrated system, and this is reflected in the literature. Indeed, this 'divide and conquer' approach is often the only practicable solution to the understanding of complex environmental systems. This approach is less appropriate in consideration of wetlands, where hydrology and ecology are too closely related to be addressed separately. The most obvious example of this is the fact that the very existence and growth of peat mires largely relies upon the presence of semi-aquatic vegetation. The close interdependence of mire ecology and hydrology can be illustrated by some typical questions that can be asked about, for example, invertebrate distributions. How do they differ between a pool lying between two hummocks, and the top of those hummocks? What if that pool were seasonal - how would this affect the population? What if a storm event caused the depth of the pool to increase, and for how long?

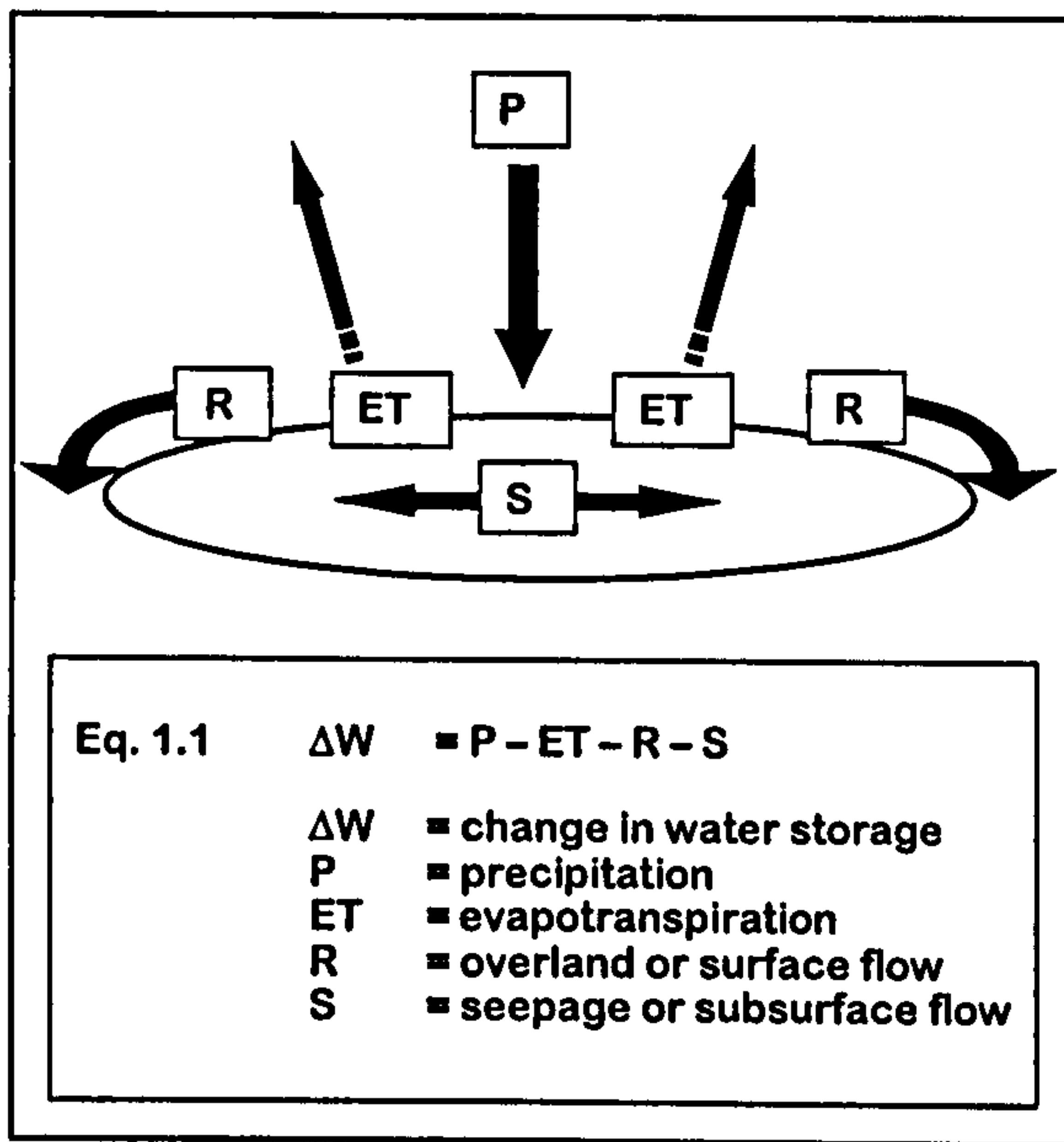
How would the decreasing area of available 'dry' hummock affect both populations? What would be the influence on the invertebrates if a nearby drain was blocked causing widespread surface flooding? How would the vegetation change as the surface area became more pool and less hummock? These are all questions which require an intimate understanding of both ecology and hydrology, and the ability to quantify accurately all of the system components, such as evapotranspiration, hydraulic conductivity of peats, infiltration and surface flow rates. Whether a system is 'pristine' or degraded, these interdependent factors must be combined to achieve a balanced understanding of the wetland ecosystem. The most logical framework for the representation of these factors in an integrated form is their combination in a systematic model.

WETLANDS AND MODELS

Practitioners of wetland ecology and hydrology (hydroecology/ecohydrology) must necessarily base their management decisions on a conceptual model of a wetland system. The effectiveness of management actions is entirely dependent on the reliability of the model to which they refer when considering the system. This applies whether management aims are concerned with conservation or 'improvement' of wetland for agriculture, or both, as in the many areas with multiple stakeholders. The calculation of hydrological phenomena are largely based on standard methods and formulae developed for use in mineral soil over the last 100 years. These methods have varying degrees of success according to the suitability of their governing equations to the medium in question (heterogeneous peat) and their scale of application. Much the same can be said for other analytical and numerical models derived from such governing equations. The scale issue generally has been the subject of considerable debate within the hydrological community, and forms an area of very active contemporary research (see, for example, Dagan, 1986, Nachabe and Morel-Seytoux, 1995).

At the most basic level, the simplest conceptual model representing system processes of a wetland consists of a mass balance equation for the entire wetland (Equation 1, Figure 1). This extremely simple model does not provide any information about the spatial and temporal distribution and movement of water within the

Figure 1. Primary model of mire water balance.



wetland - most frequently the issue of greatest concern. The most well known example of such an analytical model, at least among wetland ecologists, is Ingram's groundwater-mound theory of the dimensions and growth of a raised mire (Ingram, 1982). Ingram proposed that in a groundwater mound maintained 'through a dynamic equilibrium between recharge and seepage...developed in a homogenous, isotropic porous medium through which water flows in accordance with Darcy's law, the potential distribution must conform with Laplace's equation which can be used, where geometry is simple, to predict the relationship between height and width of the groundwater mound for any combination of discharge with hydraulic conductivity', and that 'The shape of the mound can also be approximated using Dupuit-Forchheimer theory' (see below). Making these assumptions, and using solutions given by Childs (1969) for the geometry of groundwater tables with lines of equipotential which are parallel, circular or elliptical, Ingram derives a relationship between the dimensions of a raised mire, the net recharge, and the hydraulic conductivity of the peat (Equation 2), and also provides the equation describing the cross-sectional shape of an idealised mound as following an elliptical profile. Ingram tested this hypothesis against observations of topographic levels at Dunn Moss, East Perthshire, and concluded that 'the elliptical shape and proportions of the mire surface are in agreement with this model'.

Equation 2 $U/K = H_m^2/L^2$

U = net recharge = lateral discharge by seepage to lagg
K = hydraulic conductivity
 H_m = maximum height of the mound
L = radius of mire

The application of this analytical model to many cases is potentially flawed, as it relies on homogeneity and isotropy of peat on a large scale, which is rarely, if ever, the case. The method also relies on the application of Darcy's equation (Equation 3) and the Dupuit-Forchheimer assumptions on the same scale. The established mathematical basis of groundwater flow will not be discussed further here, but is described in detail by, for example, Harr (1962), Bear (1979), Smedema & Rycroft (1983), Zaradny (1993), Bos (1994), and Viessman & Lewis (1996). The Dupuit assumptions can be summarised as follows:

- that the hydraulic gradient is equivalent to, and given by, the slope of the water table, which is generally small;
- that flow is approximately horizontal;
- that equipotentials are vertical planes normal to flow.

Equation 3 $Q = K A dH/dL$

where Q = rate of flow [m^3s^{-1}]
K = hydraulic conductivity [ms^{-1}]
(coefficient of proportionality)

Darcy's Equation of flow through a porous medium, which is both homogenous and A= cross sectional area normal to the direction of flow [m^2] isotropic (in effect one-dimensional), dH/dL = piezometric head gradient [m/m] described by Darcy in 1856.

To apply Ingram's analytical model, in addition to conformity to these conditions, there must also be no surface flow (discussed below), as all flow in the model is assumed to be described by Darcy's equation, accounting only for saturated subsurface flow. Although Darcy's equation can be shown to be valid at the laboratory scale, at the field scale the physical quality of peat is likely to be extremely variable, differing both laterally and vertically. In addition, other factors may also affect hydraulic potential, such as pools, drains, and even footpaths. The same considerations will apply to the Dupuit assumptions: flow may be seen to be horizontal over a small enough

distance, equipotentials may be vertical to flow, and over a larger scale the hydraulic gradient may be indicated by the slope of the water table, usually observed by a transect of dipwells.

When an analytical solution is judged oversimplistic, a numerical solution should be selected (Anderson and Woessner, 1992). For the case of a groundwater mound with complex geometry, for example, Ingram (1992) stated that 'using analytical solutions borrowed from other contexts, and supplementing these with numerical analyses' the effect of peat removal on the groundwater mound can be demonstrated in a model form - effectively employing a numerical groundwater model.

All numerical models consist of a governing equation, initial properties and boundary conditions. They may be one (essentially a vector), two- or three-dimensional, or, somewhere in between either of two states, in which case they are referred to as quasi-dimensional, and models may be 'steady-state' (with no change in water storage) or 'transient'. In the case of two- or three-dimensional models, properties and equations of flow are applied to a zone or to a cell within a grid of specified scale, which constitutes the representation of the subject area. Any flux between adjacent grid cells is calculated using the governing equations, from the initial conditions at the beginning of each time-step, according to the specified boundary conditions. Each grid cell may be assigned different properties, and is allowed to interact with adjacent cells, therefore allowing a degree of heterogeneity, determined by the scale of the grid. The solution of the partial differential equations describing groundwater flow is typically obtained through one of various different iterative techniques (see, for example, McDonald and Harbaugh, 1988, Hill, 1990).

It would not be appropriate to discuss here at length all of the forms and individual specifications of the many academic and commercially available hydrological models (for further information on such models, see Singh, 1995, or Refsgaard, 1996), but it is necessary to outline those most popular models which have been applied to wetlands, and their operational basis. From here on, 'model' refers to a numerical representation of hydrological behaviour, whether surface, subsurface, atmospheric or inter-pore, where calculations are necessarily performed by a computer.

Several groundwater model programs or codes have been applied to mires including

MODFLOW, developed by McDonald and Harbaugh (1988) on behalf of the US Geological Survey, and DRAINMOD (Skaggs, 1980), developed by Prof. Skaggs at the Water Resources Research Institute, University of Carolina. Some models which include unsaturated zone and surface water processes are also suitable for modelling mires, including SIMGRO (Querner, 1988), and SHETRAN (Parkin, 1996).

In the USA, DRAINMOD has been used extensively to model wetland situations. 'It can be used for those wetlands that are wet because they are poorly drained and the water lost by ET is less than that received from rainfall. The model does not treat those wetlands which are wet because of over-bank flooding from adjacent streams' (Skaggs, pers comm., 1998). That does not mean to say it cannot deal with surface water, and it has been applied to assess both the impact of peat mining (Gregory *et al.*, 1984, Konyha *et al.*, 1988) and the hydrological and hydrochemical potential of wetland buffer zones (Chescheir *et al.*, 1988), in areas with strong surface water regimes.

Also developed in the USA, MODFLOW has apparently been applied less to mire situations, although it has been used in attempts to integrate ground and surface water behaviour (Yan-Jiansheng & Smith, 1994). In the UK, Bromley and Robinson (1995) applied MODFLOW to areas of Thorne Moors, Yorkshire, and were able to use the calibrated model to assess the various scenarios resulting from the creation of buffer zones between peat-cutting areas and the National Nature Reserve. They draw the conclusion that the model output accuracy is limited by the accuracy of the input parameters, which in turn require more attention. MODFLOW was also applied to Wedholme Flow, Cumbria by MacAlister (1996); however calibration of model parameters proved difficult in this case, and it was concluded that the model could only be considered a good estimate of hydrological behaviour if a more appropriate method for measuring hydraulic conductivity *in situ* (the piezometer method was applied - Dielmann and Trafford, 1984) could be designed, and if evapotranspiration could be assessed more accurately. However, the main problem encountered during the modelling process was the lack of representation of surface flows.

The SIMGRO model, although focussed mainly on the (saturated) groundwater system, also simulates the unsaturated zone (over homogenous subregions of an area), and

surface flows. It has been applied to a bog reserve in the Netherlands, to try to determine potential bog areas from assessment of downward seepage by subdividing the area into peat thickness classes (van Walsum and Joosten, 1994); however, this work only considered downward water movement, and the critical area of lateral runoff was not addressed. SHETRAN, developed at the University of Newcastle upon Tyne based on the SHE catchment model (Abbott *et al.*, 1986), simulates integrated three-dimensional variably-saturated (i.e. saturated and unsaturated) subsurface flow and surface water flow, including plant-soil interactions, and has been used in a number of studies involving groundwater-surface water interactions.

Three problem areas then emerge within the context of trying to construct and test a whole system hydrological model for peat mires, for which better process understanding is required: surface water, hydraulic conductivity, and evapotranspiration, the most neglected of these being surface water.

ELEMENTS OF A MIRE WATER BALANCE - PREDOMINANCE AND MODELLING POTENTIAL.

Hydraulic Conductivity

Investigation of the movement of water throughout wetland bodies has to date concentrated mainly on estimates and measurement of groundwater movement, represented largely by the hydraulic conductivity (K) of peat, both saturated and unsaturated. There is no doubt that the potential for subsurface flow through peat of varying permeability, is critical to mire water balance. Over the last 50 years, since Kirkham (1946) proposed his field method for recording permeability below the water table, an extensive body of work, produced both in North America and Eastern and Western Europe, has been published concerned with the measurement and calculation of the hydraulic conductivity of various peats: Boelter (1965), Paivanen (1973), Bavina (1974), Rycroft *et al.*, (1975), and Galvin, (1976), to name only a few of the many published papers which could be seen to develop Kirkham's 'auger hole' method. Even before Kirkham's publication and the subsequent development of his methodology for peat hydrology, work based on very similar principals was published in the Soviet Union by Erkin (1937, 1940), while the earliest published K values that could be found were those of

Malmström (1925), given for various peat substrates (earlier still, Aiton (1811) discussed the 'close and compact nature' of 'moss-earth'). It would be inappropriate in this context to discuss their findings in detail, but suffice to say that what all studies have in common is extremely low recorded values of saturated hydraulic conductivity, ranging from 0.0086md^{-1} for highly decomposed moss peat (Romanov, 1968), to 0.12md^{-1} for moderately decomposed moss with woody fibres (Boelter, 1965). In contrast, considerably higher values have been recorded in the undecomposed surface *sphagnum* layer, for example 346md^{-1} (Boelter, 1965).

Many factors may influence low recorded values, including inappropriate modes of measurement, those employed being originally designed for mineral substrates of very different physical properties to peat, and also emerging areas of investigation such as the influence of gas accumulation within the pore space (Baird *et al.*, 1997). However, the obvious conclusion to be drawn from the low subsurface conductivity of such high recharge regimes, is the prevalence of surface- and near surface-water processes (within the seasonally unsaturated acrotelm), yet it is this element of the water balance which is the most poorly understood and quantified.

Evapotranspiration

An important component of the water balance of mires is the water loss through evapotranspiration, which is intimately linked with surface conditions. Evapotranspiration includes evaporation from bare soil, vegetation surfaces, and open water as well as transpiration by vegetation. In general, evapotranspiration rates are controlled by atmospheric conditions as well as plant physiology, the physical nature of evaporative surfaces (soil, vegetation, or open water), and soil moisture content (Ward and Robinson, 1990).

The main methods in standard practice used for measuring evapotranspiration include lysimeters, evaporation pans, water balances, soil moisture changes, and semi-empirical formulae using meteorological data (Maidment, 1993). In a research context, laboratory studies of individual leaves may also be used (Crundwell, 1987). Weighing lysimeters are the most direct method of measuring evapotranspiration, and have been used for peat soils at an upland site in the Balquidder catchments (Wright and Harding, 1993), although this study was for a grassland site on

a hillslope. Lysimeters with open bases have been used for wetland sites (Gilman, 1994) - these were considered to be more practical to install under saturated conditions.

In mires, water availability is often assumed not to be a limiting factor, so that evapotranspiration occurs at the potential rate. Many studies have related evapotranspiration from vegetated mires to open water evaporation. The ratio of actual evapotranspiration to open water evaporation can exceed unity, due partly to differences in the surface area and aerodynamic resistance of vegetated and open water surfaces (Crundwell, 1987). The conclusion that evapotranspiration from bog Sphagnum can be higher than open water evaporation; provided supply is not limited, was supported by Schouwenaars (1993). However, in drier conditions, actual evapotranspiration can be reduced significantly when the water table falls. Schouwenaars (1992) noted from lysimeter studies that Sphagnum, which has no root system, depended upon water supplied by capillary rise when the water table level was only 10 cm below the ground surface, and tended therefore to dry out and act as a mulch, whereas plants with a root system continued to transpire at close to the potential rate.

Surface Water

Ponding of surface water, a common feature of all wetlands, occurs when the rate of infiltration of water supplied to the 'soil' surface is exceeded by the rate of supply and when groundwater flows converge in an area of seepage. The rate of infiltration into soils in general was considered by Childs (1969) to be affected by the surface hydraulic conductivity and prevailing hydraulic gradient, reflecting conditions throughout the soil profile. The rate of infiltration under constant intensity rainfall is not constant, but decreases over time as the soil becomes saturated near the ground surface (Hillel, 1982), leading to 'infiltration excess' surface water. The infiltration rate may also be affected by the accumulation of gas within pore space, by the migration of pore blocking particles, and by 'surface-crusting', all processes likely to occur in wetland situations. But the most obvious reason why the rate of infiltration may reach a negligible level and ponding occur at a mire surface in particular, is due to 'saturation excess' when the water table reaches the surface (due to precipitation or a groundwater source), the soil pores being fully saturated, and the subsurface soil hydraulic conductivity being so low that little saturated

flow takes place (demonstrated by the low recorded hydraulic conductivities).

Devito *et al* (1996) note the functional importance of surface flows in valley mires with high water tables; it is clear that once the water table reaches the surface, the rate of surface flow will overtake that of subsurface flow through the peat, being by far the 'easiest' route for water to take. All flow follows a 'pressure head gradient', moving along an energy grade line (Ven Te Chow, 1959) from high potential to low, but as subsurface flow is subject to additional frictional and adhesive stresses, which require energy to overcome (Hillel, 1980), such flow requires a greater head than the flux of an equivalent volume of water at the surface. In wetlands with organic soils of characteristically low recorded hydraulic conductivity, particularly close to the surface, the situation is exacerbated. The hydraulic behaviour of the seasonally unsaturated acrotelm, will of course also depend on characteristics such as length of saturation period and hence degree of decomposition of organic material, compaction, and other local site considerations likely to determine the porosity and hydraulic conductivity of the layer.

In the application of MODFLOW to the hydraulic behaviour of Wedholme Flow, Cumbria (MacAlister, 1996), the recorded hydraulic conductivity was so low (geometric mean of 0.013 md^{-1} within the acrotelm, defined by lowest annual water table as 0-0.5m from surface; geometric mean of 0.008 md^{-1} within the catotelm) that the head gradient calculated by the model in order to maintain a steady state over a 140m transect was 0.154 (head range from 6m to 916m). As such heads are impossible the only conclusion to be drawn from this scenario is that the majority of flow is not occurring within the peat, but is predominantly overland.

Accepting that for the long periods of time the water table is at the surface in many mires, flow will then be predominantly shallow surface flow, via transient pool and channel networks, through submerged and non-submerged vegetation. This situation, with flow occurring within the microtopographical landscape of a mire surface, in patterns determined by both rising water levels resulting in the creation of an open channel network, and by the prevailing hydraulic gradient, is illustrated in Figure 2.

Figure 2 shows one possible scenario as the water table reaches the surface and water begins initially to pond (Figure 2b - water level is 5cm above datum), then as ponded depth

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increases pools become channels and flow occurs down the hydraulic gradient (Figure 2c - 10cm above datum), and for sufficiently intense storms the flow may approach two-dimensional surface runoff (Figure 2d - 15cm above datum). This is a process which can be readily observed in the field, but is not easily quantifiable. As the position of the free water surface changes both in space and time, the flow conditions within the transient 'channel' network, and in fact the dimensions and properties of the channels themselves, such as roughness, also change. Moreover, the boundaries of the channels are themselves porous, consisting as they do, of mainly living vegetation, so that, as Feng and Moltz (1997) point out, flow in this low velocity, high resistance situation, is more akin to diffusion or flow in a porous media. Although this diffusional flow accounts for a proportion of total flux, equations of flow through a porous media, essentially derivations of Darcy's law, cannot be applied to calculate flow with a free water surface. The surface fluxes in question are more properly described as flow through a vegetated channel. These microtopographical flows must be aggregated up to the macroscopic scale for use in full-scale models of mires. One possible method was presented by Spiksma and Schouwenaars (1997), who represented 'small-sized mosaic patterns' of

open water in wetlands using a quasi two-dimensional diffusion-based model based on fractional areas of inundation and non-inundation, and concluded that problems still remain in such modelling due to lack of information on depression storage and resistance to movement of surface water through surface channels and aquatic vegetation.

The standard approach to calculating flow in an open channel, is to apply a solution such as the Manning Formula, which includes a roughness coefficient, traditionally applied to turbulent open channels, and extended more recently by Abdelsalam *et al.*, (1992), for use in wide, vegetation clogged channels. Turner and Chanmeersi (1984), formulated an alternative relationship for shallow flow through non-submerged vegetation, which Feng and Moltz (1997) believe to be more sympathetic to their own diffusional concept than the Manning equation. Their WETFLOW model (Feng & Moltz, 1997) is a transient, two-dimensional, diffusion based surface flow model, which incorporates zero flow conditions, and transient, irregular internal boundaries - factors previously missing from existing models. It does not, however, include evapotranspiration, precipitation, or infiltration.

FIGURE 2 Schematic representation of rising surface water levels and surface water flow through a hummock-hollow complex over three time steps (t_{1-3}).

Fig. 2a Microtopography (5cm contours)

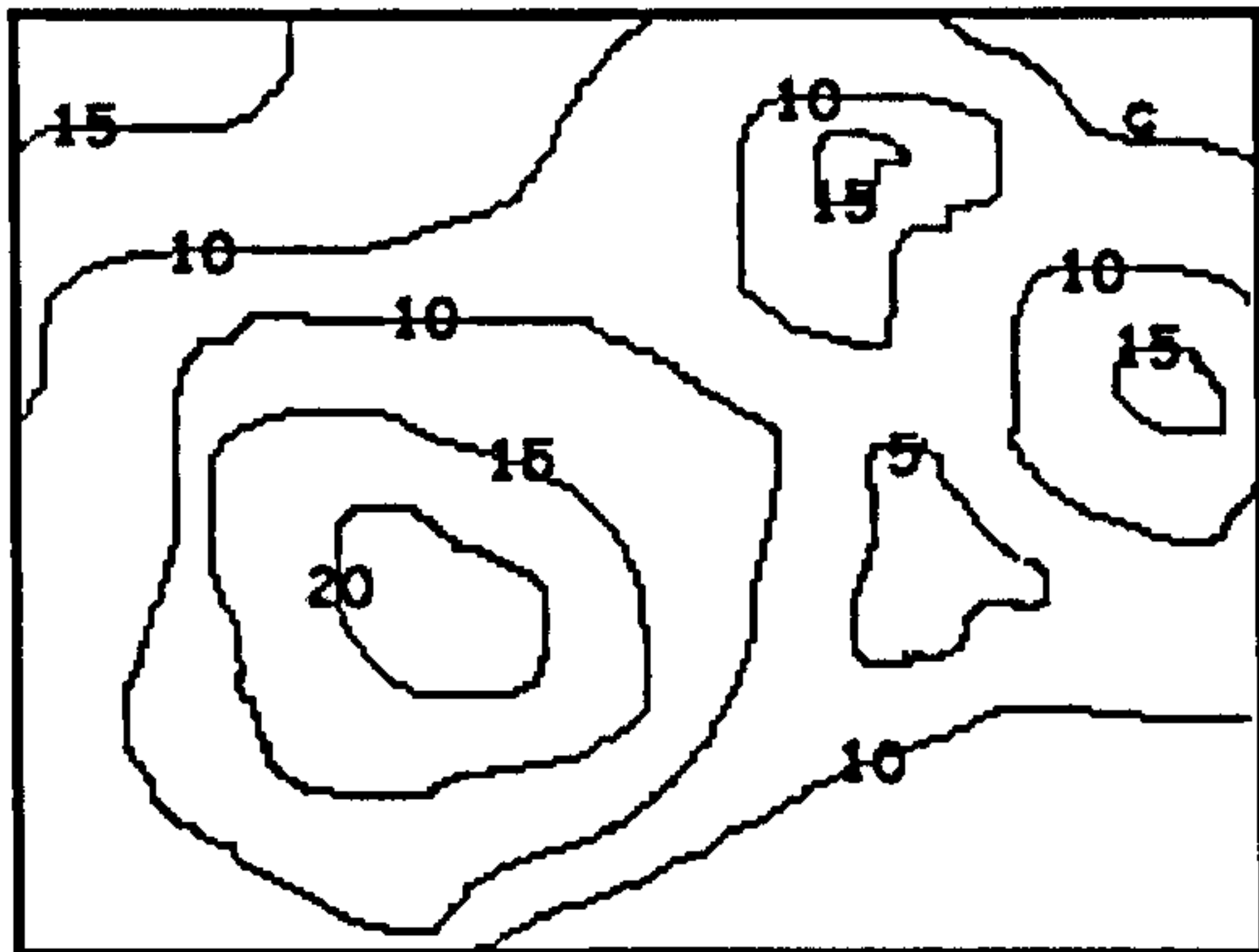


Fig. 2b Surface water level, t_1

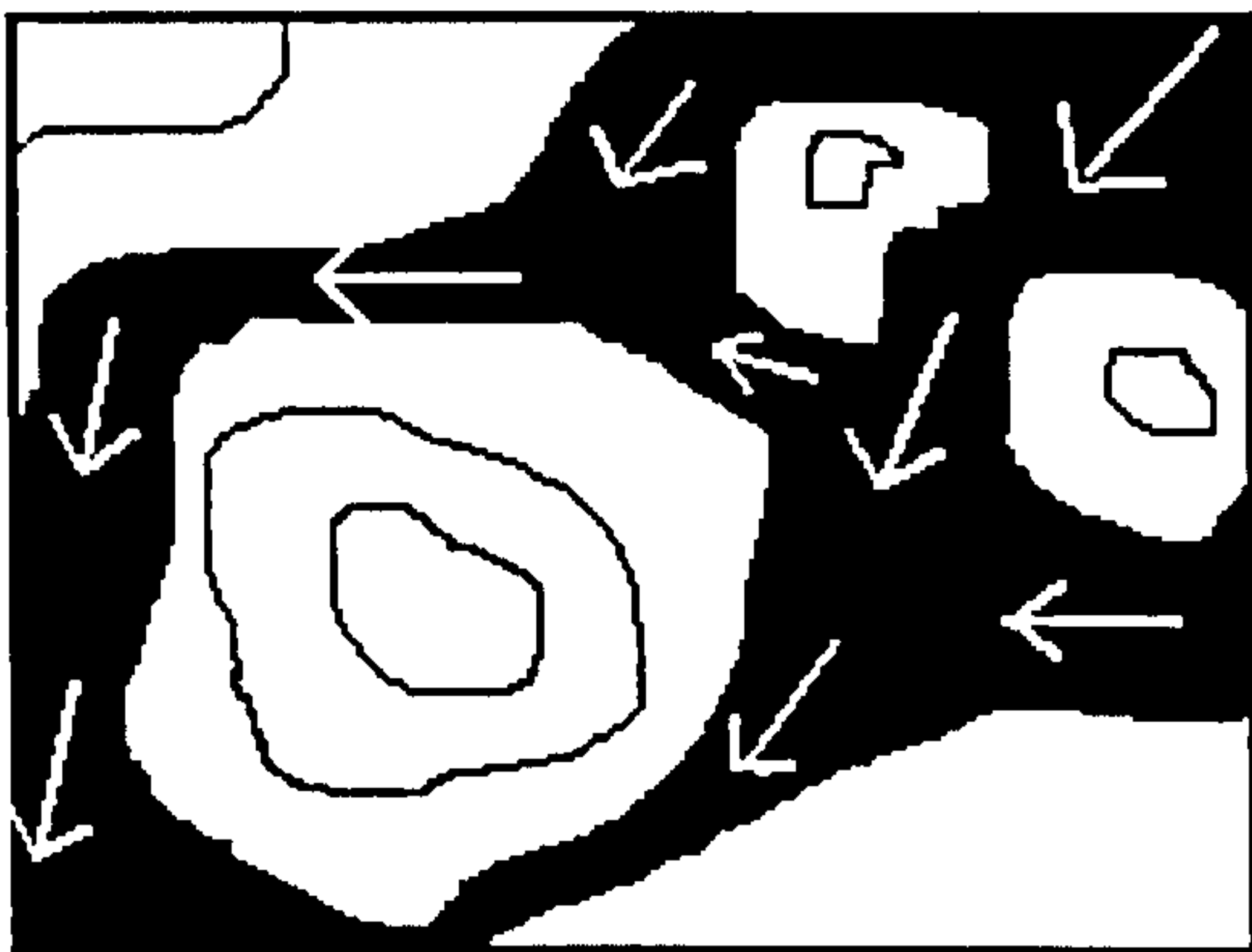
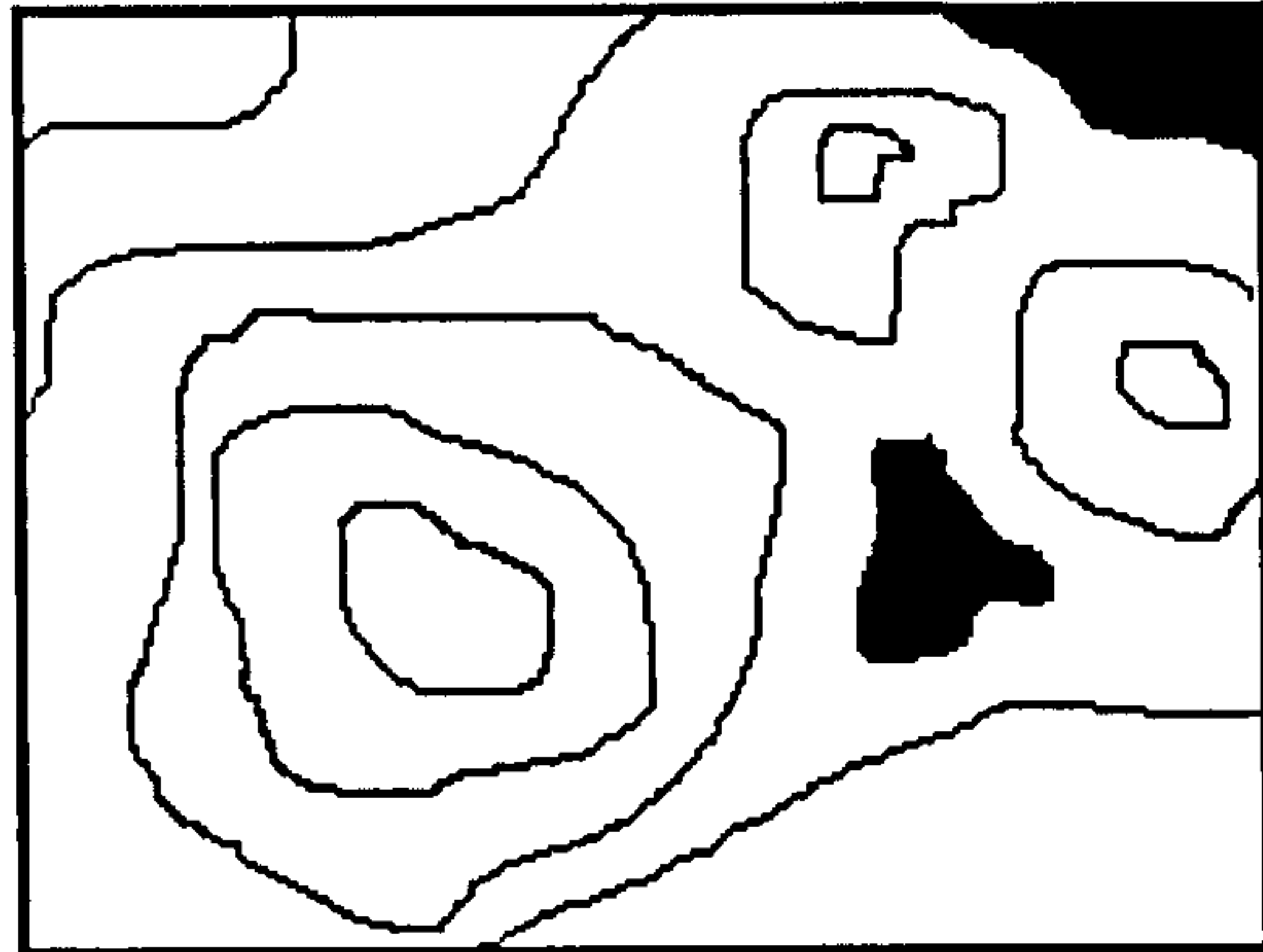


Fig. 2c Increased surface water level - surface flow as pools link, t_2

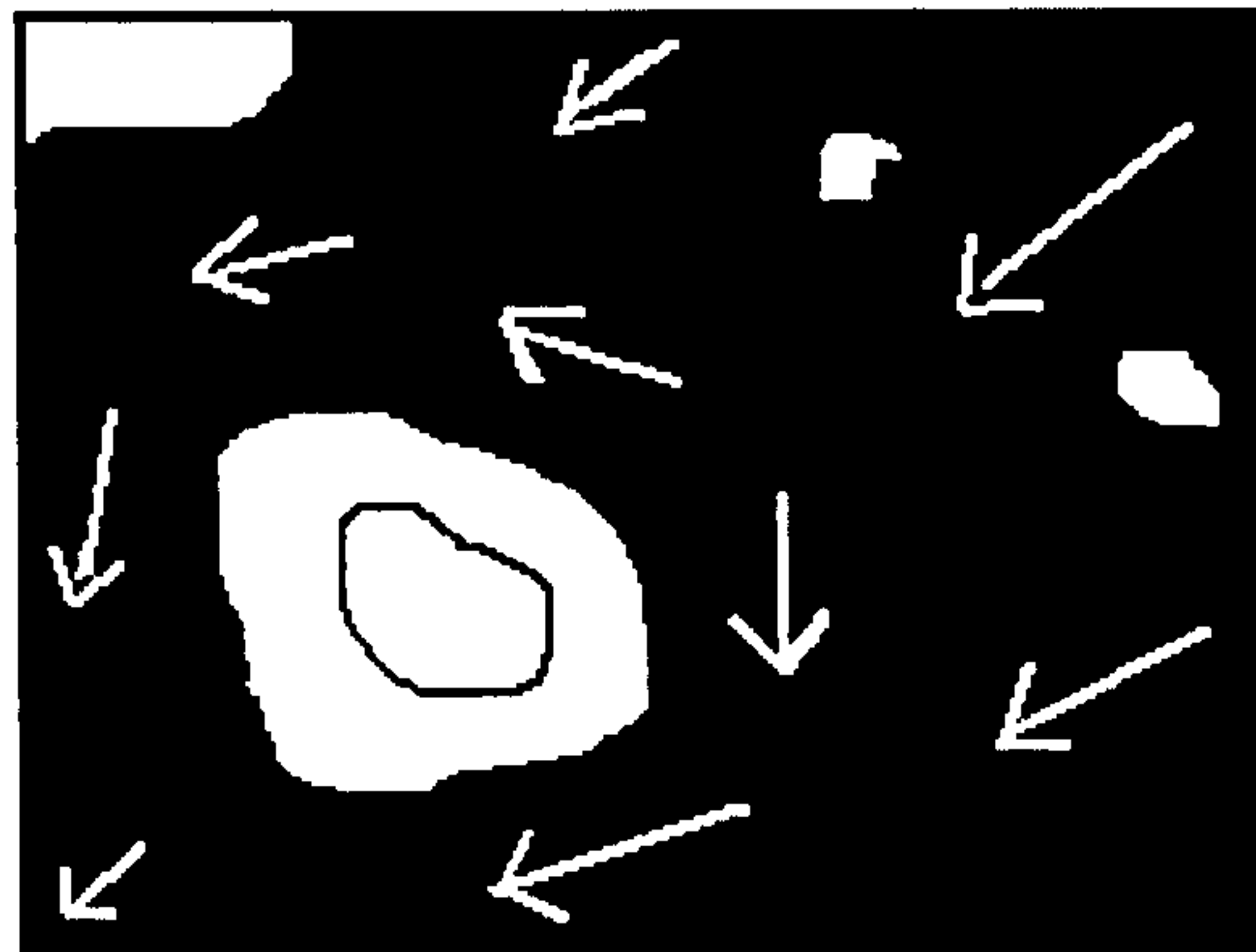


Fig. 2d Surface water level and flow, t_3

← **HYDRAULIC GRADIENT** ←

CONCLUSIONS

We have discussed the main areas of current research in mire hydrology, and have argued for a move towards the development of integrated models which include both surface and subsurface processes. The development of such a 'whole system model' for peat mires is made difficult by the lack of understanding of physical processes, particularly those at or near the ground surface. Studies aimed at improving understanding in this area depend upon an appreciation of the different time-scales and spatial scales within which surface and subsurface systems interact. A correct representation of water flows at the appropriate scales in models (particularly the micro-hydrology of the pools and hummocks within which different species thrive) is important not only for peat mire hydrology, but is critical for

the development of an understanding of the interactions between hydrology and ecology, for both flora and fauna; this intrinsic link between physical and biological processes remains almost entirely neglected.

Until accurate quantitative and qualitative measurement of surface water processes receives the attention it deserves, and until predictive scenarios of such processes can be validated, large scale expensive wetland management projects will remain subject to trial-and-error methods, rather than being based upon a thorough scientific basis, and progress towards understanding the ecology of peat mires will be less fruitful than it could potentially be.

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FIELD STUDY OF SWAMPS AND WETLANDS

Charlotte MacAlister, Research Fellow, Centre for Land Use and Water Resources Research, University of Newcastle-upon-Tyne, UK.

Summary

The main aspects of hydrological monitoring of a wetland system are outlined within the framework of an idealised water balance for a generic wetland type. The importance of clear design criteria and project objectives is discussed. Detailed advice is given where appropriate, on the construction and operation of field test equipment, and sample data from the monitoring strategies described are presented. Some established and some more experimental techniques are described, while the focus of methodology is operation and application with limited facilities, budget and personnel. This approach is favoured rather than extensive discussion of every technique, which given the rate of developments in this ever expanding field would be impossible.

Keywords: wetland, swamp, mire, bog, peatland, hydrometry, hydrological monitoring, wetland hydrology, restoration, rehabilitation, precipitation, rainfall, evapotranspiration, evaporation, transpiration, lysimeter, watertable, recharge, subsurface flow, groundwater flow, piezometer, surface water flow, hydraulic conductivity, infiltration, surface water, weir, flume, water quality, maintenance,

Glossary:

Acidic: pH < 7 (base poor)

Aerobic: in the presence of molecular oxygen.

Alkaline: pH > 7 (elevated concentration of base cations, hence usually more nutrient rich).

Anaerobic: anoxic condition; absence of molecular oxygen; oxygen not freely available to chemical or biological processes usually due to water-logging.

Anthropogenic: development or genesis influenced or instigated by human input or interference.

Blanket Bog: often extensive mire, forming by peat accumulation over undulating terrain in response to very humid climate and reduced rates of decomposition of organic matter, therefore often widespread at high altitudes and where temperature is low and precipitation high.

Cut-over: mire surface disturbed by peat removal often to depths of 10m or more.

Drawdown: depression in water level adjacent to pumping wells, drain or steam channels, where the direction of water movement (or hydraulic gradient) is influenced by a fall in hydraulic head.

Eutrophic: mineral (nutrient) rich.

Fen: minerotrophic mire, sometimes divided into poor fen (acidic) and rich fen (slightly acidic to alkaline).

Fen Carr: fen with scrub or woodland.

Hollow: a depression between hummocks, periodically inundated forming small pool complexes with associated vegetation (often referred to as hummock-hollow complex).

Hummock: a mound formed by growing vegetation, where species are largely determined by local watertable. Dominant species usually bryophytes such as Sphagnum sp. (often referred to as hummock-hollow complex).

Hydrometry: measurement and monitoring of hydrological characteristics.

Intact mire: mire which has not been disturbed hydrologically by human intervention.

Lagg: Stream or phreatic zone at the margin of a peatland, often exhibiting enhanced nutrient status and associated vegetation due to accumulation of nutrients leaving the mire and a lowered watertable due to drawdown by drainage channels.

Mesotrophic: intermediate mineral (nutrient) status (see Oligotrophic and Eutrophic)

Microtopography: small scale variations in surface elevation such as hummock-hollow complex.

Minerotrophic: nutrient status influenced by groundwater inputs previously percolating mineral substrata - may be eutrophic, mesotrophic or oligotrophic.

Mire: a peatland where peat is currently accumulating. Often used to refer collectively to swamp, bog, fen, moor, muskeg and peatlands in general.

Oligotrophic: mineral (nutrient) poor.

Ombrotrophic: precipitation only water and nutrient supply - therefore typically oligotrophic.

Ombrogenous: peat formed under ombrotrophic conditions.

Peat: unconsolidated soil type formed by the accumulation of partially decomposed plant material, deposited under saturated conditions, consisting of a minimum of 30% (dry weight) organic matter.

Peatland: peat-covered terrain including but not exclusively, swamps, bogs, and fens.

Raised Mire: ombrotrophic bog with convex cupola (or domed central zone). May form over undulating terrain but mire surface does not reflect underlying topography.

Swamp: may be used to describe peat and non-peat forming wetlands of varying pH and nutrient status from mire to marsh, but often refers to wooded mire types with minerotrophic inputs.

Wetland: (1.) Area of land covered or saturated, temporarily or permanently, due to natural or human influence, by a depth of water, static, flowing, fresh, brackish or salt, not exceeding 6m (at low tide in the case of marine habitats) - Ramsar definition. (2.) An area saturated or inundated by ground or surface water at a frequency or duration sufficient to support under normal circumstances a vegetation assemblage typically adapted to saturated soil conditions - US Army Corps of Engineers definition.

1. Introduction

Hydrological monitoring of wetlands (hydrometry) is the regular recording of a parameter indicative of a hydrological process, and the interpretation of the resultant data set in order to characterise that process. Across the globe there are no two identical wetlands. Morphological and anthropogenic influences on the vast range of wetland sites world-wide are likely to be equally diverse, as are the scales of hydrological processes within wetland systems, the proportion of open water to terrestrial habitat and the reasons for embarking on a monitoring program. It follows that in order to be effective the monitoring strategy employed at any site should be specific to that site. Before embarking on any program of hydrological monitoring, the aims and objectives of the program should be clearly identified. The success of a monitoring scheme will be dependent on both the effectiveness of design and on maximal utilisation of the data collected.

Figure 1 illustrates a potential distribution of the major hydrological processes to be monitored within an idealised wetland system. The inset to Figure 1 indicates the potential range in scale of hydrological processes within a wetland. The micro-relief within a 1m quadrat has been mapped on a 0.05m grid, revealing a range in topography of 0.28m over 1m², so that at the given watertable (at datum) approximately 50% of the area is occupied by open water.

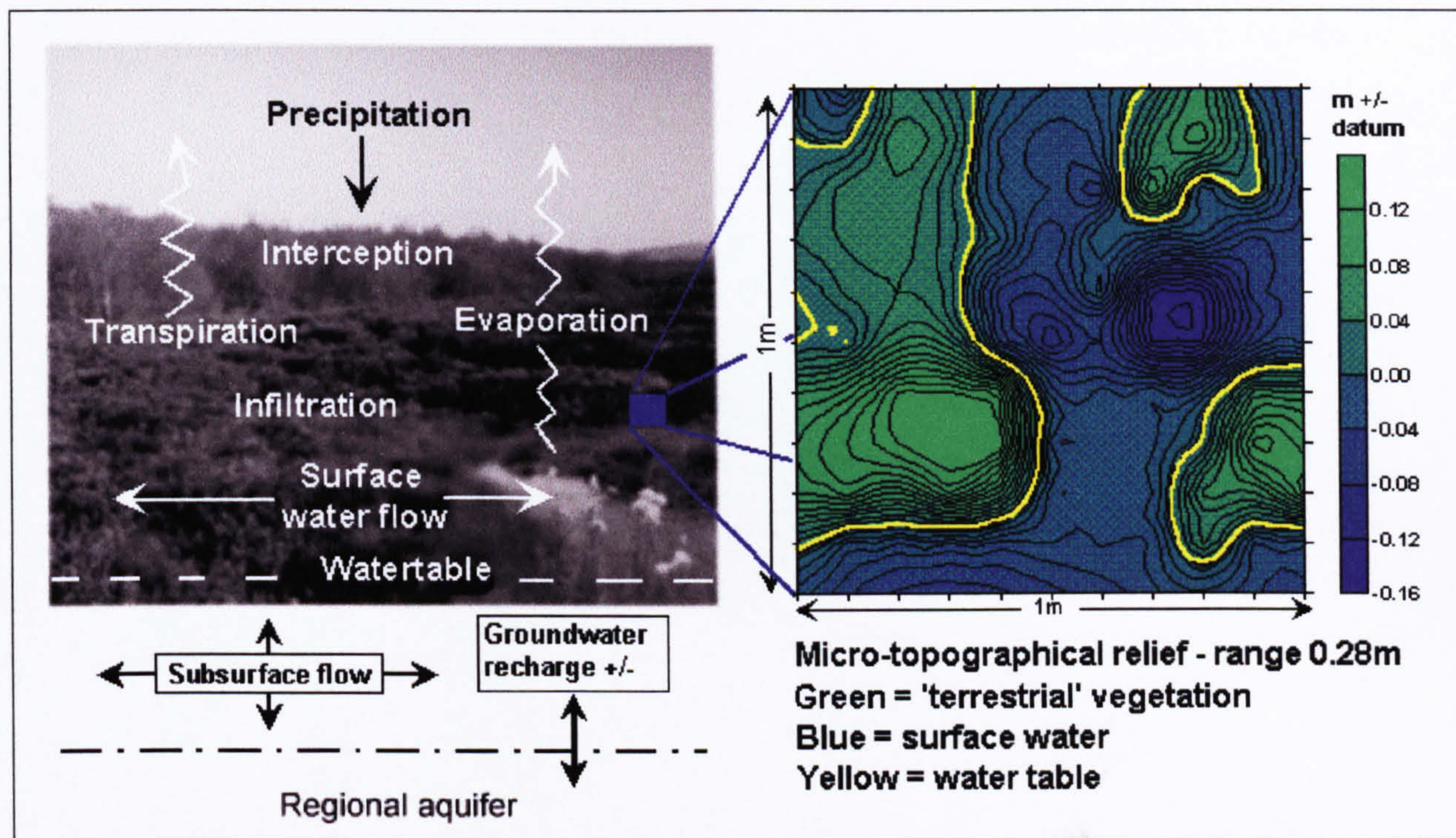
Equation 1. Wetland water balance:

$$\Delta S = P - ET \pm SS \pm GW \pm SW$$

where: ΔS = change in water storage
P = precipitation (rain and snowfall)
ET = evapotranspiration (combined evaporation and transpiration)
 $\pm SS$ = subsurface flow in and out of the wetland
 $\pm GW$ = groundwater flow in and out of the wetland
 $\pm SW$ = surface water flow in and out of the wetland

Equation 1 provides a simplified analytical model of a wetland water balance. The components of this simplified model will of course vary considerably between sites, and it is these differences in the wetland hydrologic cycle, along with regional biological and geochemical conditions that define site characteristics, from blanket bog and raised mire, to fen and swamp. This simple model provides a framework within which to illustrate some of the methods that can be employed to monitor wetland hydrological processes. Each element of the water balance will be addressed in turn in Section 3, Monitoring Methodologies.

Figure 1. Large and small-scale wetland water balance. Inset: 1m² quadrat showing micro-topographical relief and potential for areas of open water within the undulating surface.



Temporal and small-scale spatial variations in hydrological processes are not immediately evident in the water balance model described by Equation 1. In order to achieve meaningful outputs towards the project aim, the time available for monitoring and the pace of individual processes should be considered carefully. For example, where restoration or rehabilitation of a degraded system is a long term management aim, details of seasonal fluctuations in water levels across an entire site may be an objective, whilst the discharge rate of one particular drain during a storm event may be an additional objective on a different spatial and temporal scale. Where a site is contaminated and has potential for groundwater discharge, the conductivity and head differentials in subsurface layers may be of particular consequence during periods of maximum potential evapotranspiration, in addition to any diurnal fluctuations in water levels due to evaporation or the influence of tidal regimes. It may be necessary to establish at a particular site the distribution of inputs between groundwater and near surface or rapid overland flow. Whilst such flows may be simultaneous they occur at very different rates, therefore inputs and outputs which may be measured or calculated at different spatial and temporal scales must be integrated to be useful. Additional scale considerations arise when functional links to ecology are also a concern. The effects of disturbance for example, may only become evident over several seasons, whilst functional links operating on a micro-spatial scale (Figure 1: inset), such as establishment of typical vegetation assemblages, may develop over meso-time scale.

2. Planning a monitoring scheme.

In addition to systematic differences in temporal and spatial scale of hydrological processes, the required degree of accuracy of any measurement should be determined at the outset of any monitoring program. This will usually be dictated by the project aims and budget, but should none the less, receive scrutiny. Correctly calibrated electronic sensors and automated data-logging equipment can be accurate to fractions of a millimetre, but can be expensive and may produce data that will not be utilised. Manual readings may be more suitable where required recording frequency is less intensive, but may be less accurate, introducing operator error as well as potential hydrological and ecological disturbance. In sensitive areas it may be more appropriate to install equipment that need only be visited bimonthly avoiding for example, bird nesting and breeding seasons, and reducing trampling which may influence the local hydrological regime. Differences from site to site can be extreme - in some cases access may be by boat only, in others it may be necessary to construct a boardwalk, whilst in many sites only rubber boots may be essential!

When designing a monitoring program for any wetland:

- Project aims and objectives, both short and long term should be clearly identified.
- The required temporal and spatial scale of any parts of the monitoring network must be determined prior to implementation.
- The appropriate degree of accuracy and measurement scale of any instrumentation should be agreed.
- Suitable monitoring methodologies and equipment should be identified within the limitations of budget and habitat constraints including access and disturbance.
- Collation and analysis of resultant data should be ongoing so that appropriate changes to monitoring strategy can be made.
- Utilisation of data sets must be maximised otherwise both time and money will have been wasted!

Not all projects will involve whole site monitoring or even be new programs, so care should be taken to examine existing site data. In some cases, it may be appropriate to utilise existing equipment and networks. This can save time and money, and may highlight areas which require more investigation or pre-empt problems which could arise during monitoring.

3. Monitoring Methodologies

The following sub-Sections describe the established practices used in the field monitoring of processes included in Figure 1 and following the sequence of Equation 1. Some more experimental methodologies have also been included, but in an ever-expanding field of research, many techniques have been omitted. This guide is not an exhaustive manual but is intended to highlight a range of monitoring methods with potential for adaptation to many different situations. Much of the equipment below can be constructed at a low cost with basic facilities, and all of the methods can be adapted according to monitoring objectives. Where available, example results or data outputs obtained at wetland field sites using the methods described are presented.

3.1 Change in storage and water level fluctuation

It makes sense to begin investigations of hydrological flux within a wetland site by examining visible changes in water stored within a site. All wetlands have, by definition, a watertable that may be confusingly referred to as high or shallow, meaning at, near or above the ground surface. The actual position of the ground surface may be ambiguous, and may be arbitrarily considered the vegetated surface, or more usefully defined by reference to a fixed datum point. As the surface may itself be subject to fluctuation, especially where soils are predominately organic (peat), the relationship between the observed surface and the water level within the wetland at any time may not be a meaningful hydrological parameter. The height or elevation of the watertable is then most practically described by its level relative to a fixed datum, often outside of the wetland itself, and frequently the regional ordnance datum.

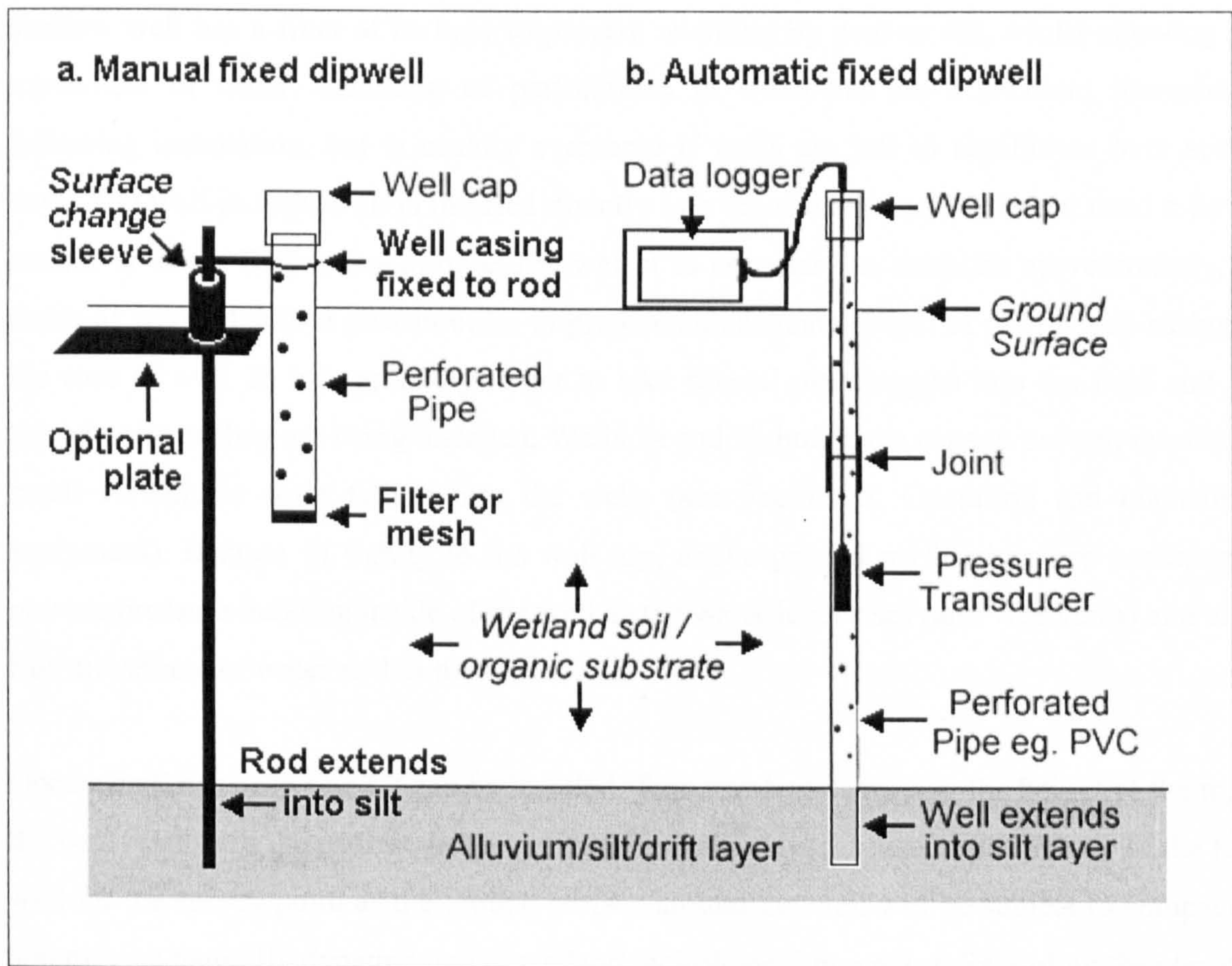
Water may be stored within the porous matrix of the wetland substrate, as open water in natural or man-made pools of varying scales (Figure 1), and in streams or drainage channels. The relationship between soil properties and changes in water storage will be explored further in terms of the specific yield (3.1.3), and subsurface flow (3.4). Water is also contained within the structure of the vegetation but this contribution will usually be ignored and is beyond the scope of this topic. However water is stored, by observing fluctuations in its apparent level the effects of inputs or outputs from the other components of the site water balance (Equation 1) can be characterised and this is addressed initially in Section 3.1.1. Whilst the spatial and

temporal range of interest in water level fluctuations will be specific to each site and program aim, it should be kept in mind when considering possible water level monitoring strategies. In particular this applies to the form of data required and this is discussed in Section 3.1.2.

3.1.1 Recording water levels in dipwells

Observations of fluctuations in the elevation of watertables, seasonal or shorter term, are usually made by recording the level in a dipwell, which may be inserted into the substrate or positioned in open water and channels. Open water level may also be recorded with a fixed staff-gauge, effectively a large rule that maybe read from a distance, then related to datum.

Figure 2. Two types of fixed dipwell



Figures 2a and 2b illustrate two types of dipwells. In both types, a perforated well casing is required to prevent the collapse of the well cavity. This can be metal or plastic. Plastic is probably the most versatile, being light and easy to transport, relatively easy to perforate with an electric drill or handsaw, and cut to length, whilst it is also strong enough to withstand the pressure of insertion. In addition, many gauges of pipe, especially the type used in household plumbing applications have standard fittings such as joints and caps, which may be either screw and push-fit, or solvent-weld (requiring glue). All of these are easy to assemble in the field.

Both wells in Figure 2 are fixed to the firm, underlying material. This is particularly important where there is a potential for considerable lateral flow or movement in the ground surface. As wetland substrates consist largely of water, they can exhibit a high degree of buoyancy, so that submerged equipment can float to the surface particularly if equipment internal cavities contain air. The well in Figure 2a is anchored to the underlying material by a metal rod to which it is fixed above the surface so that it can be removed and cleaned if necessary. This shallow well has a filter at its base to prevent in-filling by peat or silt, whilst allowing free movement of water. Blocking of perforations in wells can be a problem immediately following installation, but is usually overcome if wells are left to equilibrate over several days. The well in Figure 2b is inserted directly into the substrate and does not need a further anchor or filter. Before installing either well it is necessary to establish approximately, the depth of wetland soil or peat in order to prepare an adequate length of rod or well casing. In the case of well 2b it is probably easier to take several pipe lengths into the field and join them in-situ as they are being installed. Wells 2a and 2b both have caps to prevent insects and small vertebrates from falling into the wells (see Section 5. Operating and maintaining equipment). If these fit tightly to the well top, above ground perforations are necessary to prevent pressure building inside of the well as the water level rises (and vice versa) and allow free movement of water within the well.

Once a well has been fixed it can be levelled. This involves surveying the height of the top of the well relative to the nearest datum point. It is established practice to use the top of the fixed well for the survey point as the ground surface around the well will be subject to compaction and may be naturally dynamic due to wetland hydrological processes. Recording the elevation of the well top relative to a known datum allows direct comparisons with water levels in other wells. Often the nearest fixed datum point which may be located on a permanent feature may

be some distance away. Care must be taken when using traditional levelling techniques to relate fixed points to datum and closure errors must not exceed acceptable limits. Surface movement during surveying can introduce large errors. Developments in Global Positioning Systems (GPS), which use satellites to locate the surveyor in the horizontal and vertical plane, usually via a hand held unit and a manually located base station, are expected to increase in accuracy and become more accessible to a wide range of users in the near future. The removal of selective availability of signals, imposed ostensibly for military security reasons, is likely to accelerate development of satellite data utilisation. Whilst the accuracy of some currently available GPS systems may be limited, they remain far less time consuming and labour intensive than traditional levelling techniques. The range of error in elevation produced using remote sensing techniques has also fallen considerably in recent times, and its accuracy is expected to continue to improve in the near future, providing a viable alternative to manual surveys of remote wetland areas.

When the well level has been established regular recording of water levels can begin. Well readings can be either manual (Figure 2a), or automated (Figure 2b). Manual wells are usually read by inserting some form of water level sensor, attached to a measuring tape (flexible or rigid) into the well, and reading the distance from the top of the well when the sensor is activated. Sensors come in many shapes and forms, but are commonly some form of float-switch wired in series to a torch or buzzer with a small battery. These can be easily constructed, or purchased relatively cheaply. In some cases, it may be possible to use a narrow ruler or tape inserted into the well and observe at what level it touches the water surface. Whichever method is used, it should remain constant to maintain continuity of recording and reduce potential errors.

Automated wells contain a sensor or float. Sensors remain in-situ below the lowest potential water level in the well. Once inserted and allowed to settle, its level does not change. Sensors also come in various shapes, forms and degrees of accuracy, depending on the manufacture and project specification. The diameter of the sensor should be accounted for when well casing is installed, and pipe of internal dimensions adequate to accommodate the sensor used. Pressure transducers, which record a pressure head of water above a sensor diaphragm, are commonly installed as water level sensors within dipwells. It is necessary in such cases to make occasional manual readings of water levels within automated wells to relate the head above the sensor to depth below the well top. The pressure transducer is attached to a data

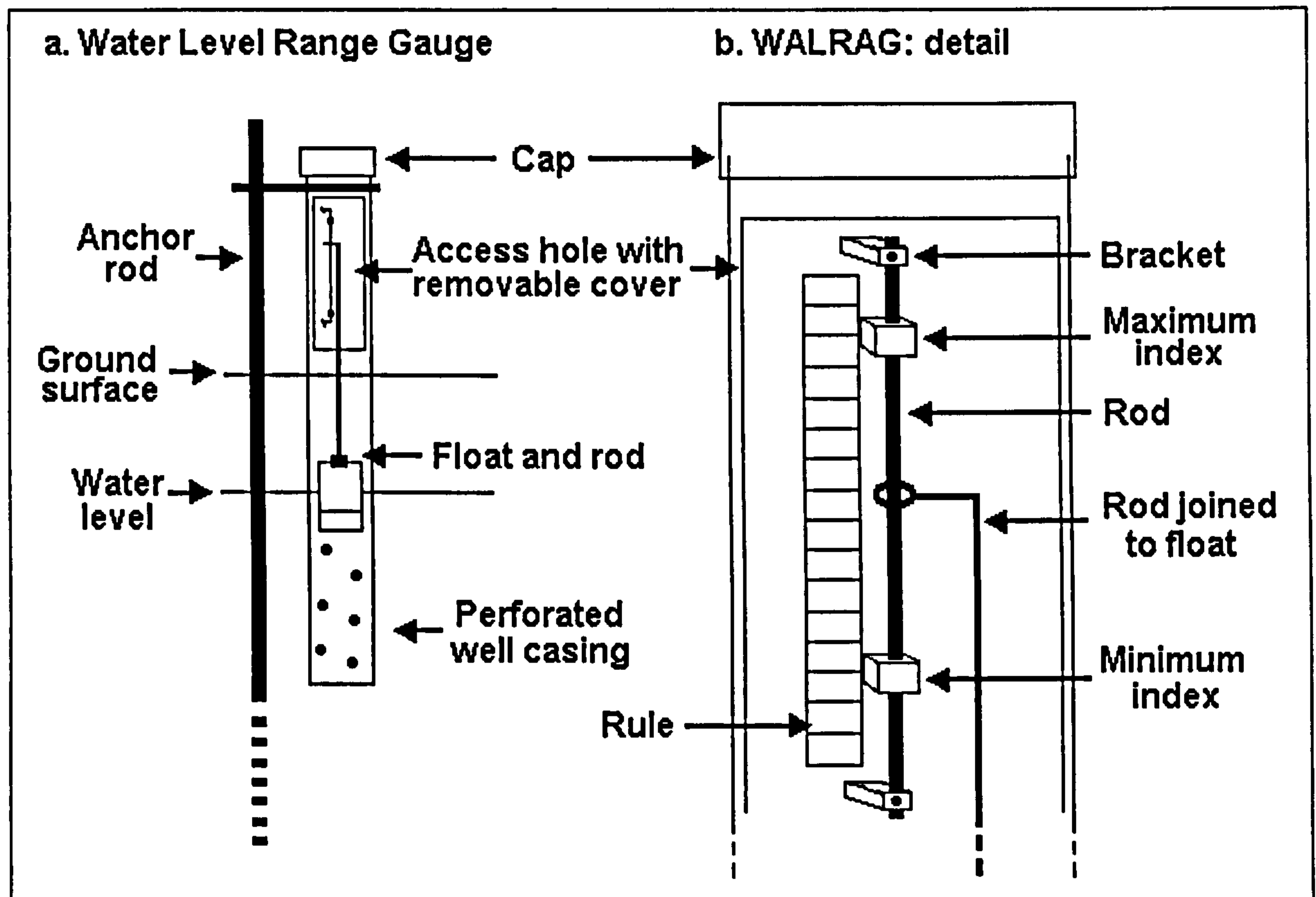
logger with a power source, which records the head, usually in metres of water, at user specified intervals. This is then downloaded in the same way as an automated raingauge (see 3.2 Precipitation). Floats resting at the water surface are usually attached to a pulley-wheel mechanism at the top of well. As the float rises or falls with the watertable, the wheel turns and the degree or number of rotations are recorded by a data logger and can be translated into change in water level. The degree of accuracy of the mechanism is usually determined by the diameter of the pulley-wheel.

A third type of well exists which could be described as semi-automated and is a kind of hybrid between manual and automated, although it requires no electrical equipment. The Water Level Range Gauge or WALRAG (Figure 3), developed at the University of Dundee and Macaulay Land Use Research Institute, Scotland, is an adaptation on the basic dipwell design (Figure 2). It includes a float, connected to rod with an arm that slides over a second rod. Threaded over the second fixed rod are two maximum and minimum level indicators, usually cubes of closed cell foam. The arm of the float rod moves up and down as the water level in the well changes, pushing the level indicators to the extremes of its range. The range of this movement is read from a rule adjacent to level indicators. The well should extend further above the ground or mean open water surface than a standard dipwell so that the reader can more easily view the level through the cut-away Section. The well casing diameter may also have to be increased to accommodate the float, rule and arm. In all other aspects, the WALRAG design is identical to a standard dipwell: it is easily constructed from perforated plastic pipe; it must be anchored into solid substrate; and it should be levelled to a permanent datum. The basic design can be easily modified to suite local conditions and available materials. It may be necessary to include an additional rod bracket to the float arm to prevent rotation within the well. Other potential adaptations include the accommodation the level indices within a track, in which the terminal of the float rod, enlarged with a nut for example, is also threaded (Figure 3b).

The water level in the WALRAG is read manually as any dipwell, or from the level indicated by the rod. Knowing the length of the float rod, this can be subtracted from the observed, minimum and maximum indices giving the range of the water level during the recording period, which can be related to other locations sharing the same datum. Where a WALRAG is located in a large pool, lakeshore or tidal area, the float and level indicators may be

susceptible to disturbance by waves. To prevent this the casing should not be perforated along its full length, but only some distance below the minimum water level.

Figure 3. Water Level Range Gauge – WALRAG.



The WALRAG is not of course truly automatic, as it is not capable of continuous recording and the current, minimum and maximum levels it provides must be recorded manually at the required frequency. However, where the range in watertable is required, for example diurnal fluctuation, the WALRAG provides a low cost, low maintenance solution with no battery and no additional computing equipment required.

In addition to the adjustments made to dipwells to record minimum and maximum water levels, dipwells can also be modified to monitor fluctuations in the ground surface. The well in Figure 2a has an optional submerged plate added to the anchor rod. The plate with a sleeve enclosing the anchor rod has been buried away from the well to minimise disturbance to the

watertable. If the rod top has been levelled then actual change in ground surface relative to an external fixed datum can be recorded.

3.1.2 Dipwell networks and recording frequency

We have stated that the response of the watertable observed in dipwells can be used as an indicator of increase or decrease in storage as a result of inputs or outputs of water to the wetland system. Equal in importance to the design of a dipwell, is the number and strategic positioning of well networks, and the recording frequency. The location of wells relative to each other and to features of hydrological importance, such as drainage channels or springs are critical in the planning of project design. Wells may be placed randomly, in a grid pattern, or in straight lines called transects. The regular spacing of wells can reveal hydraulic gradients, recharge zones and potential preferential flow patterns. For example, the zone of influence of a drain on the local ground-watertable may be examined, as could any subsequent effect of damming or blocking the drain at different depths. However, placing wells in regular patterns may infer linear relationships where these do not exist. Conversely, random distributions may miss linear relationships entirely.

Differences in recording frequency may also both reveal or miss patterns in hydraulic regimes. Daily, weekly or longer recording intervals may highlight seasonal or bulk variations in storage at a site, with the effect of rainfall mitigated by evaporation or overland flow for example. This form of data is often used to make assumptions about the stability of hydraulic regime at a particular part of a site, or to examine the success of restoration works. Where data concerning rapid processes such as the succession to overland low during a storm event, are required, then recording frequencies must be more intensive (3.5.2 Recording near-surface and surface water flow). Additional confusion may arise from misrepresentation of data sets. For example, where range in groundwater level is in question (say for establishment of certain vegetation species), are minimum and maximum levels over a given period or observed levels at a specified times required? These two types of data may become more useful by combination, say daily groundwater level observed manually at 09.00, with weekly minimum and maximum at the same location by some form of automated level (3.1.1 Recording water levels in dipwells). They should not however be confused – the lowest recorded level at 09.00 within a week of daily data is not the minimum water level during that period. It is the lowest level within the ‘observed’ data set. The range in water levels would be more accurately

described by data from a semi-automatic well (3.1.1 WALRAG) or a continuous water level recorder (3.1.1 pressure transducer) both giving the actual minimum and maximum.

There are no hard and fast rules concerning placement and reading of wells and so careful planning is needed to match these to specific project aims. An example of data collected using levelled dipwells is given in Figure 4a, in the form of a transect plot, with the actual ground surface and water levels recorded in dipwells. The x-axis of the plot represents metres from an intersecting drain, which was blocked after two years of data collection. In this case, the aim of monitoring was to identify any changes in groundwater levels in both intact and cut-over mire surfaces after management intervention. Plotting the watertable relative to datum shows that the watertable of the intact mire area remains close to the ground surface (the dashed line) throughout, and does not appear to be effected by the drain blocking in 1991. In fact, its lowest level during the recording period, in 1996, can be attributed to the particularly dry summer of 1995. In contrast, the watertable across the area of mire that was previously subject to large-scale drainage and peat removal, responds drastically to the blocking of the drain. Whilst the drain was functioning, the watertable here remained below the surface and largely followed the topographical pattern created by the mining process. Not surprisingly, in the months following the drain blocking the watertable rises dramatically, so that even following the dry summer of 1995, it remains at or above the surface along the length of the transect. Further investigations could focus on the potential for manipulating the watertable in the mined area, using weirs in the blocked drain in order to create specific hydrological conditions for establishing vegetation.

The fluctuating water level recorded over a 48-hour period, in an automated dipwell 90m from a boundary drain, on an intact area of raised mire is shown in Figure 4b. Such response of water levels in wells over discrete, closely monitored periods can be used to determine other hydrological parameters, some of which are discussed in Section 3.4: Subsurface and groundwater flow. It can also be used to estimate the influence of *bulk* soil properties, on the release or uptake of water from the wetland substrate, often referred to in terms of specific yield.

Figure 4a. Spring watertables on both intact mire and previously mined mire surface intersected by a drainage channel blocked in January, 1991: Wedholme Flow, UK.

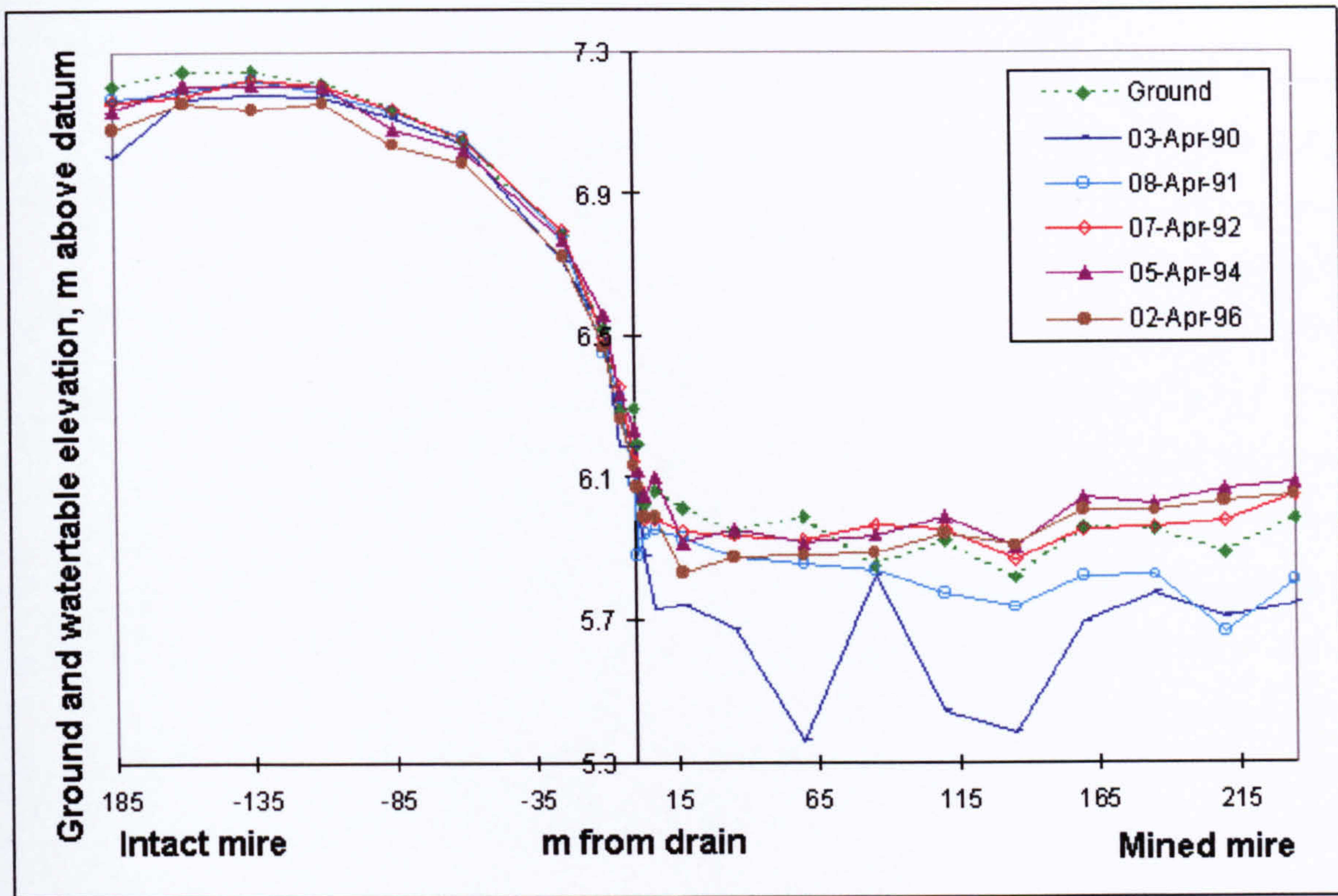
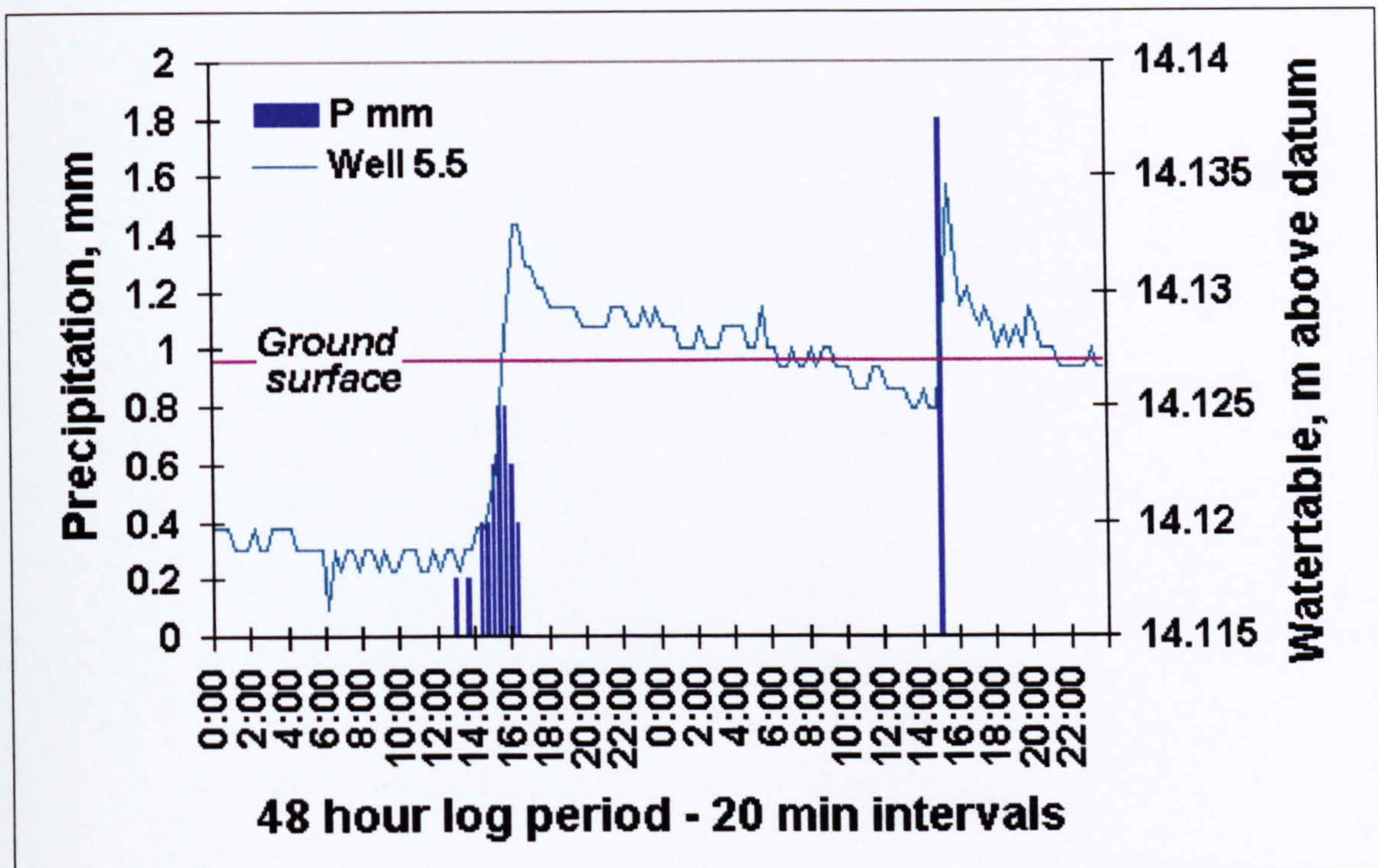


Figure 4b. 20-minute precipitation and dipwell level logs, 24/10/99 - 26/10/99, Wedholme Flow, UK.



3.1.3 Watertable fluctuations and specific yield

It has been established that observations of changes in the wetland watertable can be used as simple indicators of change in water storage. For example, output from the system by evapotranspiration will result in a fall in the watertable whilst recharge in the form of precipitation will cause the watertable to rise. Given that the watertable is likely to be close to or at the surface, the response to a rainfall event is likely to be rapid. The rate of response by the watertable will be mitigated by the rate at which water arriving at the surface is transmitted through any unsaturated layer above the watertable. Any redistribution of water within both the saturated and unsaturated zones will be determined by the physical properties of the soil pores (particularly size and connectivity), the soil component proportions (minerals, organic matter, air and water) and soil forming processes. For example, organic or peat soils, common in many wetland biotopes, are characteristically highly porous and may consist of 90% water by volume. The porosity and hydraulic conductivity of such a soil will be determined largely by the peat forming vegetation (woody, sedge or moss), the degree of humification and compaction at any one location.

The extent to which any rise in watertable due to an input of water is influenced by bulk soil properties is referred to as the specific yield (S_y) of the soil or substrate. (Strictly, the specific yield is the amount of water that can be freely drained under the influence of gravity, that is, against the retention capacity of the soil and is expressed as a percentage of total volume.) Any rise in watertable will also depend on the initial position of the watertable prior to any addition, therefore the specific yield is also a function of the depth of the unsaturated zone. We can express the specific yield (%) in terms of the percentage of recharge (net precipitation = P_{net}) that contributes to watertable rise (Δh):

Equation 2.
$$S_y = (P_{net}/\Delta h) 100$$

If a consistent watertable response to precipitation is observed, then the bulk change in storage (ΔS) for other instances can be estimated from specific yield:

Equation 3.
$$\Delta S = S_y * \Delta h$$

where S_y is a percentage and Δh is the change in watertable.

Both of these relationships are very general and should be applied with caution, as they will not hold for all circumstances. Recording the change in stored water by fluctuation in the watertable due to precipitation over a determined interval, where the watertable is permanently close to the surface, is subject to several sources of error:

1. interception and evaporative losses;
2. storage in the unsaturated peat zone;
3. open water storage and lateral flow exacerbated by high phreatic level.

Errors 1 and 2 are likely to increase in shorter recording intervals with lower precipitation. Error 3 will increase proportionally over longer periods with higher rainfall when the watertable may reach the surface causing both overland flow and storage in temporary pools, especially within hummock-hollow networks. Where surface gradients are higher, overland flow will be accelerated with the potential for local preferential flows. An average of multiple estimates from different length monitoring intervals is preferable to reduce errors.

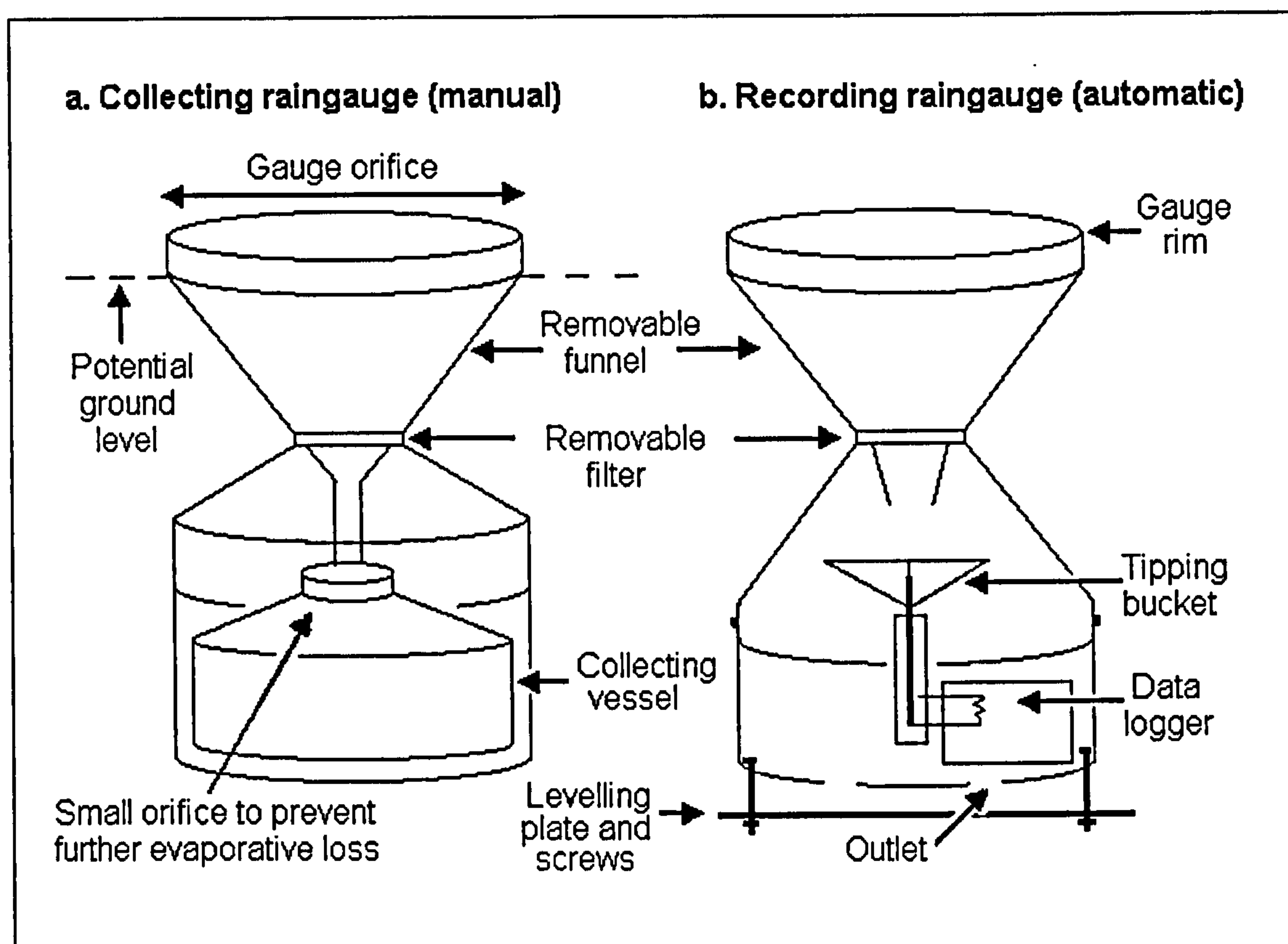
Estimates of specific yield from field data are determined largely by the circumstances preceding the rainfall event and the physical properties of the logging dipwell location. Specific yield may be overestimated where: watertables in deep undisturbed peat are characteristically stable with very little subsurface flow likely (3.4 Subsurface and groundwater flow); hummock-hollow sequences are by definition a series of pools and small mounds of living and decomposing vegetation (largely moss) (3.5 Surface water flow). In such microtopography, it is particularly difficult to define a ground surface. With little potential for subsurface saturated flow, and porous mounds of partially decomposed vegetation composing a large area of the surface along with a pattern of small pools and transient channel networks, there is considerable potential for transition to rapid near surface and overland flow as the watertable rises. In this situation, lateral flows are likely to exert a greater influence on rising watertables overcoming any control by specific yield. This condition is not specific to peat mires and may occur in any wetland.

3.2 Precipitation

Of all inputs into a wetland system, precipitation (rain, hail, and snow) is the most readily recorded. In the case of ombrotrophic (atmosphere-fed) mires, precipitation may be the only input. Rainfall measured using a raingauge (Figure 5) to catch vertically falling drops, is the most accurately recorded form of precipitation, being the least prone to turbulence around the gauge orifice, which can deflect droplets and result in an underestimation of precipitation. This effect is most apparent in snowfall where it may be necessary to compare gauge results to a record of depth and estimates of the density of a known volume of snow compared to its melt-water volume. In general, the further from the ground the gauge the greater the potential for turbulence, and so some gauges are buried with the orifice at ground level, whilst many gauges are designed to reduce turbulence.

There are two main types of gauge: a collecting or manual gauge (Figure 5a) and recording or automatic gauge (Figure 5b). In both cases, rain is collected in the gauge orifice of known area, typically 127mm in diameter and 305mm above ground in the UK, and 203mm and 305mm in the USA. In the manual type gauge, rainfall is collected in an internal container. The volume of water in the container is then recorded manually at regular intervals and emptied, so that cumulative volume divided by gauge orifice area gives a point measurement of the depth of rain falling within the given recording interval. This type of gauge is easily constructed and has many uses particularly in educational environments. The main decisions to be made are the recording interval, and the time of day at which recording will take place. For example if recording daily rainfall at 9am every day, the rain-day will begin and end at 9am, so that if a depth of 2.5mm was recorded for Tuesday 5 May, it will actually have fallen between 9am on Tuesday 5 May and 9am on Wednesday 5 May. This can result in underestimation of the daily totals. Collecting gauges are usually used for recording intervals of one day or longer.

Figure 5. Collecting and Automatic recording raingauges.



Automatic rain gauges are either continuous, recording a change in a collected level, usually on a chart, or more popularly, they contain a small tipping-bucket which tips when filled with a known volume, activating a reed-switch and sending an electrical pulse to a connected data-logger (Figure 5b). The data logger can be programmed to report the number of tips (usually translated directly as a depth) during any given interval specified by the user, or to record events – individual tips. Such data is most useful when rainfall intensity over a shorter period is of interest, for example during investigations of surface run-off, soil infiltration, or rainfall interception studies.

The data contained within the rain gauge logger will normally be downloaded onto a microcomputer in the field via a communication cable, but may also be collected remotely via a modem link if this is fitted to the logger unit. The interval at which downloading occurs is usually determined by the user's demand for data, the memory capacity and battery power consumption of the data logger. Various forms of computer and accompanying software can

be used, from notepad or laptop to hand-held units. The mode of downloading is usually determined by the project technician or scientist and logger manufacturer at the time of purchase. In this fast developing area many new forms of equipment are being introduced continuously.

All raingauges may be used individually when making point measurements or as part of a network where it is necessary to assess the variation in rainfall across an area or the 'areal rainfall'. Raingauges may also be stand-alone units or may form part of a larger Meteorological recording station (MET station) (Figure 6). A MET station may be manual but is more likely to be automated, in which case, the recording gauge would be connected to the MET station data logger along with the other station sensors. (see 3.3 Evaporation and Transpiration)

Raingauges should always be placed in a position that exhibits the typical conditions of the assessment area, so that in a study area with a typically open aspect for example, a gauge would not be placed under a tree. They must be protected from disturbance by humans and other animals, usually by a fence some distance from the gauge. Given the wet and easily trampled wetland surface conditions, it maybe useful to bolt the gauge or its levelling plate, in the case of tipping-buckets, to a large slab or paving stone to prevent movement and keep the gauge level. Gauges must be kept free from debris and should usually contain some form of removable filter that can be cleaned if blocked by the insects that seem inevitably and fatally attracted by its flower-like appearance. (see Section 3. Operating and maintaining equipment)

3.3 Evaporation and transpiration

Where the supply of soil water or open water is not limiting, evaporative loss or output from a wetland may account for 50% or more of the precipitation input. Inadequate estimates of this contribution can introduce a high degree of inaccuracy into a site water balance. Evaporation is in the simplest terms, a net movement of water vapour molecules away from an evaporative surface and as this cannot be recorded directly in the field this leaves three options. Those factors controlling the process recorded, most basically: energy input into the system as net solar radiation and the resultant air temperature, humidity and turbulence or wind speed, then use a model to calculate evaporation. Alternatively an empirical measure of the direct effect of the loss of water vapour molecules from a known volume (of soil or water) can be recorded as a change in mass, or in the case of a pan, the depth of open water. Evapotranspiration can also be estimated from observations of the diurnal fluctuation in the monitored watertable. In addition, new techniques that use remotely sensed data, such as satellite and radar imagery, are currently expanding and are likely to become more widely applied in the near future.

As it is often difficult to determine what proportion of water vapour is leaving a site as a result of direct evaporation from a surface or open water, and that which is being actively transpired by plants, the two are usually addressed together as total evaporation or *evapotranspiration*. This may be calculated as actual and potential evapotranspiration from meteorological data (MET data) collected locally and using information about the vegetation at the site, it may be measured directly using a lysimeter, or it may be estimated from observed changes in bulk storage.

The main difference between wetland and other habitats in which evapotranspiration is commonly recorded (usually agricultural environments) is the mixture of open water, emergent and terrestrial vegetation. It is possible due to the potentially large leaf surface areas of hydrophytic plants with limited stomatal control, and wide variations in aerodynamic resistance, that evapotranspiration from wetlands can exceed open-water evaporation. The most similar habitat with which a comparison could be drawn would be a paddy-rice system. Whether potential evapotranspiration is calculated or measured directly, an adjustment to include the proportion of site surface area covered by open water during the period in question must be made.

3.3.1 Models for calculation of evapotranspiration

Many different models and modes of calculation exist for evapotranspiration (ET). The algorithm applied is usually determined by the type of meteorological and vegetation data available. As evaporation is discussed at length elsewhere, we will only consider details necessary to understand the need for field data collection. In addition to net solar radiation, air temperature, humidity and wind speed, atmospheric parameters, evaporation pan coefficients, soil water availability, salinity, and most importantly for the portability of standardised calculations, information on the vegetation type and its growth stage can all be included in existing models. The advent of widespread fast microcomputers has enabled the development of existing models and reduced their calculation time so that many factors can now be included. The Food and Agriculture Organisation of the United Nations (FAO), has played a large role in the development of these models, and computer programs based on FAO standardised calculations are now widely available.

The most widely applied models are the Thornthwaite and the Penman-Monteith models. The highly empirical Thornthwaite model has been widely adopted because of its convenience and simplicity: potential evaporation is expressed as a function of mean air temperature and daylight hours, although neither of these relate directly to evaporation. Care must be taken when using this indirect measure, as it is likely to result in large errors in unstable atmospheric or variable climates for example, coastal or maritime climates. The Penman-Monteith model, or set of Equations, includes both climatic, soil and vegetation factors, and hence has greater data demands. The Equations estimate the *drying power* of the air, the *heating power* of solar radiation to cause evaporation from surfaces, whilst incorporating functions of soil moisture, aerodynamic characteristics, growth stage factors, such as leaf area index, and physiological factors, such as stomatal resistance to transpiration of the vegetation. Many modified versions of the Penman-Monteith algorithms exist and have been incorporated into prognostic systems of varying scales of which the UK Meteorological Office Rainfall and Evaporation Calculation System (MORECS) is one well-known example. Given the adaptability of the Penman-Monteith model, it is likely to be a practical solution to wetland evapotranspiration estimation.

The minimum dataset parameters usually required by most ET software packages are listed in Table 1, along with other potential parameters that may be included. Units have not been

specified as these vary widely, and the package will usually ask the user to specify which unit they are using.

Table 1. Minimum and additional data parameters required by standard software for evapotranspiration calculation.

Minimum data parameters	Additional/alternative parameters
Time and date including year	
Latitude and longitude of station	
Mean air temperature	Minimum air temperature Maximum air temperature
Average relative humidity	Minimum relative humidity Maximum relative humidity Average vapour pressure Average absolute humidity Average specific humidity Dry/wet bulb temperature Dewpoint temperature
Average wind speed	Atmospheric pressure
Net radiation	Incoming solar radiation Reflected radiation
	Albedo
	Sunshine hours
	Lysimeter reading
	Pan evaporation
	Soil heat flux
Measured grass/vegetation height	Leaf area index
	Grass reference ratio

Having selected a calculation, the minimum necessary data parameters and their mode of collection can be identified. In some cases it may be possible to derive data from local MET stations particularly where there is a statutory requirement to divulge, or where monitoring programs are educational or have charitable status and data may be obtained without financial cost. However in many countries, such data must now be bought, and the expense this involves may make rental or purchase of equipment to be located on the site economic. If data are required for a pre-monitoring period then purchase may be the only option. Another factor to consider is the locality of the nearest station: the local climate within a wetland is likely to be very different to that of a surrounding agricultural or urban area. For example, detailed meteorological data are usually collected at airports, and these are often freely available, but how similar are conditions in an airport likely to be to those in a wetland habitat?

If the decision is made to collect data on-site then the sensors necessary for the data parameters should be identified and incorporated into a weather or MET station. As with the rain gauge, this may be manual or automatic. Whichever of these is chosen they can contain similar sensors. Given the falling price and increased availability of electronic scientific equipment and the advantages of automated recording, the most practical form of monitoring equipment is an automated, multi-sensor, weather station (MET station). Along with user specified sensors, this will contain a data-logger. This allows the station to be left for considerable lengths of time between downloading of recorded data depending on the battery or power source, the memory capacity of the logger and the number and frequency of sensor readings to be saved. A rain gauge will normally be included as a standard sensor within the station, and an automated MET station has the operational and data advantages stated for an automated raingauge (3.2 Precipitation). Briefly, the recording interval of each parameter and period between downloads can be specified by the user, limited only by the logger memory capacity. Hence real-time recording can occur and visits to the site may be limited, reducing disturbance and interference. The need to download because of limited battery power can also be eliminated by incorporating a small solar panel and rechargeable batteries in the station. If the station is fitted with a modem and data are downloaded remotely, only maintenance visits are necessary (see 3. Operating and maintaining equipment).

Figure 6 shows an automated station and illustrates the sensors used to collect weather data and to calculate evapotranspiration.

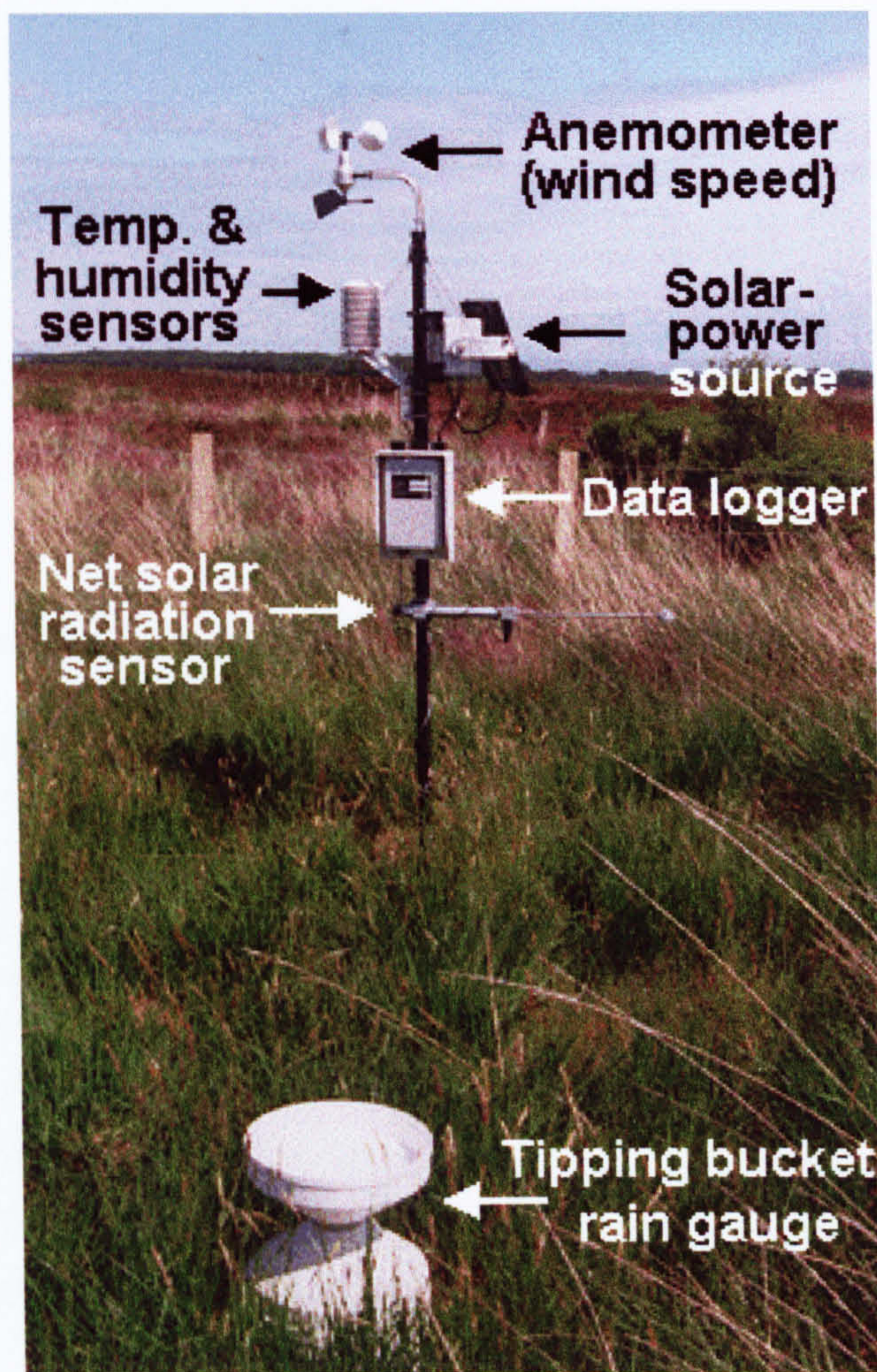


Figure 6. Automated MET station, Wedholme Flow, UK.

3.3.2 Direct measurement of evapotranspiration: lysimeters and pans.

If the growing vegetation, its root zone (in the case of vascular plants) and soil can be contained, so that hydrological exchanges are minimised and lateral flows eliminated, loss of water from this isolated zone by evapotranspiration can be recorded. This is the function of a lysimeter. A lysimeter contains an *undisturbed* sample or monolith, of vegetation and its root zone, as similar as possible to that outside of the unit. Within this unit it is desirable, though not always achievable, to maintain the watertable at a level equivalent to that of the surrounding area. This is of particular importance in a shallow watertable situation. The area immediately outside of the lysimeter should also be maintained in an intact form, minimising any differences in both consumptive use and turbulence. Lysimeters come in two forms: weighing and non-weighing. In a weighing lysimeter, the only input is precipitation and the only output evapotranspiration. The lysimeter container, in which identical conditions to the surrounding environment are maintained as closely as possible, is weighed at specified intervals and the change in mass due to precipitation or evapotranspiration is recorded. In a non-weighing lysimeter, seepage through the root zone is collected in a container at its base, and the difference between input and drainage computed for a given period. Non-weighing lysimeters may be of less use in wetlands where the watertable is at, or close to the surface, hence making the isolated containment of seepage problematic.

Evaporation pans, which come in many dimensions and can be either sunken or above ground, manually read or automated, are in effect sealed pools, with only precipitation input and evaporation output. They can be used to provide an index of the cumulative effect of air temperature, humidity, wind speed and net radiation, and to relate different vegetation types or cover within a site or at different locations. In the agricultural environment, pans are often used to provide reference evaporation to which crop evapotranspiration can be related using an established crop coefficient. Established crop coefficients (which are also applied in most ET algorithms) and guidelines on their use and application are provided in the FAO Irrigation and Drainage Papers 24 and 56. These international standards include growth stage and crop coefficients for some temperate climate wetland vegetation.

Evaporation data have rarely been collected for bryophytes which dominate many ombrogenous and oligotrophic wetlands. In wetlands where emergent and terrestrial vegetation, seasonal and permanent pools and channels are common, a combined network of weighing lysimeters and pans may provide additional insights.

The dimensions of both lysimeter and pans and their locations are critical to optimisation of results. As has been mentioned previously, turbulence is only one of the many factors contributing to evapotranspiration. If this is altered by disturbance of local conditions during installation and subsequent visits, a source of error will be introduced. An additional factor influenced by the size of a lysimeter is interception of precipitation by vegetation (3.3.4 Interception and Evapotranspiration). Both of these effects are likely to be mitigated by the size of the unit. However the very nature of a wetland, which often makes access difficult and accentuates any form of disturbance will in many cases, make installation and operation of all but the smallest units difficult if not impossible. Another factor related to the size of the lysimeter, in particular a weighing lysimeter, is the total mass of the filled unit. Whether the balance used to record changes in mass is contained within the sunken lysimeter casing, or the lysimeter is removed for weighing, the balance must be accurate enough to record the possible range of change in mass. In many cases no mains power source will be available on site and the balance may need to both portable and battery powered. To this end a *weighing micro-lysimeter* having a potential filled mass within the range of the common battery powered balance, was designed at the University of Newcastle for use in wetlands with high watertables. Micro-lysimeters have been used successfully in many wetland systems including mires, fens and paddy rice fields, in addition to systems with more sandy soils.

A plan of the Newcastle weighing micro-lysimeter, filled weight approximately 6kg, is presented in Figure 7. Lysimeters of this design were used in a network of six, along with four pans of similar volume, in an area where watertables were also monitored continuously, at Wedholme Flow, Cumbria, UK. Figures 8a & b show one of the lysimeters filled and ready for weighing, and in situ at the site. The pans used were the same volume and constructed from the same material (waste or 'soil' pipe) without the additional fittings. Thermometers were positioned within and outside of the lysimeters to monitor any temperature differences.

Figure 7. Weighing micro-lysimeter plan.

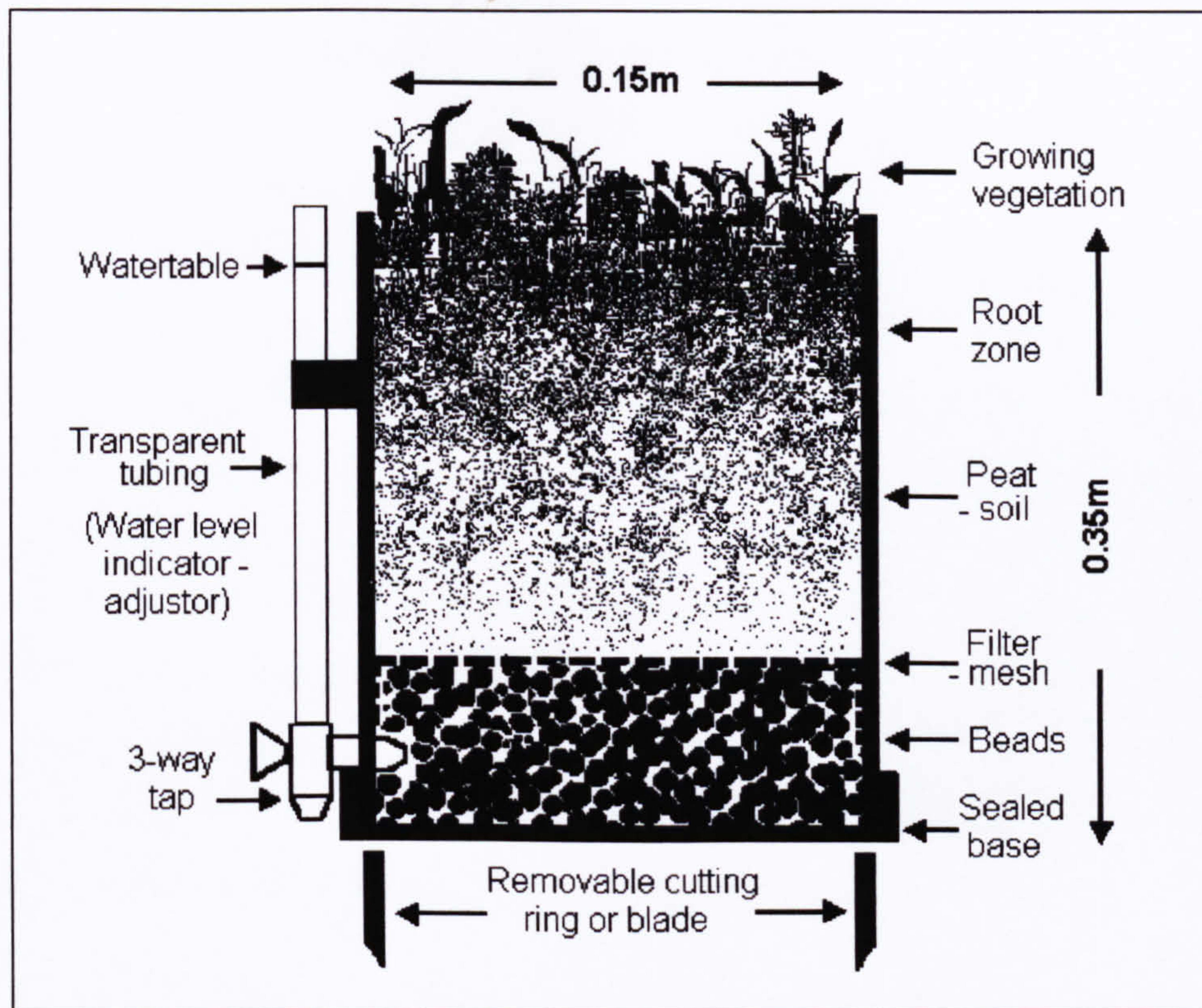


Figure 8a. Lysimeter ready to weigh

b. Weighing lysimeter *in situ*



The lysimeter contains an undisturbed core of vegetation and root zone extracted by inserting into the ground the bottomless tube with a removable blade section to the required depth (level with the ground surface). An intact turf is then removed from the ground adjacent to the lysimeter. A plate can be inserted under the blade section and the whole instrument removed. A second plate is then placed on top of the lysimeter, which is inverted whilst the blade and excess soil are removed and replaced in the hole. A perforated container, large enough to house the entire lysimeter including the tap (Figure 6), is then placed in the hole created to prevent it from collapsing and allowing the lysimeter to be easily removed and replaced during weighing. The turf removed to access the base of the lysimeter is then replaced with minimum disturbance. The container is perforated if the high watertable and the volumetric water content of the substrate are likely to cause it to float, as in this case. Enough peat or soil is removed from the base of the lysimeter to allow a filter or mesh to be placed in the bottom of the container, and the space created is then repacked with non-saturating beads. Small polystyrene beads such as those used to prevent damage to electrical equipment in transit, are quite suitable. The base of the lysimeter is then sealed and a tap is inserted into a pre-drilled hole in the side of the casing.

The reason for creating an artificial layer within the lysimeter is that where necessary, the water level inside the lysimeter must be manipulated to match the local watertable. It must also be monitored during weighing to ensure it is representative of the surrounding area. This can be achieved using a 3-way tap, inserted into the bead layer. Whilst the tap is open to the length of transparent tube, fixed vertically to the outside of the lysimeter, the internal water level will be indicated within the tube. If the setting is altered, water can be released from the lysimeter or the tap can be closed for weighing. Depending on the tap orifice diameter and the size of the beads, it may be necessary to wrap a piece of mesh around the tap before it is inserted into the lysimeter casing.

When the water level in the lysimeter is equilibrated to the surrounding watertable, it can be weighed for the first time, then placed inside of the outer container so that its surface is level with its surroundings. Difficulties that exist in the construction and installation of the lysimeter are usually associated with sealing the lysimeter and disturbance of the surrounding area. Joints in the lysimeter casing should be minimised to reduce the potential for leakage and all joints must be sealed. It is usually necessary to add an additional layer of silicon gel or similar water proofing, even to pre-sealed joints. All maintenance should be carried out away

from the lysimeter 'hole', and trampling minimised by standing on boards (see 3. Operating and maintaining equipment). In addition, when selecting materials and constructing the lysimeter, attention should be paid to the maximum weight of the balance to be used in the field. It is possible that following heavy rainfall the lysimeter weight will increase beyond the balance maximum. If the lysimeter is fitted with a tap as shown in Figure 7, a measured volume of water may be drawn prior to weighing, and its mass added to the final Figure. This volume must then be replaced in the lysimeter and the initial watertable restored before it is reinstalled.

3.3.3 Estimation of evapotranspiration from diurnal watertable fluctuations

We have observed previously that fluctuations in the wetland watertable can be attributed to several hydrological processes, and that by examining the change in storage indicated in dipwell logs, we can attempt to estimate specific exchanges. We have established that without additional inputs of precipitation, a net loss of water from storage by evapotranspiration is likely. Both evaporation and transpiration are greatest during that part of the day when incoming solar radiation is at its greatest, giving rise to the characteristic diurnal fluctuations in watertable most apparent in the logs of continuously recording or automated dipwells. These fluctuations are often attributed to transpiration alone, but as the ground surface may intercept the watertable at many points, especially in peat-wetlands with extensive microtopographical variation, it is quite possible that evaporation will occur at the watertable interface. In such a case, it is not always possible differentiate between fluctuation due to transpiration and that due to evaporation from these integral areas of open water. Therefore, we will continue to refer to the exchange as evapotranspiration.

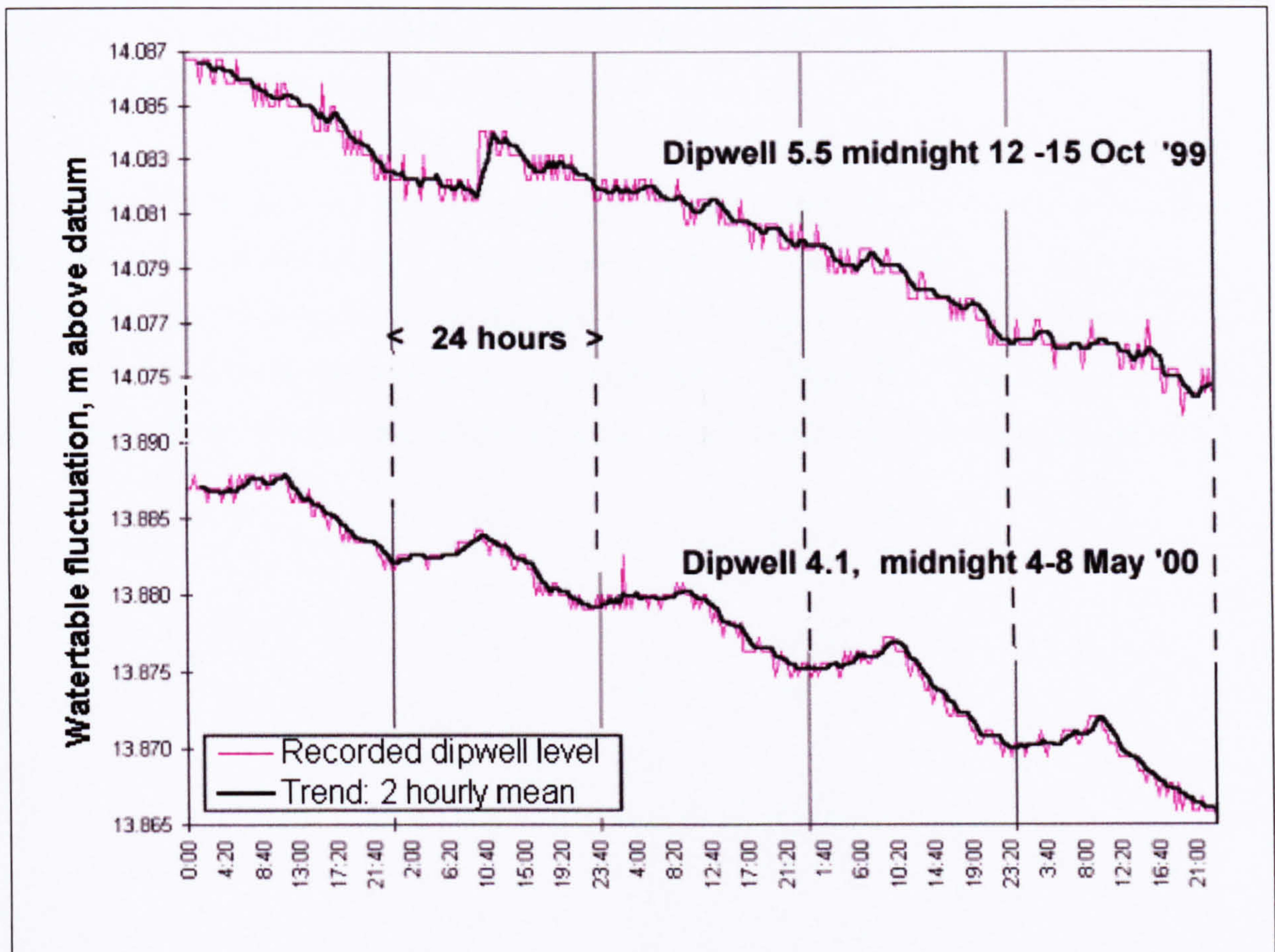
Without precipitation or lateral input, watertables fall during the day (most rapidly in the afternoon), and at night they may fall slowly, stabilise or recover where there is potential for a redistribution of water within a wetland. In the later case, there may be a nocturnal net lateral inflow where adjacent open water bodies can provide lateral recharge. Lateral inflow will also occur during the day, but this may not be apparent in dipwell logs, as any recharge will simply be replacing moisture lost to evapotranspiration. Hydrologists have observed that as inflow is likely to remain constant throughout the day, any rise in watertable at night (when ET will not occur), can be attributed directly to net lateral influx. If the gradient of nocturnal rise in watertable (r) is accepted as the continuous rate of lateral influx over a 24-hour period, then a potential daily rise can be calculated ($24r$). We know that changes in watertable due to influx or loss are mitigated by soil properties within the saturated and unsaturated zones, such as pore size and distribution, and we can estimate the combined influence of soil properties on any change in storage at a particular location, in the integrated form of specific yield (S_y). (see 3.1.3 Estimating specific yield)

If we observe the net fall in watertable due to evapotranspiration (et) over the 24 hour period and add this to the extrapolated gain due to influx, mitigated by specific yield, then the actual loss due to evapotranspiration (ET) can estimated:

Equation 4. $ET = S_y / 100 (24r + et)$

This principal holds true only where the rate of lateral flow can be attributed to soil properties included in the term specific yield. Where rapid routes for recharge exist, such as weaknesses in the substrate or overland flow is possible, this relationship will not be observed (measurement of these properties will be discussed in Sections 3.4 and 3.5).

Figure 9. Watertable fluctuation during 5-day continuous logging periods for two dipwells, Wedholme Flow, Cumbria, UK: both the recorded dipwell level (20 minute recording frequency) and the 2-hourly mean levels are plotted.



There is a distinct unimodal diurnal fluctuation during the May log. A similar pattern exists in the October log but is less discernible. Diurnal fluctuations may not always follow strict patterns, and can display a high degree of seasonality. The mid-October watertable plotted in Figure 9, falls steadily throughout the logging period, although it does appear to level out between midnight and noon. However the early May watertable plotted in a different dipwell, appears to follow a regular daily pattern, falling between around 10:00 and 23:00 and recovering up until noon in some cases. In both cases, no precipitation was recorded during the logging period, and both dipwells were in similar topographical locations, with similar vegetation cover (dominated by *Sphagnum* moss with occasional *Ericaceous* shrubs). However the fall in the watertable during the May logging was approximately double that of the October period. Differences are likely to be due to seasonal factors. At this latitude (almost 55° north), there are considerably more daylight hours in May as mid-summer approaches, than in October. In addition to long days, the May log is likely to have followed a typically wet spring, contributing to more depressional storage, hence more potential recharge, and the marked diurnal fluctuations.

Great care should be taken when calculating evapotranspiration from watertable fluctuations, and such estimates should not be considered in isolation from other methods. The capacity for lateral flow should never be underestimated, and this is especially the case in high watertable environments with the capacity for rapid near-surface exchanges. No evapotranspiration value can be considered absolute, and a comparison of several estimates should always be made.

Table 2 includes actual evapotranspiration estimates for the raised mire, Wedholme Flow, UK, using micro-lysimeters and pans (3.3.2), and watertable fluctuations observed in a dipwell (3.3.3). Potential evapotranspiration is included using weather data collected on site using an automatic MET station (3.3.1), and calculated by the Ref-ET program using the American Society of Civil Engineers Penman-Monteith calculation (3.3.1), along with the potential ET estimate given by the UK Meteorological Office MORECS calculation (3.3.1).

Table 2. Weekly recorded P, ET, estimated PET totals (mm), Wedholme Flow, UK.

31-May till	Recorded on site:				Ref ET (model)	MORECS VALUES:		
	total P	Lysimeter	Pan	Dipwell		PE Soil	PE grass	PE O-W
06-Jun	44.40	31.22	-	-	3.64	10.10	13.40	13.50
13-Jun	22.00	24.15	-	-	9.73	15.11	17.50	21.80
20-Jun	0.60	10.68	6.09	8.10	14.97	21.10	21.20	25.70
27-Jun	2.40	6.93	5.95	19.00	11.22	15.90	17.30	20.50
04-Jul	0.80	5.53	6.16	7.68	12.88	16.70	16.80	19.90
11-Jul	26.40	21.42	23.59	7.74	10.08	14.10	16.70	18.80
18-Jul	0.80	6.58	5.88	-	12.53	16.70	16.30	19.90
25-Jul	0.00	7.00	5.74	-	12.04	17.10	16.90	21.30
01-Aug	10.60	27.72	28.07	-	10.43	16.90	17.10	19.40
08-Aug	20.80	12.39	12.60	-	8.12	14.40	14.70	17.30
Total	128.80	153.62	94.08*	42.52**	105.64	158.11	167.90	198.10

***94.08** total recorded ET in 8 weeks – using weekly mean, 10 week total = 117.6mm

****42.52** total recorded ET in 4 weeks – using weekly mean, 10 week total = 106.3mm

In the case of the recording period outlined in Table 2, the lysimeter measurement was close to the mean of all methods employed, with the lowest estimate being the Ref ET model output and the highest being MORECS open water. Four out of the seven methods employed imply a moisture deficit during this recording period which was actually mid-summer.

3.3.4 Interception and Evapotranspiration

An additional consideration in the estimation of evapotranspiration from a natural or non-uniform vegetation cover, is that of interception (Figure 1). A considerable proportion of precipitation may be trapped in the plant canopy and never reach the soil surface or become available for plant uptake, hence transpiration. This *interception* may, never the less, evaporate from intercepting plant surfaces at a rate determined by canopy characteristics such as height, density and resulting temperature and turbulence. In some areas of research, such as forest ecology, attempts to record canopy interception have been made using large containers below the canopy (effectively oversized rain gauges), whilst also recording areal precipitation above the canopy. Such experiments are likely to be impractical in most cases, however evapotranspiration recorded in lysimeters should take account of mass changes due to direct evaporation from the canopy. Errors here are likely to be introduced where lysimeters or lysimetry networks are not truly representative of field conditions due to disturbance or inadequate representation of certain vegetation assemblages. When calculating evaporation using Penman Monteith or similar models, care should be taken to account for spatial variability in potential evapotranspiration due differences in vegetation canopy characteristics across a site.

3.4 Subsurface and groundwater flow

There are no truly *direct* methods of *measuring* actual subsurface flow in a wetland, in the field. That is, flow within the porous media of the wetland substrate in any direction, whether internal exchange within the wetland, output or influx, to and from an external aquifer. Techniques that strictly control the influx, usually by a constant head device, and record output from a known volume of wetland soil, must be carried out on an extracted monolith of the substrate in the lab. Such procedures, whilst standardised in mineral soils, have a varying degree of success with wetland soils, especially peat, which is notoriously difficult to extract without causing an unacceptable degree of disturbance. This is however, like many areas of wetland hydrometry a developing area and it is likely that techniques, which are currently experimental, will be wider used in the future. The high water content and heterogeneity of wetland soils also create difficulties for indirect measurement in the field.

In Section 3.1.3, the examination of watertable fluctuations to estimate specific yield was discussed. This is an indirect method of assessing the influence of soil properties on the movement of water in the subsurface. The rate at which water can move through the soil is referred to as hydraulic conductivity. The rate at which precipitation arriving at the soil surface can percolate through the root zone is referred to as infiltration rate. In terms of practical field measurement, it may be considered equivalent to the effective hydraulic conductivity of that layer, being determined largely by the maximum rate at which water can move through that zone, the initial water content and the depth of any ponded water. Water arriving at the *surface* may pond if it has to infiltrate a crusted soil surface or a dense layer of vegetation. There may also be a time lag between water arriving at the surface and its infiltration into the subsurface if the rate at which it is supplied to the surface exceeds the hydraulic conductivity of that material (infiltration excess), or if the watertable is already at the surface (saturation excess). Water will move through the saturated subsurface zone at a rate determined by the soil hydraulic conductivity, the hydraulic head at that point, and the adjacent hydraulic head.

Like specific yield, hydraulic conductivity is an integral of the soil matric properties that control water movement. As we cannot easily assess these properties in the field, we measure the ability of a soil to conduct water.

The relationship between flow and hydraulic conductivity is described by Darcy's law:

Equation 5. $v = -K \, dh / dx$

where: $v =$ apparent velocity of water (m/d)

$K =$ hydraulic conductivity (m/d)

$h =$ hydraulic head (m)

$x =$ distance in flow direction (m)

and therefore: $dh / dx =$ hydraulic gradient (dimensionless)

The hydraulic head can be defined as the potential energy (literally elevation) and pressure energy per unit weight of water.

In Darcy's law, hydraulic conductivity is the constant of proportionality to head change over a given distance, where flux is from a region of high to low head (or high to low potential energy). The application of dipwell transects to observe hydraulic gradients was discussed in Section 3.1, where it was established that a gradient could be observed perpendicular to a drainage channel, for example. Where the distance over which head change occurs is very small, so that $dh/dx = 1$, or a hydraulic gradient of unity, the conductivity can be regarded as equivalent to the apparent velocity. So that, where it is possible to detect a hydraulic gradient and assess the hydraulic conductivity we can estimate potential flow along a line of equipotential forces.

3.4.1 Determining hydraulic conductivity and infiltration capacity

The established methodologies for recording both hydraulic conductivity and infiltration rate in the field are relatively simple adaptations of the same technique. In the saturated condition water is removed from a cavity of known dimensions and the rate of refill is recorded, whilst in the unsaturated condition water is added to a cavity, and the rate at which it leaves is recorded. With calibrations for the cavity dimensions, the rate of influx is assumed equivalent to the hydraulic conductivity of the surrounding material. Both recharge and depletion tests have many potential sources of error and are inherently flawed in the typically heterogeneous, anisotropic material that constitutes a wetland soil. The measurable properties of all wetland soils will vary according to preceding conditions, such as interval since last rainfall event, with shrinkage and swelling of soil common, and compaction inevitable. A large variation in recorded conductivity is common and it may even prove difficult to replicate a result at one location, as the disturbance to the medium during the test is inevitable. However, in the absence of any practical and proven alternative, the only solution is to complete the maximum possible number of replicates of each test. Sensitivity analysis should also be applied when utilising field assessed infiltration capacity and hydraulic conductivity within larger schemes, and a reasonable range of standard error included.

Many hydraulic conductivity and infiltration capacity models exist as the topic has been extensively researched in the field of soil and agricultural sciences. Discussion here will be limited to two techniques that have been extensively applied in wetlands:

- the auger-hole or piezometer method using the Kirkham analytical solution of hydraulic conductivity
- the double ring infiltrometer using the Green-Ampt Equation

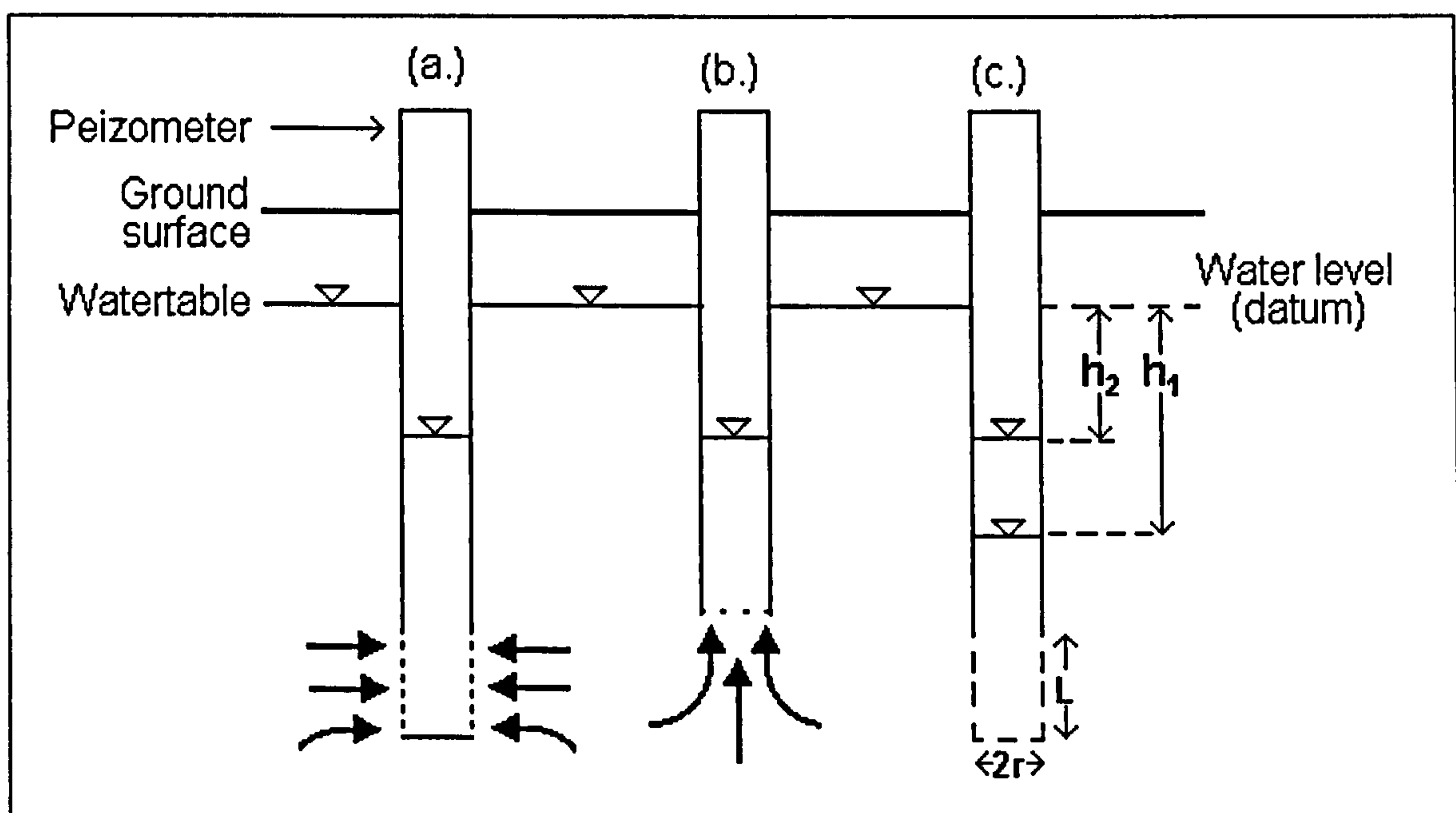
The auger-hole, piezometer method, pumped-borehole and slug test all refer to the same process, in which a cavity is created and water added or extracted. The mode of application or extraction differs between tests. In steady-state methods, a continuous head is applied either by pumping or with a constant or elevated head device. In unsteady-state tests, there is typically one extraction or addition, and the rate of recovery (Figure 10) or depletion (Figure

11b) is recorded. Accepting the difficulties inherent in maintaining a specified head, unsteady-state methods are more commonly applied to wetland soils.

Wetland soils are very often unstable and as high volumetric water contents are common it is usual to line the auger hole using a length of pipe, creating a simple piezometer. The pipe used for dipwells is usually suitable, although it should not be perforated along its length. It may be left open at both ends or some form of filter or *cage* can be constructed around the cavity at the submerged end of the pipe. In theory, if the cavity has open sides and a closed base (Figure 10a - solid lines), then horizontal conductivity over the cavity depth will be recorded. An open base and closed sides will theoretically record vertical conductivity at the orifice depth only (Figure 10b - solid lines). In practice, flow to or from the piezometer is likely to be radial in both cases (Figure 10a&b - all lines). If the pipe is perforated or if an actual dipwell is used, then the hydraulic conductivity will be an estimated average conductivity for the extent of the well depth. Piezometers of any length can be constructed and are usually installed approximately 1-2m apart in *nests*, extending across a range of depths, from the surface layer into the deep soil.

Figure 10. Piezometers used for recovery and depletion methods of recording:

- (a) horizontal hydraulic conductivity**
- (b) vertical hydraulic conductivity,**
- (c) the functions of hydraulic conductivity.**



Water is removed from a piezometer (usually with a hand pump) in which the water level has been allowed to equilibrate with the surrounding watertable, and recording of recovery begins immediately. Initial and subsequent equilibration can take several days in some wetland soils and so it may be more convenient to use an automatic water level recorder, such as the pressure transducers described in Section 3.1.1, than to record the level manually. Above the watertable, water is added to the piezometer and recording of the rate of depletion begins immediately. This is effectively a small-scale version of the infiltration method described below.

Several analytical models of hydraulic conductivity can be applied to recovery-depletion times recorded in piezometers. However most assume an incompressible substrate or were conceived in terms of relatively short recovery times and are therefore not applicable to many wetland soils. One of the most frequently applied solutions for hydraulic conductivity using auger-hole data, which has been widely applied to depleting and recovering piezometer tests, is the Kirkham Equation. Referring to Figure 10c, hydraulic conductivity (K) is defined as:

Equation 6.
$$K = \frac{\pi r^2 \ln h_1/h_2}{C (t_2 - t_1)}$$

where, r = radius of the piezometer
 h_n = distance to datum of water surface at time t_n
 C = shape factor

Rearranging Equation 6,

Equation 7.
$$h_1/h_2 = \frac{K C (t_2 - t_1)}{\pi r^2}$$

so that K can be calculated from the gradient of a log normal plot if it is linear, or from linear Sections of a plot for specified periods.

The shape factor (C), is obviously a critical function in the calculation of hydraulic conductivity. Many different methods of estimating its influence exist, based largely on the dimensions of the piezometer inlet, and in some cases relationship between the depth of the

piezometer, proximity to any impermeable layer and the elevation of the watertable at various junctures. As with evaporation parameters, many of the standardised methods are documented in the FAO Irrigation and Drainage manuals.

Various simplified relationships exist, but should only be applied with caution as each has a specific limitation:

Equation 8. $C = 4 \pi r$

where r = radius of a sphere

Equation 9. $C = 2 (\pi A_s)^{1/2}$

where A_s = surface area of the piezometer tip

Equation 10. $C = \frac{2 \pi L}{\ln L/r}$

where L = piezometer (inlet) length
 r = piezometer radius

Equation 8 should only be applied to piezometers with spherical tips, whilst Equation 9 is valid only when the length to diameter ratio (l/d) of the piezometer inlet is between 4 and 10 and Equation 10 applies when this is greater than 4. In the case of vertical flow piezometers of the design illustrated in Figure 10b, the length to depth ratio is zero, therefore this solution is invalid. Where no obvious formulation applies, standardised tables, such as the Youngs table of values should be referred to. These can be found in Irrigation and Drainage manuals.

In addition to the piezometer method which is commonly applied, two other methods may be encountered. Small scale pumping tests where drawdown adjacent to a well from which water is removed at a constant know rate can be applied where facilities allow. A large-scale pumping test has also been employed in isolated cases on some peatlands, where flow rate between parallel drains of a recorded head gradient is measured. This test involves a large

degree of disturbance to the site and is unlikely to be suitable where conservation or restoration is a concern.

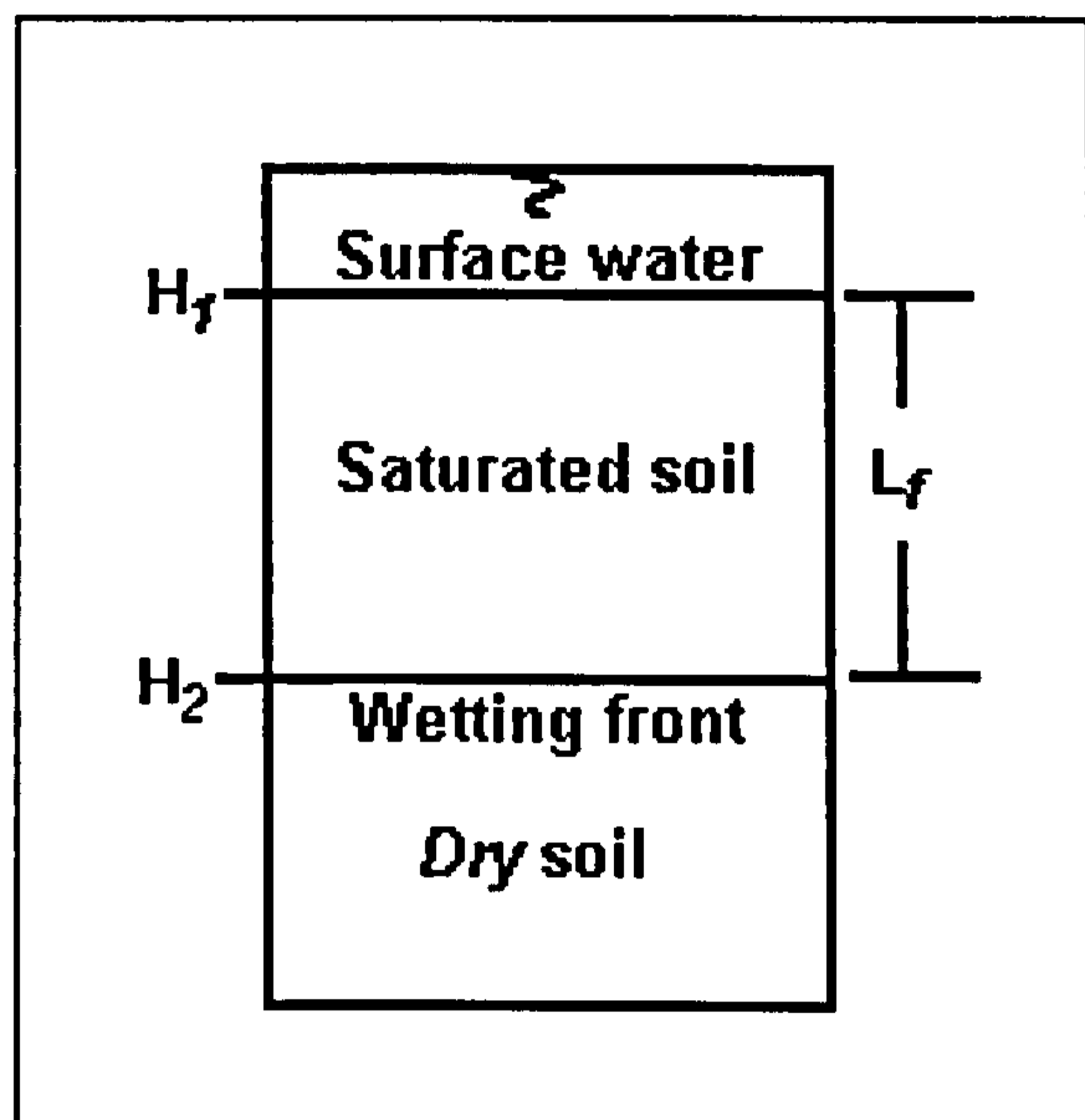


Figure 11a. Schematic representation of infiltration and the Green-Ampt parameters with ponded ground surface conditions and a saturated condition to the wetting front.

Figure 11b. Diagrammatic representation of the double-ring infiltrometer

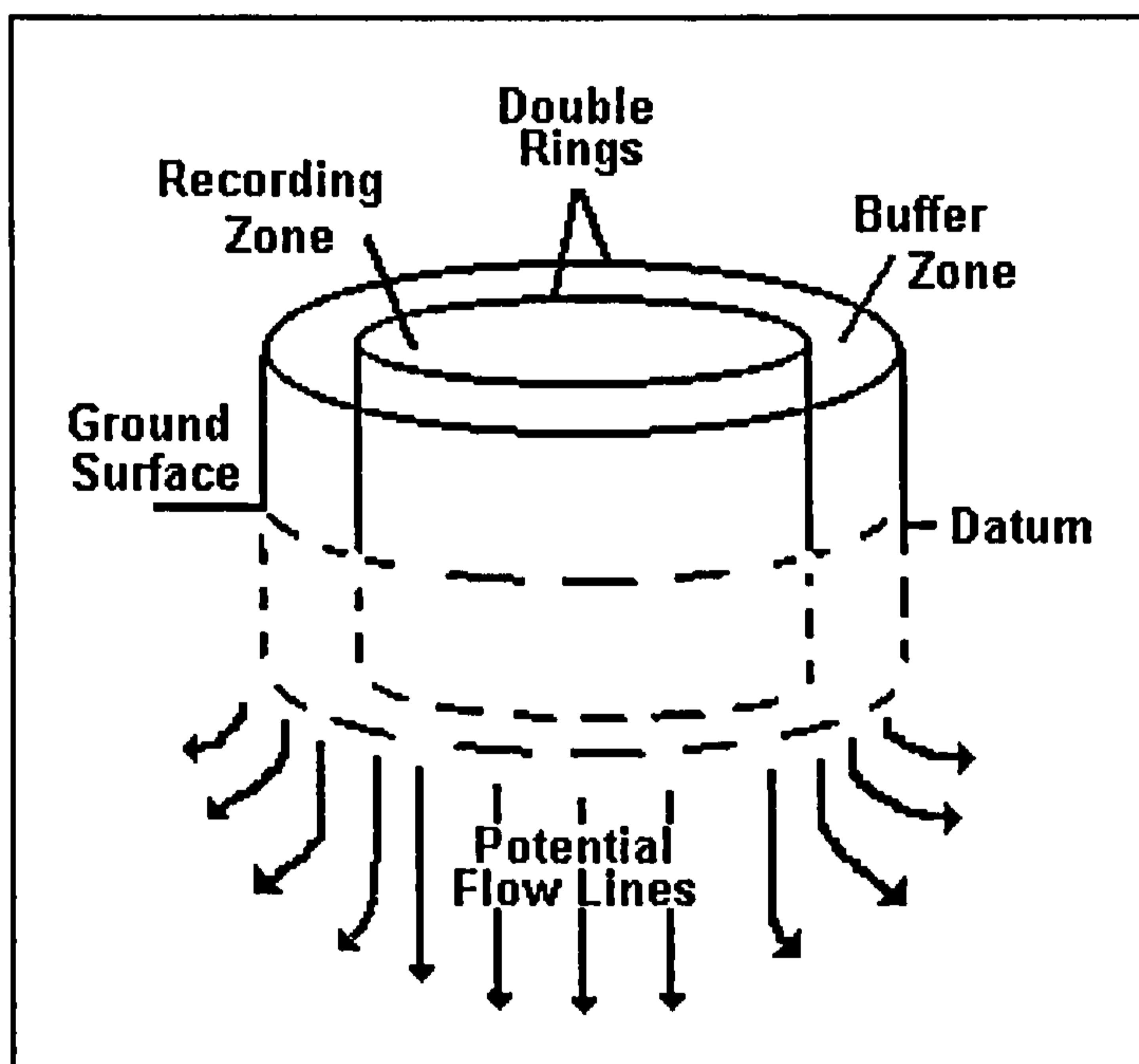


Figure 11a illustrates a schematic view of infiltration. Direct application of Darcy's Law to the water levels in Figure 11a gives:

$$\text{Equation 11.} \quad f = -K (H_2 - H_1) L_f$$

where,

- f = infiltration rate,
- L_f = length of wetted zone,
- K = hydraulic conductivity of the wetted or transmission zone
- H_1 = hydraulic head at soil surface (depth of ponded water)
- H_2 = hydraulic head at wetting front

The transmission zone is assumed saturated as the surface is ponded and column continuous. The soil water pressure head (negative) at the 'wetting front' h_f , where $H_2 = h_f - L_f$, can be expressed as positive suction $S_{av} = -h_f$, such that,

$$\text{Equation 12.} \quad f = -K (h_f - L_f - H_1) L_f$$

$$\text{Equation 13.} \quad f = K (S_{av} + L_f + H_1) L_f$$

Cumulative infiltration, F , may be expressed as,

$$\text{Equation 14.} \quad F = (\theta_s - \theta_i) L_f = M L_f$$

where,

- θ_s = wetted zone volumetric water content
- θ_i = initial volumetric water content
- M = soil water deficit or *fillable* porosity

If H_1 is assumed to be negligible compared to $S_{av} + L_f$, then substituting $L_f = F/M$ into Equation 14 gives the form of the Green-Ampt Equation:

$$\text{Equation 15.} \quad f = K + K M S_{av} / F$$

Substituting in Equation 15:

Equation 16. $f = A/F + B$

where, $A = K M S_{av}$
 $B = K$

In this form, B is essentially the saturated hydraulic conductivity of the wetted zone neglecting the effect of trapped air. A can be derived from experimental infiltration data.

This derivation assumes a ponded surface, with infiltration rate equal to infiltration capacity, and so is particularly suited to the *infiltration excess* situation observed on wetland surfaces. This situation is replicated by the use of the infiltrometer. In the case of lower intensity rainfall events or the initial period of a storm event, precipitation may arrive at the surface at a rate less than the saturated infiltration capacity.

At the wetland field site, the cylindrical rings of the infiltrometer are inserted through the vegetation to an approximate depth of 15cm below the surface or datum, or to the point at which degree of decomposition made identification of plant species by eye impossible (*vegetation has become soil*). Both rings are filled simultaneously whilst the water depth and cumulative infiltration recorded in the inner ring. The outer ring creates a buffer to lateral flows. Infiltration may be recorded over varying periods from minutes to days.

In order to calculate the Green-Ampt parameters using the double-ring infiltrometer, cumulative infiltration, F , is recorded, and plotted against time. The gradient of the resulting curve gives the infiltration rate, f . If $1/F$ is then calculated and plotted against f , and a line of best fit is drawn through the data points, the parameters A and B can be calculated. A is the slope of the line and B is the intercept at f (y on the axis, $1/F=0$). The B value is simply the potential rate of infiltration when no infiltration has yet occurred (when $1/F=0$) and is as such the hydraulic conductivity. It can then be compared to the measured saturated hydraulic conductivity.

Although originally designed for use on bare soil, the double ring infiltrometer was considered suitable for use in the wetland field sites, particularly where an undulating microtopography has developed. In such cases, the flooded inner ring compares favourably to

a transient pool with no surface outlet or the same pool before the surface water level reaches a depth at which pools link, becoming channels. The saturated surface condition created by flooding the rings provides a close comparison to the field condition during storm events, particularly in the hummock-hollow surface complex. The rings of the infiltrometer were inserted through the vegetation, with the surface defined as organic soil by degree of decomposition. This is an established method of defining peat types, with scales such as the von Post Humification Scale [1-10]. It is important that the infiltration should be recorded through a vegetated surface or as close to the undisturbed field situation as possible. In addition, the differing vegetation composition within the inner ring may be recorded for comparison with vegetation and infiltration results from other tests. Infiltration rate may also be estimated in a non-saturated form using a rainfall-simulator type experiment - effectively by constructing an outdoor shower with recordable input and infiltration rates.

3.4.2 Assessing hydraulic gradient

In Section 3.1 it was established that the watertable observed in a transect of dipwells could be used to illustrate a hydraulic gradient. It should be clarified that the watertable is the upper limit of an unconfined aquifer, at which the pore-pressure of the substrate is equal to atmospheric pressure. The surface is usually defined by interpolation between points at which the hydrostatic head is known, also referred to as the potentiometric surface. The hydraulic gradient is created by adjacent and different hydrostatic heads having different potential energy, so that the potential for exchange, movement or flow is from a high potential to a low potential, hence a gradient arises.

In an unconfined aquifer, the hydrostatic head can be observed in a well, perforated along its length or using piezometer with a single opening at a specified depth (see 3.4.1). In the case of a piezometer inserted below the watertable in an unconfined aquifer, the observed level after equilibration will be equivalent to the potentiometric surface. The length of the equilibration period will be determined by the hydraulic conductivity of the substrate. If there is a marked difference between the observed piezometric head and the established local watertable, and operational errors such as blocked pipes have been eliminated, then it is likely the observation point is located in an area of groundwater recharge or seepage. For example, if the water level in the piezometer is 0.5m above the ground surface in an area with no

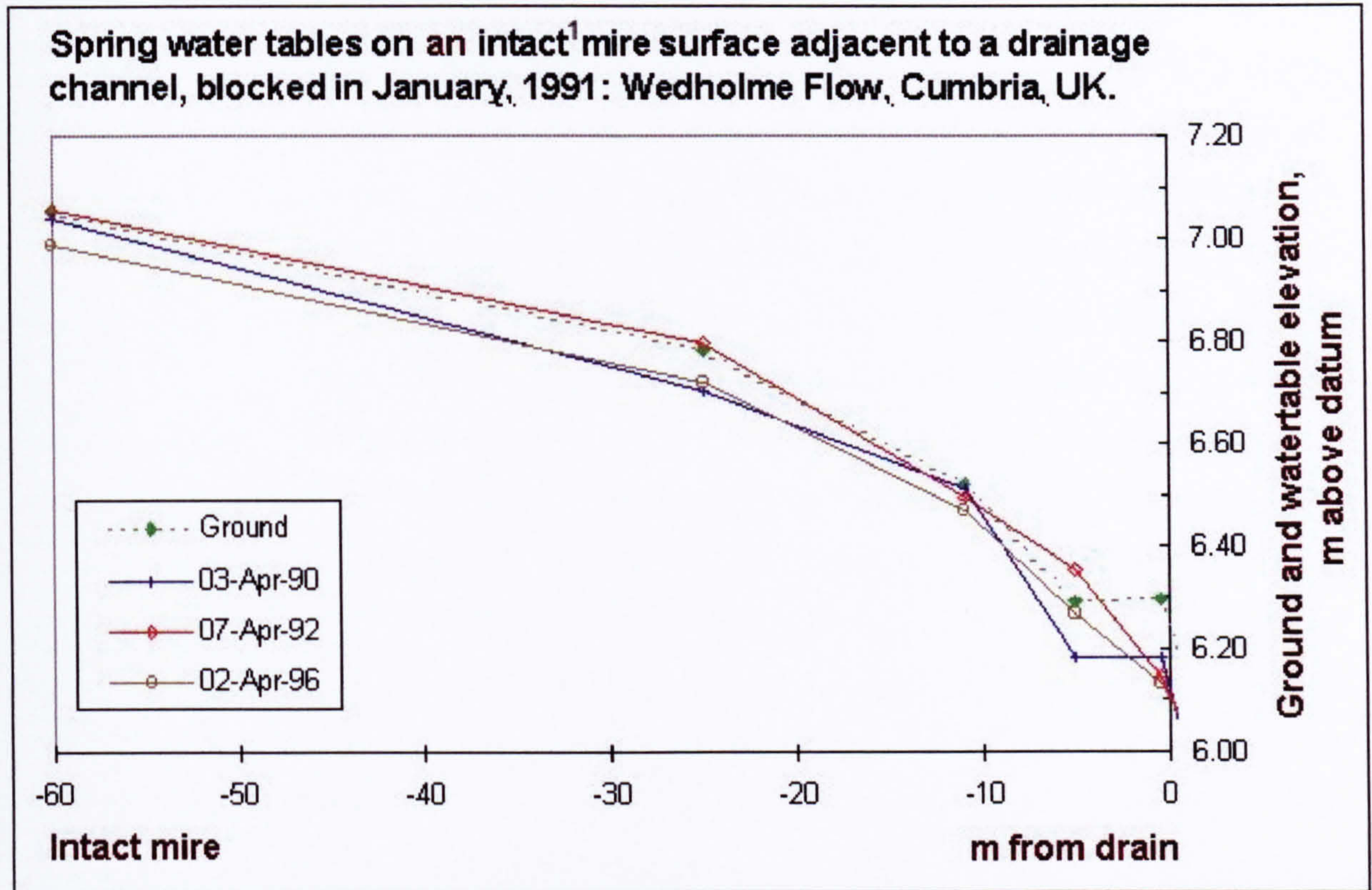
standing water, then it is likely that ground water is recharging the wetland aquifer. In such cases, the point at which highest hydrostatic head is recorded vertically 'below' the watertable, but potential for exchange is still from high to low energy therefore an influx into the aquifer.

In some cases the aquifer that forms the main body of a wetland may be referred to as *perched*, where it is underlain by a discontinuous, semi-permeable or impermeable bed, and situated some height above the regional aquifer. The potentiometric surface of such aquifer may be regarded as equivalent to watertable.

Figure 12 plots the watertable relative to datum in a 60m length of dipwell transect perpendicular to a drainage channel, previously illustrated in Figure 4a, showing also the surveyed ground levels. The watertable can be observed to follow the ground surface closely during the April watertables displayed, with one marked difference. The drainage channel was blocked in January 1991, to assist the re-wetting of the adjacent mined area. This effectively increased the hydrostatic head in the form of the water surface in the drain, which became a deep pool. Before the increase in water level in the channel, the watertable close to the drain (within 10m) followed the shape of the ground surface almost exactly. Following the blocking of the drain, the shape the watertable close to the drain changed. The new shape and gradient assumed by the watertable appears to be determined by the adjacent hydrostatic head rather than soil hydraulic properties such as increased hydraulic conductivity in the aerated zone beside the drain.

This does not explain entirely the need to investigate hydraulic gradient. It has been established that flow direction will be from a zone of high energy or head to a lower head and so identifying potential flow directions in the form of falling heads can be critical in understanding the dynamics of a system. If we also consider the Darcy Equation (Equation 5), we see that change in head with respect to length (change in the x, y, or z plane) or head gradient, is critical to the calculation of flow rate. Where initial estimates of flow capacity are in question, or when an initial analytical estimate is required for calibration purposes and refinement of design criteria, it may prove useful to employ observed head gradient in the Darcy Equation.

Figure 12. Hydraulic gradient indicated by a dipwell transect perpendicular to an old drainage channel.



¹ the term 'intact mire', in this case, refers to an area of mire which has not been subject to peat cutting but is disturbed by adjacent peat cutting and active drainage. 'Intact' in this sense is interchangeable with 'uncut'.

3.5 Surface water flow

In a habitat with a watertable at or near the surface for much of the time, characterised by a combination of open water and terrestrial features, open or surface water flow will undoubtedly be a dominant hydrological process. Even where open water may not be clearly identified, rapid flow through the litter layer and growing plant stems will be an immediate consequence of a high watertable. Already we have identified two forms of open water flow within wetlands. First, flow of water within a defined channel by virtue of its potential energy head, or *stage*, within a natural or man-made channel. This is mitigated by resistance at the channel boundaries which may be bare or vegetated. Second, there is shallow flow or run-off across the wetland surface through and over vegetation and bare surfaces, occurring as a *sheet* or in transient pool and channel networks. This form of flow though commonly observed is far more difficult to quantify. In addition to its transient nature it may be indistinct from near-surface porous flow within the zone where the actual surface is difficult to define. Where open drain channels also exist, removal of such near surface and surface flow from the wetland area will be accelerated. This situation can be observed in many wetland types, and is most common in upland peatlands where shallow open drains have been employed ostensibly to improve the quality of herbaceous vegetation for grazing livestock by lowering the watertable. Shallow open-drain systems are relatively ineffective in lowering the watertable in low conductivity substrates, such as the typical organic peat soils found in these situations. The effect of the shallow drain networks is mainly to accelerate removal of recharge. The influence on a catchment hydrograph however can be easily observed as quickflow, and as the gradient of the rising limb of the hydrograph increases. Given that the majority of rainfall occurs in the uplands, this is likely to become of increasing concern to water managers as the frequency of downstream flooding, commonly on developed floodplains increases resulting in extensive damage to property and business. Accuracy in the forecasting of such events would be increased if flow rates in the uplands were known.

Open water flow is most frequently measured in terms of depth, velocity or discharge within a channel or control structure of known dimensions. Where such defined channels exist, flow can be measured using standard techniques that are as numerous in form and dimensions as channels themselves. These methods can be divided into two main groups. First, those that record velocity in a channel or pipe of known cross sectional area (and water depth in the case of an open channel) using some form of flow meter of which many are commercially available. These will not be discussed further as their operation is self-explanatory. The second group measures depth in a *control structure* such as a weir or flume. The difficulty in applying these methods in wetlands arises from the need for adequate head difference in typically low gradient channels, in particularly where weir structures are concerned. The greatest difficulty in measuring open-water flow in a wetland habitat is likely to be that no distinct channel can be identified. Many channels are of a transient nature, on either season or shorter time scale such as a single storm event. An experimental technique to quantify this type of flow is discussed in Section 3.5.2.

3.5.1 Recording surface water flow in control structures

There are many different shapes and forms of control structures and this aspect of their operation will not be discussed at length, as it can be found in the large number of informative textbooks and technical manuals available. It is probably most useful to outline the theoretical principals of operation and describe main differences in structures. Control structures alter the flow conditions in a channel so that they conform to empirically determined standards. They are often sub-divided into two types of structures, namely weirs and flumes, although they can also be combined. Essentially the control structures constrict flow, resulting in critical flow conditions such that a *critical velocity* is reached usually a very short distance upstream of the structure. Critical flow or velocity, V , is defined as:

Equation 17. $V = (gD)^{0.5}$

where g = acceleration due to gravity
 D = hydraulic depth

Hydraulic depth in an open channel is given by the cross sectional area normal to flow direction divided by the width of free water surface.

The free-flow discharge, Q_f , is a function of depth or head, h_u , measured at this predetermined location on the upstream side of the structure (Figure 13).

Equation 18. $Q_f = f(h_u)$

When flow downstream of the structure is such that the upstream critical depth is exceeded and flow velocity is less than the critical value, flow is described as *submerged*. Figure 13 illustrates the position of flow conditions in an open channel. In such a flow regime, the increase in tailwater flow depth (downstream of the structure), Δh_d , will result in an increased upstream head of Δh_u (where Δh_u is less than Δh_d). If a structure is operating within submerged flow conditions then up and downstream depths must be recorded, where submergence (S) is given as,

Equation 19. $S = h_d / h_u$

The submerged flow rate, Q_s , is a function of head loss and submergence:

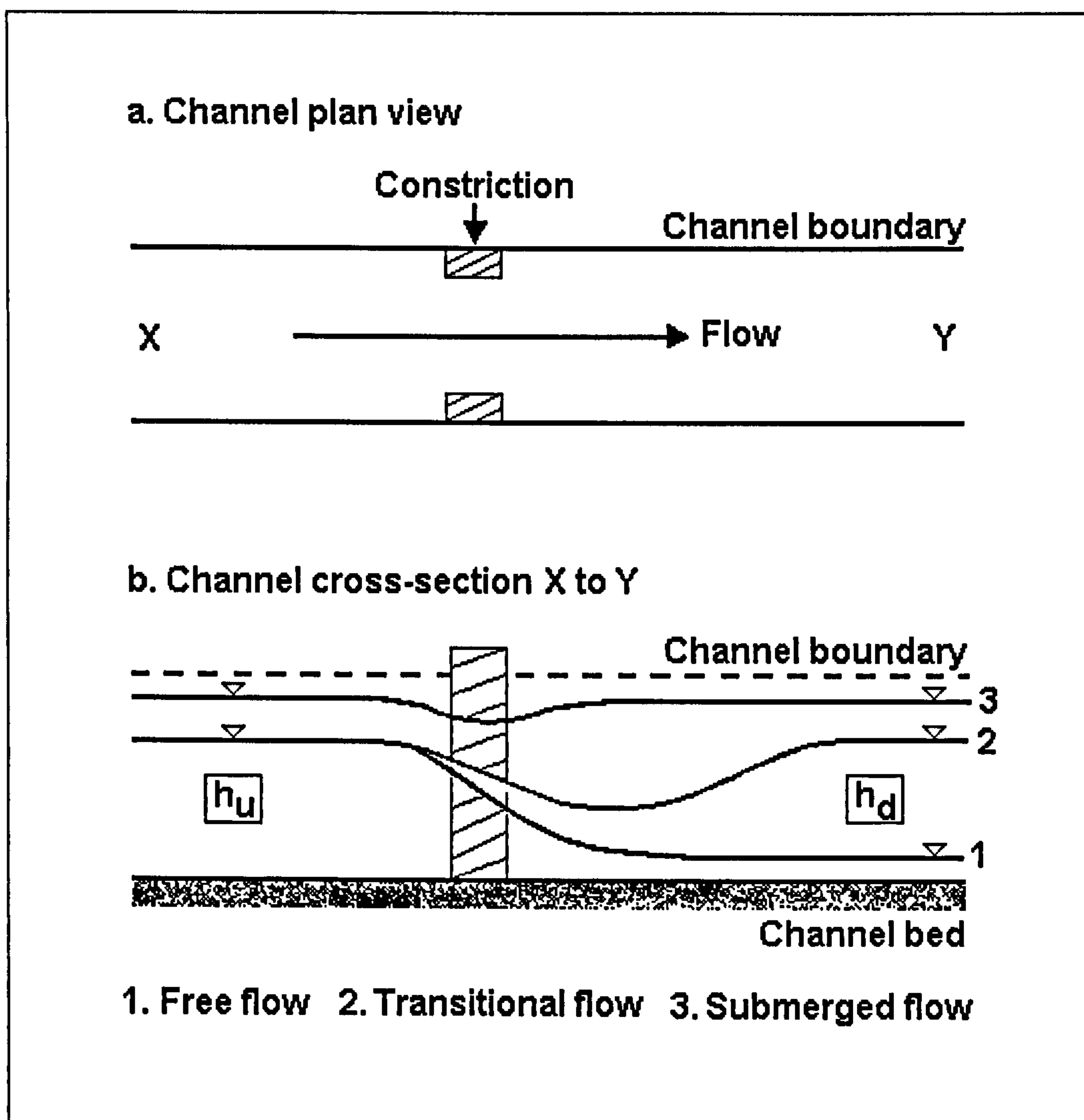
Equation 20. $Q_f = f(h_u, h_d) = f(h_u - h_d, S)$

Wherever possible when designing and installing a structure, the potential for succession to submerged flow should be anticipated to prevent a constricting structure designed for free flow operating under a submerged condition. Where head differences are marginal, as is common in many wetlands, this may be difficult and is a critical design criterion.

Weirs and flumes come in many different shapes and forms but are essentially constructed to predetermined dimensions, of which the effects of constriction on flow have been determined empirically. Given these dimensions and a known head or depth within the range of criticality a structure-specific formula can be used to calculate discharge. Flumes that essentially create a *throat* within the channel can be subdivided into those which induce critical flow in regions of parallel flow and curvilinear flow, where linear flow conditions are usually better defined. Weir structures are often much simpler structures, usually some form of plate with a *cut-out*

central Section with empirically determined dimensions. They are often considered to result in more accurate discharge calculations than flumes but they also require a greater head difference to operate in free flow conditions. Both structures can be automated using pressure transmitters or more commonly float mechanisms (3.4.2 Assessing hydraulic gradient). The biggest obstacle to the utilisation of control structures in wetland hydrometry is the low gradient situation common in most wetland habitats.

Figure 13 (a) Plan view of channel, stage X to stage Y. (b) Three flow conditions and water surfaces: free-flow (1), transitional flow (2) and submerged flow (3) within a theoretical channel constriction, which could be either a weir or flume.



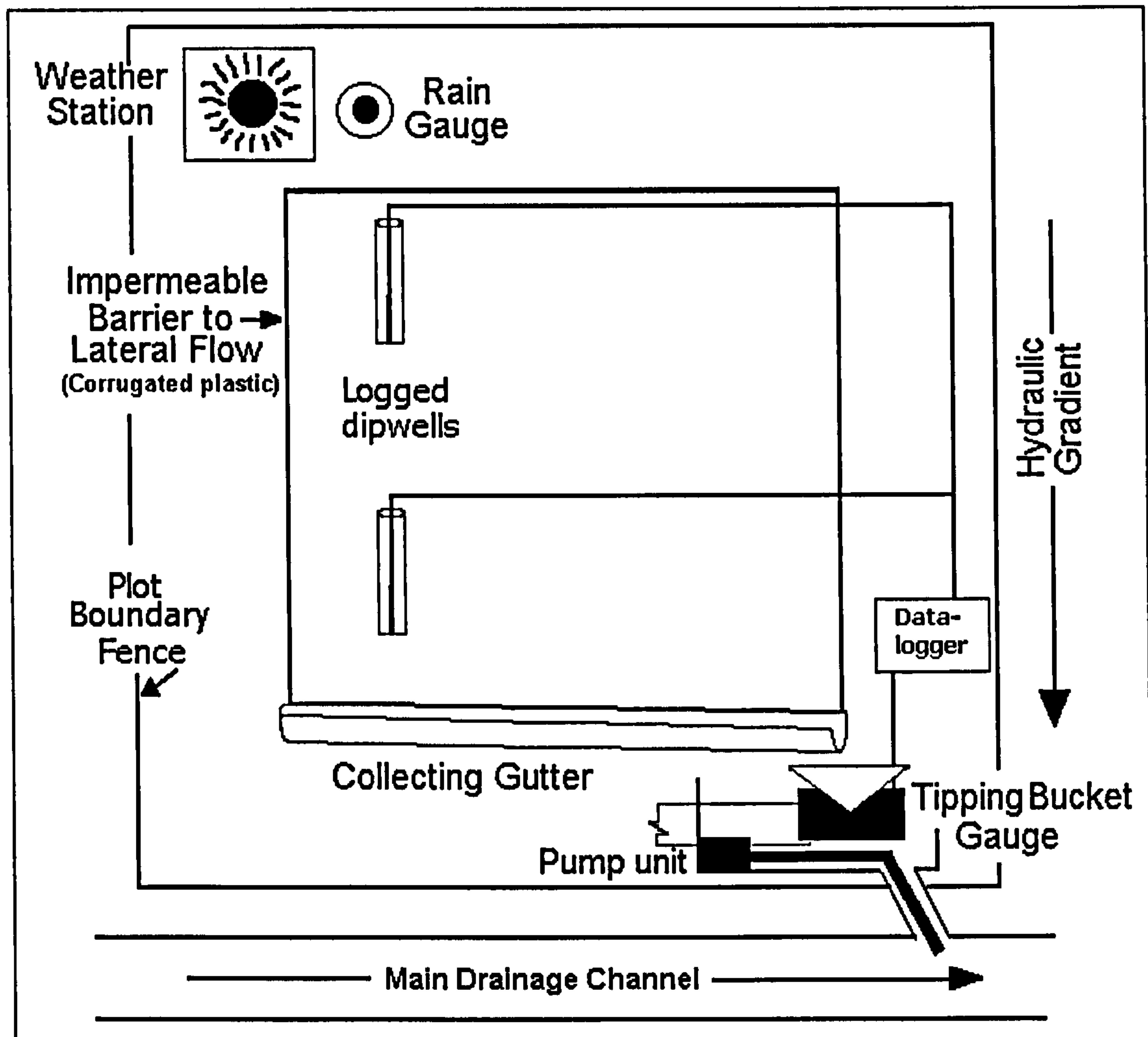
3.5.2 Recording near-surface and surface water flow in transient pool-channel networks: experimental catchments.

Where it is necessary to assess surface water flow in a wetland, or at least the potential surface component of a site water balance, direct measurement in regions with transient or barely definable channels present a difficult problem. Whether flows arise because of a high watertable (saturation excess), or due to a low infiltration capacity, for example a crusted surface (infiltration excess), it may be difficult to make more than a best estimate of the surface flow component. In many cases, it may not be possible to differentiate between what is strictly overland flow and porous flow within saturated surface media. The use of tracer and dilution tests can have limited degrees of success in shallow water systems where flow through dense vegetation both submerged and non-submerged, may cause an unacceptable degree of disturbance. Such tests are more successful in defined channels.

Where flow routes are naturally indistinct, the option remains to define a discrete test region and record the *runoff* from an isolated area where inputs can be clearly defined.

Figure 14 illustrates in plan view the surface and groundwater-monitoring plot installed at Trough End Bog, Northumberland National Park, UK. No scale has been included on the plan and this would vary from plot to plot according to site-specific factors. The Trough End plot was 100m². It should be noted that the experimental error (mainly due to increased infiltration immediately next to the barrier) would be reduced proportionally in larger plots. Visual observation of the site and above surface dipwell levels indicated that surface water was present for a large proportion of the time during both summer and winter. In characterising the hydrology of the site for conservation purposes, it was deemed necessary to quantify this component of the water balance more accurately and to produce a hydrograph representative of the site.

Figure 14. Experimental Surface Water Monitoring Plot (SWaMP), Trough End Bog, Northumberland National Park, UK.



The plot was orientated adjacent to the predetermined hydraulic gradient and flow barriers were inserted to a depth below the annual minimum watertable and beyond the maximum shallow drain drawdown depth, excluding surface and subsurface lateral flows. Inputs to the plot were then reduced and precipitation was recorded using a tipping-bucket rain gauge with a data logger. It should be noted that if the barriers are left in place during dry periods, dehydration within the plot may be accelerated without the buffer of the surrounding watertable to maintain wetness. However this was not observed in the Trough End plot, where rainfall continues throughout the summer season. Corrugated plastic is a suitable material from which to construct the no-flow barriers, being rigid, inert, reusable, whilst over-lapped

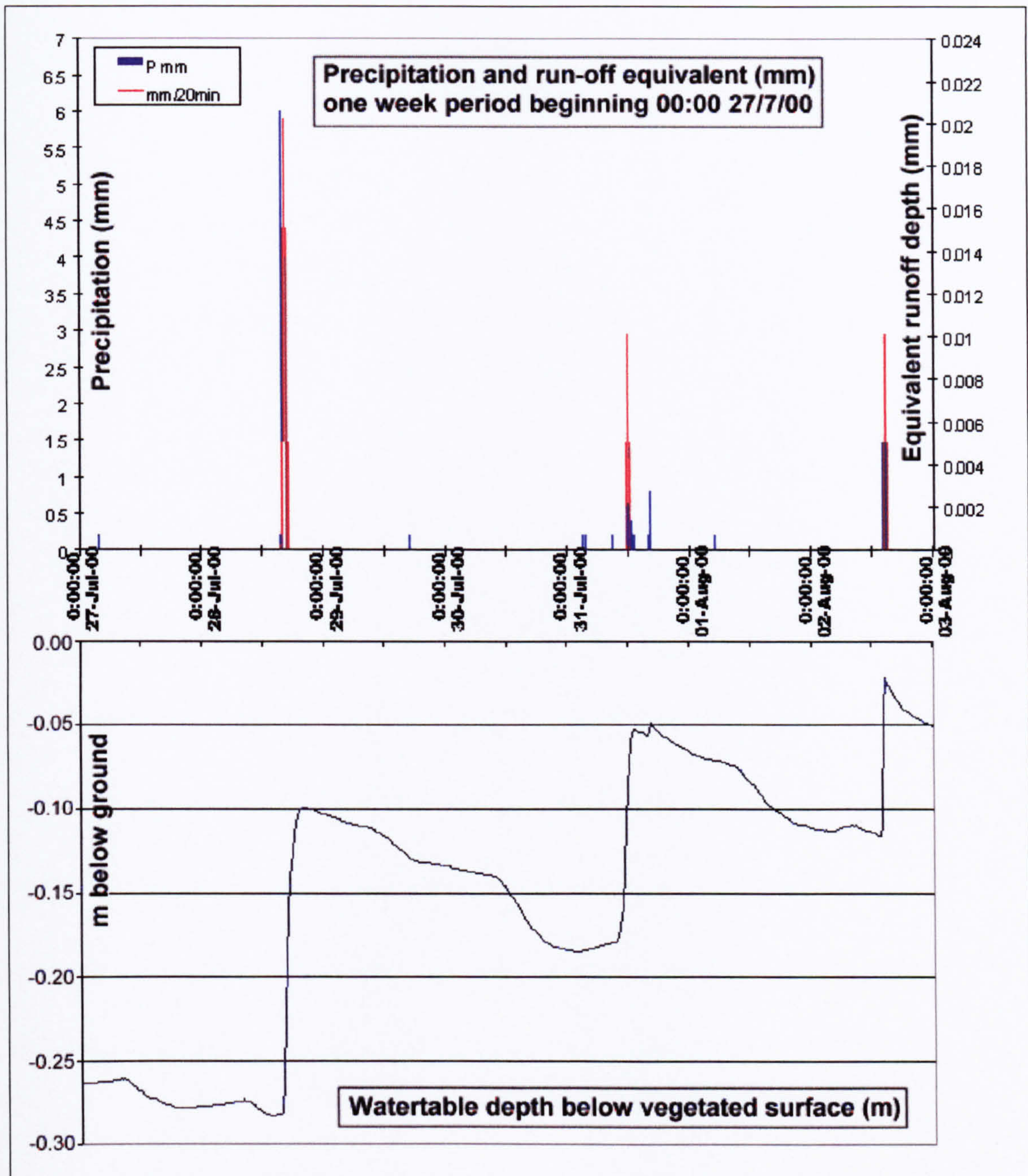
in an inter-linking fashion to prevent leaks. It is also light and flexible therefore easy to transport, which is a major advantage in the field! At the lowest point in the plot, surface water is directed into a collecting gutter below the level taken as the surface-zone, in this case the living zone of the non-vascular plants. Standard domestic guttering formed an adequate collecting channel in this case but in the case of larger areas and higher flow rates, a channel with greater flow capacity may be required. At the Trough End plot this was held in place using flow barrier material, but angle iron or wooden battens for example are also suitable. Guttering must be installed so that there is adequate head gradient to ensure rapid flow into the tipping-bucket gauge, from which it is then directed out of the plot. In low gradient situations, it may be necessary to install the tipping-bucket gauge within a submerged container and empty this periodically using a pump. At Trough End plot, the gauge was contained in a large trough (intended for animal water supply) containing a float switch and a small marine electric pump powered by a 12-volt car battery. This proved adequate, but in an ideal situation a renewable power source would be utilised such as a small wind turbine or solar cell. This reduces the number of visits necessary to change batteries, the subsequent costs, and disturbance to the site.

The influence of recharge on the plot is also observed as fluctuating groundwater, in this case recorded using pressure transducers within dipwells installed in the plot. Groundwater fluctuations in dipwells, runoff via the tipping bucket and site precipitation were all logged continuously using data logging equipment (3.2 Precipitation, 3.4.2 Assessing hydraulic gradient). It is unlikely that manual readings in this situation would be adequate, as it is necessary to log several factors at one time and to record storm events 24 hours a day.

The hydrograph, Figure 15, shows the recorded rainfall, runoff and groundwater level from the plot over a one-week period. Runoff events recorded during this period are apparently very *flashy* and do not account for a large proportion of the rainfall recorded on a 20 minute logging interval (less than 2%). Other logging periods at the site using the same interval, recorded runoff volumes four times the incoming precipitation during prolonged showers. The runoff values presented in the hydrograph are represented as an equivalent depth in mm, using outflow totals for the 20-minute interval. If the data are presented as cumulative totals over an hour say, the proportion of rainfall becoming runoff appears much larger. The distance between the vegetated surface and the ground watertable decreases steadily as rainfall

continues. The data presented were collected during the driest part of the year, yet the watertable has reached the surface after three substantial rainfall events.

Figure 15. Precipitation, runoff and groundwater levels recorded in the Surface Water Monitoring Plot (SWaMP), Trough End Bog, during the period 27th July - 2nd August 2000.



The Trough End SWaMP was an experimental venture and much of the equipment was constructed for the purpose. Whilst equipment cost was relatively low, man-hours and site visits were high. Many experimental errors and equipment failure problems were encountered and consequently a great deal of data was effectively lost during the monitoring period. This situation is typical of experimental hydrometry and it is stressed that such an approach is not suitable where accurate data must be obtained in a short length of time.

4 Water quality in wetlands

It is not possible to discuss wetland hydrology without mentioning water quality. This is of increasing importance as interest in constructed wetlands is growing rapidly. It is likely that within the monitoring strategy of any wetland, whether it is managed for conservation or water treatment, some measure of water chemistry will be taken. This may vary from nitrate to metal species concentration and pH, to biological contamination such as faecal material, to mention only a few. A water quality monitoring scheme should be designed using the same criteria as a hydrometry scheme, the main difference being that most measurements will be carried out away from the site in a laboratory, given the difficulties of conducting any experiment in a inhospitable environment. Field activity is likely to take the form of sample extraction of ground and surface water. Some simple tests can be carried out on site. The parameter most likely to be measured in the field on a regular basis is pH, using a portable pH meter with a probe that can be inserted directly into the sample. Other commercially produced 'probe' type meters are currently available for various elemental concentrations, and are becoming increasingly accurate as demand itself grows.

Groundwater samples can be taken from dipwells following a manual water level reading. Where automated water level readings are recorded in the same dipwell, care should be taken to note the exact time of the reading, so that any rapid change in level and recovery can be explained. Following the removal of a sample adequate time for water level recovery must be allowed before subsequent level readings are made. Where the watertable is close to the surface, samples can be removed most simply using a small container attached to a rod, lowered into the well. Where the level makes this difficult (it is obviously not practical to carry a rod much longer than 1m) a telescopic rod may be employed. Telescopic pointers or radio aerials and carpenters tapes all make good alternatives to solid rods. However the container arrives at the water surface the receiving vessel into which the sample is transferred for transport should be washed in the sample to prevent cross contamination. Pumps may also be used to remove a sample but these are more likely to increase the chance of contamination. Surface water samples may be removed in the same way.

5 Operating and maintaining equipment

The monitoring of any environmental variable in the field can be fraught with difficulties that are only increased by the extremes of temperature and moisture often experienced in wetlands. The potential for equipment failure increases when it is left unattended for long periods of time and where interference by animals or unauthorised humans may arise. Whilst it may be convenient to install automatic data logging equipment at a site to reduce disturbance and the need for regular manual readings, it is essential to visit equipment at reasonable intervals and ensure it is in full working order. Disturbance should be limited as far as possible during maintenance visits, by for example standing on boards. Common problems result from temperature, damp, animal and human interference.

Battery life may be reduced considerably at low temperatures, while temperature difference between water-proof sensor or logger units may result in condensation, causing moisture to collect within the unit. If wiring connections are wet, short circuits can cause equipment failure. Pre-filled desiccant bags should be placed within such 'sealed' units and replaced at regular intervals. Bags can usually be reused after drying in an oven at a low temperature. Care should be taken to prevent ice forming on equipment, which may require additional insulation. Ice can also form in dipwells making them impossible to read. Where sensors are placed within wells likely to freeze, it may be necessary to refer to manufacturer's instruction on sub-zero operation.

Cables between sensors and logger units should be buried or placed in protective casing to prevent animal interference. It is extremely disheartening to return to a unit to download data, only to find a rodent has chewed through an exposed 10cm of cable within an hour of installation so that all of the monitoring period has been wasted. Given problems likely to occur during installation of loggers and sensors it is wise to re-visit newly installed equipment early in the logging period. This is especially important in remote locations. Where sensors or loggers are positioned within a larger container it is not unusual to find small mammals or reptiles sheltering as they can gain access via any small hole or crack. This may cause problems where animals chew plastics or cable. Where venomous snakes are present, extra care should be taken when lifting containers as it is not unknown for snakes to nest under them.

Another form of animal interference can arise from birds perching on equipment, damaging or simply fouling exposed sensors. Potential perches can be wrapped in various materials to make them less attractive to birds.

One of the most commonly encountered form of indirect interference is the blocking of dipwells and rain gauges by insects and plant remains. A loose fitting cap placed on well tops can prevent them trapping insects. Cutting down vegetation close to rain gauges before seed heads appear stops a lot of wind blown debris reaching the gauge. Within all gauges there should be a removable filter, and this must be cleaned regularly during summer months to prevent it becoming blocked by dead insects and vegetation.

Good camouflage, adequate fencing, and warning signs (such as 'HIGH VOLTAGE!') can usually reduce potential interference by unauthorised humans. Of course, if a vandal is determined to destroy equipment he or she can see and access, there is very little that can be done. In this case wetlands have an advantage over most habitats. If visits to equipment can be minimised then it can be placed in the wettest, least hospitable part of a site that monitoring objectives will allow. As much installation work may occur in the driest season, wet season high water levels must always be considered. It may become necessary to access some equipment by boat at certain times of the year.

During all fieldwork activities, the health and safety of personnel must be ensured at all times.

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1. Introduction

The hydrological characteristics of raised mire complexes have been the subject of many studies over several decades. Still the heterogeneous nature of these ombrotrophic mires, occurring in many cases in glaciated and widely varying regional topography, demands a cautious approach when generalising the hydrology of such peat deposits. This situation is further complicated where the mire morphology is disrupted by human activity such as artificial drainage and peat removal. Undisturbed mires maintain a phreatic surface close to the ground and can be considered relatively hydrologically stable, with a streamflow response similar to that of an unregulated reservoir (Verry *et al.*, 1988). As Verry and Boelter (1975) observed, 'this is contrary to popular belief' which states that mires have a regulating influence on discharge. Bay (1969) also concluded that the mires in his study of Minnesota catchments had no regulating effect on observed discharge. The formation of raised mires by terrestrialisation of open water bodies means that open water areas in undisturbed bogs tend to be relatively shallow and occupy a small proportion of total mire area. The storage potential of the peat body however is high, with potential volumetric water content of up to 0.97 in saturated, undisturbed peat (Ivanov, 1981).

The profile of an intact mire is described by the concept of diplotelmy (Ingram, 1982, Ingram and Bragg, 1984). The upper layer within the zone of fluctuation of the water table is referred to as the *acrotelm*, or living layer of vegetation dominated by *Sphagnum* moss species and their slightly humified remains. Below the water table anaerobic peat of greater humification and bulk density is referred to as the *catotelm*, the boundary between the two layers being determined by the minimum phreatic level (Ivanov, 1953, cited in Ingram, 1978). The accepted generalisations concerning the morphology and hydraulic

characteristics of undisturbed mires are that degree of humification and bulk density increase with depth below surface, whilst hydraulic conductivity and specific yield fall (Boelter, 1965, Romanov, 1968, Rycroft *et al.*, 1975, Ingram, 1978, van der Schaaf, 1999). The phenomenon of 'peat piping' (subsurface preferential flow paths within peat) could be considered an exception to this rule (Holden, 2000). Given that storage potential is high and ground water flow is slow (see Section 4.2, Table 3) it should not be surprising that an undisturbed mire will respond to recharge in a similar way to contained open water: it is effectively a reservoir overflowing. The surface and near surface flow mechanisms of intact mires, though less well understood, point to a rapid succession to saturation-excess overland flow regimes (Burt *et al.*, 1990, Holden, 2000). The microtopography of inter-linking hummocks (ridges) and hollows (pools-channels) created by the ongoing *Sphagnum* moss species succession is indicative of such flow processes over extended periods.

The flow processes of mires that have been drained artificially are more difficult to define. When a mire is utilised for peat removal the acrotelm is removed, exposing catotelm peat, which is 'dried' by employing open drains at varying intervals to lower the watertable. Very few mires remain undisturbed in the UK and in most cases artificial drainage influences flow processes in some way. Many sites have been reduced in area by peripheral drainage enabling agriculture to encroach upon the mire body, whilst in Northern Europe and North America mire surfaces have been lowered extensively by the removal of peat for horticulture and fuel. The impacts on mire morphology and hydrology of such practices are wide ranging. The rate at which recharge is removed from the site will increase and can be observed in stream discharge following a storm (Kløve & Bengtsson, 1999). Watertable draw-down adjacent to drains results in desiccation of peat,

shrinkage, extensive cracking and subsidence, exacerbated where peat mining operations have meant the removal of the acrotelm and the exposure of bare, highly humified, catotelm peat. Considering the low hydraulic conductivity of such peat, the extent of draw-down may be limited to regions close to the drains, with the phreatic level remaining relatively high. However, given the high degree of exposure, potential evaporation (Brooks, 1988) and propensity for near surface and overland flow at such sites, the likelihood of increased erosion and slumping becomes the greatest concern. Under such conditions the establishment of vegetation communities with the potential to ameliorate such processes is extremely difficult.

This chapter examines the ecohydrological characteristics of a raised mire complex, Wedholme Flow, Cumbria (National Nature Reserve, Site of Special Scientific Interest, candidate Special Area of Conservation - European designation), and attempts to identify the key differences in observed behaviour in areas having varying degrees of anthropogenic disturbance. The lasting influence of abandoned peat cuttings as reflected in the current hydrology and vegetation assemblages is examined and the influence of ongoing adjacent peat mining activity is considered. The reserve managers, English Nature, aim to restore damaged areas to functioning mire and would benefit from a hydrological model capable of predictive assessments of the effect of different interventions. The long term aim of this project has been to provide such a model and the ecohydrological investigation has focused on acquiring the site data necessary to achieve this goal.

The main characteristics of Wedholme Flow, its history and management strategies at the site are introduced in Section 2. In order to formulate a monitoring strategy for the site, it

was necessary to define different zones, in terms of disturbance with associated hydrology and vegetation. An initial visual assessment of the main mire surface conditions in terms of vegetation assemblages and level of disturbance was made and compared with groups identified in the site conservation management plan. The groupings identified are described in Section 2.

New monitoring programs were initiated within the different zones identified. Because of the large areas involved and the need to define hydrological boundaries for modelling purposes, transects intersecting different zones were employed. Survey and hydrometry was focused in these areas. In some cases a series of parallel transects formed a grid over limited areas. As indicated watertables have been monitored at Wedholme previously, and where possible existing transects and data were incorporated as monitoring was extended. In all, three consecutive study programs were instigated at the site, and data from all of these projects are combined in this paper. Existing topographical data are included and combined with manual levelling and 3-dimensional digital co-ordinates, so that vegetation and hydrological data are represented in relative co-ordinates, slope and a common (ordnance) datum across the site.

The data utilised are the combination of three monitoring programs at Wedholme Flow over the last decade:

1. Long-term hydrological monitoring (1990 - 1996) of water tables and precipitation by the site managers, English Nature.
2. A three year (1997 - 2000) intensive monitoring program of 'intact' site hydrology, vegetation and microtopography in order to develop modelling techniques for raised mires, carried out by the University of Newcastle in collaboration with English Nature.

3. An investigation into short term hydrological differences (October 2000) between two areas of abandoned peat cuttings adjacent to active peat removal activity, by the University of Newcastle in collaboration with the Universities of Central Lancashire, and Nottingham-Trent, commissioned by English Nature.

1.1 Objectives

An objective of the program was to characterise the ecohydrology of the site in order to create a dynamic model of its functioning hydrology. For the purpose of this paper the monitoring methodology and results for each of the identified ecohydrological components of the system are outlined individually. With the site divided into zones according to disturbance, the vegetation communities along a transect were surveyed and classified in terms of the National Vegetation Classification (NVC). The survey and data analysis methodology, along with results are described in Section 3. In addition to intra-site hydrological characteristics, it is necessary to approximate a water balance for the mire and so meteorological data collected at and close to the site during the last decade are presented in Section 4. The meteorological components of the site water balance have been recorded in increasing detail and the progression in methodology is described. Long and short-term patterns are discussed and on site, short-term data collection methods and results are described, including the use of an automatic weather station, estimation of evapotranspiration by lysimetry and by calculation. The hydrology of the different zones within the mire are explored in terms of watertable fluctuations in the long and short-term, along selected transects across the bog and described in Section 5. The section is subdivided to incorporate the data collected in the three different monitoring programs on different temporal and spatial scales, at different regions within the mire. The flow and

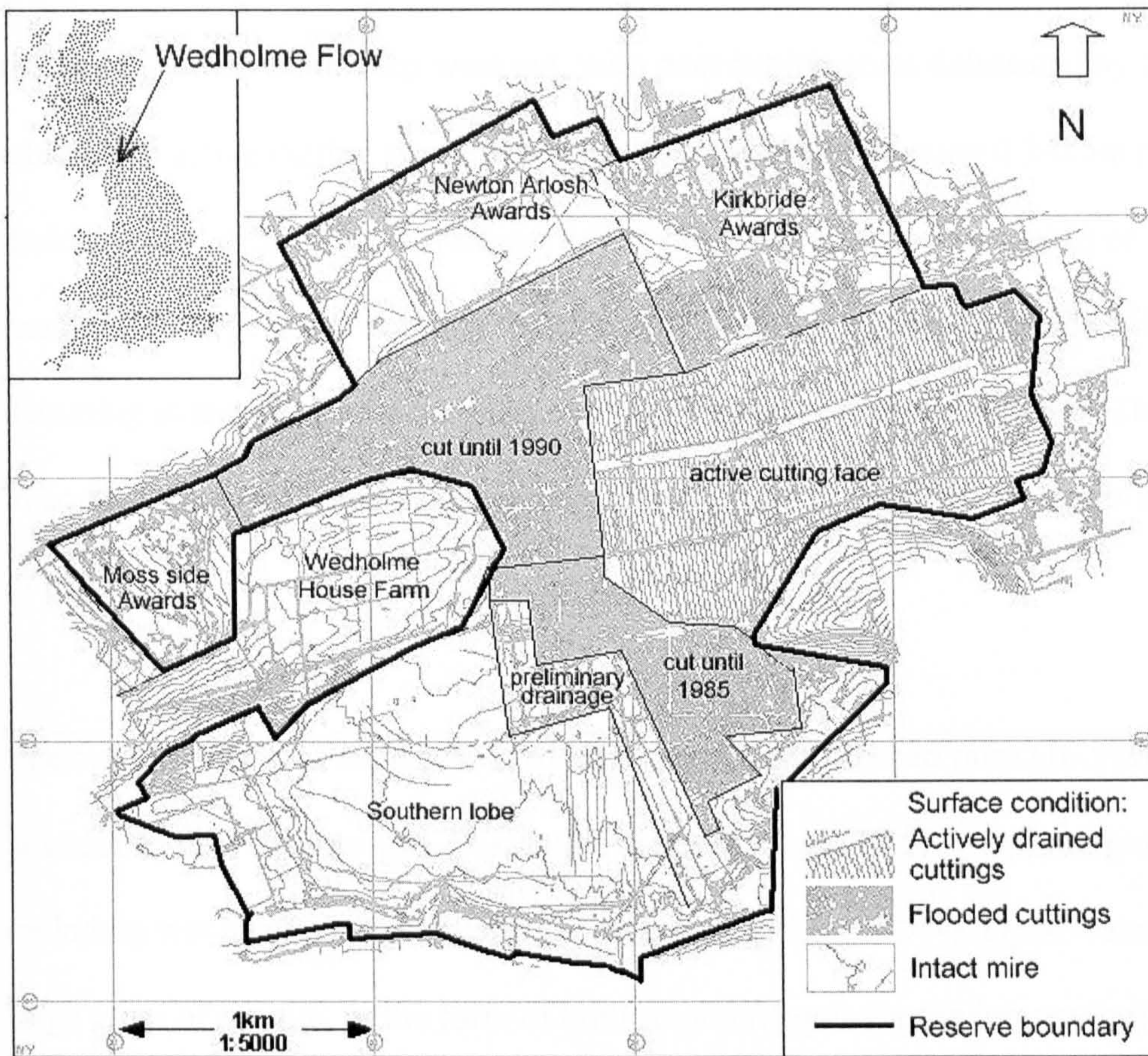
storage characteristics examined within the different site zones and within the diplotelmic mire structure are outlined in terms of methodology and results in Section 6. Comparison of topographic survey data for the site revealed potential evidence of subsidence at the site and this is discussed in Section 7. Finally, the main conclusions of the ecohydrological study are outlined in Section 8.

It is intended that data collected during this extensive monitoring program are utilised in the modelling exercise described in Chapter 4, which explores the effects of different management scenarios at the bog using MODFLOW (Harbaugh and McDonald , 1996) simulations of disturbed and intact mire areas from this study.

2. Study area

A designated Site of Special Scientific Interest (SSSI), Wedholme Flow (NY220530) (Figure 1), is the largest of the lowland raised mires that comprise the South Solway Mosses National Nature Reserve (NNR), and was recently designated as candidate Special Area of Conservation (cSAC). The mire reserve is managed by English Nature, the statutory conservation body for England. Aims of site management are to maintain hydrological and ecological integrity of intact mire areas and to restore disturbed areas to active mire (peat accumulating systems with highly specialised flora and fauna) by re-establishment of stable hydrological conditions comparable to intact zones. The site ranges from 10 to 18m above ordnance datum, with peat accumulation of 1 to 12m over boulder clay deposited during the Scottish re-advance glaciation (Jarvis *et al.*, 1984). The original peat dome is now much reduced due to direct peat removal, desiccation and slumping. Alluvium and marine deposits are present locally and may underlie some parts of the bog. The site is bounded by drumlins to the west, south and east. The bog drains to the R. Waver to the south and west, flowing into Moricambe Bay, 2km to the west. To the north and east (via Monk's Dike) Wedholme drains to the Wampool Estuary and Moricambe Bay by the R. Wampool. The topographical situation of the site and its underlying geology mean that it is ombrotrophic, receiving recharge in the form of precipitation only. The 10-year mean precipitation for the site is 896mm, with considerable variation including 567mm in 1996 and 1003mm in 1999 (Section 4).

Figure 1. Main: Boundaries, cutting areas and intact mire surface at Wedholme.
 Inset: Location of Wedholme Flow (NY220530).



The area has a long history of peat cutting and parts of the 780ha site are still referred to as ‘Awards’, made to local parishes for peat-fuel and utilised until the middle of the twentieth century (Mawby, 1995). As a result land ownership across the site is complicated with many small ‘mineral rights’, purchased where possible by English Nature (English Nature, 1995). In areas where peat has been cut within the last century for domestic use, including the Kirkbride Awards to the north east, Newton Arlosh Awards to the north and Moss side Awards to the north west, small-landholdings account for between 50-90% of ownership (Mawby, pers. com., 2001). During the nineteenth century drains were also used by landowners and Parishes to define boundaries within the bog. The current extent of today’s site boundary is largely the result of drainage at the periphery during agricultural

development. With improvements in technology enabling mechanised drainage, intensive peat extraction began around 1945, utilising around 60% of the remaining mire. Arterial drains between 2-2.5m deep were cut, with peat cutting areas delineated by 1.5m drains. In addition to active cutting areas, new areas were marked out using 0.3-0.5m narrow slot drains. Many of these areas were never worked. The restoration program of English Nature has focused largely on reversing the effects of drainage across the site by infilling and damming channels using peat, plastic piling and corrugated metal sheets. This program is in contrast to the ongoing drainage over 20% of the site to enable the commercial removal of peat.

The current mire area can be divided into primary undisturbed mire (16.5%), regenerating abandoned peat cuttings (39.7%), active peat workings (20.5%), and marginal habitats including wet heath, wet grassland and wooded lag fen (23.7%). Open water also occupies large areas of the site, in the form of both seasonal pools (in the intact mire) and blocked drainage networks (old peat workings). Figure 1 illustrates the current differences in mire surface condition and drainage regimes, revealed by aerial photography (some clarity is lost in reduction of the map). The digital data used to produce figure 1, were provided by the English Nature Mapping Unit and created by photogrammetric mapping from 1:5000 aerial photographs. At the end of September 1994, when these photographs were taken, the abandoned cutting areas appeared largely as open water - individual drains are not visible as in the maintained drainage regime. This reveals the extent of the permanent pools produced by drain blocking and the subsequent inundation of lower lying areas between peat ridges. Ridges are created when vegetation is cleared in preparation for mechanised sod-cutting, made increasingly effectively by the use of a screw levelling machine (Cooper & McCann, 1995). The low areas in between the ridges are exposed catotelm peat of

higher humification and bulk density. The maintained drainage network of the active peat cutting area appears in distinct contrast to the largely isolated areas of intact mire to the north and south-west and the farmland occupying the high ground north-west of the weather station (figure 8). The farmland is isolated hydrologically from the mire reserve by boundary interceptor drains, roughly 1.5m deep.

The differing physical condition of the mire surface can be attributed to the pattern and time scale of disturbance at Wedholme including period of and time since cutting, in addition to the removal mechanism, depth and extent of peat cutting. In the most southerly part of the southwest lobe, ancient peat cuttings dating from the early 1800's (EN, 1995) removed a thin layer of surface peat that has now entirely re-vegetated naturally.

Mechanised peat cutting occurred between 1976 and 1985 in the northern arm and eastern part of the southern lobe. English Nature did not gain control of this area until 1993, at which point remedial measures to prevent its further deterioration were instigated. Peat removal in the area between the Wedholme House farmland and Newton Arlosh Awards continued until 1990, at which point English Nature took control of the abandoned cuttings and began a program of drain blocking. The main boundaries and cutting phases of Wedholme are illustrated by figure 1.

The differences in hydrological condition across the mire can be defined largely by the vegetation assemblages and simple observations of the physical condition of the surface, for example apparently wet and stable with standing water, or dry and cracking. A general assessment of this type is necessary before any detailed monitoring or survey work can be engaged. A monitoring strategy can then be determined.

English Nature's management plan (EN, 1995) for Wedholme Flow notes three surface conditions. A visual assessment was made of these groups and their main features are described in brief below as: intact raised mire; abandoned peat cuttings (of which 3 sub-groups can be identified); and intact but moribund mire. In addition, currently active commercial peat cuttings outside of the control of EN should be included.

Intact raised mire: vegetation assemblages in this continuously wet zone are typical of active raised mire communities. The surface of the zone is characterised by a pattern of hummocks and hollows (micro-ridges and pools) (Sjörs, 1948, Masing, 1982, Lindsay *et al.*, 1985, van der Molen, 1992) with a gradation of *Sphagnum* species from *S. cuspidatum* in the pools of the hollows, through *S. tenellum*, *S. subnitens*, and *S. capillifolium* in the low hummock and lawn, to *S. magellanicum*, *S. rubellum* *S. pallustre* and *S. papillosum* in the mid to high hummock. The drier hummock tops are home to ericoid sub-shrubs and several species of *Cladonia*. *Rhyncospora alba*, *Andromeda polifolia*, and *Vaccinium oxycoccus* are widespread across the hummocks and *Sphagnum* lawns, while *Drosera rotundifolia* and *D. anglica* are locally abundant on pool edges and micro-channels where *Narthecium ossifragum* can also be found in small patches. Hollows remain moist throughout the year, with *Sphagnum* bleached by dehydration, reducing evaporation in drought periods across the entire surface. Early summer vistas of this surface are dominated by the seed heads of *Eriophorum vaginatum* (which is not sufficiently abundant to be tussock forming) and *E. angustifolium*, found in more permanent water tracks, such as hound and deer trails. This species rich (only a few of the plants found are mentioned here), stable wet community would be the target of management efforts

in an ideal situation. It also supports a wide range of vertebrate and invertebrate fauna (EN, 1995).

The surface here is not entirely untouched, being intersected in some areas by old parish boundary and marker drains in both the southern lobe and the Awards (Moss side, Newton Arlosh and Kirkbride) (figure 1). It is clearly differentiated from the moribund zones close to current, maintained boundary drains.

Abandoned peat cuttings (I) ‘ancient’ 1800’s, southern lobe: entirely re-vegetated

surface with communities ranging from *Calluna* dominated dry baulks (ridges), including small, stunted patches of *Betula nana* (separating old cuttings), *Molina* flushes, wet ericoid sub-shrub/sedge complexes and well developed mire indistinguishable from intact surfaces.

Abandoned peat cuttings (II) cut 1976-1985, southern lobe: the ground surface here is markedly different to any ‘intact’ zone. The level of disturbance is severe, and changes to topography are clearly evident. A ridge and cutting pattern oriented down relatively steep slopes, toward deep arterial channels, mean that the cuttings are still draining today. Whilst cutting ceased in 1985, EN did not gain control over the area until 1993, at which point a program of drain blocking was instigated in an attempt to halt further dehydration of the peat. This has had some degree of success in lower lying areas (the cuttings), which appear wetter, and where flow has been impeded sufficiently for shallow pools to form, *Sphagnum cuspidatum* is colonising. Down-slope in the deeper pools created by blocking arterial channels, large rafts of *S. cuspidatum* have formed and lawn Sphagna (*S. capillifolium*, *S.*

papillosum) are beginning to appear at pool edges. The sides of these permanent pools are populated by *Eriophorum* sp. and occasional *Juncus* sp. The higher intercepting ridges remain dry, with dominant *Calluna*, *Molinia*, some sedges and stunted *Betula*.

Management impeded drainage in this region is obviously encouraging the re-growth of mire species, but bare peat areas remain and evidence of dehydration and cracking can be seen at the surface. Erosion of the bare peat by run-off is also evident in the low areas between the balks. Areas of old cuttings bounding the intact region of the south-west lobe, where the slope is much smaller, are clearly wetter and more stable. Here communities are difficult to distinguish from any found in the intact region.

Abandoned peat cuttings (III) cut 1976-1990, north and north-west : cuttings here were abandoned in 1990 at which time EN gained access and began remedial drain blocking immediately. In contrast to the cuttings of the southern lobe, the slope here is small and the ground surface is quite flat. Ridge-cutting patterns still occur but are much less marked. The slope increases close to the arterial drains of the active cutting zone, where erosion of the bare peat surface by surface flow is evident. There remains a considerable area of bare peat in this cutting zone (approximately 30%) but there is a greater area of open water, which is being colonised by *Sphagnum cuspidatum* and *Eriophorum* sp. at pool edges. In some wet areas *Juncus effusus* appears, possibly as a result of bird use of the large, shallow pools created in the cuttings by drain blocking, flooding and over-topping. Dry

areas occur on higher baulks between cuttings and these are dominated largely by *Calluna* and *Molinia*.

Commercial peat cutting area: peat is currently extracted from this area using a 'milling' technique, which creates large, flat 'fields' of bare peat intersected by a network of deep (>2m) arterial drains. The cutting face is outside of the scope of this investigation, but its surface can easily be described as bare, dry, catotelm peat.

Moribund bog: in addition to the marginal, 'non-mire', habitats not addressed by this study, some physically intact areas of mire are effected by adjacent activities. Close to boundary drains the mire surface may remain intact while the vegetation is changed considerably by lowered watertables. In this lag region, considerably more vascular species are found and bryophytes may be entirely absent. Typical vascular species seem to include *Molinia caerulea*, *Holcus mollis*, *Anthoxanthum odoratum*, *Potentilla erecta*, *Myrica gale*, in addition to many other herbs. These communities tend to transform gradually into *Calluna* dominated stands within around 25m and then into more typical intact mire, with *Sphagna* based populations as the water table reaches the surface, and the influence of the drain is reduced.

3. Vegetation Monitoring Methods

The vegetation of the intact southern lobe and its cut-over northern arm were surveyed in more detail in the summer of 1998 as part of the 3-year intensive monitoring program. The survey encompassed all of the mire surface types identified at the site: intact-moribund, intact, preliminary drainage but no cutting, cut until 1986 and cut until 1990 (Figure 1). Transects were devised, along which vegetation, invertebrates and hydrological functions could be monitored for all of these surface types. The aim of the survey was to identify the range of vegetation communities, particularly in relation to restoration management and hydrological characteristics monitored in the same region (Section 5). Species percentage cover was recorded in 1m² quadrats, with three replicates, at varying intervals along the transects determined by dipwell spacing.

A full list of vegetation species found in the survey is included in Appendix I. The quadrat data for each survey point were classified according to the National Vegetation Classification scheme (NVC) (Rodwell, 1991) using TABLEFIT (Hill, 1992). The TABLEFIT program classifies vegetation assemblages by measuring the goodness-of-fit of survey data to association tables. An indication of goodness-of-fit of the NVC communities determined by TABLEFIT is given in Appendix I. Table 1 outlines the NVC communities found along the survey transects at Wedholme. The changes in vegetation with surface condition are illustrated in Figure 2.

Table 1. Distribution of vegetation assemblages at Wedholme Flow categorised according to the National Vegetation Classification (NVC).

NVC community	Constant species	NVC sub-community	Constant species	Community-habitat physiognomy
sub-comm. only	<i>Calluna vulgaris</i>	H 1b H1e		closed canopy <i>Calluna</i> dominated heath (0.5- 1m height); <i>Cladonia</i> abundant (1c); virtually no other associate species (1e)
sub-comm. only	<i>Calluna vulgaris</i> , <i>Deschampsia flexuosa</i>	H 9c H9e	<i>Molinia caerulea</i>	moderate-free draining dry heath dominated by <i>Calluna</i> ; open canopy with <i>Deschampsia flexuosa</i> & <i>Molinia</i> ; impoverished ground layer; sparse <i>Vaccinium myrtillus</i> (9c)
M 2	<i>Sphagnum cuspidatum/recurvum</i> , <i>Erica tetralix</i> , <i>Eriophorum angustifolium</i> , <i>Drosera rotundifolia</i> ,	M 2b	<i>Sphagnum recurvum</i>	bog pool & wet hollow component of patterned mire; wet lawn where micro-topography ill-defined (2b): vascular species scattered with low cover
M18	<i>Sphagnum papillosum</i> , <i>S. tenellum</i> , <i>S. capillifolium</i> , <i>Erica tetralix</i> , <i>Calluna vulgaris</i> , <i>Eriophorum vaginatum</i> , <i>E. angustifolium</i>	M18a	<i>Sphagnum magellanicum</i> , <i>Andromeda polifolia</i>	raised mire & blanket bog dominated by <i>Sphagna</i> - vascular sp. subordinate; highly developed differential micro-topography; clear zonation of <i>Sphagna</i> relative to water level; extensive, luxuriant, undulant carpet (18a)
M19	<i>Calluna vulgaris</i> , <i>Eriophorum angustifolium</i> , <i>E. vaginatum</i> , <i>Sphagnum capillifolium</i>	M19a		<i>Eriophorum</i> -ericoid sub-shrub dominated blanket bog; <i>Sphagna</i> may be prominent in wettest parts; hummock-hollow relief poorly developed if present
M20	<i>Eriophorum vaginatum</i> , <i>E. angustifolium</i>	M20a M20b		species poor, degenerate ombrogenous blanket & raised mire; <i>E. vaginatum</i> dominant in tussocks; shoots of <i>E. angustifolium</i> in wet runnels, often bare peat (20a); occasional ericoid sub-shrubs - more common in transition to <i>Calluna-Eriophorum</i> mire (20b)
M25	<i>Molinia caerulea</i> , <i>Potentilla erecta</i>	M25b	<i>Anthoxanthum odoratum</i>	mire fringe-drain side on moist but aerated soil; <i>Molinia</i> dominant; diverse range of grass & herbs; <i>Anthoxanthum</i> extensive (25b)

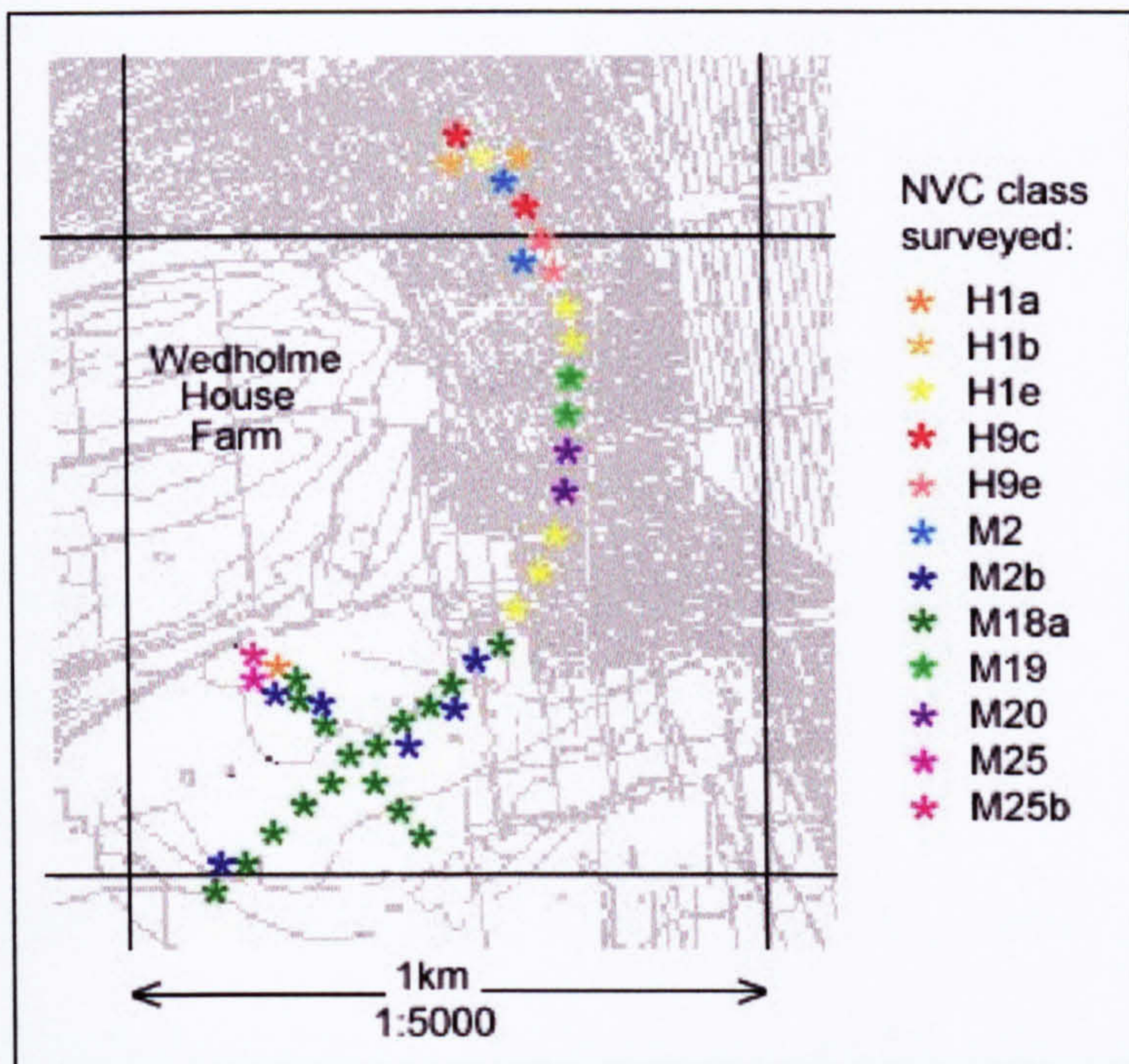


Figure 2. Distribution of National Vegetation Communities (NVC) surveyed in the Southern Lobe and abandoned cuttings of Wedholme Flow.

3.1 Classification of vegetation communities.

Descriptions of the NVC groupings of survey data distinguished by TABLEFIT, confirm the visual assessment of cover types across the changing mire surface. The moribund mire adjacent to the intercepting drain with Wedholme House farmland, is classified as M25 and M25b, *Molinia-Potentilla erecta* mire fringe, into a band of H1 *Calluna* dominated heath, on high, dry ground. On the flat wet, intact mire surface beyond, classes M2b bog pool-wet hollow patterned mire and M18a *Sphagna* dominated raised mire with extensive microtopographical differentiation, are distinguished. These classes extend to the edge of the plateau into the area previously marked out by preliminary drains, at which point slope and disturbance increases. Over this more freely draining abandoned cutting area, the communities are described as closed canopy, *Calluna* dominated heath (H1) and species poor *Eriophorum* dominated degenerate ombrogenous blanket and raised mire (M20).

Moving north through the cuttings abandoned in 1986 into those abandoned in 1990, classes distinguished are almost exclusively moderate to free draining, dry heath communities H1 and H9 and their sub groups, differentiated only by the extent of *Calluna* canopy and limited associations with ericoid sub-shrubs, lichens and occasional grasses. The exception in this area are the pools created by the flooding of old drain channels and adjacent areas which have subsequently been colonised by wet *Sphagna*, largely *S. cuspidatum* and *S. recurvum*. As such, they are classified as M2 bog-pool and wet hollow with ill-defined microtopography.

In his study of Irish raised mires, van der Molen (1992) observed that hummock-hollow complexes (close to M18 with M2) are found in plateau areas where the rate of water flow is reduced, and this is clearly apparent in the surveyed areas of Wedholme Flow. In the abandoned cutting areas the dehydration of the surface due to previous drainage, the removal of acrotelm vegetation and exposure of humified catotelm peat, and increase in slope by both peat shrinkage, slumping towards deeper cuttings and the mechanical removal of the surface peat, makes re-wetting and re-colonisation by mire vegetation extremely difficult.

4. Meteorological components of the site water balance at Wedholme Flow: existing data and collection of additional parameters.

4.1 Long term monitoring.

Monitoring methods over 10-year period.

Wedholme Flow falls with the Ministry of Food and Fisheries (MAFF) agro-climatic zone 3, prescribing a mean annual total rainfall of 1045mm (P), and annual potential evapotranspiration of 444mm (PE), hence a potential recharge or net precipitation (P_{net}) of 601mm (Smith and Trafford, 1976). There are several auxiliary Meteorological Office recording stations within a small distance of Wedholme Flow, the nearest station being Drumburgh, 6km to the north-east of the bog boundary. However no stations record sufficient data for the calculation of evaporation. English Nature have recorded precipitation fortnightly using a standard manual rain gauge in the central area of the bog since April 1990, though data are missing for some periods. Precipitation was recorded consecutively at Wedholme and Drumburgh in 1995 and no significant difference was found between the two data sets (Pearson correlation value = 0.812, P-Value = 0.001). Although the auxiliary station is approximately 9km from the manual Wedholme gauge, it was considered reasonable to supplement missing precipitation data with P recorded at Drumburgh. In 1999 an automated weather station with data logger was installed at the edge of the southern lobe, in order to collect net recharge data on a short time scale, synchronised with water level measurements (see also Section 5, Figure 8).

Figure 3. Total annual precipitation (mm) 1990-2000: Wedholme Flow manual gauge (Wm), Drumburgh Auxiliary Station (Da) & Wedholme Automatic station (Wa).

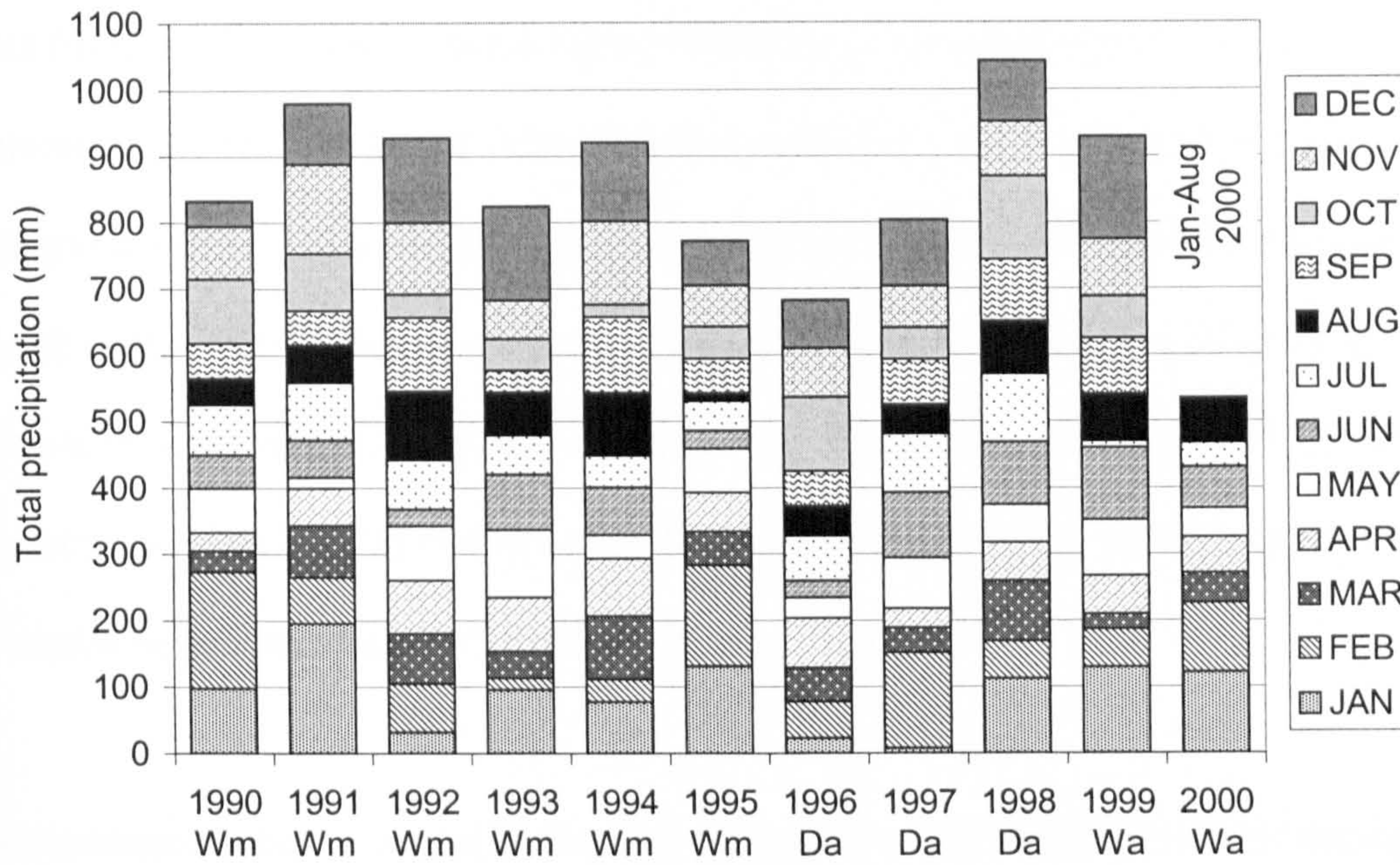
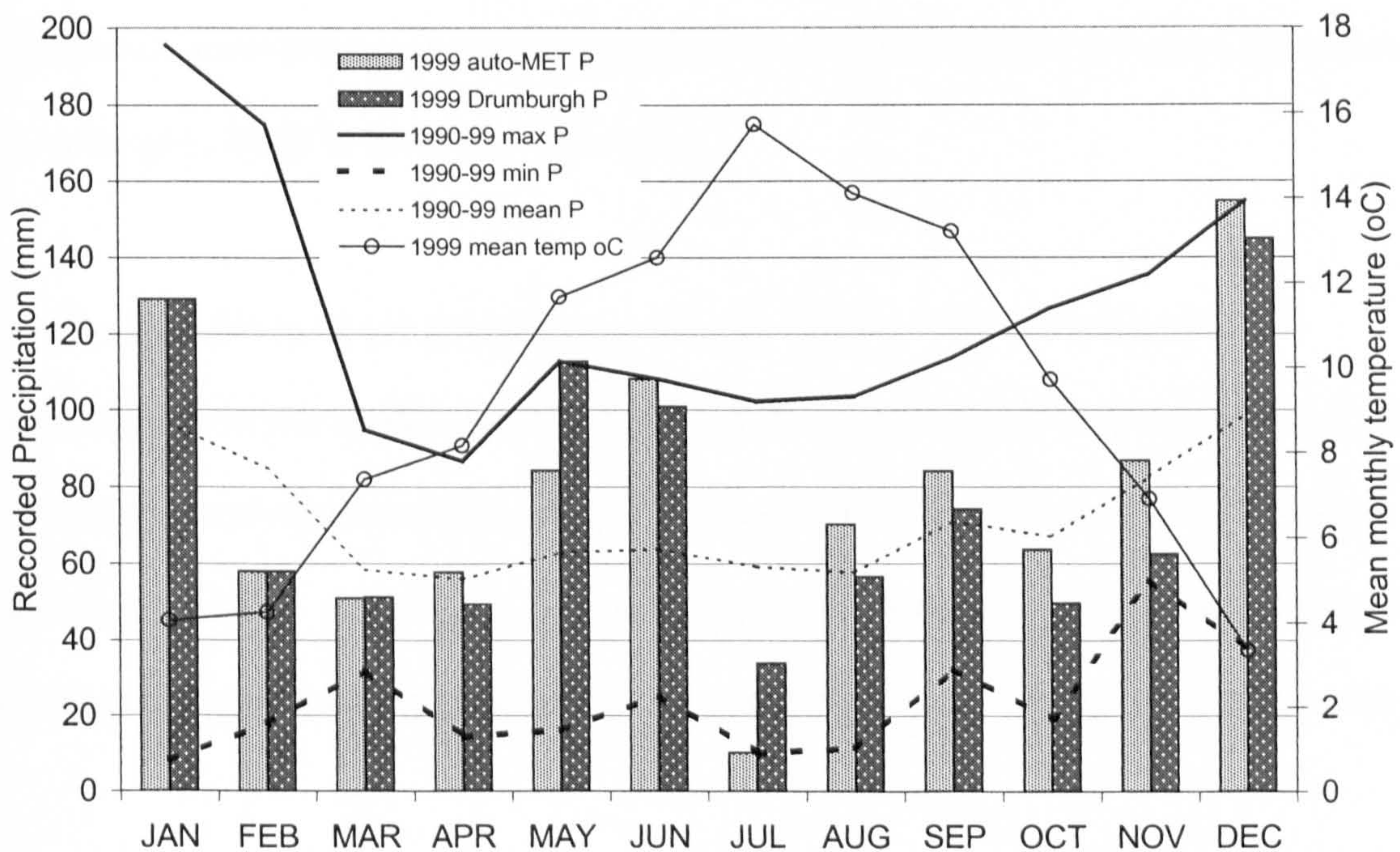


Figure 4. 10-year combined monthly precipitation - MEAN-MIN-MAX (1990-1999) for Wedholme Flow manual & Drumburgh auxiliary (mm) and 1999 monthly precipitation totals from Drumburgh & Wedholme automatic (y-axis 1); Wedholme mean monthly temperature (°C) (y-axis 2).



Long-term data set analysis.

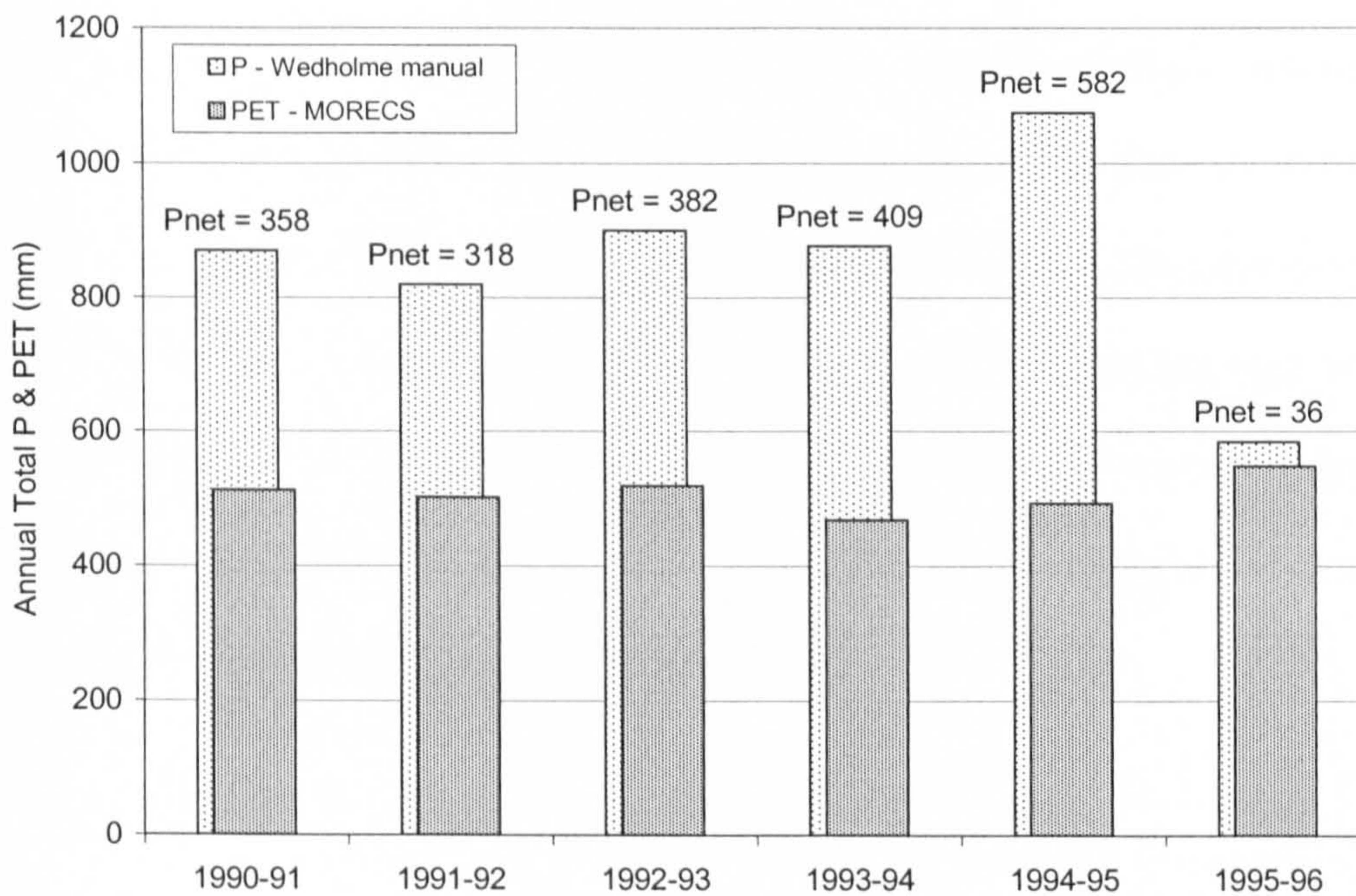
Figure 3 shows the monthly and annual total precipitation from 1990 - 2000, combining data from the Wedholme manual gauge, Drumburgh auxiliary station and the Wedholme automatic station. The precipitation data collected using the automatic MET station were integrated with existing weekly and fortnightly totals. The 1999 monthly totals can be seen to fall well within the range of values collected in the previous decade (Figure 4). They were highly positively correlated with both the 10-year mean monthly totals (Pearson correlation value = 0.732, P-Value = 0.007) and the Drumburgh monthly totals for 1999 (Pearson correlation value = 0.899, P-Value = 0.000).

Initial observations of the data set reveal a relatively even spread of rainfall throughout the year, with annual totals generally ranging between 800-1050mm, close to the agro-climatic zone total of 1050mm. The years 1995 and 1996 are exceptions to this rule having annual totals below 800mm, with 1996 representing a particularly dry year. While total rainfall is fairly evenly spread throughout the year, plotting mean monthly temperature (Figure 4, y-axis 2) along side monthly precipitation totals reveals that evapotranspiration, and hence net recharge is likely to be strictly uni-modal.

Until the installation of the automatic weather station the only net recharge values calculated for the site applied MORECS (Met Office Rainfall and Evaporation Calculation System) potential evapotranspiration (PET) values for 'upland grass cover and medium soil water capacity'. In previous studies of Wedholme hydrology (MacAlister, 1996) this proved not entirely suitable given site specific conditions such as extensive open water.

Figure 5 illustrates annual recorded precipitation and MORECS PET for Wedholme from 1990-1996, where the non-overlapping section of each bar represents net recharge. At approximately 500mm per annum, the MORECS estimate of potential ET is much lower than the MAFF agro-climatic zone figure of 600mm. This can possibly be explained by the cover type and altitude applied in the MORECS calculation, which in this case was upland-grassland, both likely to produce less evaporation.

Figure 5. Annual total precipitation, P, potential evapotranspiration, PET, (MORECS) and net precipitation, P_{net} , (mm) at Wedholme Flow, 1990-1996.



4.2 Short term parameter monitoring.

Methods: estimating evapotranspiration

The installation of the weather station¹ recording precipitation, humidity, air temperature, wind speed and direction, and net solar radiation allowed PET to be calculated for the site using a Penman type equation. It also made possible the examination of diurnal fluctuations in micro-climatic regime and storm flow events (Section 4.2). Data were collected from the automatic MET station from March 1999 until December 2000, initially at hourly intervals then at 20 minute intervals from August 1999. The program Ref ET (Allen, 1999) was then employed to calculate Penman-Monteith values for potential evapotranspiration using onsite data. For additional comparison, in June and July 2000 a set of six mini-lysimeters and three pans were constructed and installed adjacent to a dipwell transect² (Panda, 2000). MORECS PET values for soil, grass and open water were acquired for this period so that a direct comparison could be made between the methods and estimations of evapotranspiration. A further method of calculating ET from nocturnal recovery rates of the watertable was also considered³.

¹ Chapter 2, Section 3.3.1

² Chapter 2, Section 3.3.2

³ Chapter 2, Section 3.3.3

Short term data set analysis: potential evapotranspiration

Table 2 includes weekly totals for precipitation, actual and potential evapotranspiration estimates at Wedholme for a ten week period during summer 2000. Actual evapotranspiration is calculated from measurements using micro-lysimeters and micro-pans, and from observations of watertable fluctuation in an adjacent dipwell. Potential evapotranspiration is calculated by the American Society of Civil Engineers Penman-Monteith equation (Allen *et al.*, 1998) within the Ref-ET program (Allen, 2000) using weather data collected on site from the automatic weather station. The values given are based on a vegetation cover values of 72% Sphagna, 20% ericoid sub-shrubs, and 8% graminoids (mean cover type for the six lysimeters). Potential ET estimates given by the UK Meteorological Office MORECS calculation are included for three different surfaces: bare soil, grass, and open-water (O-W).

Table 2. Weekly recorded P, ET, estimated PET totals (mm), Wedholme Flow, UK.

31-May till	Recorded on site:				Ref ET (model)	MOREC's VALUES:		
	total P	Lysimeter	Pan	Dipwell		PE Soil	PE grass	PE O-W
06-Jun	44.40	31.22	-	-	3.64	10.10	13.40	13.50
13-Jun	22.00	24.15	-	-	9.73	15.11	17.50	21.80
20-Jun	0.60	10.68	6.09	8.10	14.97	21.10	21.20	25.70
27-Jun	2.40	6.93	5.95	19.00	11.22	15.90	17.30	20.50
04-Jul	0.80	5.53	6.16	7.68	12.88	16.70	16.80	19.90
11-Jul	26.40	21.42	23.59	7.74	10.08	14.10	16.70	18.80
18-Jul	0.80	6.58	5.88	-	12.53	16.70	16.30	19.90
25-Jul	0.00	7.00	5.74	-	12.04	17.10	16.90	21.30
01-Aug	10.60	27.72	28.07	-	10.43	16.90	17.10	19.40
08-Aug	20.80	12.39	12.60	-	8.12	14.40	14.70	17.30
Total	128.80	153.62	94.08*	42.52**	105.64	158.11	167.90	198.10

- data not available

*94.08 total recorded ET in 8 weeks – using weekly mean, 10 week total = 117.6mm

**42.52 total recorded ET in 4 weeks – using weekly mean, 10 week total = 106.3mm

Table 3 illustrates the net precipitation or recharge (total P - ET) calculated from the different potential evapotranspiration totals. The recharge values for the pan and dipwell having missing information are estimated using the 8-week and 4-week mean evapotranspiration respectively and should only be considered a rough approximation.

Table 3. The estimated net precipitation ($P_{net} = P - ET$) for the period 31 May - 8 August 2000, according to different methods of recording and calculating evapotranspiration. *Italicised* figures are estimates from table 2.

31-May till	Total P	Net precipitation (mm) - negative values indicate a deficit:						
		Lysimeter	Pan	Dipwell	ref ET	MOREC's VALUES: PE Soil PE grass PE O-W		
06-Jun	44.4	13.2	<i>32.6</i>	<i>33.8</i>	40.8	34.3	31.0	30.9
13-Jun	22.0	-2.2	<i>10.2</i>	<i>11.4</i>	12.3	6.9	4.5	0.2
20-Jun	0.6	-10.1	-5.5	-7.5	-14.4	-20.5	-20.6	-25.1
27-Jun	2.4	-4.5	-3.6	-16.6	-8.8	-13.5	-14.9	-18.1
04-Jul	0.8	-4.7	-5.4	-6.9	-12.1	-15.9	-16.0	-19.1
11-Jul	26.4	5.0	2.8	18.7	16.3	12.3	9.7	7.6
18-Jul	0.8	-5.8	-5.1	-9.8	-11.7	-15.9	-15.5	-19.1
25-Jul	0.0	-7.0	-5.7	<i>-10.6</i>	-12.0	-17.1	-16.9	-21.3
01-Aug	10.6	-17.1	-17.5	0.0	0.2	-6.3	-6.5	-8.8
08-Aug	20.8	8.4	8.2	<i>10.2</i>	12.7	6.4	6.1	3.5
Total	128.8	-24.8	<i>11.2</i>	<i>22.5</i>	23.2	-29.3	-39.1	-69.3

During the recording period outlined in Table 2 (31 May - 8 August 2000), the lysimeter measurement was closest to the mean of all methods employed, with the lowest estimate being the Ref-ET model output and the highest being MOREC's open water value. Half of the methods employed imply a moisture deficit during this recording period which was actually mid-summer (Table 3).

The pan and dipwell estimates of ET were low, but should be treated with caution being composite values of recorded and mean ET. Both methods are also subject to potentially high levels of error¹. The pans employed were smaller than standard pans and as such subject to proportionally greater inaccuracies. Great care should also be taken when calculating evapotranspiration from watertable fluctuations, and such estimates should not be considered in isolation from other methods. The capacity for lateral flow should not be underestimated, and this is especially the case in high watertable environments with the capacity for rapid near-surface exchanges typical in mires. Figure 6 illustrates how rainfall and lateral flow can influence ET estimates made from groundwater measurements using actual daily data (missing records are not represented). The watertable falls steadily during from the 14th to the 19th, then on the 20th it rises following rainfall. Rainfall occurs again on the 21st and the watertable continues to recover. It rises without further rain the following day, so that we can surmise it is recovering due to lateral redistribution of ground water within the mire catchment. The same pattern is apparent on the 24th and 25th. The possibility that ET may be higher following rainfall should not be dismissed as erroneous - if the watertable is closer to the surface the potential for ET will increase as a more shallow unsaturated zone will result in a reduction in the matrix forces limiting soil water movement. Interception and low infiltration rates will also increase the volume of surface water available for evaporation. Any open water that has not been accounted for may increase the potential ET to a values closer to the MORECS open water estimate.

In figure 7 the recorded midday temperature (°C) and humidity (%) are compared to daily actual ET recorded using the mini-lysimeters, pans and dipwell measurements, and potential ET calculated using Ref-ET. Not surprisingly, the Ref-ET potential ET values are

¹ Chapter 2, Sections 3.3.2 & 3.3.3

highly positively correlated with temperature ($P=0.04$) and negatively with humidity ($P=0$). This should be expected as these values are used to calculate ET in the Penman-Monteith equation (Allen *et al.*, 1998). Evapotranspiration recorded by the mini-lysimeters was significantly correlated with temperature ($P=0.06$) and ET recorded in the mini-pans fell within the 90% confidence interval when correlated with mini-lysimeter values ($P=0.08$). Temperature and humidity are not of course the only factors contributing to evapotranspiration, some of which are included in potential ET calculations, whilst it is the aim of lysimetry that they are represented in actual ET estimates with minimum error¹. No evapotranspiration value can be considered absolute and a comparison of several estimates should always be made.

¹ Chapter 2, Section 3.3.1

Figure 6. Watertable fluctuation and total daily precipitation recorded daily (at 12:00) (y-axis 2) and total daily evapotranspiration calculated from mini-lysimeters, mini-pans, watertable records & potential Ref-ET program (y-axis 1), 16/06/00 - 27/06/00.

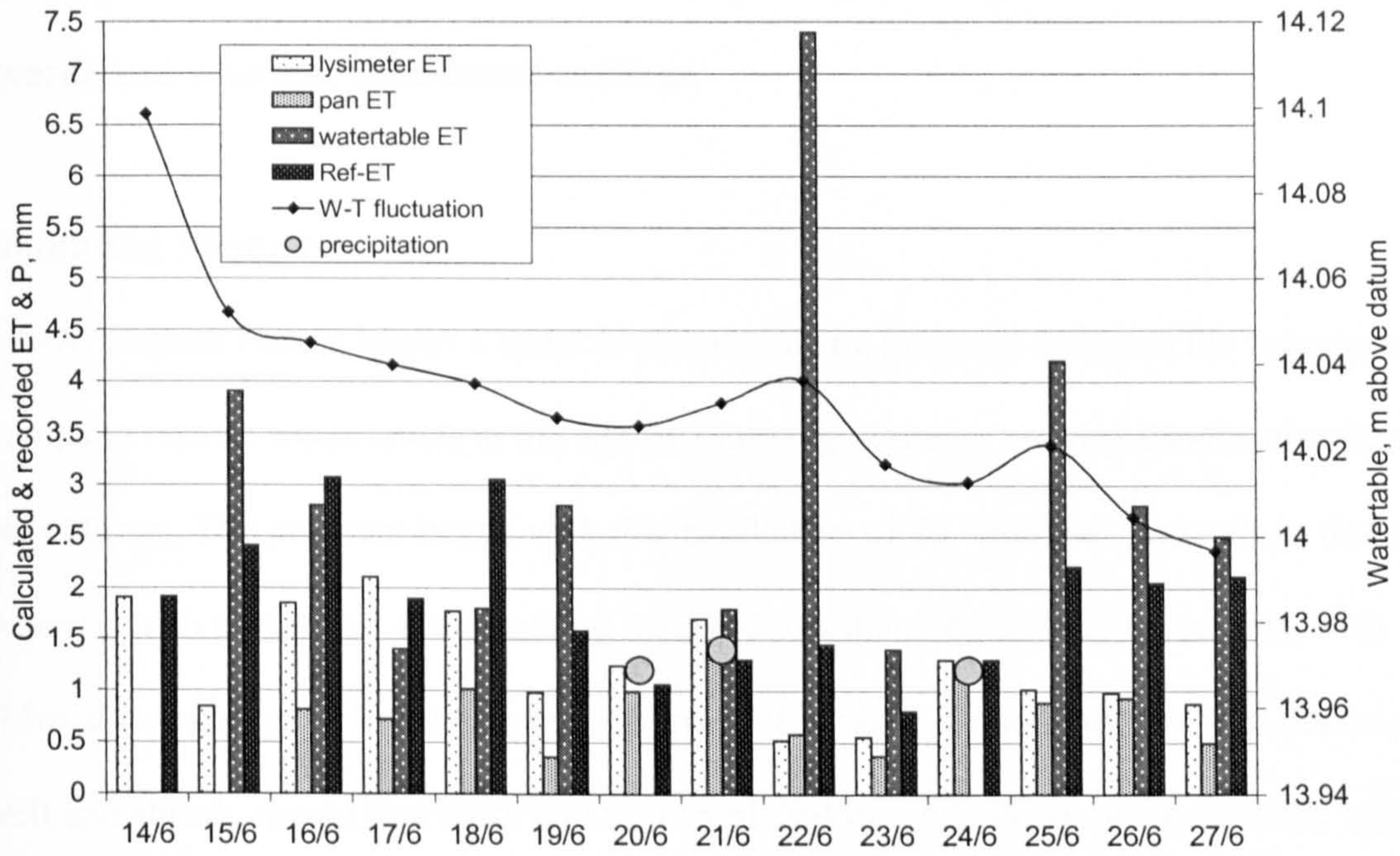
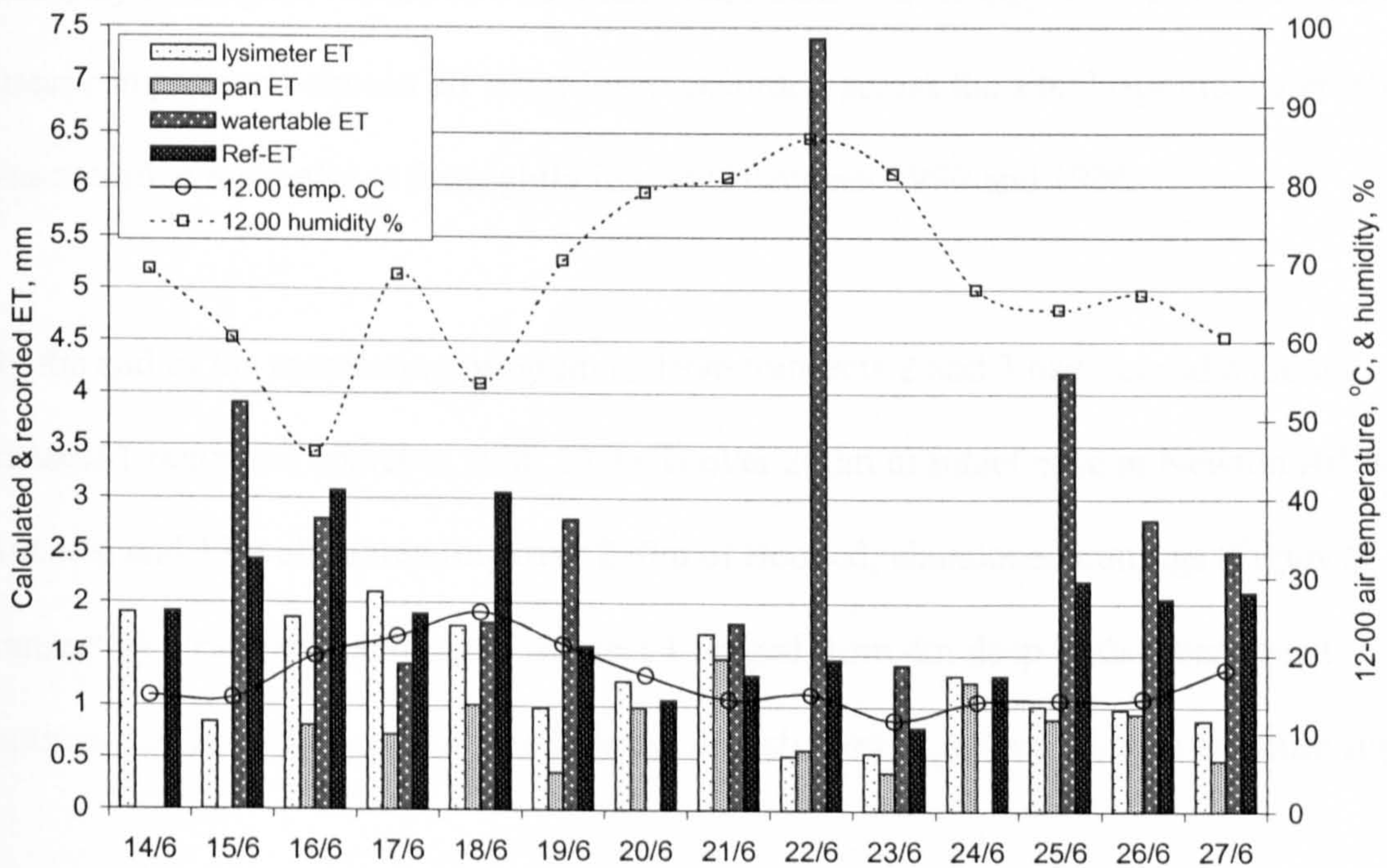


Figure 7. Air temperature and humidity (at 12:00) (y-axis 2) and total daily evapotranspiration calculated from mini-lysimeters, mini-pans, watertable records & potential Ref-ET program (y-axis 1), 16/06/00 - 27/06/00.



5. Monitoring hydraulic behaviour at Wedholme Flow from watertable fluctuations

5.1 Long-term watertable fluctuations from weekly readings in Newton Arlosh

Awards and adjacent abandoned cuttings.

Monitoring Methods

In 1990 English Nature began a water level monitoring program to assess the success of attempts to restore water levels at the site by blocking drainage networks in the abandoned peat cuttings. The program began with the installation of 70 'shallow' dipwells in three transects, with perforated 40mm tubing installed to a depth of 0.85m (1m lengths with 0.15m above ground)¹. Problems with disturbance by animals and humans, and due to peat swell and shrink, meant that these had to be replaced in 1992. Forty-one new wells were inserted to the full depth of the peat and into the underlying mineral sub-soil. Eight peat anchors were also distributed throughout the transects in an attempt to monitor any change in the mire surface level¹. The ground elevation, dipwell tops and anchors were levelled manually by English Nature to a common, false datum at the edge of the mire, allowing direct comparison between all water levels recorded across the site. Depth to water table was recorded manually at fortnightly intervals between 1990 and 1996.

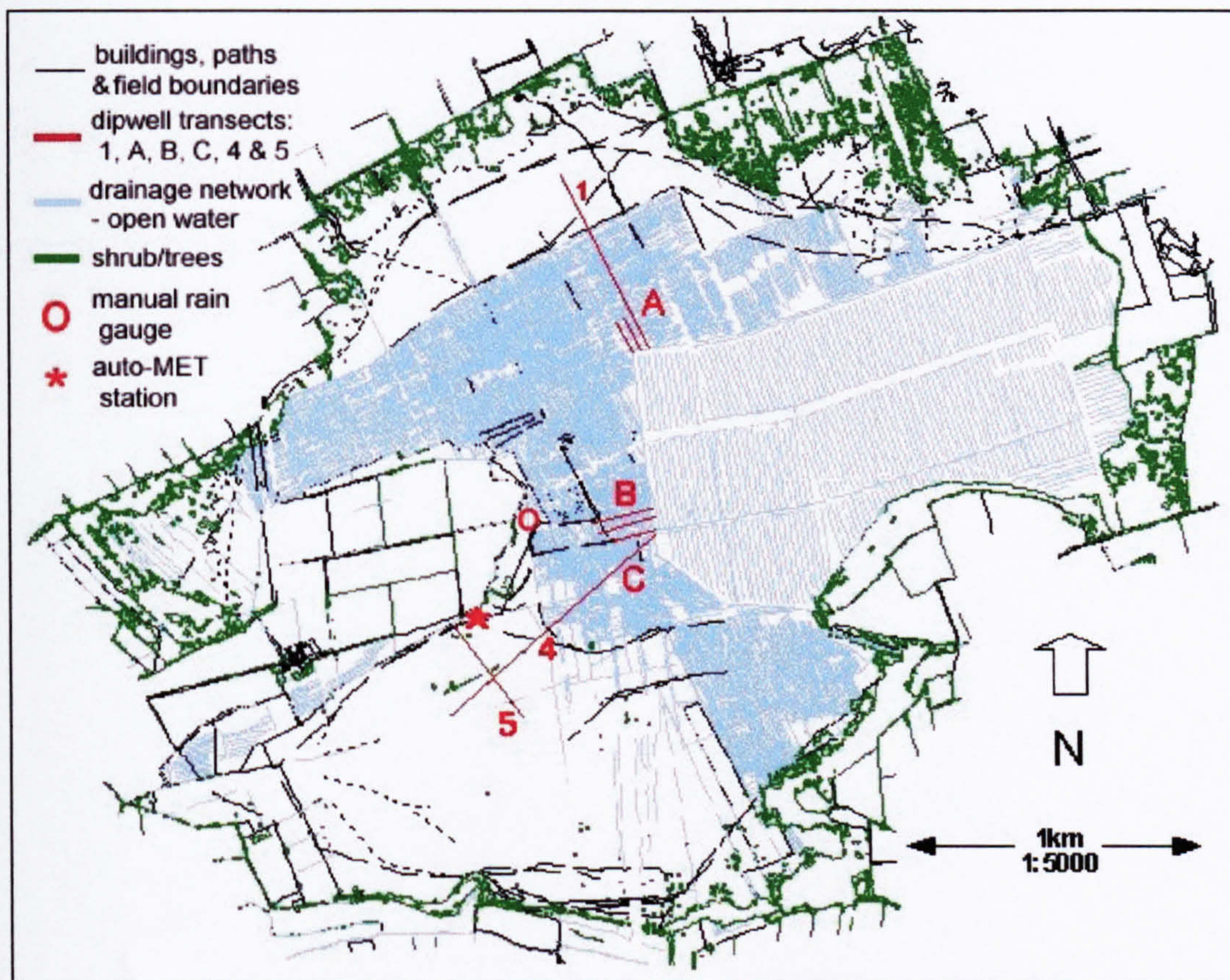
By the end of the monitoring program in 1996 transects 2 and 3 had been abandoned. Only transect 1 remained operable, with 13 wells over 260m of intact mire in Newton Arlosh Awards, and 13 wells extending over 230m of flooded, abandoned cuttings (Figure 8, transect 1). Peat depth across the transect 1 ranged from 4m deep in the abandoned cuttings, to 7m in the centre of the Newton Arlosh 'dome', with a slope at the mire surface

¹ (Chapter 2, Section 3.1.1).

of 1:1100 and 1:150 respectively. The abandoned cutting surface was left relatively level by the peat removal process, whilst a considerable slope exists in the 'intact' mire, particularly in the 50m zone adjacent to the blocked drain where the gradient increases from 1:150 to 1:50 (Figure 23 k & l).

Data from this program were analysed previously in White and Butcher (1994) who examined data collected to that date, and by MacAlister (1996) in particular reference to their replicability by the MODFLOW hydrological model. Hydraulic conductivity of peat at different depths and distance from the drain was also recorded during the 1996 study (Section 5).

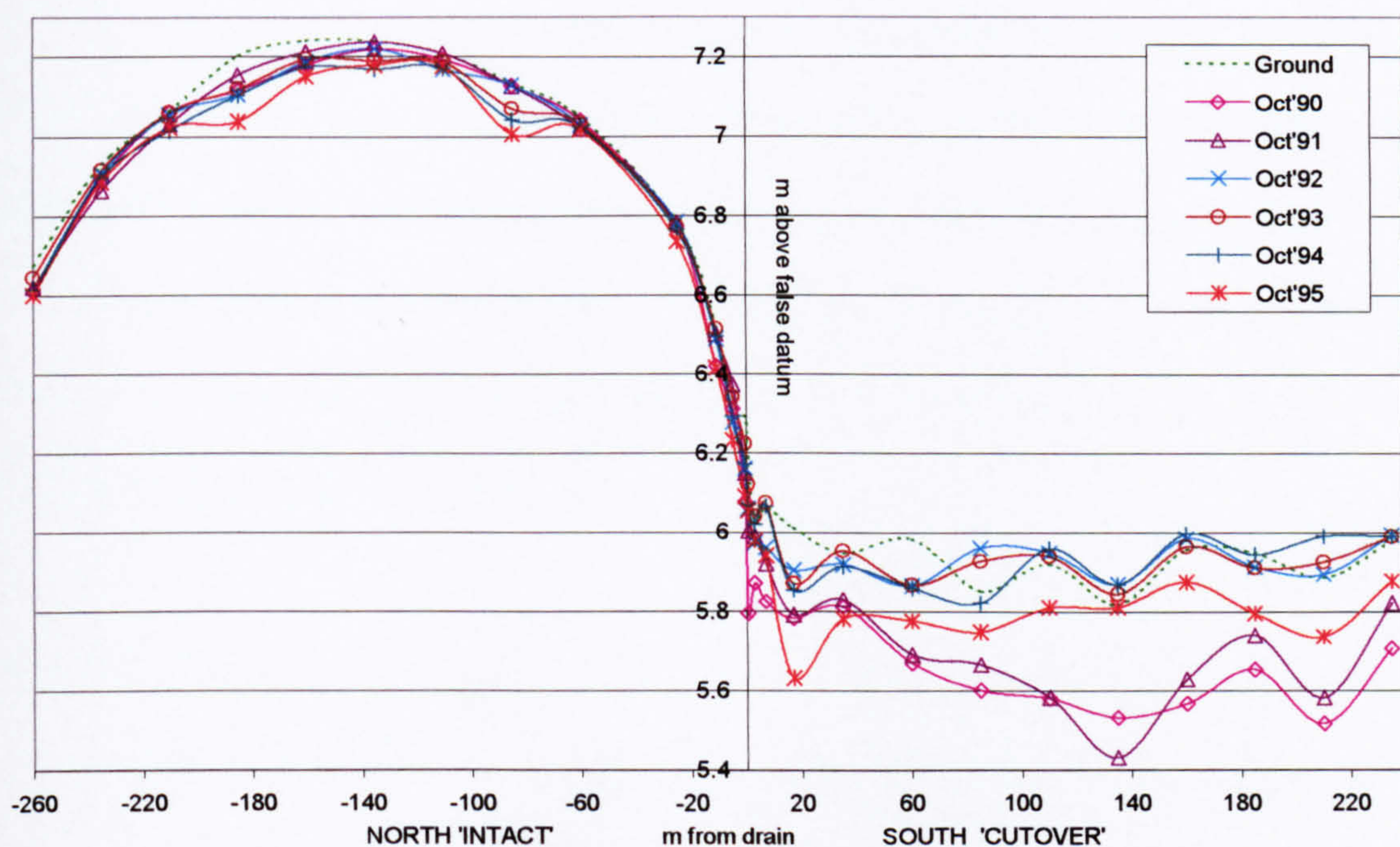
Figure 8. Hydrological monitoring network at Wedholme Flow including dipwell transects and meteorological equipment.



Results

Figure 9 shows the observed watertable recorded for the two years preceding and the years following the blocking of the main drain central to transect 1. The program of damming and drain blocking over the abandoned cutting area including the main drain which bisects transect 1, began in January 1992, so that 1992-5 can be considered post-restoration years whilst drainage was active during 1990 and 1991. The watertable response to drain blocking is clear in the cut-over area, where the October watertable is considerably and consistently higher in the years 1992-5. During the monitoring period net precipitation was lowest in 1995 (figure 3) and this is reflected in the 1995 watertable in the intact (north) and cut-over (south) sections of the transect. At the scale displayed in figure 9, there is little obvious change in intact zone behaviour following drain blocking, with the water table remaining close to the surface throughout, with the exception of two points on the 'shoulder' of the dome. Examination in the field does not explain why the watertable is lower in these areas, but this may be elucidated by a more detailed survey.

Figure 9. Transect 1, dipwells N13-S13, autumn groundwater levels: 1st week of October 1990-95.



5.2 Short-term watertable fluctuations from automatic logging dipwells and weekly readings in the Southern Lobe

Methods

In July 1998, in a joint program between English Nature and CLUWRR, two new dipwell transects were installed in the southern lobe (Figure 8, transects 4 & 5), the largest intact area of mire, in which little previous investigation had taken place. The aim of the program was to collect data in order to validate a hydrological model for raised mires that could be used in the future as a management tool. Twenty-one dipwells were installed in two perpendicular transects, with a total length of just under 1km. Transect 4 consists of 11 wells distributed over 480m, extending across 460m of intact mire and 20m of mire with preliminary drainage (both NVC communities M2, 2b & M18a). Transect 5 shares its 8th well with transect 4 at their intersection, and extends across 390m of intact mire (NVC M2, 2b & M18a), although its first 50m cover a marginal surface adjacent to the Wedholme House farm interceptor drain (NVC H1a & M25, 25b). The topography of the area was surveyed using an automatic level so that well levels could be recorded relative to ordnance datum. Transect 4 has a slope of around 1:500, falling away either side of the intersection, while transect 5 is almost flat, sloping gently into the southern lobe (1:2500). Within the immediate influence of the boundary drain the first 37m of transect 5 are steeper (1:50). Peat depths along transect 5 were recorded ranging from 2.35m close to the drain to 9m in the central region, and in transect 4 from 8.8m in the area of preparatory drainage to 6.7m at the western extent.

Perforated, 40mm dipwell tubes were installed to the full depth of the peat and anchored in the underlying mineral soil, which could also be related to ordnance datum. Water levels

were read manually on a weekly basis, and pressure transducers with data loggers were installed in dipwells at different locations across the transects. Pressure transducers (Druck model PTX530) were employed with multi-channel data loggers (Technolog model Newlog Universal logging Module and 2 Channel Interface Unit). Five transducers and 3 loggers were available. These were moved between wells in an attempt to best characterise short-term fluctuations across the area under different rainfall intensities. Moving the equipment was both difficult and labour intensive, and so moves had to be limited. The strategy most likely to yield useful results was judged to be spacing the transducers along one of the transects. The outputs could then be applied easily to model transects. An automatic weather station (Environmental Measurements) was installed at the edge of the mire close to transect 5. During monitoring periods of short-term water level fluctuation, all data loggers recorded on 20-minute intervals. Within the monitoring program hydraulic conductivity (Section 5), vegetation assemblages, microtopographical variation and invertebrate populations were also surveyed across this area.

Results

The extensive data sets collected during this 3-year monitoring scheme have been summarised in a series of charts:

Figures 10-15 utilise weekly water level data, displayed as watertable above ordnance datum, which can be compared to the surveyed ground level also plotted. Figures 10 and 12 show the summer (late July) watertable in the intact southern lobe in three successive years. Figures 11 and 13 show the winter watertable (end of December) in this area for 1998 and 1999. Figures 14 and 15 indicate the seasonal watertable trends throughout 1999 in transect 4 and 5.

Figure 16 illustrates the watertable distance from the ground surface, from weekly readings throughout 1999 and columns represent the monthly rainfall totals. The water levels were recorded in four dipwells, two each from transects 4 and 5. Dipwell 4.3 is 31m from the blocked slit drain which crosses transect 4. Dipwell 4.9 is a large distance from any active drain (306m from the slit drain and roughly equidistant to Wedholme House boundary). Dipwells 5.3 and 5.9 are 17m and 287m from the Wedholme House Farm boundary drain respectively.

Figure 17 plots the standard deviation from the mean level of all weekly watertable measurements in the period 29/7/98 - 6/9/00, for all wells in transects 4 and 5.

Figure 18 plots the watertable response to rainfall, recorded by pressure transducers in transect 5 dipwells 5.1, 5.2, 5.3, 5.6 and 5.7 being 2m, 7m, 17m, 137m, and 187m from the boundary drain respectively, for the period 00:00 16th May till 00:00 19th May 2000. Figure 19 plots the watertable response to rainfall, recorded by pressure transducers in transect 4 dipwells 20m, 6m, 31m, 56m, and 106m away from the blocked drain channel, over 48 hours from 00:00 25th till 00:00 27th April 2000.

Figures 20a-e demonstrate diurnal fluctuations in watertable, observed over 72 hours, logged on a 20-minute interval, in five adjacent wells (4.1-4.5), between 00:00 28/04/00 and 00:00 01/05/00. Figures 21a-e demonstrate watertable fluctuation in the same wells logged at 20-minute intervals over five days from 4th till 8th May 2000. The logged water level data are plotted directly, as m above datum, and the 2-hourly mean level has been plotted as a trend line for each dipwell level. No rainfall was recorded for either period.

Figure 10. Summer watertables recorded in transect 4 dipwells, last week in July 1998-2000.

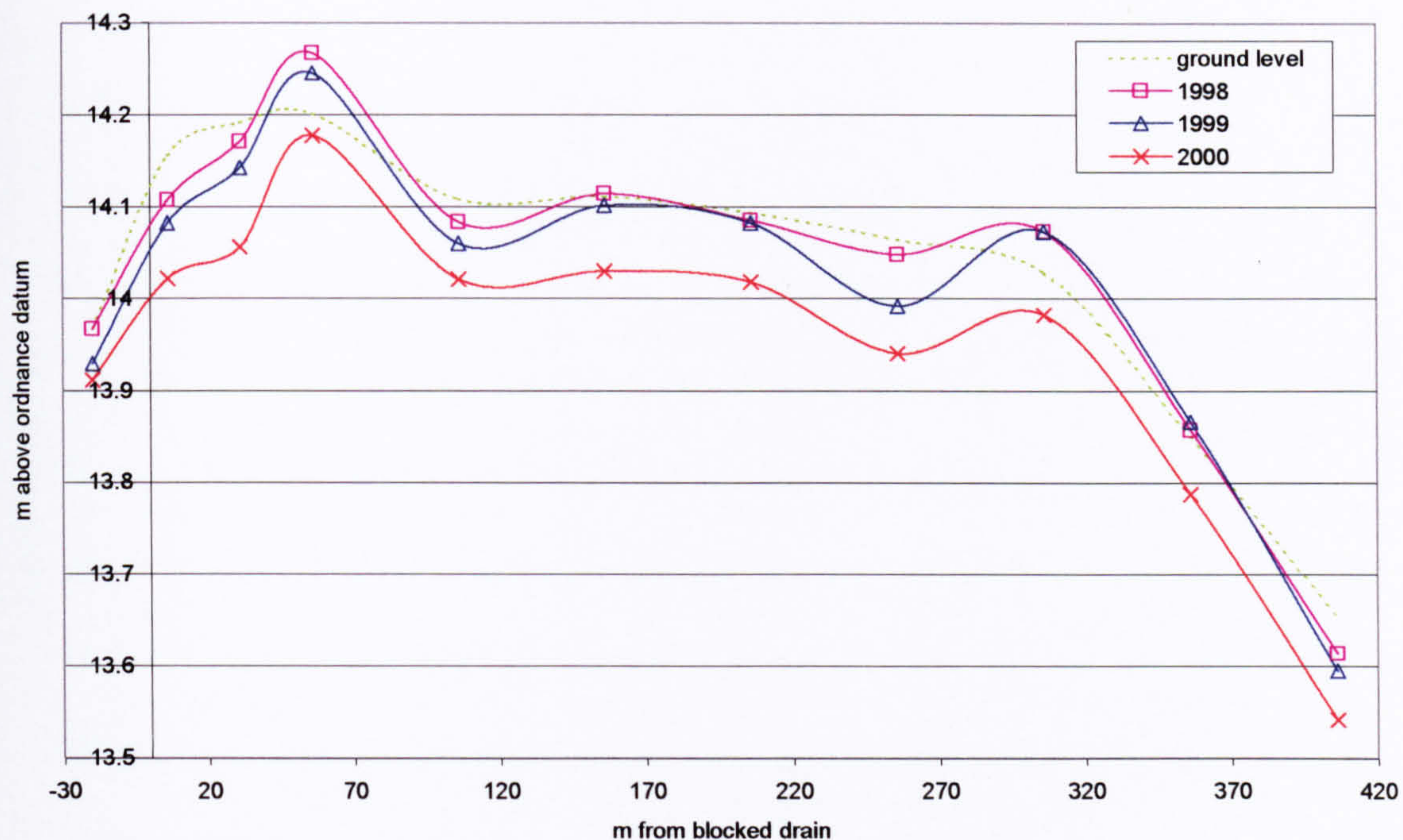


Figure 11. Winter watertables recorded in transect 4 dipwells, last week in December 1998-1999.

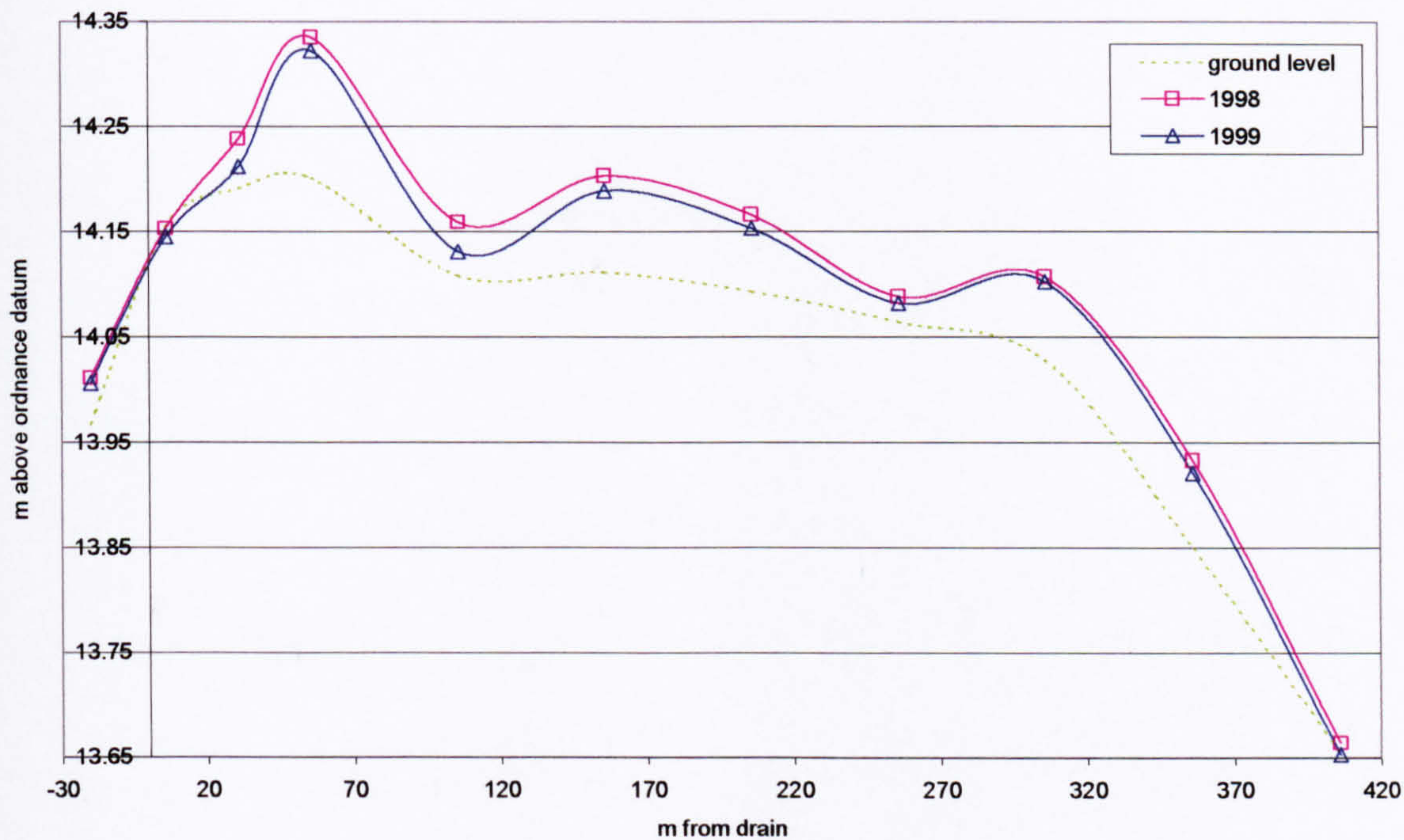


Figure 12. Summer watertables recorded in transect 5 dipwells, last week in July 1998-2000.

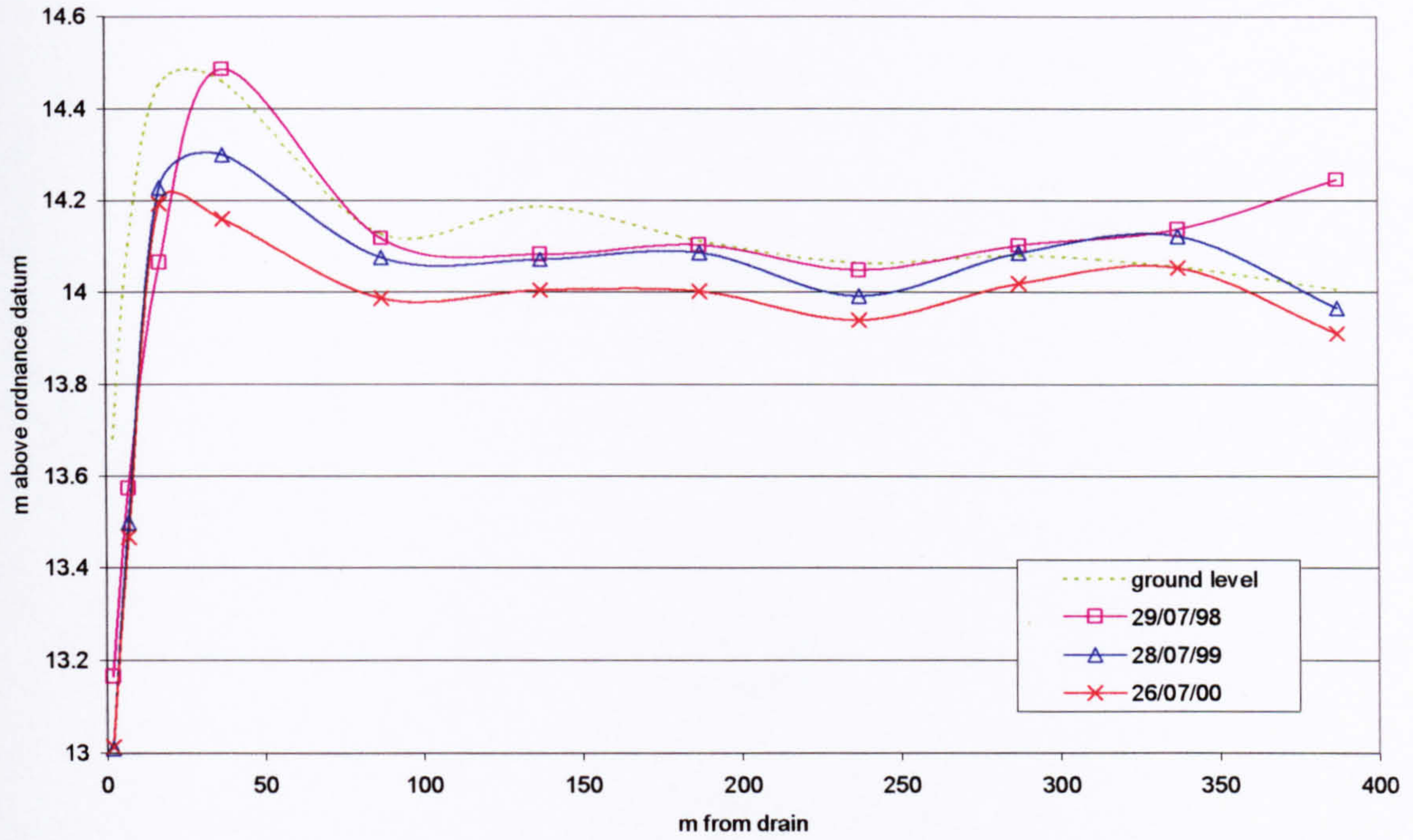


Figure 13. Winter watertables recorded in transect 5 dipwells, last week in December 1998-1999.

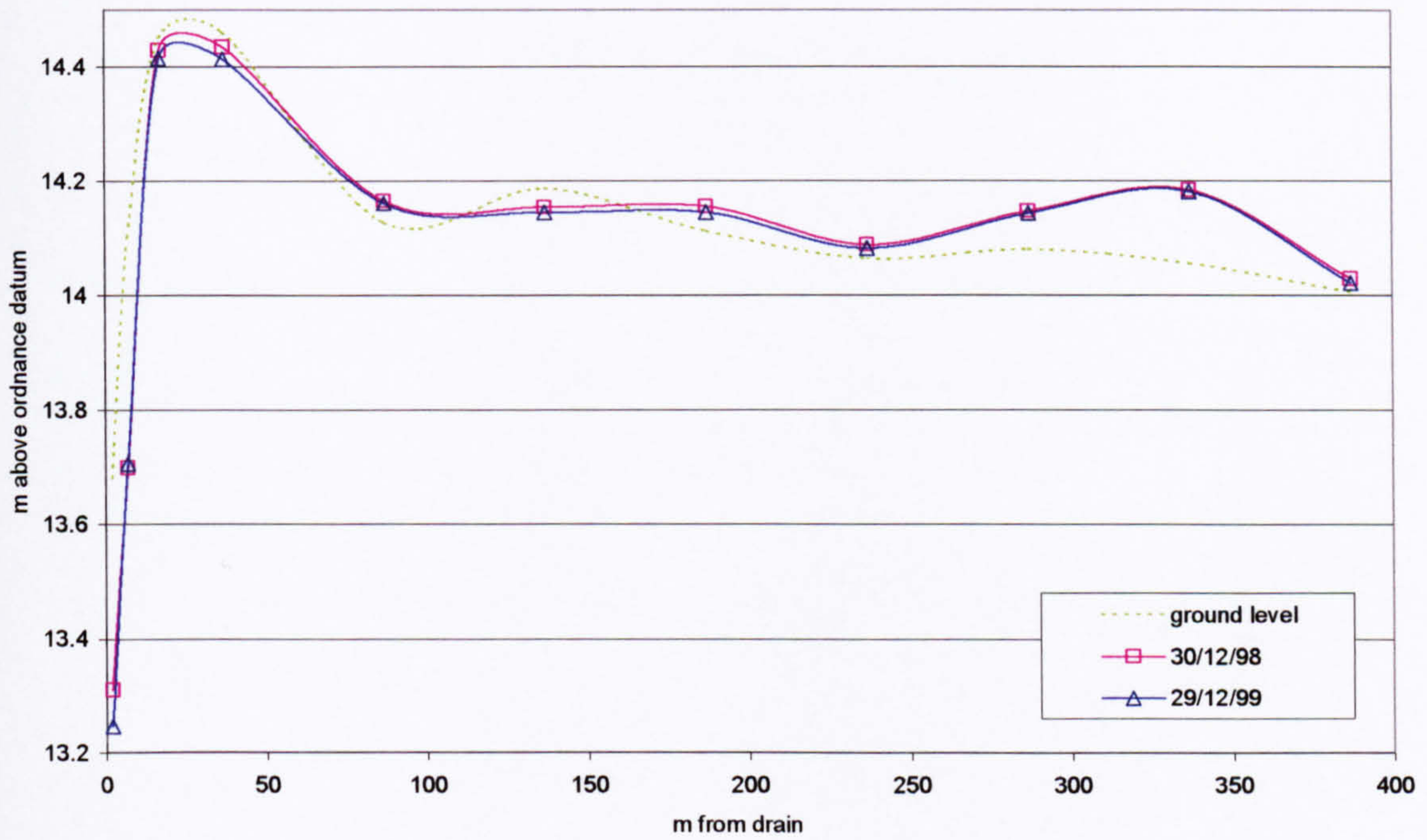


Figure 14. Seasonal watertable fluctuation, transect 4 dipwells, 1999.

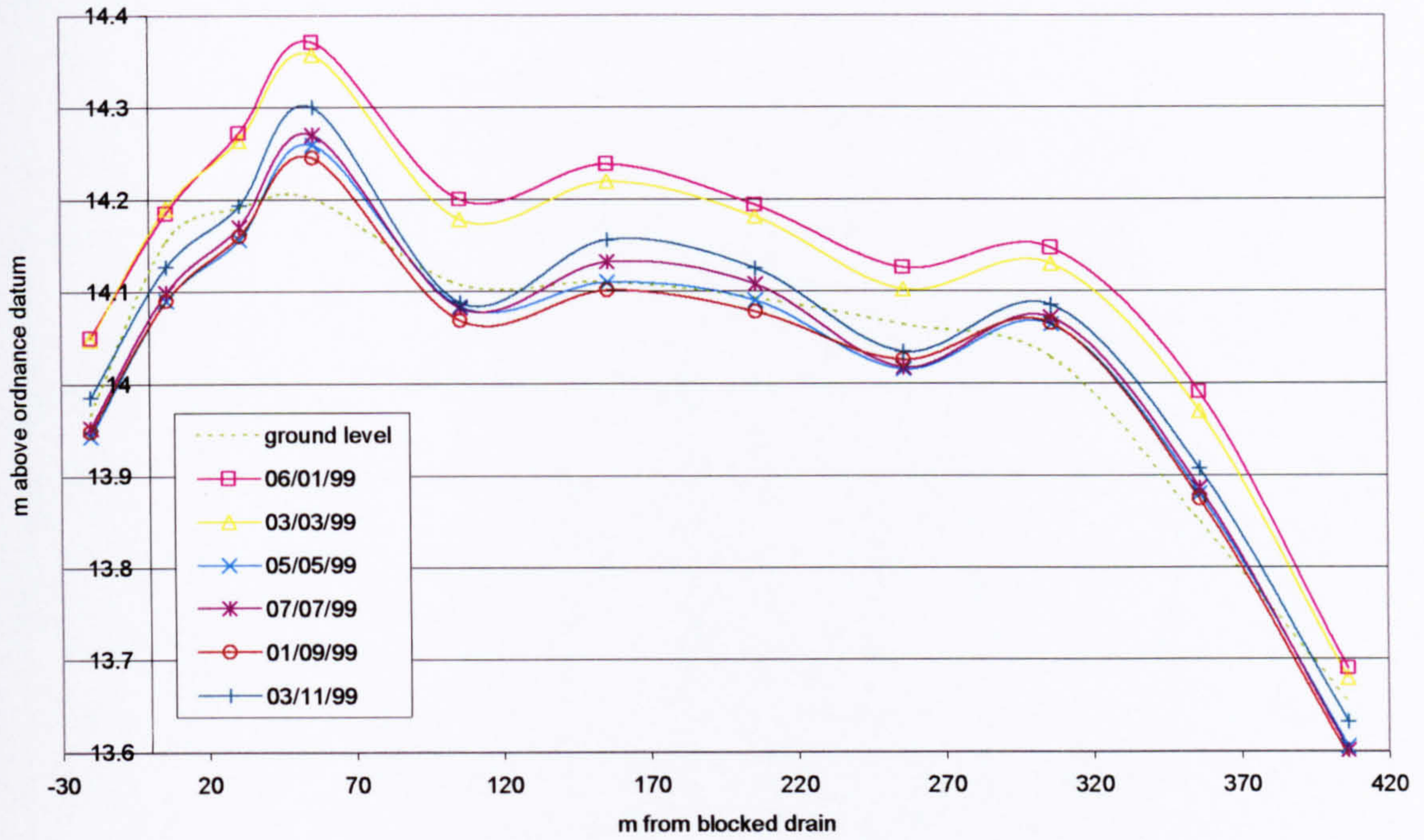


Figure 15. Seasonal watertable fluctuation, transect 5 dipwells, 1999.

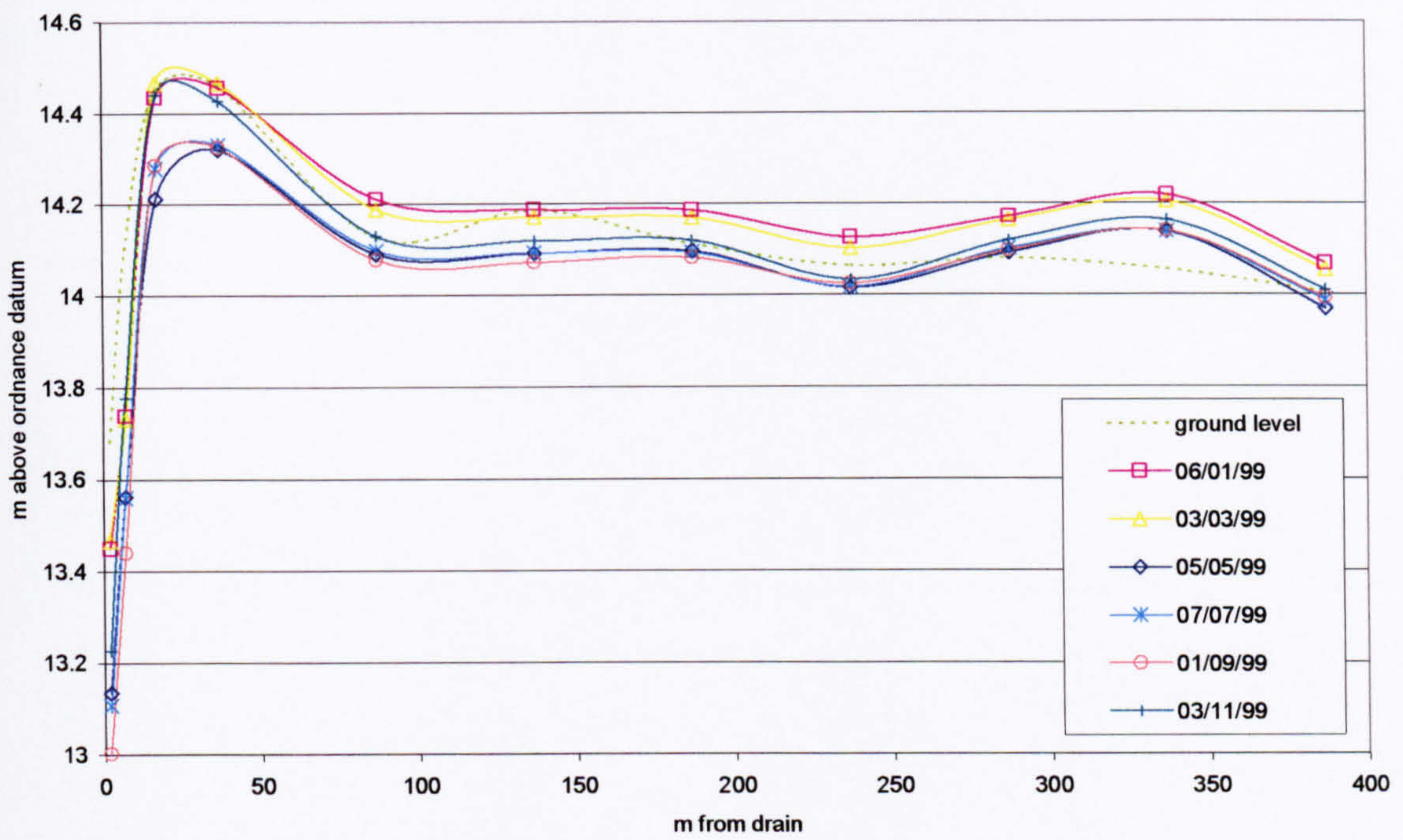


Figure 16. Watertable fluctuation 1999, as distance above and below the ground surface (m), in wells 5.3, 5.9, 4.3 and 4.9 and total monthly rainfall (mm).

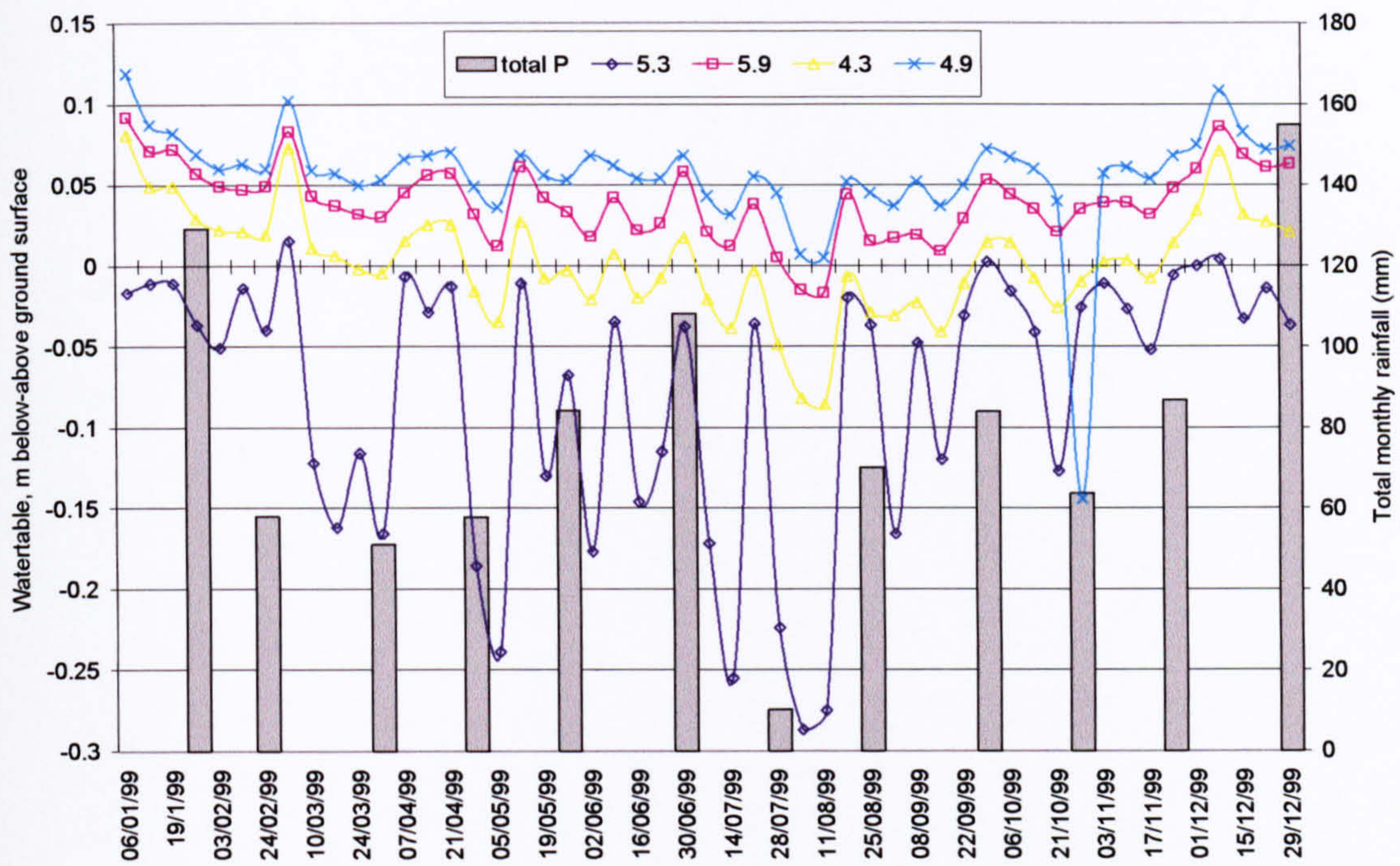


Figure 17. Standard deviation from the mean watertable, weekly-recorded dipwell levels, transects 4 and 5, 29/7/98 - 6/9/00.

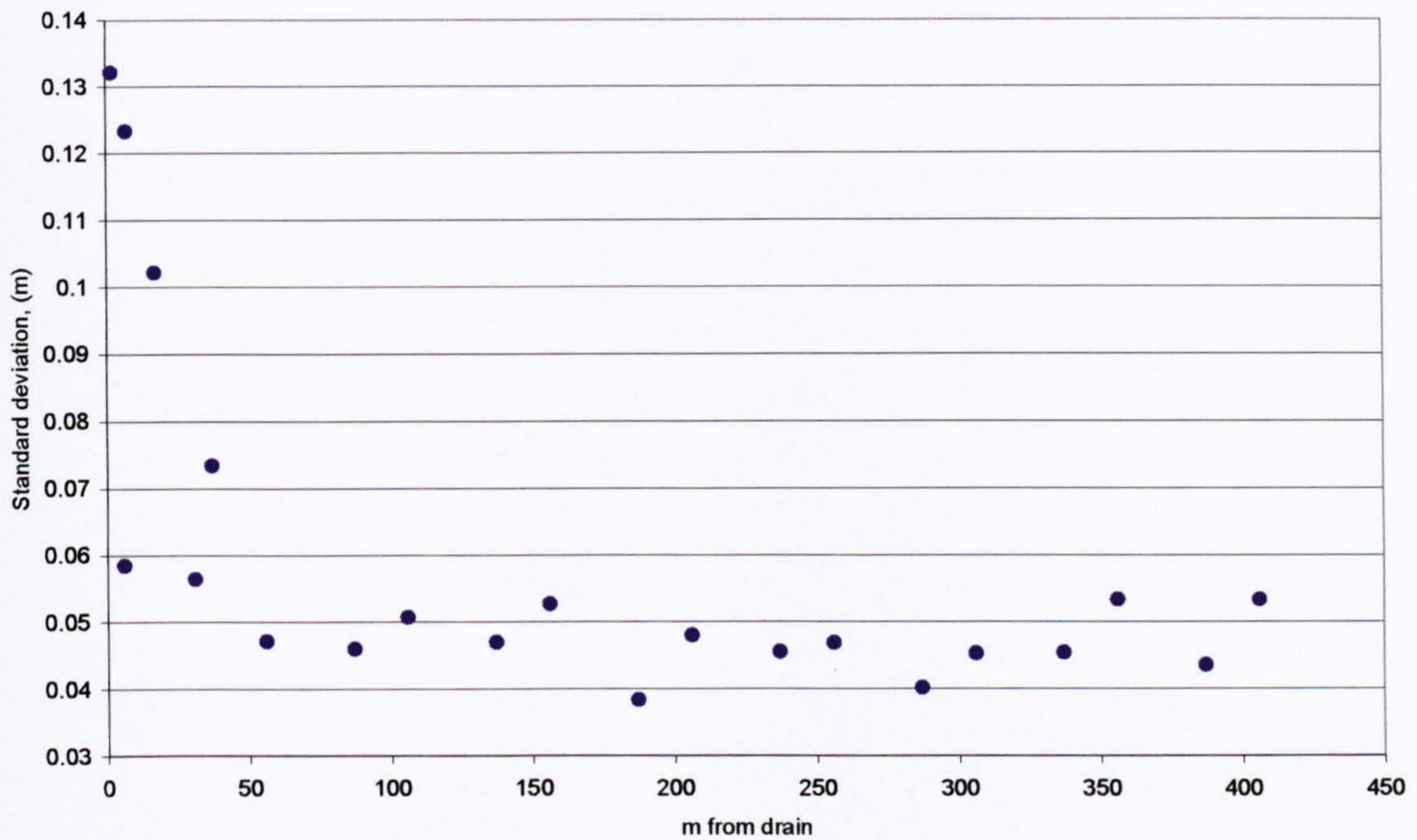


Figure 18. Watertable fluctuations in dipwells 5.1, 5.2, 5.3, 5.6 & 5.7 (m above ordnance datum) and rainfall (mm), recorded at 20-minute logging intervals from 00:00 16/05/00 to 00:00 19/05/00.

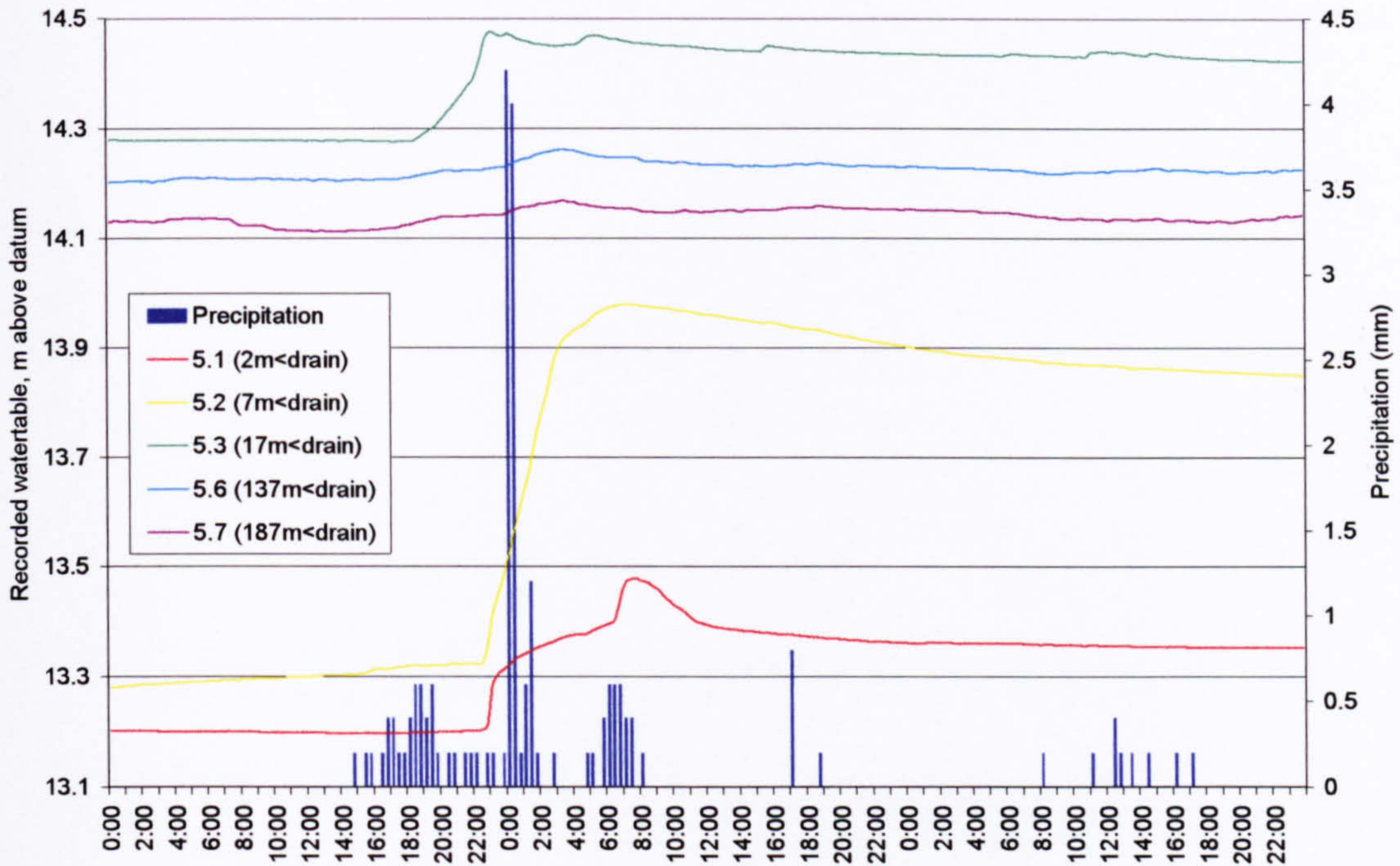


Figure 19. Watertable fluctuations in dipwells 4.1, 4.2, 4.3, 4.4 & 4.5 (m above ordnance datum) and rainfall (mm), recorded at 20-minute logging intervals from 00:00 25/4/00 to 00:00 27/4/00.

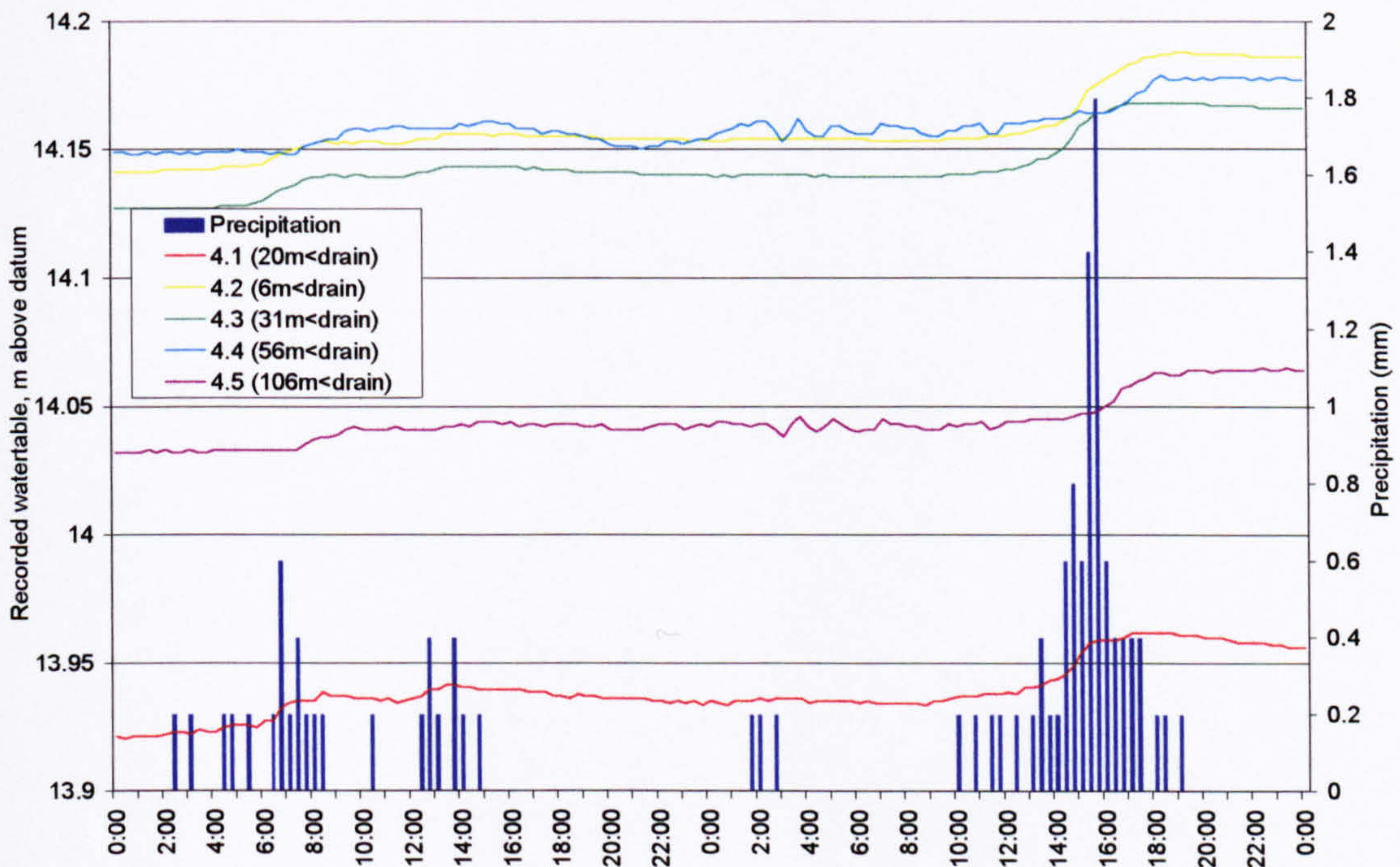


Figure 20a-e Diurnal fluctuations in watertable logged on a 20-minute interval over 72 hours, in five adjacent wells (4.1-4.5), between 00:00 28/04/00 and 00:00 01/05/00. Trend line: 2-hourly mean level.

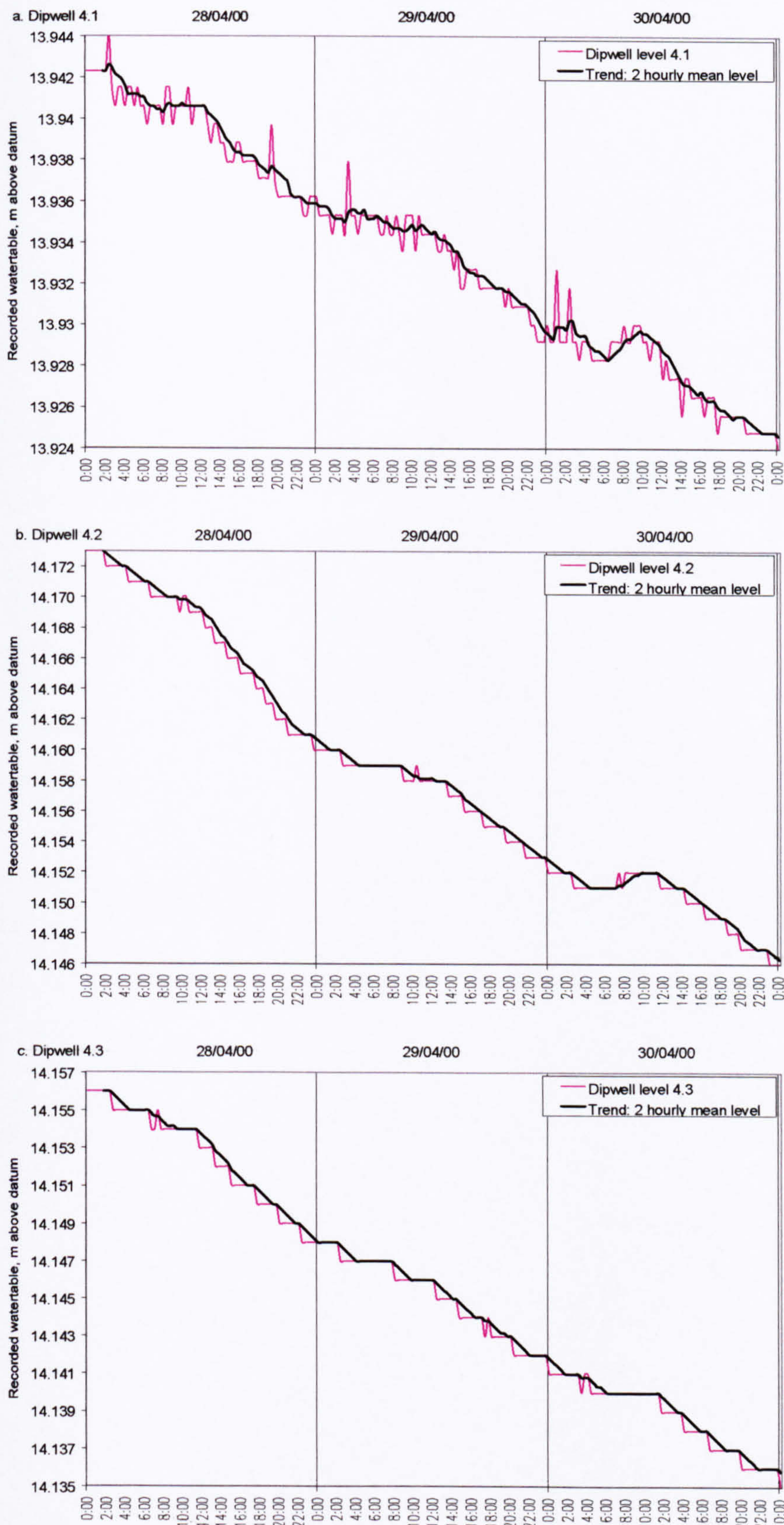
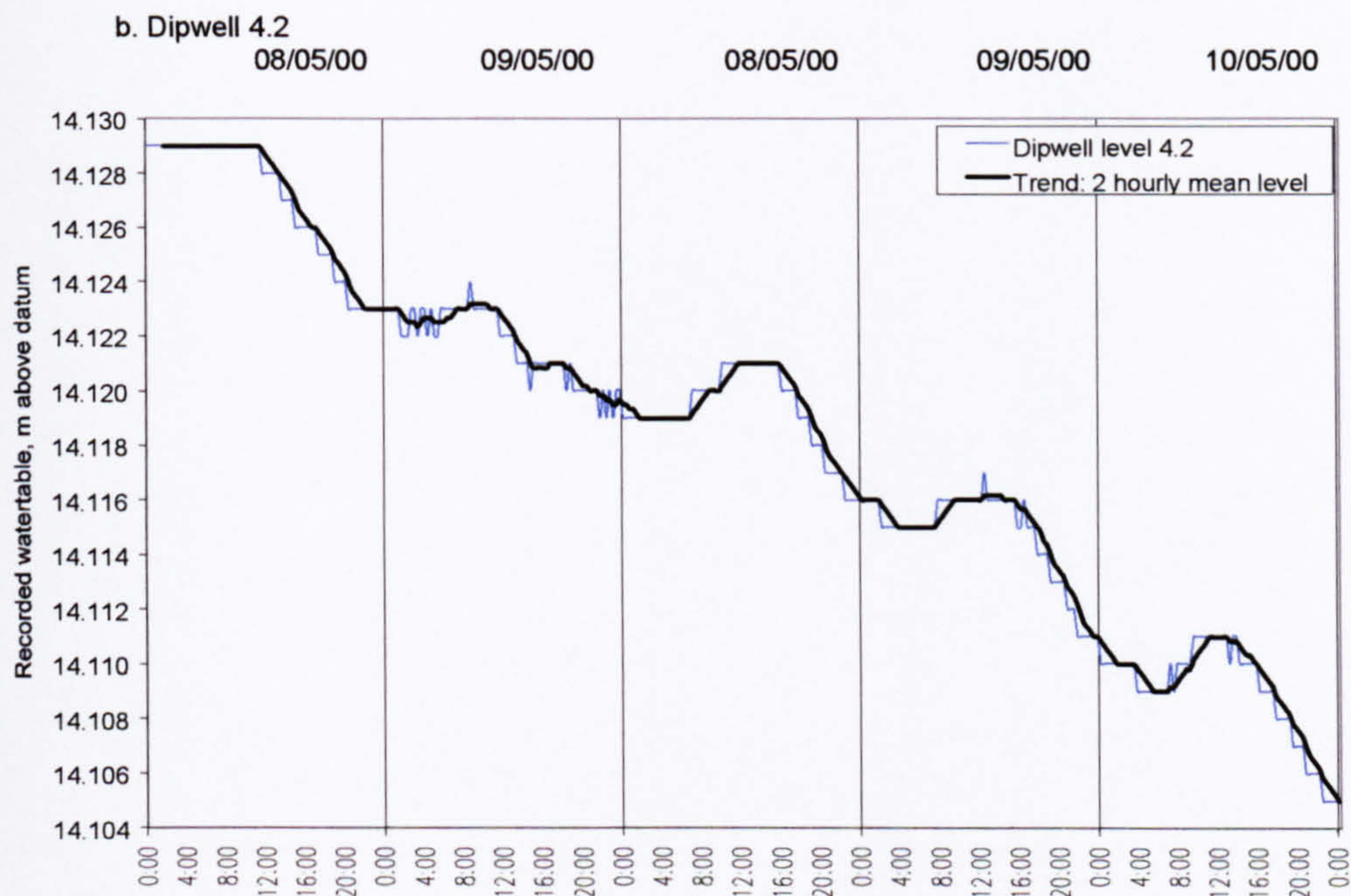
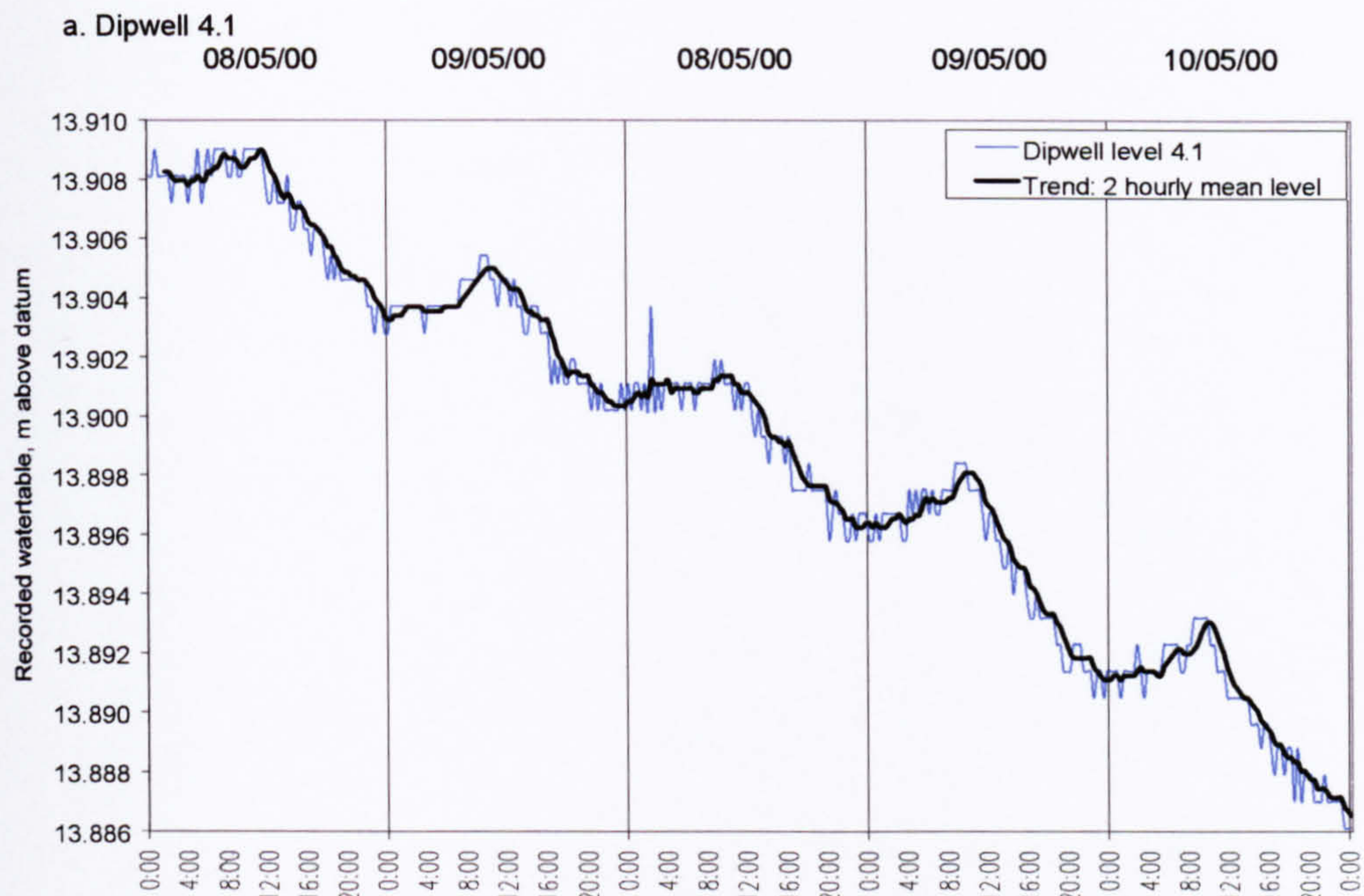
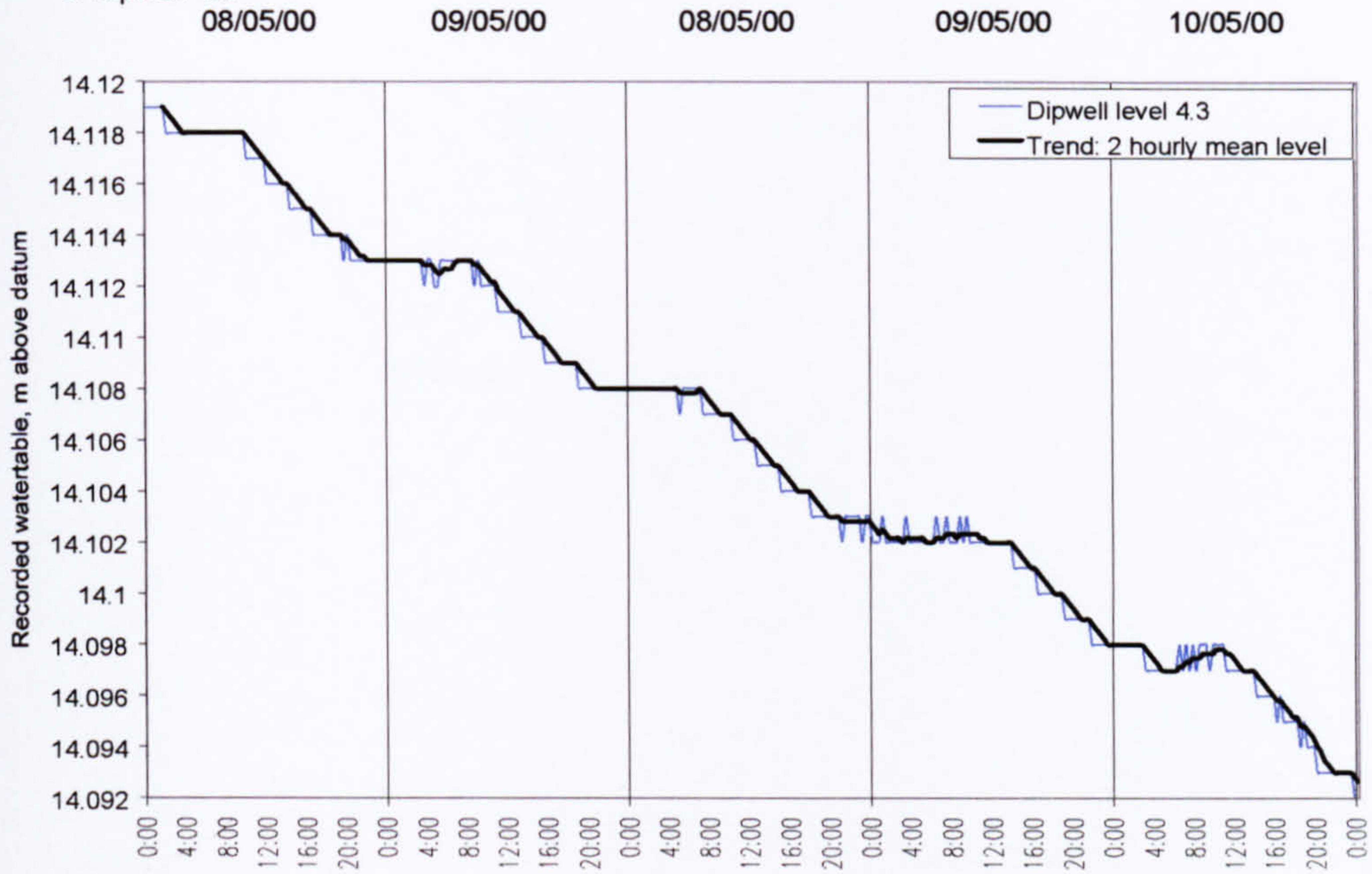




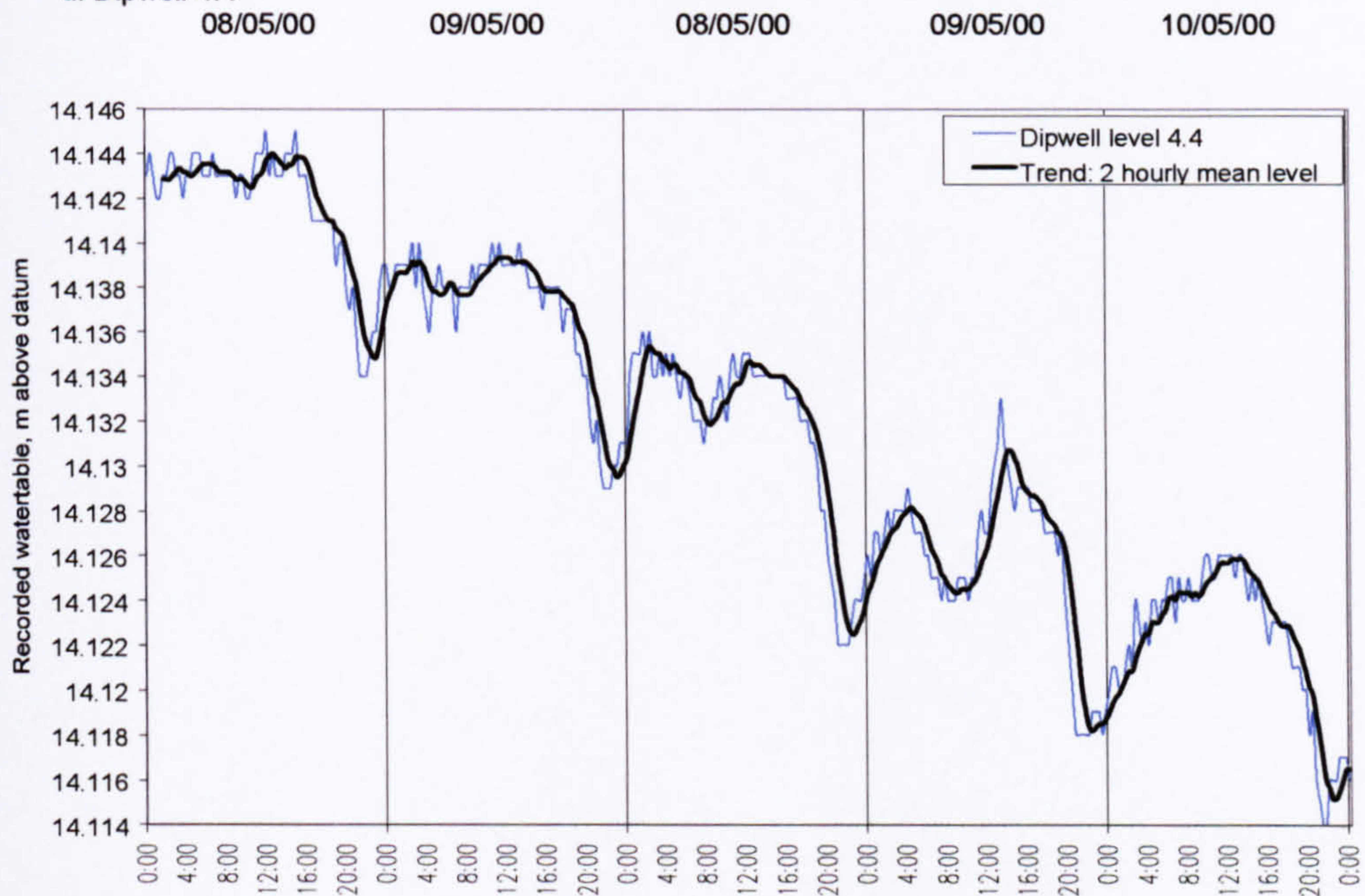
Figure 21a-e Diurnal fluctuations in watertable logged on a 20-minute interval over 72 hours, in five adjacent wells (4.1-4.5), between 00:00 04/05/00 and 00:00 08/05/00. Trend line: 2-hourly mean level.



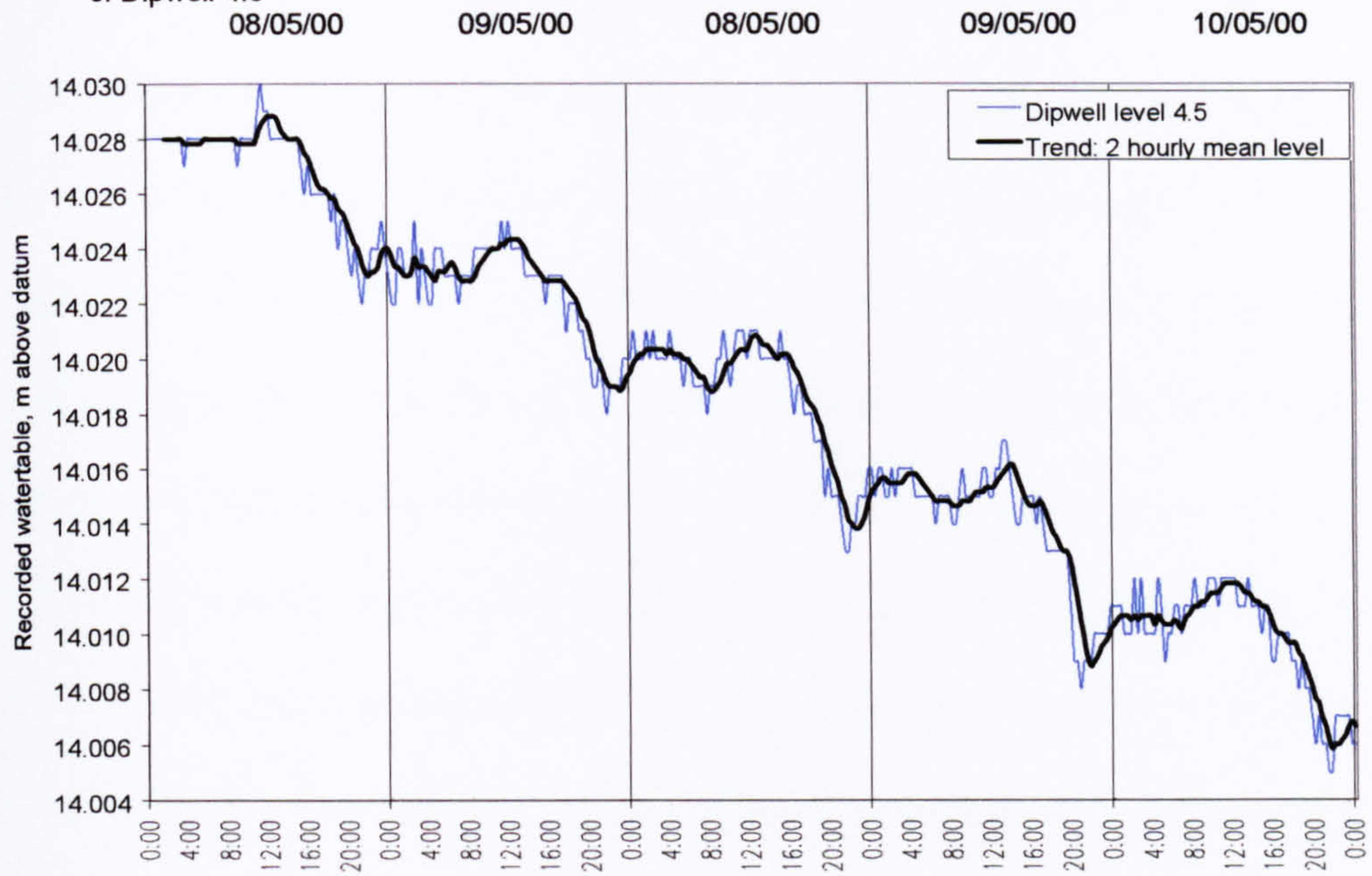
c. Dipwell 4.3



d. Dipwell 4.4



e. Dipwell 4.5



The summer watertable of July 2000 in transects 4 and 5, shown in figures 10 and 12, is the lowest of the three monitoring years, however figure 3 does not indicate that rainfall for the six preceding months is any lower than other recorded years. Water levels have been recorded for only two winters in this area and figures 11 and 13 reveal that the watertable is at or above the surface across much of the intact mire surface and clearly higher than the summer level. Figures 14 and 15 indicate that in 1999 the watertable followed a similar trend throughout the whole year, with both transects having some surface water even during the summer months. The first 40m of transect 5 show clear evidence of the draw-down influence of the main boundary drain channel and the watertable consistently lowest here throughout the year. Beyond the topographic high at 50m, the influence of the drainage channel is less obvious, with watertable fluctuation from the mean showing no clear trend beyond this point. The standard deviation from mean watertable of all well levels in transects 4 and 5, plotted in Figure 17, do not indicate any narrowing of range in the watertable beyond this point. However this does not mean that the local drainage, in particular the removal of surface water was not effected.

The influence of the boundary drain on the water level recorded in dipwell 5.3 is clearly illustrated in figure 16, and it is obvious that this area, with its rapidly fluctuating watertable could not support the same vegetation as the rest of the intact zone. The water level in dipwell 5.9 within the consistently intact mire surface, 287m from the Wedholme House Farm boundary drain, remains well above the surface with the exception of two weeks in July and August. There is also an apparent influence of adjacent drainage in the plot of water levels in dipwell 4.3, despite the fact that the nearest slit drain, and more distant main drains were blocked several years previously. The water level fluctuation in wells 4.3, 4.9 and 5.9 show a very similar response to rainfall, although the magnitude of

the fluctuation is much greater in well 4.3. There appears to be an anomalous result in dipwell 4.9 during November 1999. This is inconsistent with all other data and is then most probably due to a manual recording error.

Following the trend observed in figure 16 of increased watertable fluctuation close to the drain, figure 17 illustrates the standard deviations from the mean level of all weekly watertable measurements in the period 29/7/98 - 6/9/00, for all wells in transects 4 and 5. Deviation from the mean level appears quite obviously higher closest to the drain and remains fairly constant beyond 50m. The range of fluctuation in watertable is clearly a defining factor in the hydrological character of the mire surface, and will largely determine the vegetation assemblage at any location.

The watertable response to rainfall, recorded by pressure transducers in transect 5 and plotted in figure 18 follows rainfall in the preceding month (April 2000) close to the 10 year mean, whilst May 2000 was relatively dry at 20mm below the 10 year May-mean (figure 4). Despite the apparently low monthly total, a significant storm was recorded in the evening of the 16th May 2000. The three wells closest to the drain appear to respond rapidly to increased through-flow, whilst wells furthest from the drain seem hardly to respond to the 17mm of rain falling over 10 hours. The depth below surface of antecedent watertables, not illustrated on the graph, go some way to explaining this. The watertable close to the drain is very low initially being -0.483m, -0.798m, -0.174m in wells 5.1, 5.2, and 5.3 2m, 7m, and 17m from the drain respectively. The draw-down influence of the adjacent drain is greatest in well 5.2 and least in 5.3, while the watertable recorded in well 5.1 reflects the water level in the drain. Following rainfall over the 10-hour period, water levels in wells 5.1-3 rise by 0.178m, 0.629m and 0.175m to -0.305m, -0.169m below

ground and +0.001m above ground respectively. The recorded watertable before rainfall was +0.02m above ground in wells 5.6 and 5.7, 137m and 187m from the drain. The level continued to rise over the ten hours, increasing by 0.05m and +0.03m to +0.07m and +0.05m above ground respectively. Given such depths of surface water it is likely that overland flow processes would eventually be instigated even in this low surface gradient area. Such processes are confirmed by the vegetation assemblages in this area (M2b, M19), which are typical of wet pool and hummock-hollow microtopography indicative of surface water activity. The high watertable in this flat region provides a positive feedback mechanism for these vegetative features, which in turn develop microtopography in which trap and retain surface water. It is unlikely that this type of micro-landscape could develop over a steeper surface gradient, even if the watertable were not lowered by drawn-down and high recharge maintained a saturated near surface zone, as increased through flow rates would prevent the establishment of the hummock-hollow communities.

The increased standard deviation in watertable in dipwells close to the drain shown in figure 17, is also confirmed in figure 18, as the initially low watertable in wells 5.1 and 5.2 rise rapidly following rainfall and also fall more steeply than watertable recorded further from the drain. These typical responses have further implications for the storage potential of the peat and its capacity for rewetting (Section 5).

The watertable response to rainfall in transect 4 dipwells, plotted in figure 19, over 48 hours during 25-27 April 2000, is less marked than that of transect 5 dipwells during a similar period. In the 10 hour period from 10:00 to 22:00 26/04/00, during which time 10mm of rain fell, watertables rose by 0.023m, 0.033m, 0.028m, 0.021m and 0.022m, in wells 4.1, 4.2, 4.3, 4.4 and 4.5 respectively, to -0.007m, +0.032m, -0.023m, -0.023m and

-0.044m below the surface, with surface water at 4.2. Unlike watertable observations from transect 5, there is no clear trend of increased watertable response close to the drain channel. Whilst the well closest to the drain channel, 4.2, did show the greatest rise, this is likely to result from altered soil storage conditions during the period when the drain was active, previous to the restoration program. During this time, the hydraulic properties of the peat close to the drain would have changed due to aeration and hence accelerated humification processes. Cracks and macro pores in the peat may have occurred in the peat within the draw-down region. These processes can be observed in the peat at the mire surface, close to the active peat cutting face (transects A, B & C – Section 3).

During the logging period outlined by figures 20a-e, no rainfall occurred; therefore the diurnal fluctuations in watertable must be due to other factors. Falling watertables illustrated in the plots must be due to evapotranspiration and any rise must be explained by lateral redistribution of groundwater. In all of the five observed dipwells (4.1-4.5) the watertable falls most rapidly between midday and midnight, and in all cases this rate slows in the following twelve hours until midday. On the third day (30 April '00) outlined in figures 20a-e, the watertable actually recovers considerably in all five wells, whilst no rain was recorded. In figures 21a-e, showing watertable fluctuation in the same wells from 4th till 8th May, this trend can be observed more strongly. Again, no rainfall occurred during this five-day logging period, however the water level in all the dipwells show strong recovery patterns in the first 12 hours of each day. Dipwell 4.3 exhibits the weakest recovery during the period, but still ceases to fall in the morning of each logged day.

All dipwells were logged on 20-minute interval, however wells 4.2 and 4.3, in both figures 20 and 21, do not appear to fluctuate as rapidly as compared to wells 4.1, 4.4 and 4.5. This

may be a result of immediate local conditions but given the wells are close to well 4.1, which does appear to fluctuate rapidly, it is possible that the recorded level may have been effected by the sensitivity of logging equipment. Dipwells 4.2 and 4.3 were instrumented with individual pressure transducers but shared a multi-channel data logger. The same applied to wells 4.4 and 4.5. The water level in dipwell 4.1 was logged by individual units. Instrumental error cannot be confirmed and certainly the overall pattern of fluctuation for all wells seems consistent, so a local factor may be responsible as the wells are within a previously drained region. Neither theory can be discounted.

5.3 Short-term watertable fluctuations from daily manual readings

Methods

In autumn 2000, investigation began into the observation that abandoned peat cuttings to the north of the current cutting area (around NY217527) appeared to be re-wetting more successfully than those to the west (around NY218534). Both areas had been subject to a program of drain blocking for a similar length of time but land to the north appears wetter and more stable (no vegetation data), whilst land to the west is dry and shows signs of cracking and slumping (H1e, M19a, M20, bare peat). Time and resources for the program were limited and so an intensive investigation into short-term hydrological differences began in October 2000. Three locations were selected, two typical of the damaged mire surface in question, and one re-wetting quite successfully. Location A is north of the current cutting area (NY217527); B is west of the current cutting area (NY218534); C extends from B across abandoned cuttings and into intact mire (Figure 8).

At location A, eighteen dipwells were installed in three transects, A1.1-1.6, A2.1-2.6, A3.1-3.6, 172m, 173.5m and 162m long respectively. The transects extend from the main arterial drain bounding the cutting face, over a surface which is largely bare peat and small patches of *Calluna vulgaris*, into a very wet and inaccessible area of flooded cuttings (NVC approximated to M2, M19). In comparison to the intact surface of the southern lobe, the slope in area A is considerably steeper (1:110-1:130 entire A transects), whilst in common with transect 5, the slope increases sharply close to the main drain (1:25-1:65 A transects over 20m). The recorded peat depth was greater than 2m deep in the area around A transects, with a fall of approximately 1m in the surface level to the adjacent active cutting face, over the main arterial drain. Transect A1 joins the old transect 1, to form an

extended line spanning 260m of intact mire (Newton Arlosh Awards) and 465m of abandoned cuttings, with 27 accessible dipwells.

At location B, 23 wells were installed in three transects, B1.0-1.7, B2.0-2.7, B3.0-3.6, 240m, 239m 187m long respectively. Each transect stretches from a small area of bare peat, isolated from the active and abandoned cuttings by arterial drains, up-slope through the dry and slumping abandoned cuttings, to the heath-like (roughly H1e, H9e) ground adjacent to Wedholme House farm. Low ground between ridges left by cutting, exhibits signs of erosion by overland flow, and is largely bare peat. In the 20m zone adjacent to the main drain, locally steep gradients (1:13-1:88) were comparable to those at A (1:25-1:66). The transect area covers a relatively flat area (slope 1:210) compared to area A (1:130), at the base of a much steeper slope (1:60) leading to the mineral outcrop of Wedholme House. Peat depths were found to decline slightly up the slope away from the cutting area, from around 7.2m to 6.8m.

A third area was traversed by transect C, extending 415m across cuttings abandoned in 1985 from well B3.0 in seven additional wells, the last of which is within the area subject to only preliminary drainage. Transect C joins transect 4 at well 4.1, so that the extended 892m transect encompasses abandoned cuttings (bare peat, H1e, H9e, M20a), regenerating and intact mire (M2, M18a). The slope of the first 17m of the transect, from B3.0 to C2 is relatively steep (1:70), becoming less so in the following 400m (1:200). Peat depths range from 7.2m close to the cutting face, to 9m where transect C joins transect 4.

The wells of transects A, B and C were installed by fully inserting (minus a short above-ground section) 3m lengths of perforated 40mm tubing, capped at the submerged end.

Where the peat was less than 3m deep (in area A), pipes were inserted to the mineral subsoil and the excess was then cut off. The wells were spaced at intervals of approximately 2m, 5m, 10m, 25m and then 50m where possible. In some cases, such as the A transects, open water made access treacherous and spacing was necessarily irregular. Dipwell co-ordinates, in the x, y, and z dimensions, were surveyed using GPS instruments (*Trimble Pathfinder Pro XRS*) as both base station and rover. Data were subject to post-processed differential correction (DGPS) for further accuracy (Trimble, 1997). Several areas were re-surveyed using traditional automatic levels to confirm the accuracy of the GPS data. Transects 1 and 4 were also re-surveyed to ensure they shared a common datum with transects A-C, and could be compared directly. Spot heights were taken and the peat anchors of Newton Arlosh awards were levelled to tie in original 1990-1996 ground surface to present day mire surface (Section 7).

Well levels were recorded manually between 10am and 12am daily throughout October 2000 using an open circuit water level sensor.

Results

The daily fluctuations in watertable with precipitation, recorded in individual dipwells from transects A1-3, B1-3, C, 4, 5, and transect 1 (N-north & S-south), are illustrated in figures 22 a-k as distance, in metres, above/below ground level.

Figures 23 a-l, show the manually read watertable records taken daily throughout October 2000 and the beginning on November 2000. Watertable and surveyed ground surface are plotted as metres above datum along each transect. As all daily records could not be shown on one plot, and plots are numerous, readings taken four days apart are illustrated.

Figures 23 a-f show the entire dipwell transects A1-3 (165-175m) and B1-3 (185-235m) of the abandoned cutting areas. Figure 23g illustrates the extended transect from well B1 and the whole of the C transect, extending into the intact mire of the southern lobe and continuing along the whole of transect 4 (total length 900m). Figure 23h shows transect C, wells 1-5, plus well B1 only (200m). Figures 23i & j plot the intact transects 4 (plus well C7) (500m) and 5 (400m) of the southern lobe. Figure 23k shows the watertable and ground surface across transect 1, Newton Arlosh awards, and up to dipwell S8, south of the blocked main drain which separates the awards from the abandoned cuttings (total length 370m). The true ground surface of the drain channel is not illustrated, and so the ground appears to rise at '0', where in fact, there is a channel 2m deep. This can be seen more clearly in Figure 23l, which shows the zone extending 50m from either side of the blocked drain. The vertical scale, given on the Y-axis in m above ordnance datum, varies on each graph.

Figures 24 a & b plot the mean recorded watertable (above and below ground level) and the recorded range for each of the 91 dipwells throughout the October 2000 monitoring period. The mean and range in watertable for each dipwell are plotted against to distance from the nearest drain channel.

In general, the watertable further from drains apparently fluctuates less in response to rainfall, in both intact and disturbed areas. The trend observed in plots of intact mire transects in figure 22 (transect 1 northern section, transects 4 and 5) is for well water levels to fluctuate very little in response to rainfall, except for those closest to a defined drain (within 20m). Plots of intact transect 4 watertables (figure 22h), appear to fluctuate more than the intersecting intact transect 5 dipwell levels (figures 22 h, i). However if the vertical scale on the y-axis is compared, fluctuations are within a comparable range. Watertable fluctuations in transect 4 are not explained by the proximity to adjacent drainage as is clearly the case in transect 5, where the watertable beyond 25m from the drain does not fluctuate more than 5cm. The largest fluctuations follow the considerable storm event on the 25/10/00 when nearly 28mm of rain fell over less than 15 hours. Here the watertable recorded in dipwell 4.5 within the intact mire surface, increased by 0.075m to a surface water depth of 0.08m, then falling by 0.145m over 48 hours to a depth of -0.065m. Close examination of the local topography of transect 4 (figure 23i) reveals that dipwell 4.5 is sited within a shallow topographic low, on the 'shoulder' of the intact mire, to the east of which the drained mire surface falls away rapidly with increasing surface gradient. Transects of the watertable plotted alongside the ground surface confirm the propensity for fluctuation between ground and surface water at this point during the monitoring period. It is likely that the adjacent slope accelerates surface water removal at this point, and draw-down beyond the shoulder also increases acrotelm flux. A similar

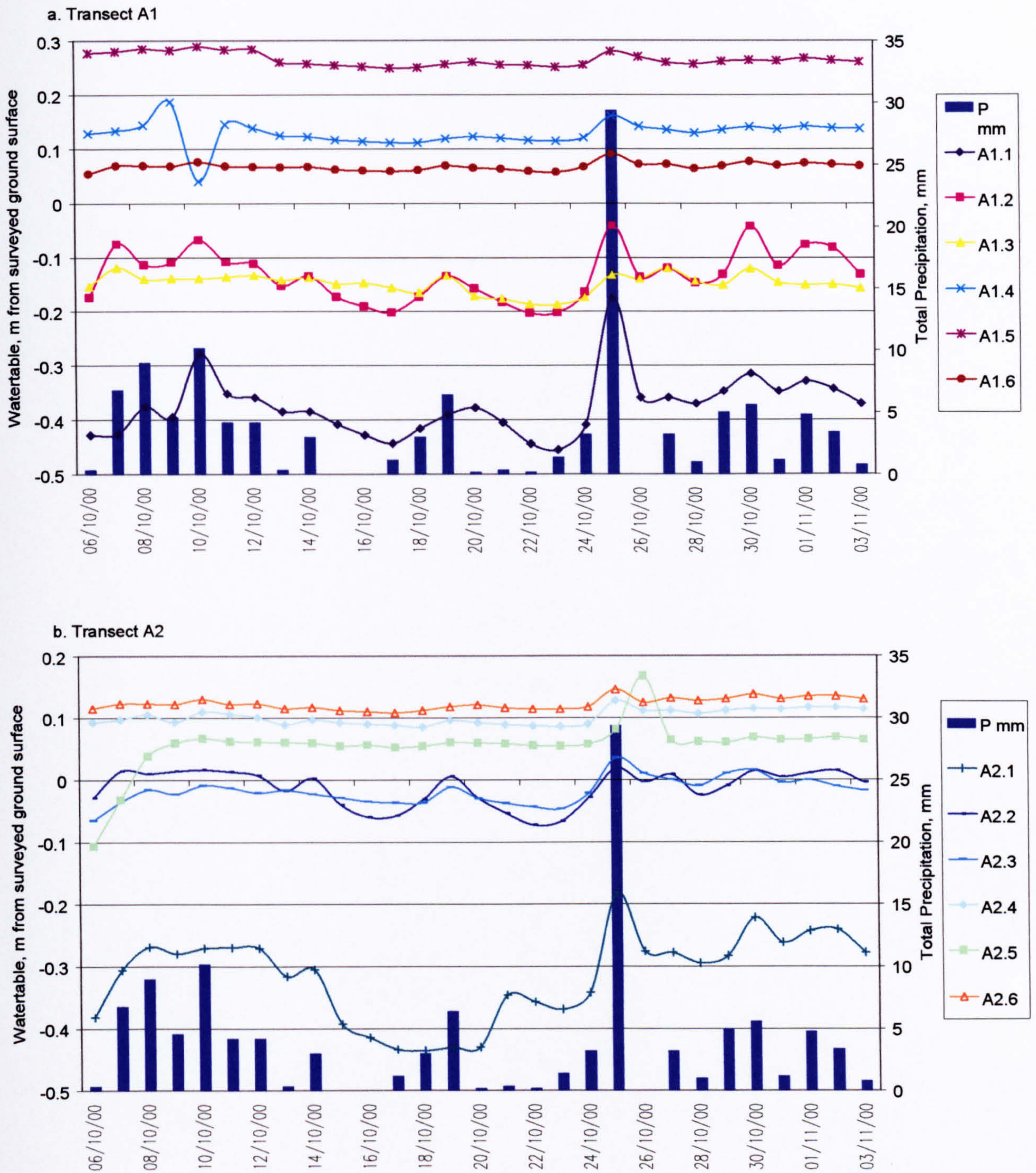
lowering of watertable on the shoulder of the Newton Arlosh dome was observed in transect 1 dipwell records.

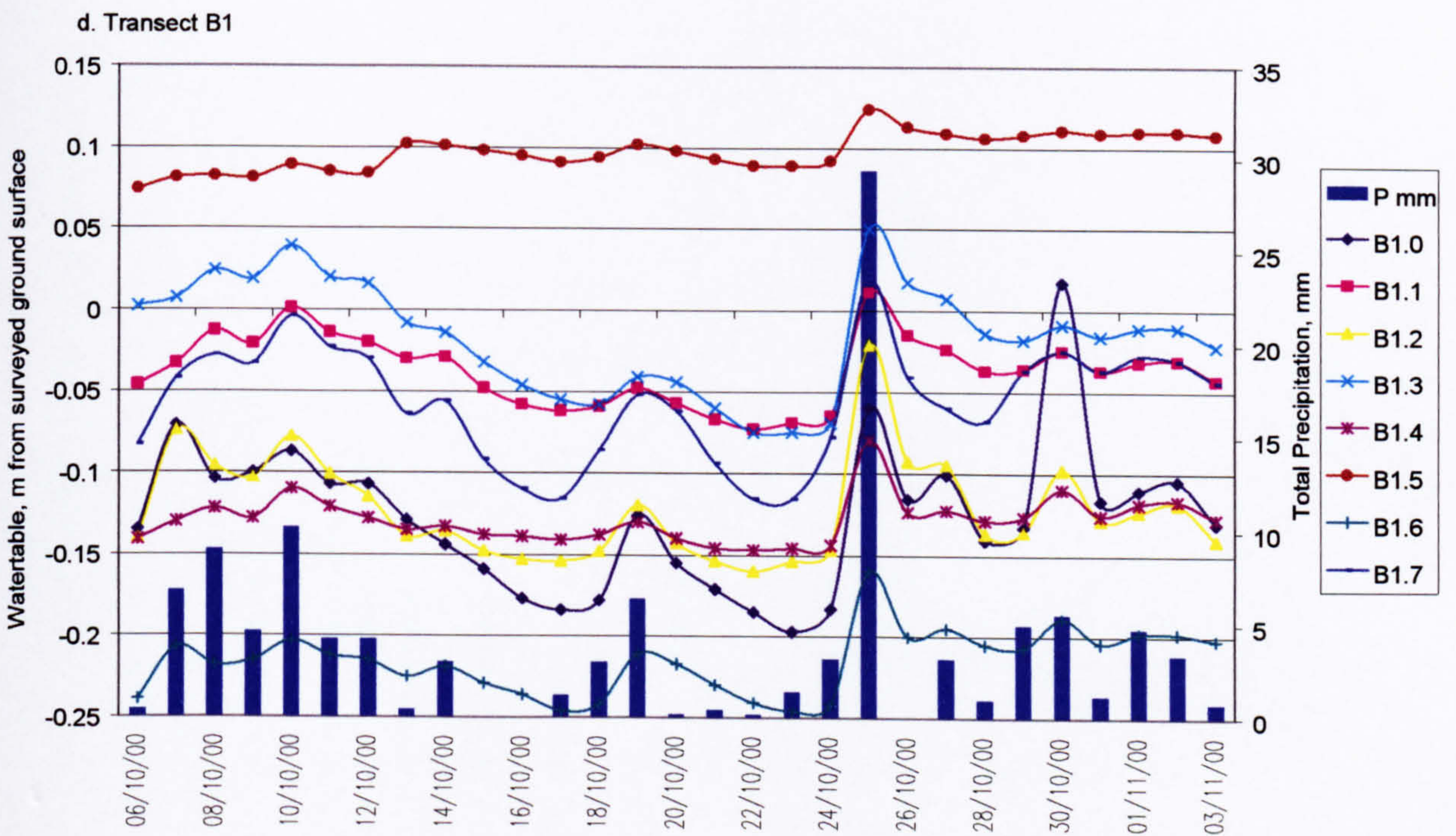
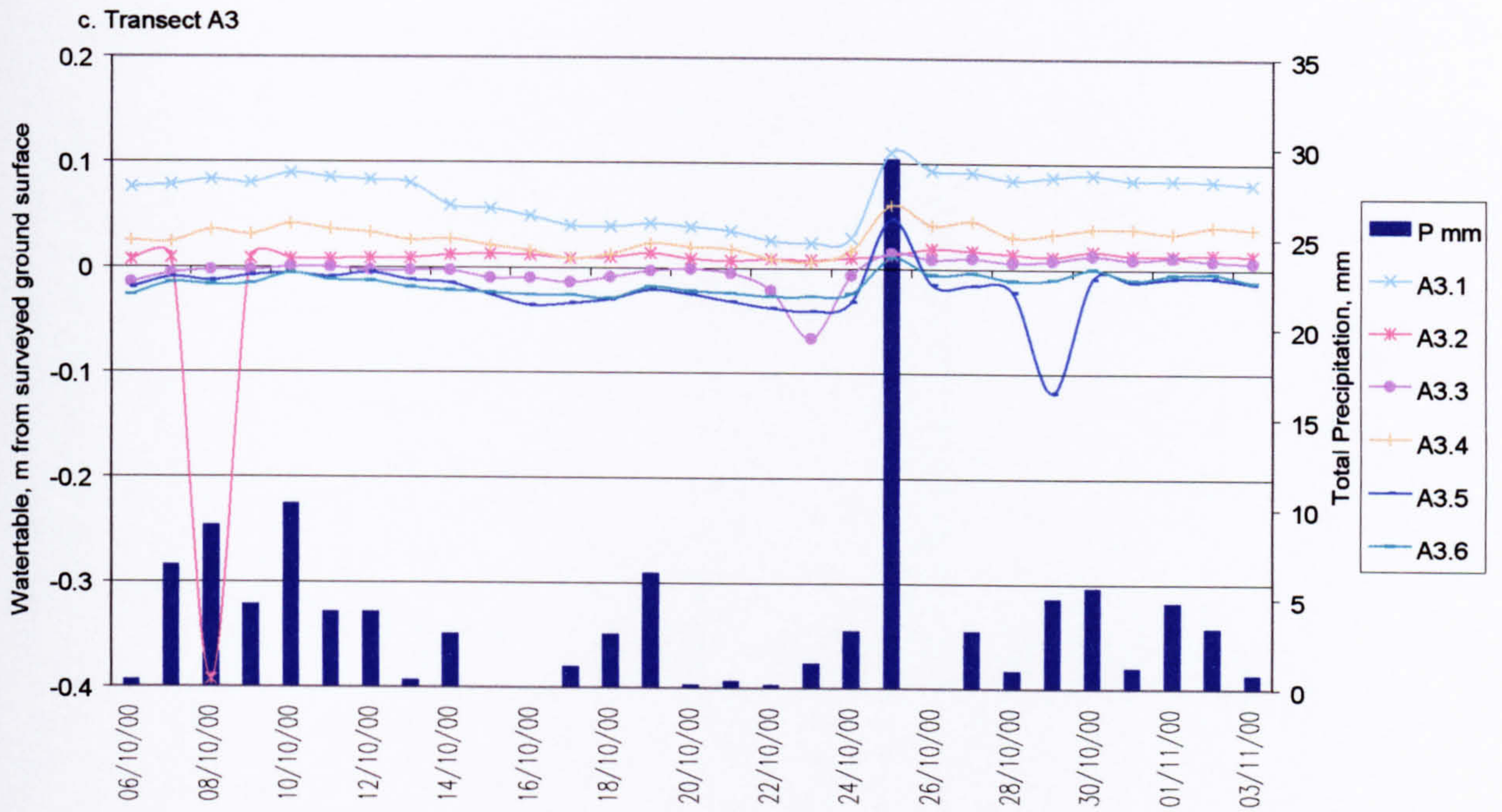
Fluctuation in water level closest to defined drainage channels can be observed in many of the disturbed locations, though the immediate effect of adjacent drainage is not always apparent. Actual drains can be difficult to define and fluctuation must be due to other forms of disturbance in several cases: well A3.5, most of transect B3 and C wells (figures 22c, f, g) are not close to maintained drains. The uneven topography of the abandoned cuttings means that effectively broad, shallow channels, approximately 5m wide and over 100m long are created between the higher (by 0.25-0.75m), dry ridge ways, or baulks. When orientated down slope, these features act effectively as shallow drains.

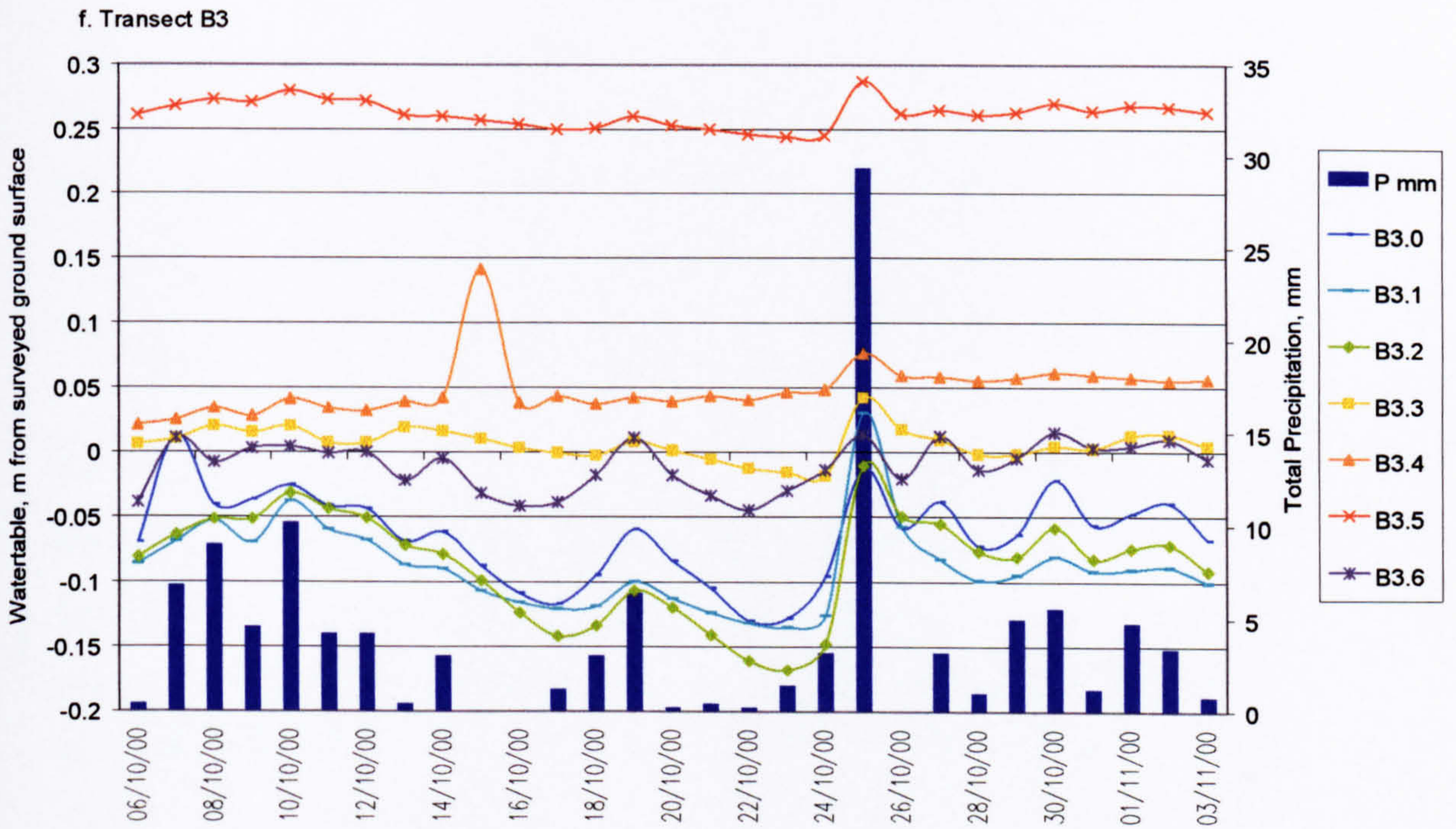
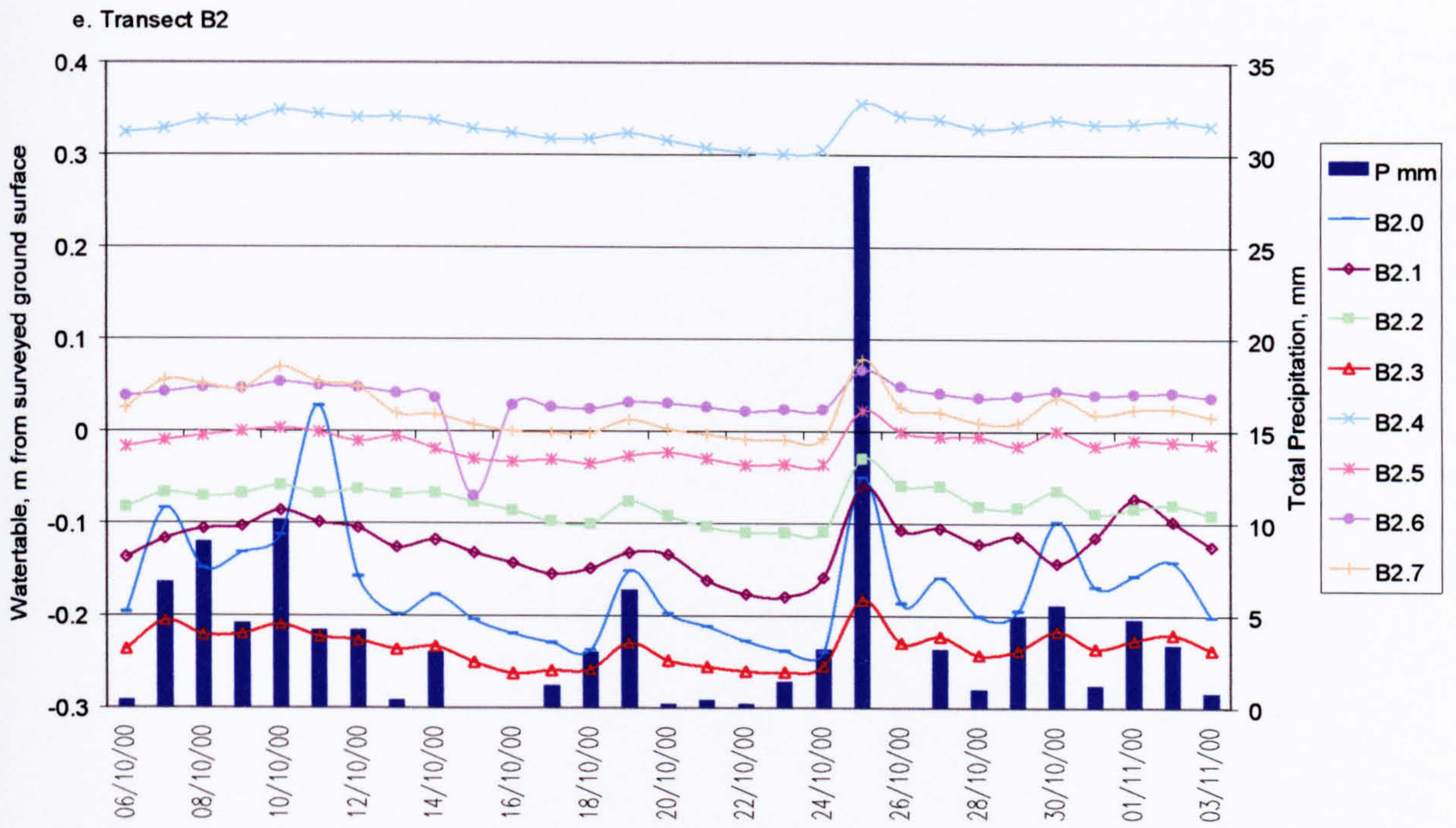
Comparing the water table profiles from disturbed transects A (Figure 23a-c), B (Figure 23d-f), and C (Figure 23g-h), leading from the active cutting area, with profiles from the intact South West lobe surface, transect 4.1-4.11 (extending from transect C) (Figure 23g & i), and transect 5.1-5.11 (Figure 23j), one difference is immediately apparent: whilst water table profiles fluctuate very little on the landscape scale, in the intact region this means it remains close to the ground surface throughout the monitoring period regardless of small topographical discontinuities (with the exception of well 4.5). The watertable shape in adjacent transects in the disturbed mire surface (A1-3, B1-3) also remains fairly consistent. However the unevenness of the topography means that the water table is above ground in topographical lows, and below in higher ground, so that the old cuttings are wet and the intercepting ridges are dry. Conversely, transect A 3.1-3.6 (Fig. 7-9), is relatively flat through strongly eroded area and exhibiting evidence of considerable surface flow activity, with discharge overflowing into the drain channel.

It can be seen quite clearly from the spread of mean October watertable plotted in figure 24a, that water levels recorded in dipwells in intact areas remain closer to the ground surface, whilst mean water levels lie at a greater distance above or below ground in disturbed areas. This is also confirmed by the fluctuation in watertables across the site, indicated by the range (max - min) in water levels recorded in individual wells during the monitoring period. A clear difference in range between wells in intact and cut regions can be observed in figure 24b, with the majority of dipwells levels in the intact mire maintaining a range of less than 0.05m throughout the monitoring period, whilst the range of disturbed sites is considerably higher. The distribution is slightly skewed as there are more wells located in disturbed mire locations, due to the focus of the hydrological investigations and the nature of the disturbed mire, which means that most dipwells must be close to a drainage channel. That does not however invalidate the findings, as it is clear from figures 24a and b, that the mean watertable is deeper and the range of fluctuation is greater in dipwells closest to drains in the disturbed mire.

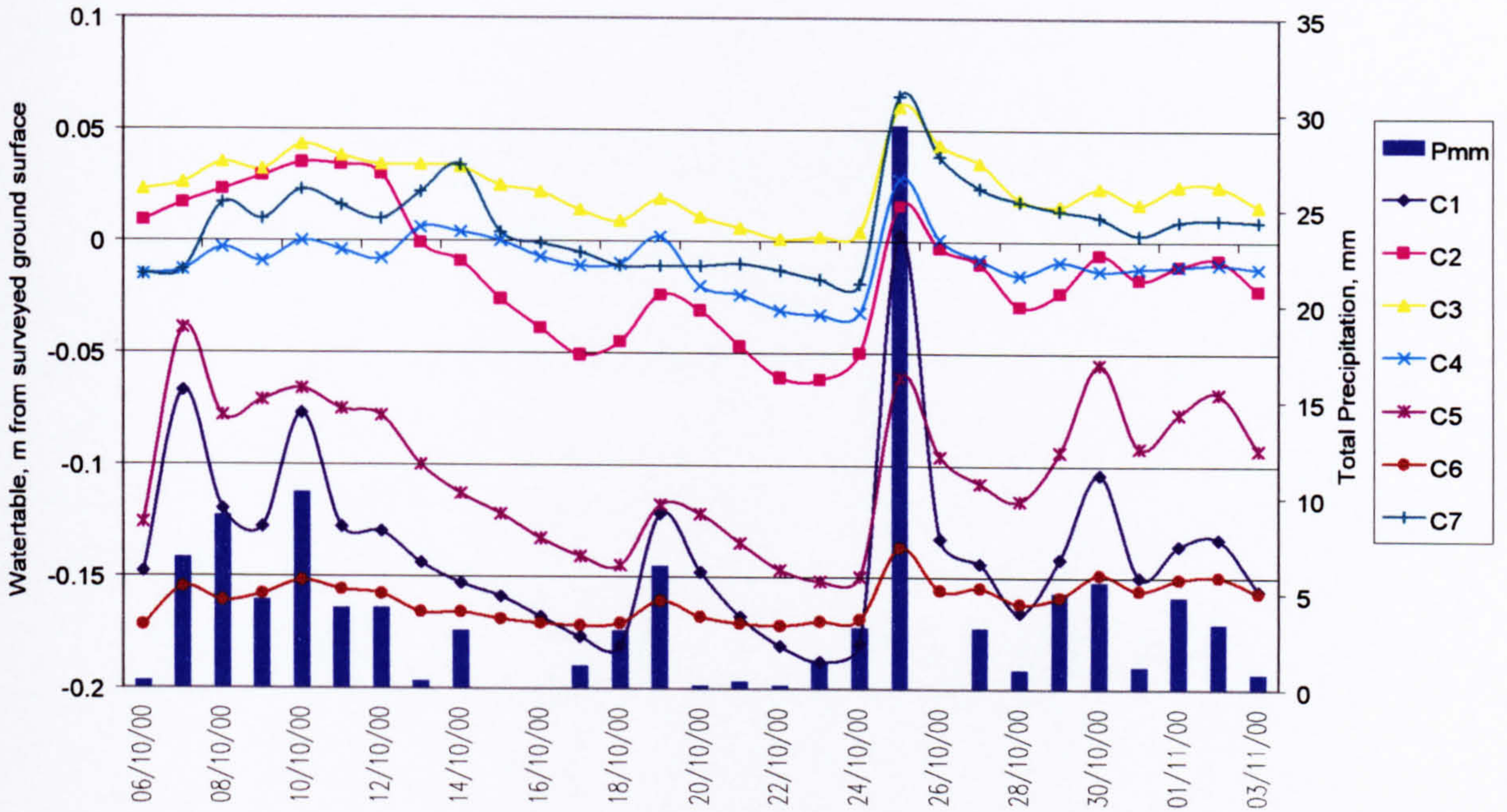
Figure 22 a-k. October daily watertable fluctuations with precipitation, recorded in individual wells from transects 1, A1-3, B1-3, C, 4 and 5 (m above/below ground level).



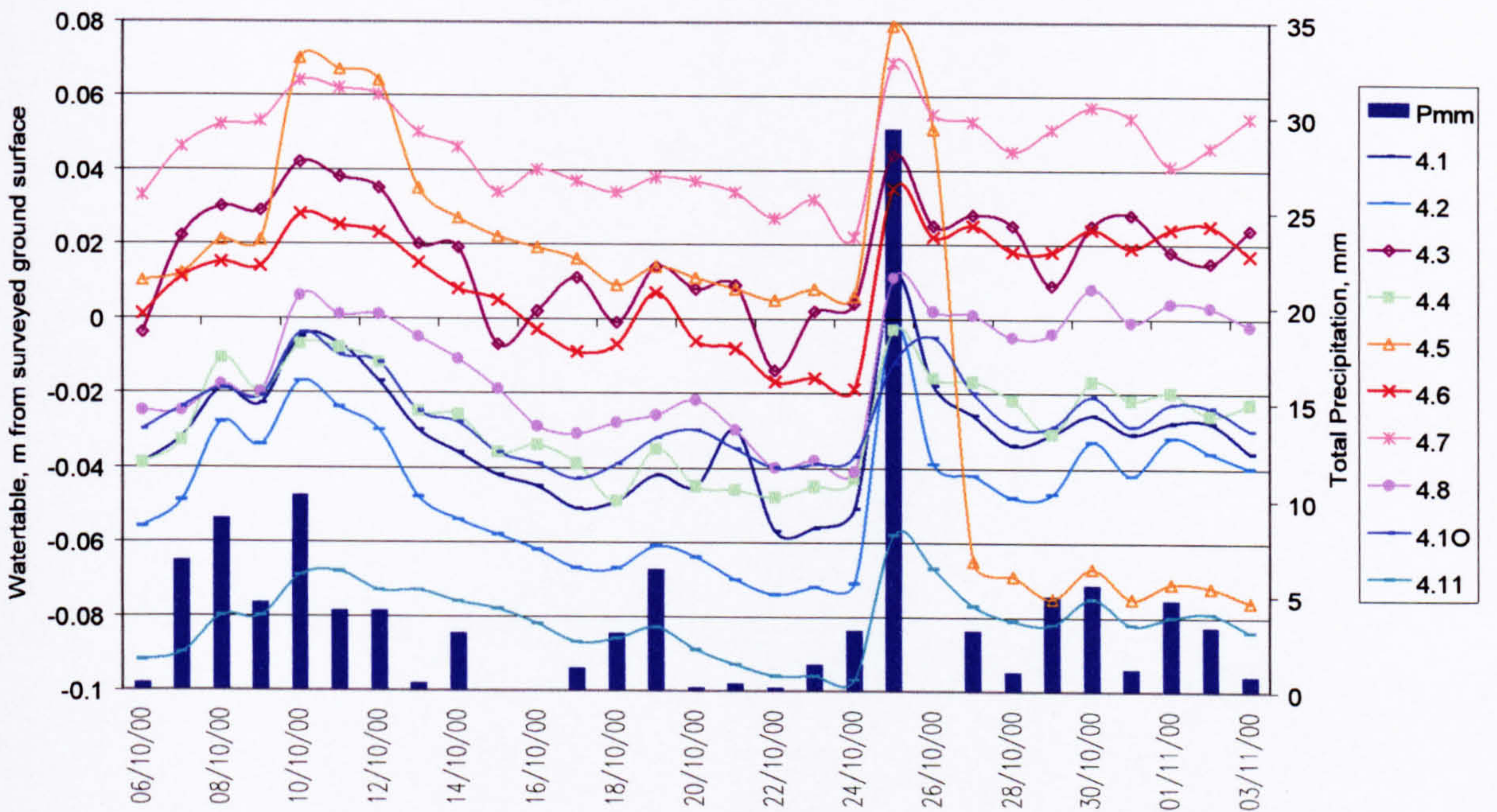




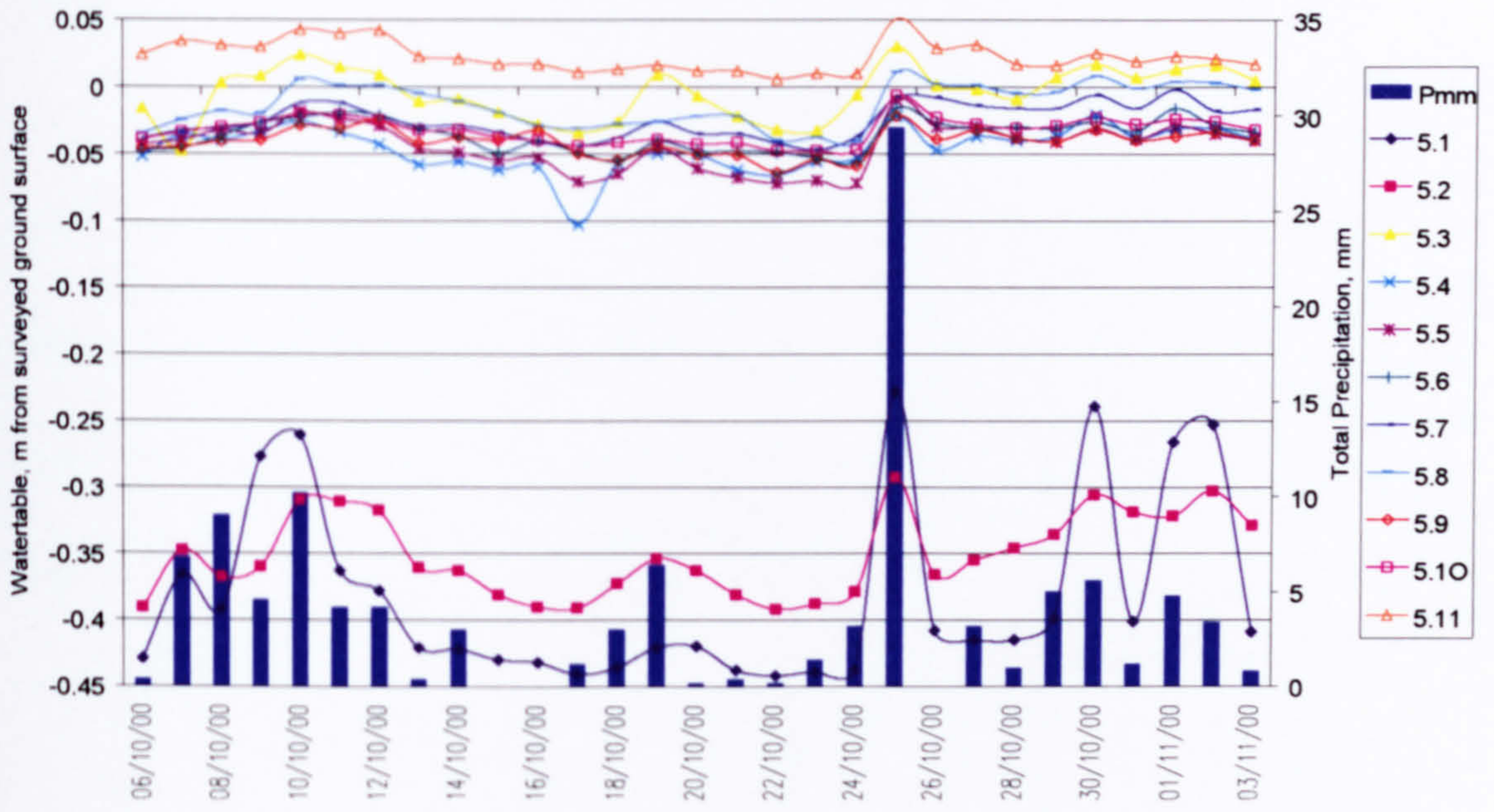
g. Transect C



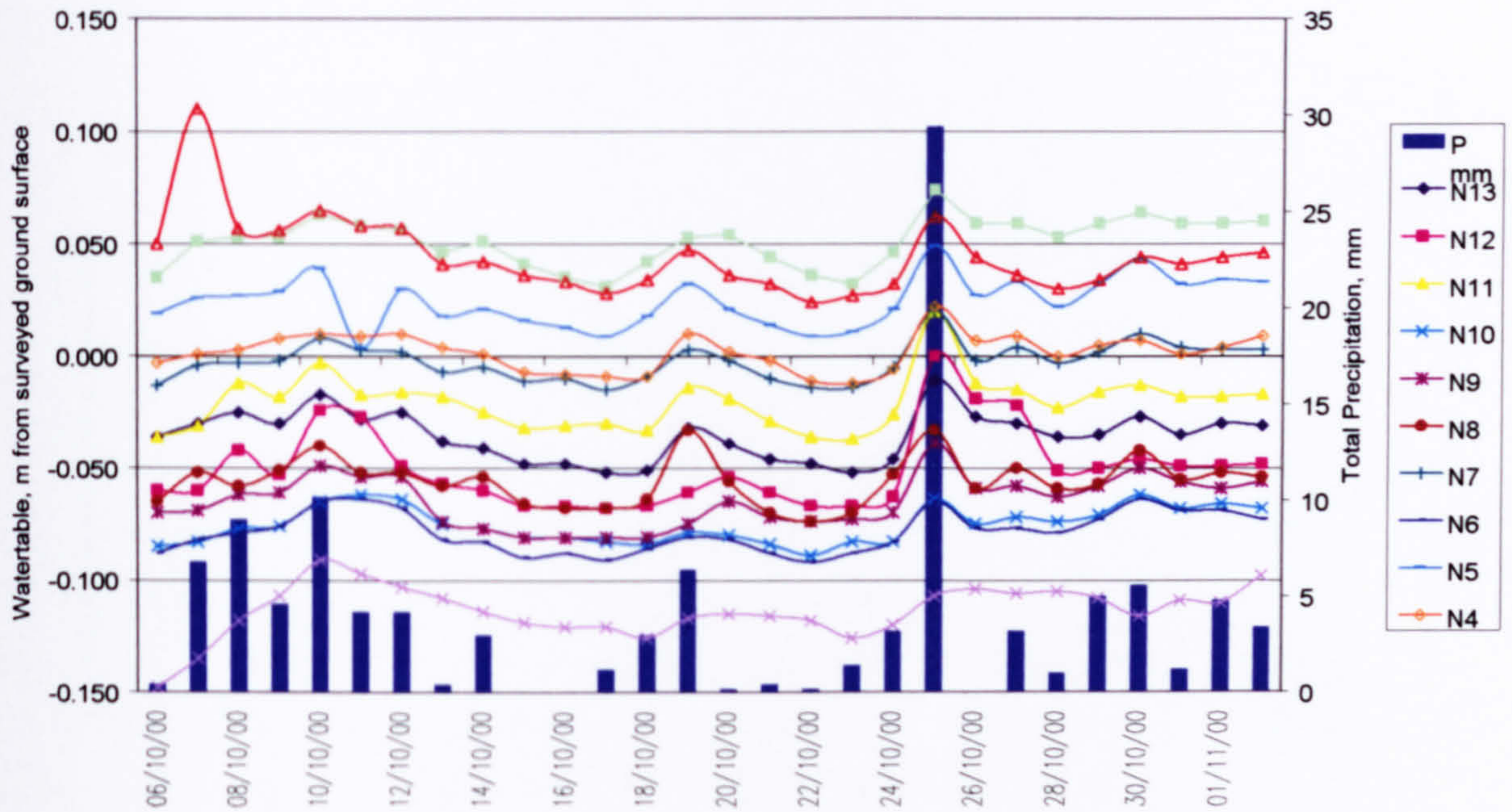
h. Transect 4



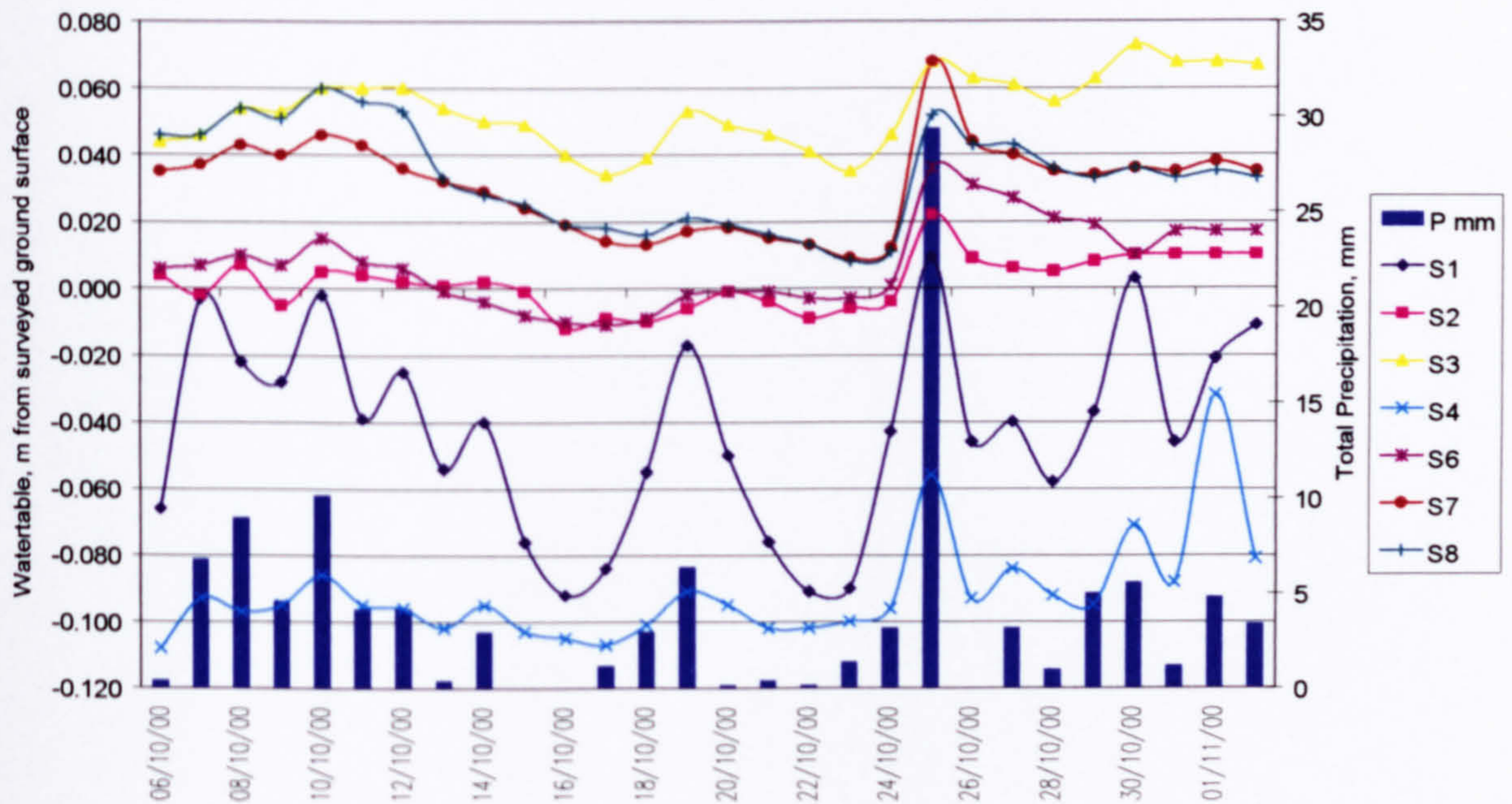
i. Transect 5



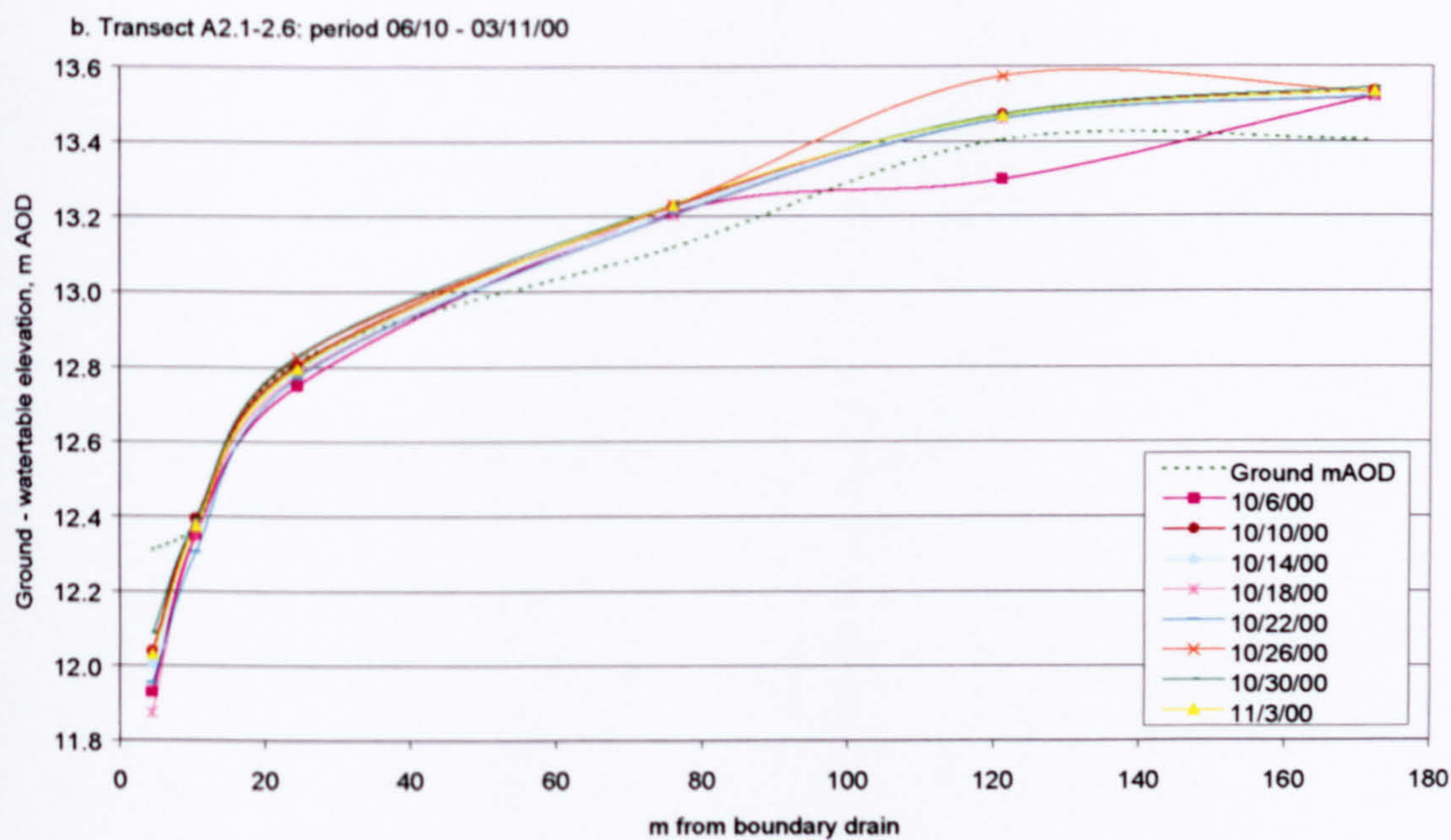
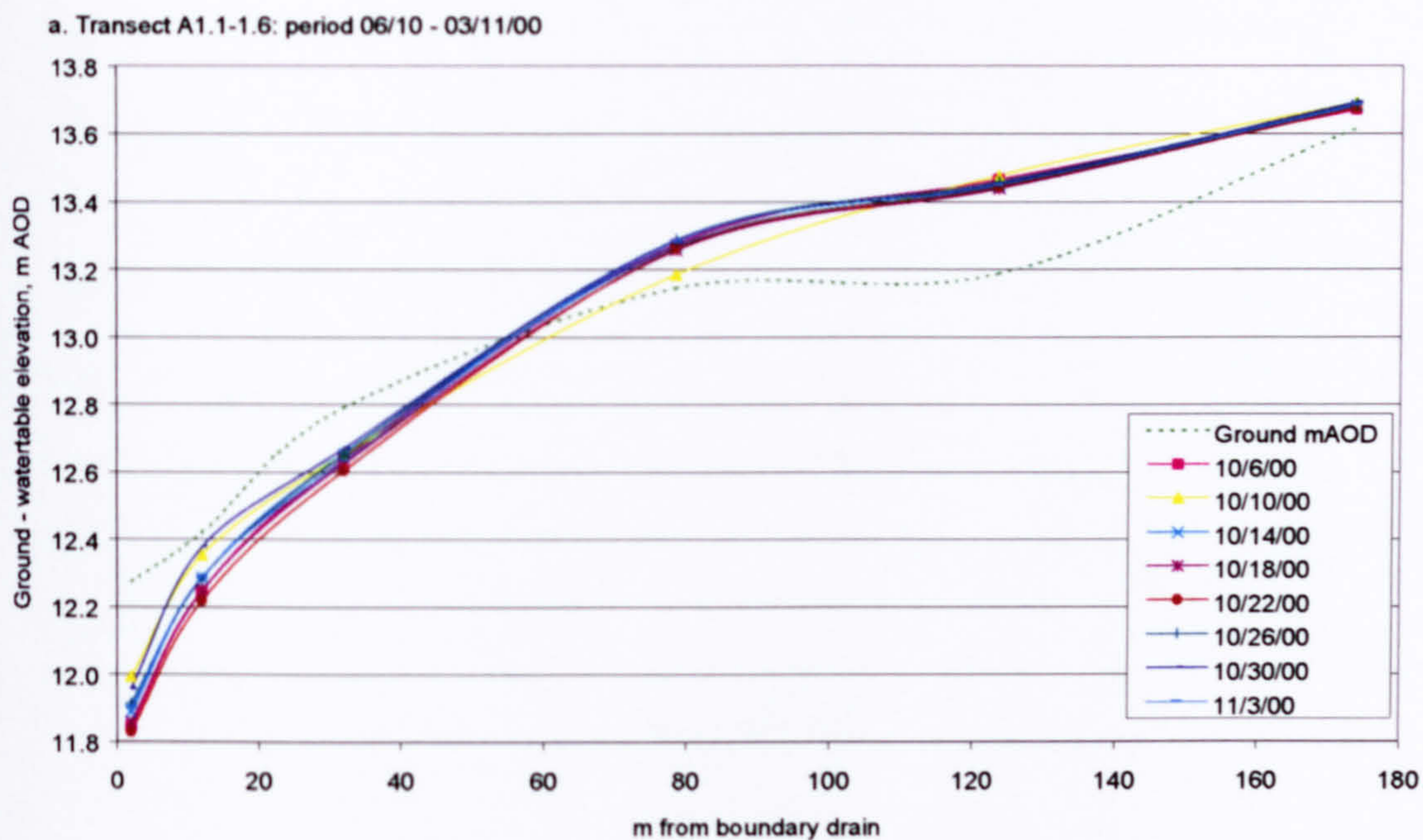
j. Transect 1 - North



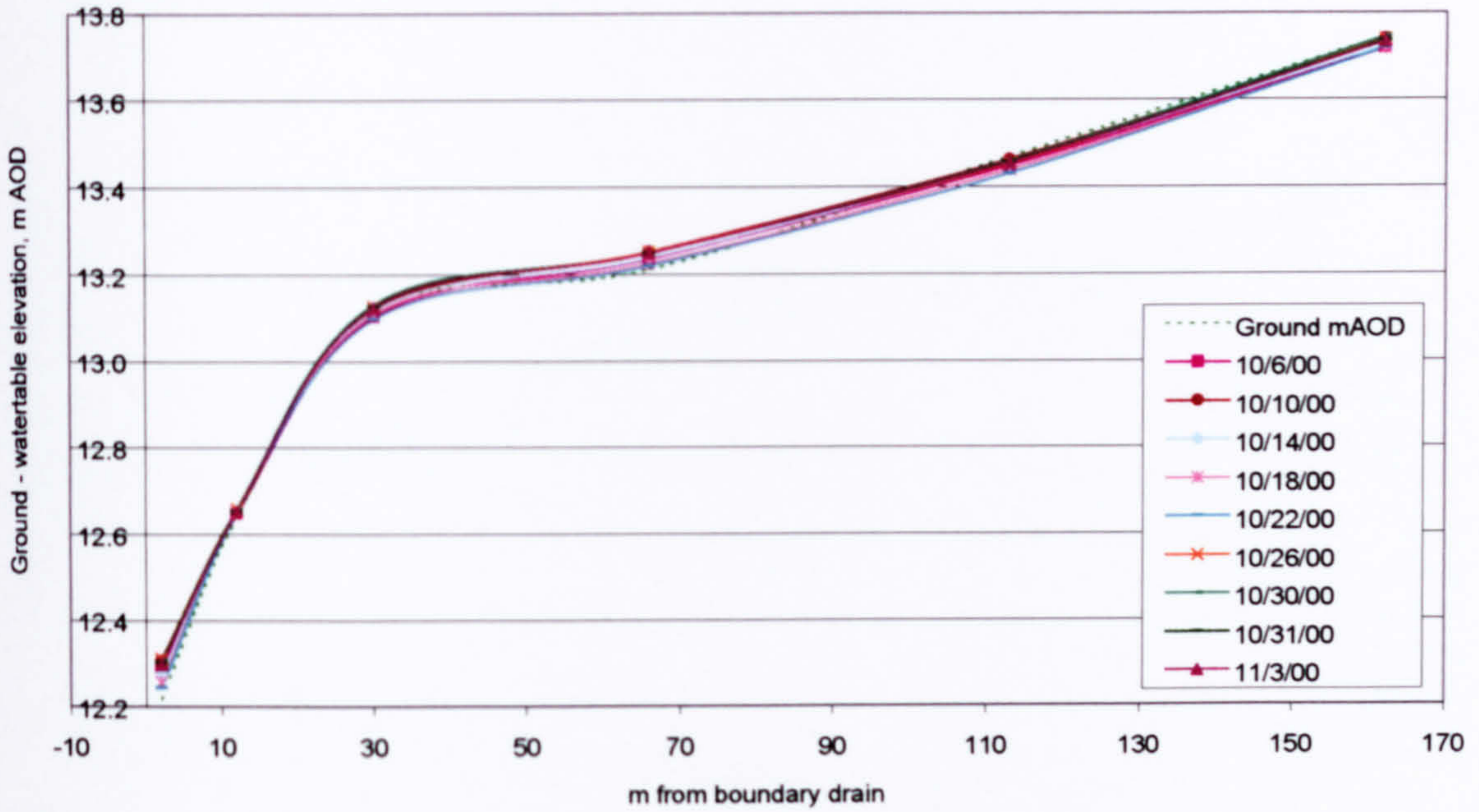
k. Transect 1 - South



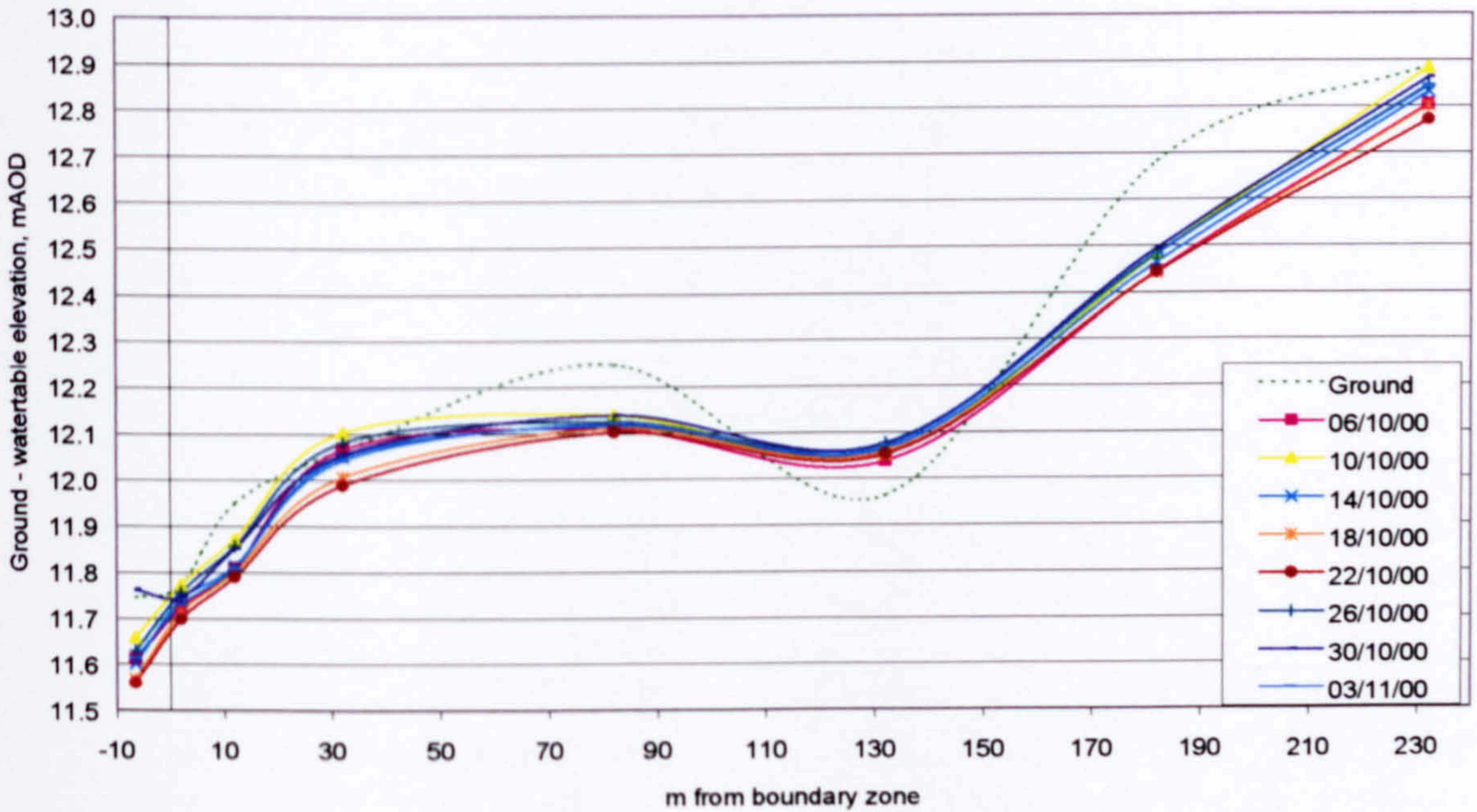
Figures 23 a-l. Daily watertable records from dipwell transects A1-3, B1-3, C and 4 (combined and separate), Transect 5 and selected wells from transect 1, 06/10/00 - 03/11/00, presented at 4-day intervals.



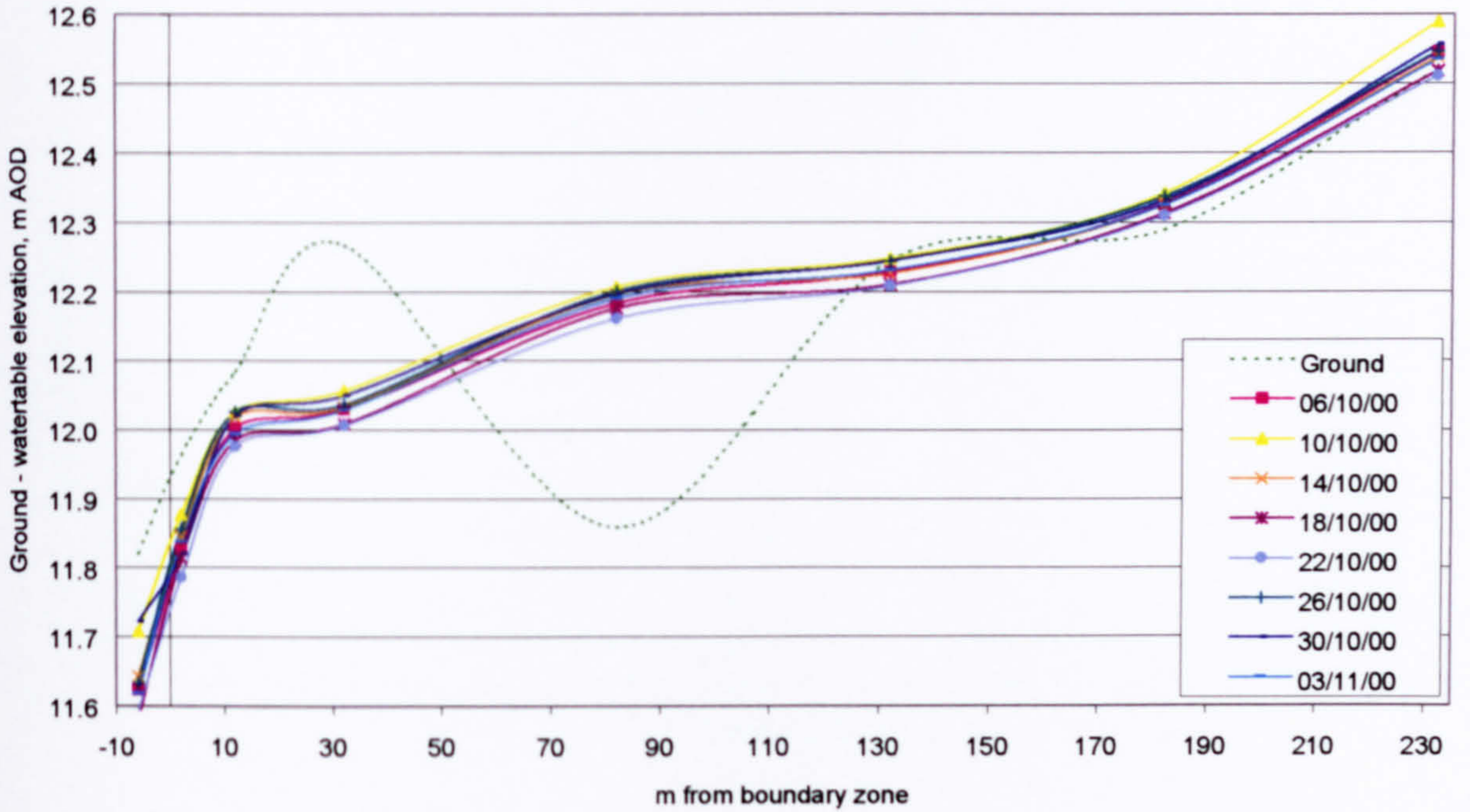
c. Transect A3.1-3.6: period 06/10 - 03/11/00



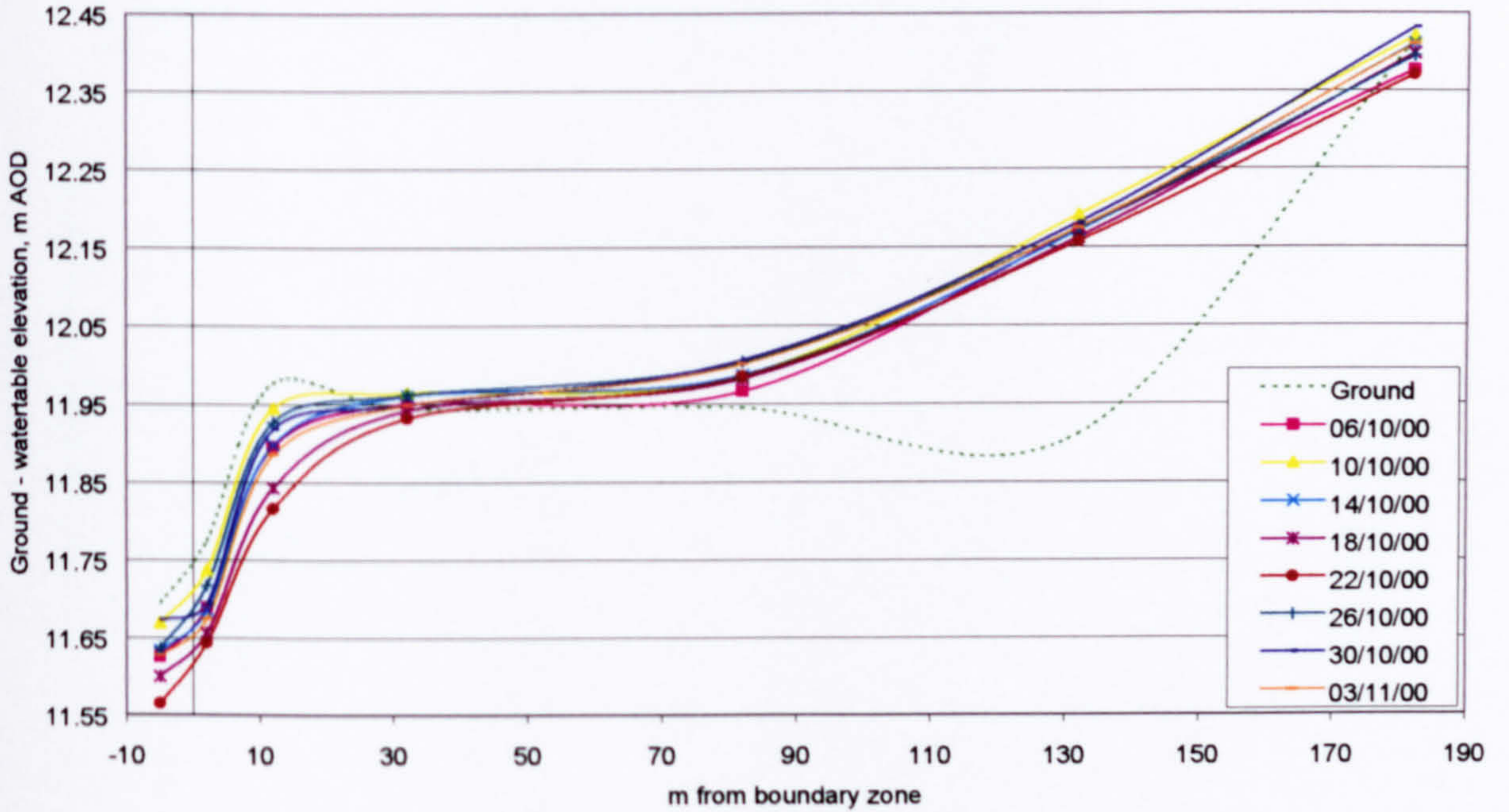
d. Transect B1.0-1.7: period 06/10 - 03/11/00



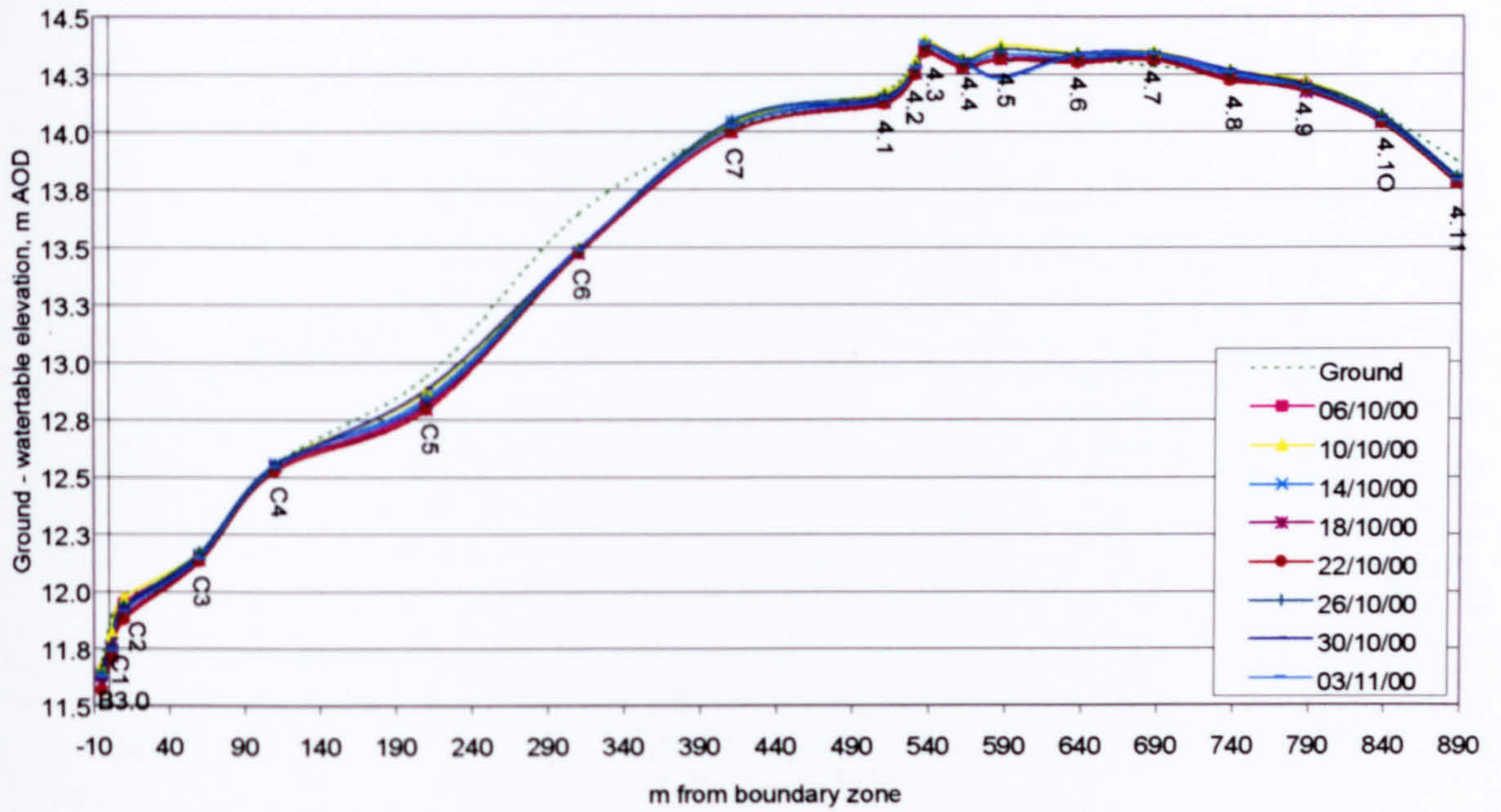
e. Transect B2.0-2.7: period 6/10 - 3/11/00



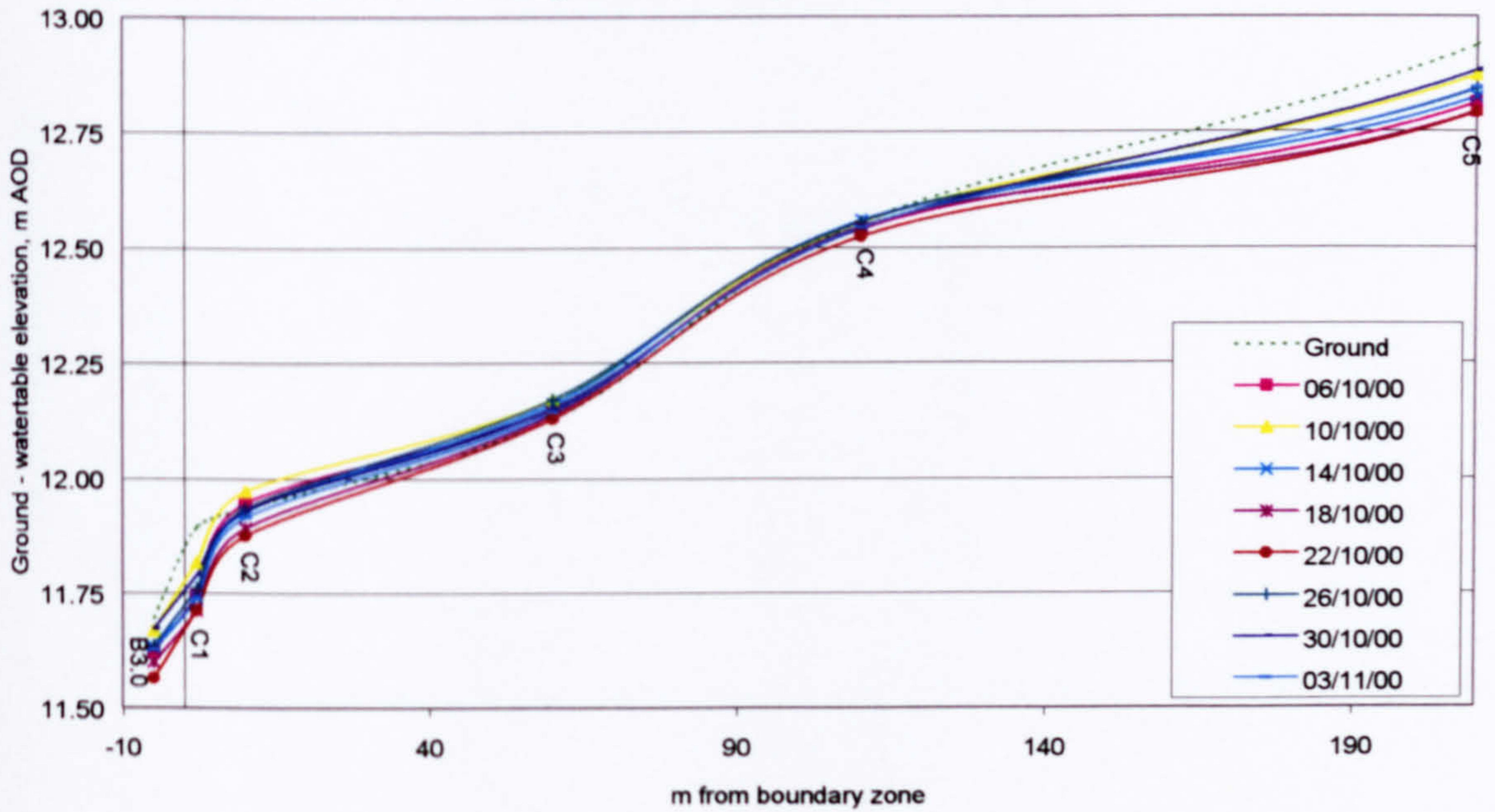
f. Transect B3.0-3.6: period 6/10-3/11/00



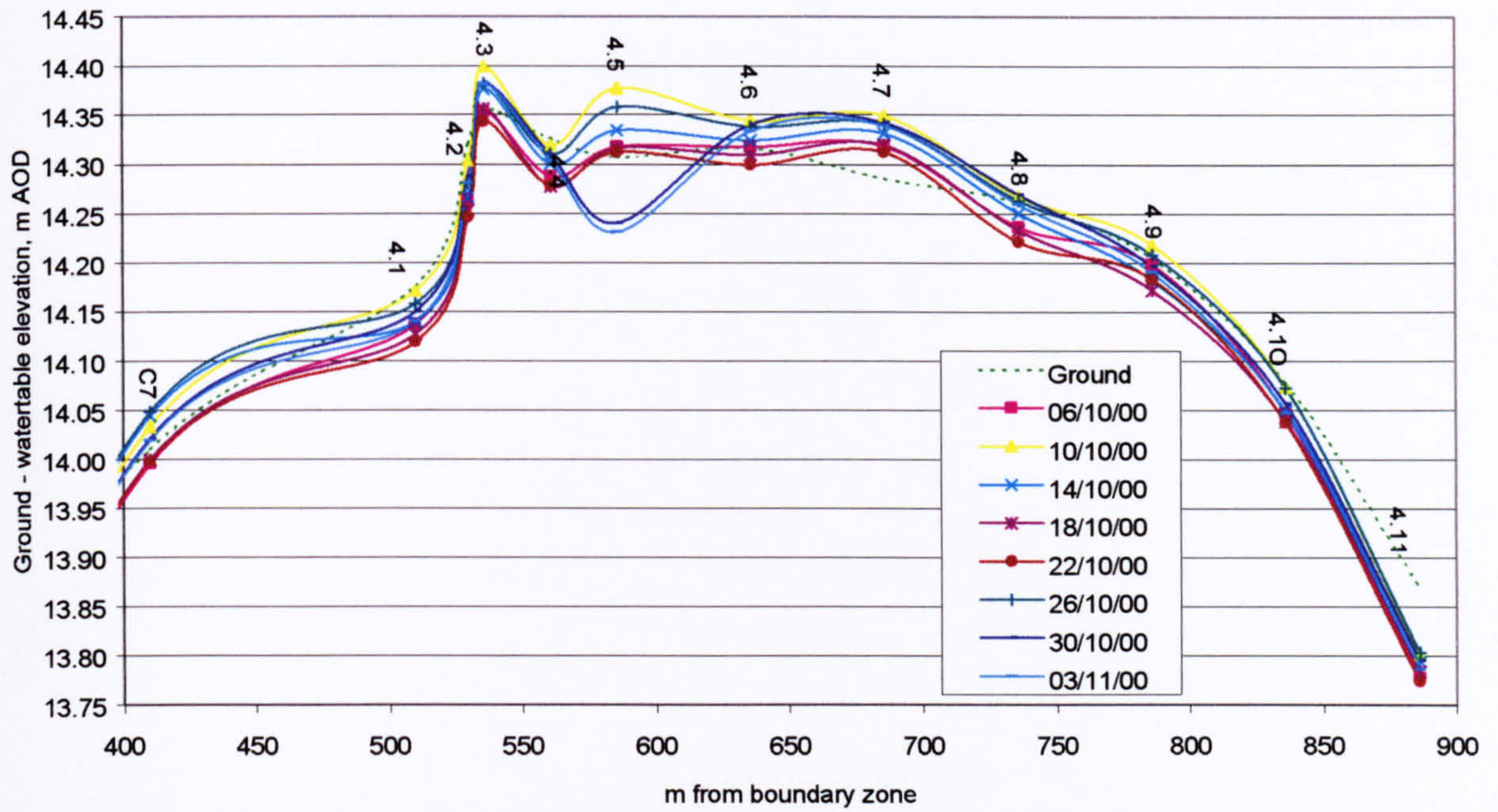
g. Dipwell B3.0 and Transect C1-7 extending to include transect 4.1-4.11: period 6/10 - 3/11/00



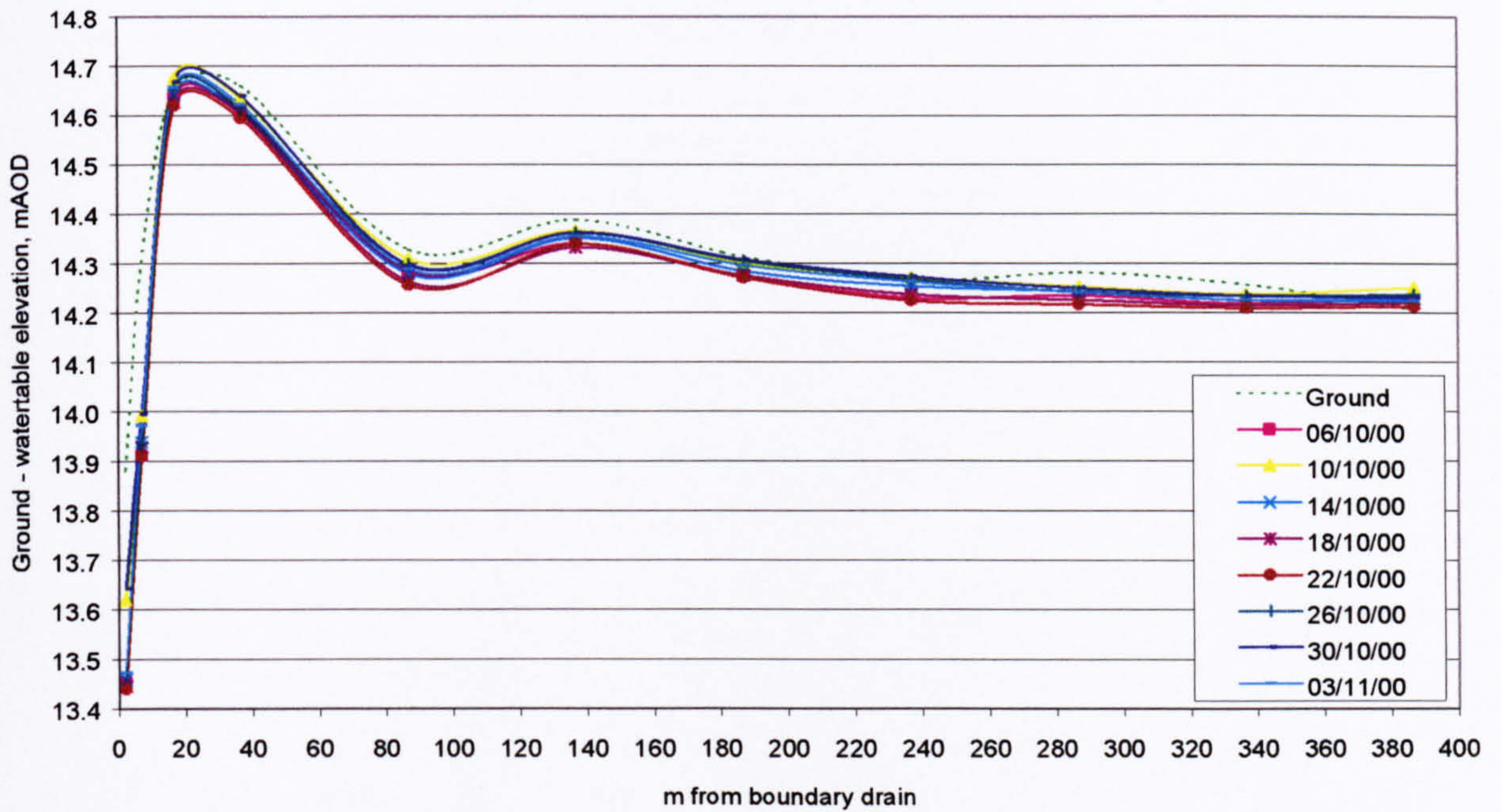
h. Dipwell B3.0 and Transect C1-5 extending 210m from drain: period 6/10 - 3/11/00



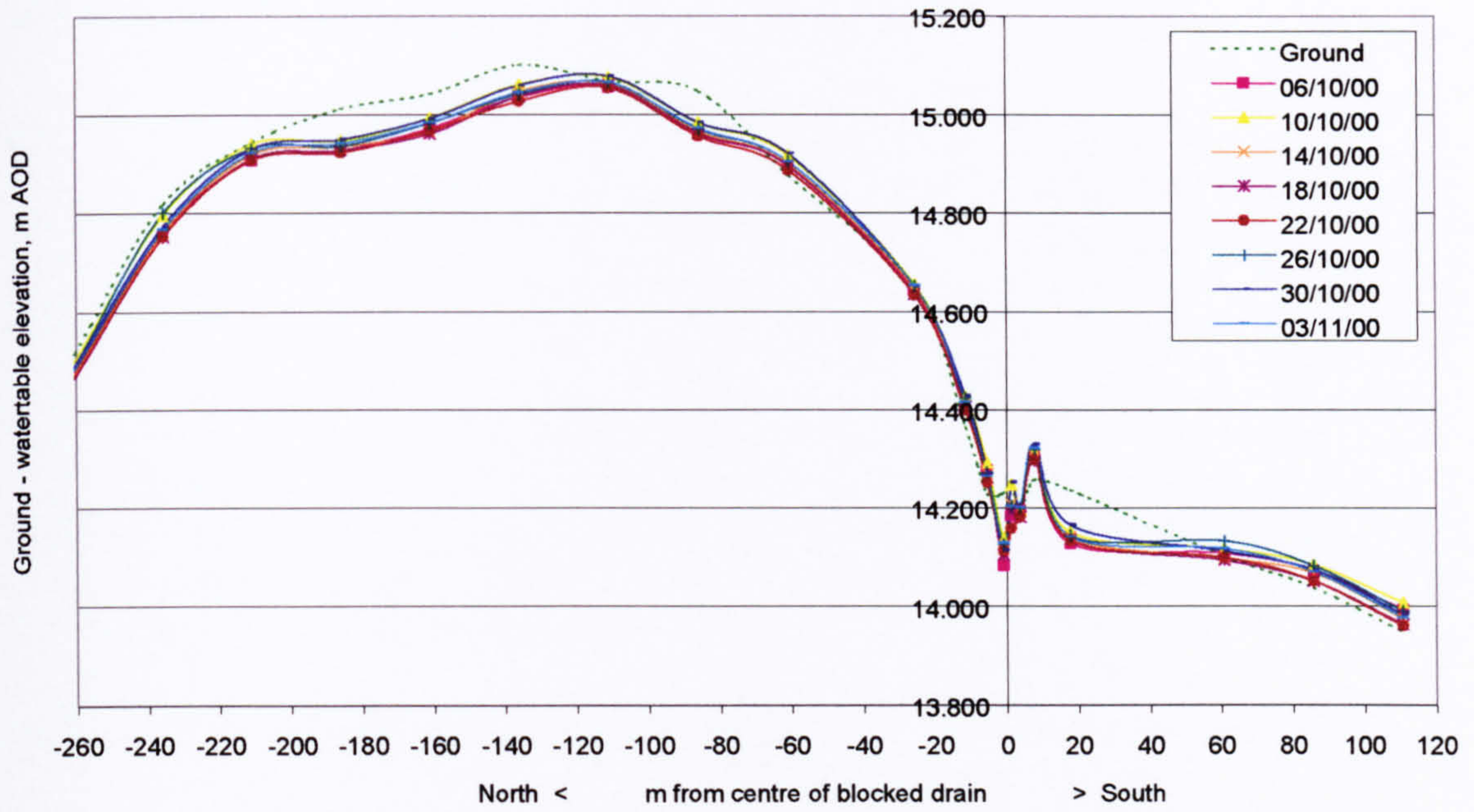
i. From dipwell C7 across 'intact zone' to include transect 4.1-4.11: period 6/10 - 3/11/00



j. Transect 5.1-5.11 : period 06/10 - 03/11/00



k. Transect 1 (N13-S8) crossing drain blocked in Jan' 1992: period 6/10-3/11/00



l. Transect 1 (N4/5-S4/5), 100m zone adjacent to blocked: 6,18,30/10 & 3/11/00

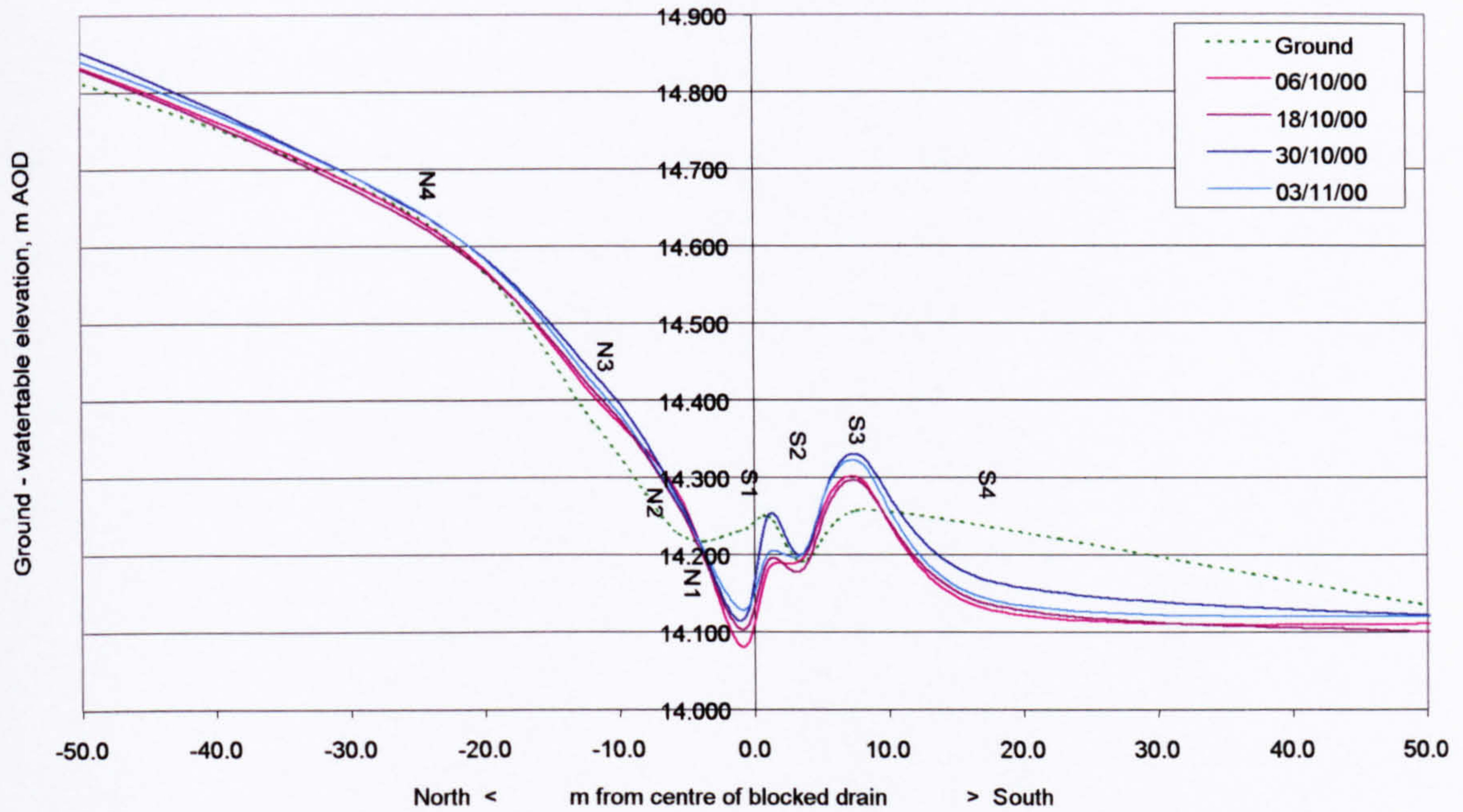
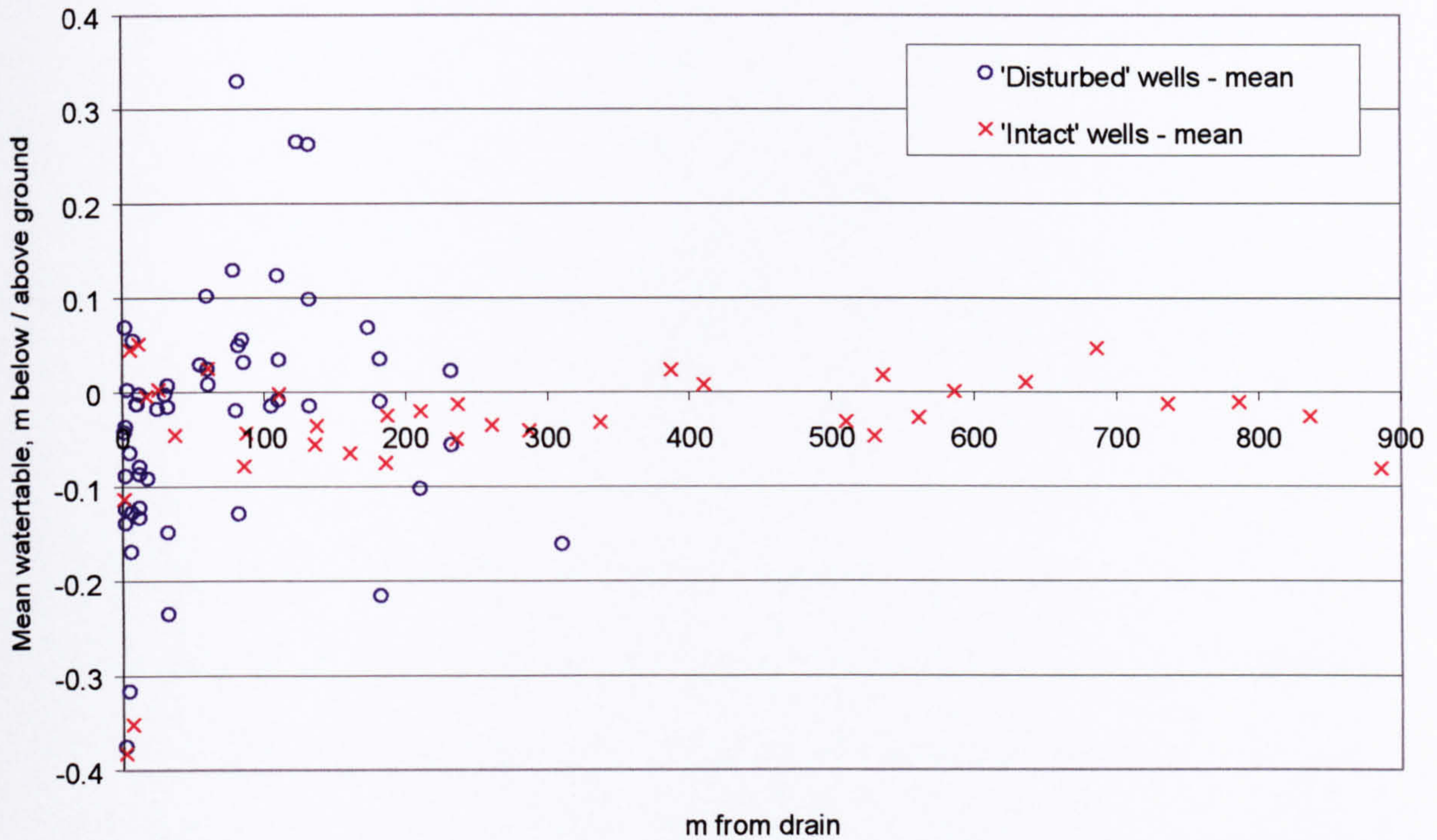


Figure 24 a & b. (a) Mean (m from ground surface) and (b) range in recorded watertable (m), October'00: 'Disturbed' wells x 55, transects A, B, C and S1-8; 'Intact' wells x 36, transects 4.1-11, 5.1-11, N1-13.

a. Mean recorded watertables



b. Range in recorded watertables

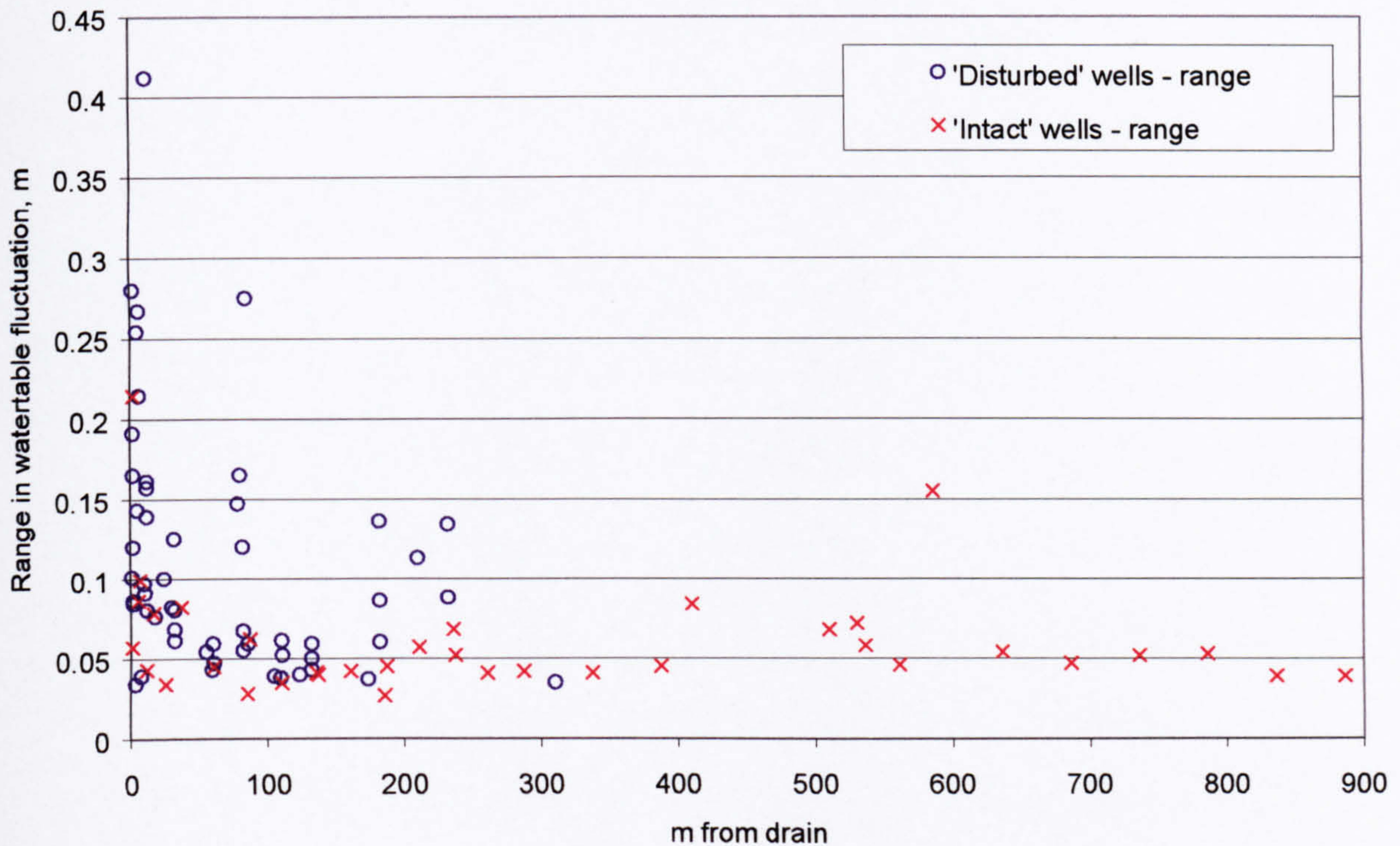


Table 4. Pearson correlation coefficients and P-values for test of linearity between distance from drain of dipwell location, peat depth, watertable mean and range, and recorded high and low watertable for the period (most significant correlations in bold type).

All wells	Watertable	Distance from drain		Total peat depth	
	Mean	0.123	0.247	0.109	0.306
Range	-0.299	0.004	-0.325	0.002	
Intact wells	Mean	0.273	0.113	0.561	0.000
	Range	-0.132	0.450	-0.416	0.013
	High	0.268	0.120	0.512	0.002
	Low	0.264	0.125	0.567	0.000
Disturbed wells	Mean	0.203	0.137	0.012	0.931
	Range	-0.304	0.024	-0.195	0.154
	High	0.128	0.351	0.029	0.833
	Low	0.255	0.060	0.124	0.366
		<i>Correlation coefficient</i>	<i>P-value</i>	<i>Correlation coefficient</i>	<i>P-value</i>

Statistical tests were carried out to examine the relationship between the range in observed water table, and both peat depth and distance from the drain, as indicators of disturbance. Initially all dipwells were included in a Pearson test of linearity. The result (shown in Table 4) was that both distance from the drain and peat depth were strongly negatively correlated with water table fluctuation range ($P = 0.004$ & 0.002 respectively). That is, there is a negative linear relationship between watertable fluctuation and both increasing distance from the drain and increasing peat depth, confirming that the watertable is more stable further from the drain. It is also more stable in deeper peat. This is not surprising as peat is deeper in the stable intact mire and it increases in depth with distance from drains and cuttings. When dipwell data from intact sites only (36 wells) were tested separately, peat depth was very strongly negatively correlated with range ($P = 0.013$), again indicating that the deeper the peat, the smaller the range in water table fluctuation during the monitoring period. Mean watertable at these sites was most highly positively correlated with peat depth ($P = 0.000$), confirming that the average watertable was highest in the deepest peat. The fact that peat depth and distance from the drain are strongly positively

correlated ($P = 0$) indicates that water table range will also decrease as distance from the drain increases. When the analysis was repeated for cut-over areas (55 wells), again distance from the drain was strongly negatively correlated with range in water table ($P = 0.024$), whilst peat depth was found to have a weaker negative correlation ($P = 0.154$).

The minimum and maximum recorded watertable in each dipwell was tested for linearity with drain proximity and peat depth. In the case of intact sites, both the highest and lowest recorded watertable, were positively correlated with peat depth ($P = 0.002$ & 0.000 respectively), so that as peat depth falls so does the watertable and higher watertables are consistently higher in deeper peat. In disturbed sites the lowest recorded watertable was positively correlated to proximity to drain ($P = 0.06$).

In most dipwells in the intact mire, when the watertable is within 0.01m of the ground surface, any rise in response to rainfall is not obvious. This is because there is very little scope here for storage and recharge must be stored in shallow pools (hollows), or must run-off via transient hollow-channel networks. The surface of the cut-over mire is generally different, with the natural vegetation and microtopography removed, and the quick-flow response to rainfall locally variable. It is possible for the initially lower watertable to rise considerably before surface water and rapid overland flow occurs, whilst an adjacent low bare peat area may respond immediately with very little storage occurring. The structure of the peat in such zones is considerably different due to dehydration during periods of intensive drainage, whilst the surface gradient may be much steeper due to peat removal. It is likely that through flow mechanisms have been altered considerable by these activities. Examination of the storage potential of different parts of the mire acrotelm may confirm such processes (Section 6.2).

6. Flow and storage potential in the diplotelmic mire

6.1 Catotelm hydraulic conductivity and storage potential

In order to estimate the potential flux of groundwater through the catotelm peat of a mire, it is necessary to establish some basic measurement of its hydrophysical properties.

Hydraulic conductivity (K) is effectively a bulk estimate of the capacity of peat to transmit liquid, determined by its physical state (antecedent moisture content, density and porosity) at the time of measurement and the hydraulic head or suction imposed by adjacent areas. It is normally attributed the dimensions depth/time, but when applied across a sub-surface layer and referred to as transmissivity, it is multiplied by the layer thickness and has the units length²/time. In a simulation of mire hydrology the transmissivity of model layers is a state variable. Given the accumulation processes of peat formation over extended time periods, it is accepted that K is likely to be highly variable over extended areas of heterogeneous mire peat, in both horizontal and vertical dimensions. In the acrotelm of uneven thickness, where a pool may be found in close proximity to a mound of barely decomposed moss (hummock), the spatial and temporal variability of K is likely to increase accordingly.

The difficulty and time-consuming nature of K measurement (Päivänen, 1973, MacAlister, 1996, Holden, 2000) means that data are often limited, however caution should be taken when generalising or up-scaling from limited measurements in estimations or simulations. In the analytical 'Groundwater Water Mound' model proposed by Ingram (1982) K is assumed to be constant throughout the catotelm. This does not truly represent the heterogeneous nature of peat. In multi-layer numerical schemes different transmissivity

can normally be applied in both the horizontal and vertical axes. The application of a bulk measure of hydraulic properties requires the acceptance of a small degree of error and simulations should be checked for sensitivity to changes in transmissivity.

Within the catotelm below the fluctuating phreatic zone, the specific yield (Sy) (strictly the amount of water that can be freely drained under the influence of gravity against the water retention capacity of the soil, expressed as a proportion of total volume), can be determined in laboratory experiments. Such tests are inherently erroneous as the removal of intact peat cores from depth and imposition of realistic surrounding conditions within a laboratory setting is difficult without considerable resources. Boelter (1965) recorded the specific yield of 0.1m extracted peat cores taken from 0-0.8m below the surface and varying in degrees of humification from living *Sphagnum* to well decomposed herbaceous peat. (The specific yield values he obtained are listed in Table 7, p.169).

The specific yield can also be described as the effective porosity, as it is a measure of the proportion of the total volume of the peat available for water storage. The relationship between the storage potential of the peat, as effective porosity, and hydraulic conductivity is described by the Kozeny-Carman Equation (Carman, 1939, Ahuja *et al.*, 1985,) (Equation 1) for calculating soil hydraulic properties from limited data sets:

$$K_{\text{sat}} = B \varnothing^n \quad \text{Equation 1}$$

where K_{sat} = saturated hydraulic conductivity; \varnothing = effective porosity; $B = 1058$ and $n = 4$ when K_{sat} has the units cm/h.

Rearranging Equation 1, the effective porosity can be estimated from hydraulic conductivity:

$$\phi = \sqrt[4]{(K_{\text{sat}} / B)} \quad \text{Equation 2}$$

This method introduces several sources of error including:

1. assumes the accuracy of hydraulic conductivity or porosity measurements;
2. introduces constants (B and n) which may differ according to soil type and condition.
3. assumes uniformity of parameters throughout the peat body.

Field method for recording of hydraulic conductivity

Hydraulic conductivity was recorded across the site within the main transect locations, using the variable head piezometer method and calculation (Kirkham, 1946, Frevert and Kirkham, 1948, Luthin and Kirham, 1949, and Reeve and Kirkham, 1951)¹. Briefly, an augered cavity is lined with tubing and the water refilling the empty pipe is removed several times to flush-out incoming peat. The steady state rate of refill is then recorded and conductivity, moderated by the position of the watertable and dimensions of the tube, is calculated according to the empirical formula²:

$$K_{\text{sat}} = \frac{\pi r_p^2 \ln(h_1/h_2)}{C (t_2 - t_1)} \quad \text{Equation 3}$$

where, h = distance to datum of the water surface at time t ; C = shape factor.

¹ described in detail in Chapter 2, Section 3.4.1.

² see also Chapter 2, Section 3.4.1 Equation 6.

This method has been applied in several previous studies of mire hydrology and the reported values are compared to Wedholme values in the discussion.

Päivänen (1973) stated that 'it is meaningless to study the hydraulic conductivity without relating it to the quality and structure of peat'. As time and resources were limited, only K measurements were performed *in situ*, however a note has been made of observed peat conditions.

Tests at 5, 25, 135m along transect 1, carried out in June 1997, employed the standardised Luthin-Kirkham methodology (Luthin & Kirkham, 1949), using open-ended piezometers of 30mm internal diameter above 0.1m open cavities. Tests carried out in June 2000, at 5m from the drain at transect 5, involved modified 30-35mm piezometers with 0.1m mesh lined cavities to prevent collapse. In later tests carried out in November 2000, 10-15m from the cutting boundary drain in transects A-C, the method was further modified with an increased 50mm diameter piezometer tube to accommodate pressure transducers, which attached to data loggers, recorded the rate of refill of the cavities automatically. The cavity depth was also increased in the automated piezometers to 0.2m. Conductivity was recorded between 0.3-0.5m (automated piezometers), 0.4-0.5m, 0.8-1.0m (automated piezometers) and 0.9-1.0m depths, whilst in the deeper peat of the intact mire surface of transect 1, it was also recorded at depths 1.4-1.5m and 1.9-2.0m. Tests were repeated a minimum of three times in each piezometer and the refill rate was found to be non-linear in all cases. This confirms previous field observations (Galvin and Hanrahan, 1967, Dai and Sparling, 1973, Ingram, 1974, van der Schaaf, 1999) that conductivity is affected by falling head and

also by the potential compressibility of the peat. For this reason conductivities were calculated from the steady state part of a plot of piezometer refill rate.

Results

The range in recorded hydraulic conductivity and mean of replicated tests from each piezometer at varying depths below the mire surface are displayed in Table 5. The range and mean effective porosity values calculated by the Kozeny-Carman equation are given as a proportion, for each test depth. The changes in mean recorded K at the piezometer test depths for each test location are illustrated in figures 25 a-g. Potential linearity between the recorded K, the piezometer test depth and the distance between the test location and the nearest drain channel has been examined and the Pearson product moment correlation coefficients and respective P-values are given in Table 6.

Table 5. Peat condition, range and mean recorded hydraulic conductivity ($K \text{ md}^{-1}$) and calculated effective porosity (dimensionless) for each location and test depth.

Test site:	m from drain	Test depth (m)	*Peat condition	Recorded range in K, (md^{-1})	Mean K (md^{-1})	Effective Porosity
Transect A	10	0.3-0.5	4	0.06135 – 0.29205	0.11750	0.149
	10	0.8-1.0	3	0.00377 – 0.00403	0.00390	0.063
Transect B	15	0.3-0.5	4	0.04199 – 0.14096	0.07694	0.133
	15	0.8-1.0	3	0.00870 – 0.07562	0.02565	0.104
Transect C	15	0.3-0.5	4	0.01232 – 0.02057	0.01780	0.092
	15	0.8-1.0	2	0.02344 – 0.16540	0.04850	0.120
Transect 5	5	0.4-0.5	4	0.01142 – 1.04321	0.08809	0.149
	5	0.9-1.0	2	0.00621 – 0.05465	0.01887	0.095
SW lobe	5	1.4-1.5	2	0.03014 – 0.06726	0.04502	0.116
Transect 1	5	0.4-0.5	4	0.00692 – 0.01200	0.00912	0.078
	5	0.9-1.0	2	0.01541 – 0.10994	0.04116	0.116
Newton Arlosh Awards	5	1.4-1.5	3	0.02831 – 0.08170	0.04809	0.118
	5	1.9-2.0	3	0.00115 – 0.00564	0.00255	0.057
	25	0.4-0.5	1	0.00056 – 0.02804	0.00396	0.071
	25	0.9-1.0	2	0.00366 – 0.21855	0.08937	0.140
	25	1.4-1.5	2	0.00669 – 0.01260	0.00918	0.078
	25	1.9-2.0	2	0.00380 – 0.00407	0.00393	0.063
	135	0.4-0.5	1	0.49611 – 0.90344	0.66950	0.227
	135	0.9-1.0	2	0.00426 – 0.00531	0.00475	0.066
	135	1.4-1.5	2	0.01886 – 0.01978	0.01900	0.093
	135	1.9-2.0	2	0.00619 – 0.02742	0.01300	0.086

*Visual assessment of peat condition:

1. moderately decomposed moss – approximate von Post humification 5-6
2. well decomposed moss – approximate von Post humification 7-9
3. well decomposed moss, woody inclusions
4. desiccated, well decomposed moss – approximate von Post humification 4-5

Table 6. Pearson correlation coefficients and P-values for test of linearity between recorded hydraulic conductivity, K-test depth and distance from drain of test location.

Hydraulic conductivities	Test depth		Distance from drain	
	Correlation coefficient	P-value	Correlation coefficient	P-value
Disturbed test sites	-0.177	0.496	-0.245	0.343
Intact test sites	-0.376	0.029	0.179	0.310

Pearson product moment correlation coefficient indicates a strong negative correlation

(P-value = 0.029 i.e. there is only a 2.9% chance that test depth and K will not observe a

linear relationship) between sample depth and recorded hydraulic conductivities from test

performed at 'intact' sites.

Figure 25 a-g. Change in mean recorded hydraulic conductivity ($K\text{md}^{-1}$) over deepening test depths for five test locations including intact (transect 1: 25 and 135m from drain) and disturbed mire surface (transects A, B, C, transect 1: 5m from drain and transect 5: 5m from drain).

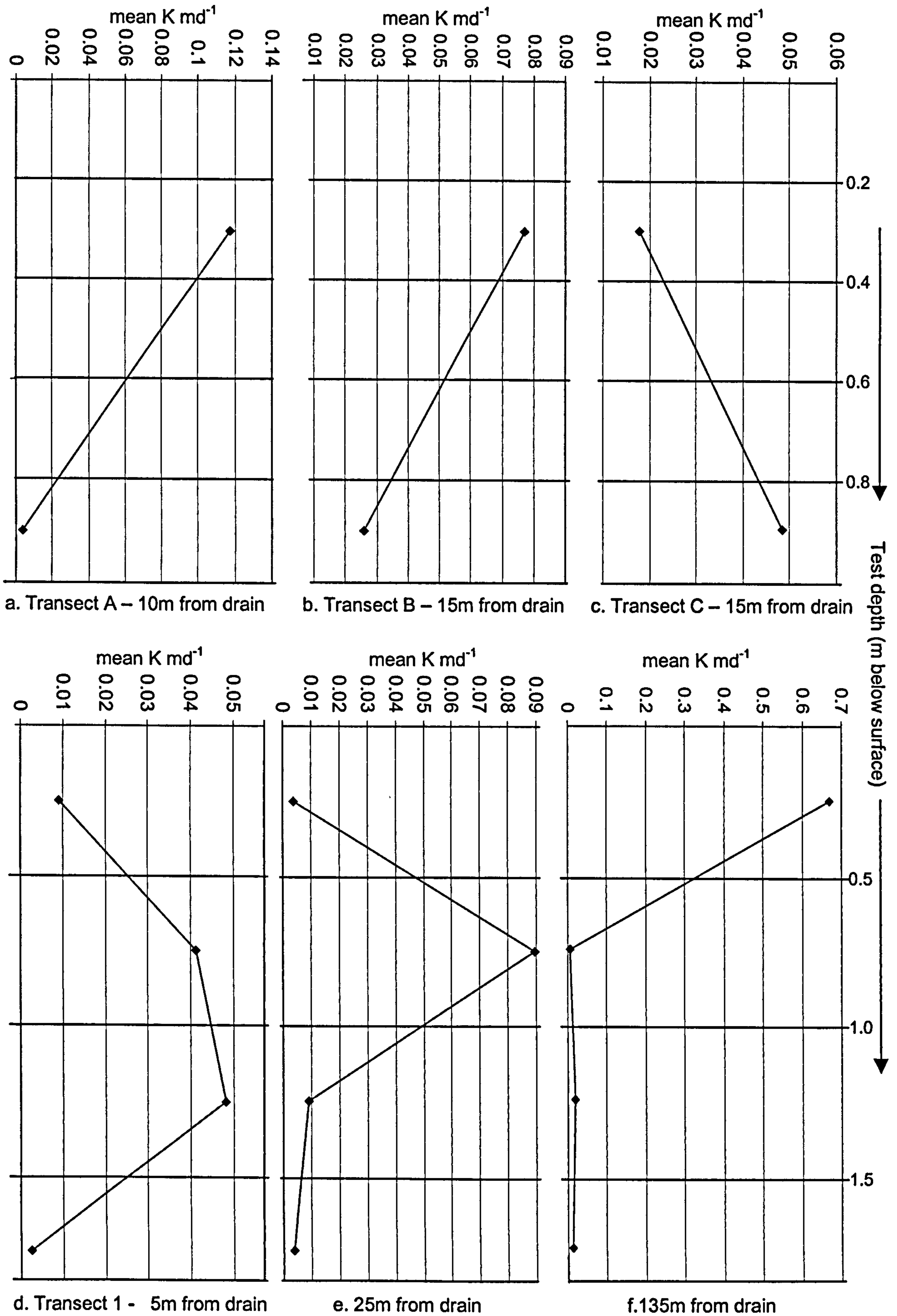
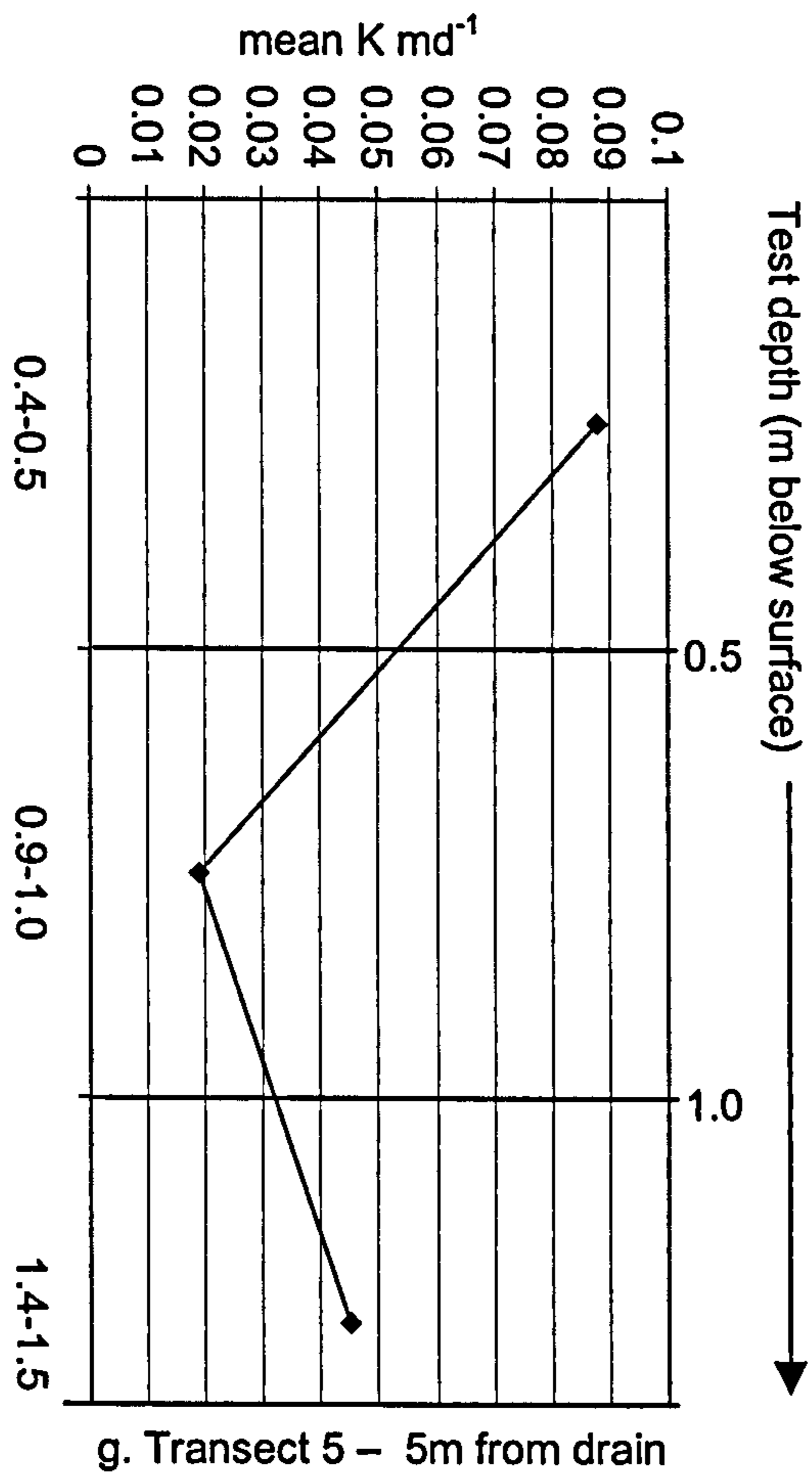


Figure 25 a-g. Continued



Discussion

Table 7 lists peat hydraulic conductivities recorded in the field in previous investigations at different sites, using the same piezometer method and Luthin-Kirkham justification as the Wedholme tests. In disturbed site transect A, recorded hydraulic conductivity at 0.3-5m depth (Table 5) is similar to that recorded by Boelter (1965) at the same depth in moss peat with woody inclusions and at a depth of 0.8m in herbaceous peat of moderate decomposition. The K-values recorded in transects B and C are of the same order of magnitude as Boelter's figures for woody, herbaceous and amorphous peats. Hydraulic conductivity recorded at 0.4-5m depth in the dehydrated and compacted peat of transect 5, 5m from the main drainage channel, is close to the sedge peat value recorded by Päivänen (1976) at 0.35m depth. The recorded K at these sites does not appear to follow an identifiable pattern (figure 25) and in test for linearity (Table 6) recorded conductivity was not correlated with depth of test or distance from drainage channel. Ideally more values are needed to confirm or dispute this pattern.

In general, the intact peats of transect 1 appear to decrease with depth (figure 25), although recorded K in the upper catotelm (0.5m deep) is anomalous. Recorded K was highly negatively correlated (P-value: 0.029) with depth for intact test locations (table 4). That is, a linear relationship exists between increasing depth and decreasing hydraulic conductivity at these locations. Insufficient data points are available to reveal any clear relationship between lowered watertable by proximity to drain channels and hydraulic conductivity. Tests performed at 135m from the blocked channel, in the central area of Newton Arlosh awards, exhibit a more typical scenario of conductivity, decreasing with depth, but exponentially higher in the uppermost layers (table 7: Päivänen, Boelter). Recorded K

here, at 0.5m depth, was close to the Päivänen figure for *Sphagnum* peat between 0.35-0.45m depth. Below this depth transect 1 recorded K-values were close to Boelter's values for amorphous peat.

Reported literature values of specific yield are limited and the calculated effective porosities in table 5 are dependent on the recorded K-values, however there are some similarities between Boelter's laboratory values for woody, herbaceous and amorphous peats at 0.5-0.8m depth and the calculated values for test sites of similar depths.

One reason for lower recorded K-values in disturbed sites at Wedholme compared to reported values from intact sites and apparent similarities between woody and herbaceous peats normally found at lower depths, is that the peat now occurring at the surface in disturbed sites is not within its natural accumulation sequence. It was previously submerged and has been compressed by overlying layers of moss peat subsequently removed during peat excavation. It cannot be compared directly to the upper layers of intact catotelm peat, or indeed to acrotelm peat of intact sites. It would be useful in future investigations to record the bulk density of peats from the sites of K-test to compare with adjacent surfaces, as an indication of previous level within the original mire structure.

Table 7. Previously reported hydraulic conductivity values for piezometer field tests (Luthin-Kirkham method) and specific yields (laboratory tests) where available.

	Peat description provided:	Depth (m)	K (md ⁻¹)	Sy
Boelter (1965)	Moss - undecomposed	0.15-0.25	32.91840	0.52
	Moss - undecomposed	0.45-0.55	0.89856	0.33
	Moss & woody inclusions – moderately decomposed	0.35-0.45	0.12010	0.22
	Woody - moderately decomposed	0.35-0.45	4.28544	0.27
	Woody - well decomposed	0.60-0.70	0.48211	0.19
	Herbaceous - moderately decomposed	0.70-0.80	0.00648	0.15
	Well decomposed [<i>presumably amorphous</i>]	0.50-0.60	0.00959	0.1
Ingram (1967)	Blanket bog – water track, amorphous	0.50	0.00017	
		1.00	0.00026	
	Mire expanse – pseudofibrous	0.50	0.00008	
		1.00	0.00005	
Sturges (1968)	Well decomposed [<i>presumably amorphous</i>]	0.46	0.00024	
		0.91	0.00016	
Irwin (1970)	Reclaimed	<i>no value</i>	1.55520	
Yamamoto (1970)	Undisturbed peat bog	<i>no value</i>	0.00864	
Dai & Sparling (1973)	Ombrotrophic <i>Sphagnum</i>	0.50	5.18400	
Päivänen (1973)	<i>Sphagnum</i>	0.25	2.63952	
	<i>Sphagnum</i>	0.35	0.56074	
	<i>Sphagnum</i>	0.45	0.49766	
	Sedge	0.25	1.27872	
	Sedge	0.35	0.14947	
	Sedge	0.45	1.51286	
	Woody	0.25	2.86589	
	Woody	0.35	2.61619	
	Woody	0.45	1.22429	

6.2 Acrotelm conductivity and storage potential

Calculating acrotelm storage coefficients from field data

Within the upper layer of the mire, the potentially high storage capacity of the acrotelm exerts a controlling mechanism over the transmission of water. The storage coefficient (S) of the acrotelm, given in Equation 4, may be estimated from fluctuations in the phreatic level following rainfall events¹ (for example figures 16, 18, 19 & 22). Again, the coefficient is determined by bulk soil properties including both peat and living vegetation in this case, and by both adjacent and localised heads increasing due to precipitation.

$$S = P / \Delta h$$

Equation 4

where P = total precipitation over the recording interval and Δh = change in phreatic level over the same period.

Recording the change in stored water by fluctuation in the watertable due to precipitation over a determined interval, where the watertable is permanently close to the surface is subject to several sources of error:

1. interception and evaporative losses;
2. storage in the unsaturated peat zone;
3. open water storage and lateral flow exacerbated by high phreatic level.

¹ See also Chapter 2 Section 3.1.3

Errors 1 and 2 are likely to increase in shorter recording intervals with lower precipitation. Error 3 will increase proportionally over longer periods with higher rainfall, when the watertable may reach the surface causing both overland flow and storage in temporary pools within the hummock-hollow network can occur. Where surface gradients are higher, overland flow will be accelerated with the potential for local preferential flows. An average of multiple estimates from different length monitoring intervals is preferable to reduce errors.

Storage coefficients within the acrotelm have been calculated at dipwell locations across the site. Within the intact mire surface of the southern lobe (transects 4 & 5) the storage coefficient could be calculated using precipitation data from the automatic weather station and watertable fluctuations recorded simultaneously in the automated dipwells. Storage coefficients for these locations were calculated from ten rainfall events of varying length and precipitation depth. In all other locations, only daily watertable data were available so that estimations here are coarser. Again the mean of ten storage coefficients, based on daily watertable records and daily rainfall totals calculated from weather station data were used.

Results

The dimensionless mean acrotelm storage coefficients estimated from daily watertable fluctuations and aggregated rainfall data for all ninety dipwell locations within both intact and disturbed mire surface are plotted in figure 26 relative to distance from the nearest drainage channel. A complete table of the plotted storage coefficient values is presented in Appendix II (table A2).

The mean acrotelm storage coefficients calculated from automated dipwell levels and rain gauge data (at 20-minute logging intervals) for dipwells 5.1-3, 5.6-7 and 4.1-5 are plotted in the bar chart, figure 27. For comparison, the storage coefficients calculated from daily data for the same wells are also included. Error bars represent the standard deviations from the presented means. A table of the storage coefficient values for logged wells versus the daily-calculated values for the same well is given in Appendix II (table A3). The Pearson correlation coefficients and P-values for calculated acrotelm storage coefficients from daily and automated dipwell readings, distance from drain of each dipwell and the peat depth at each dipwell location are given in Table 8.

Table 8. Pearson correlation coefficients and P-values for test of linearity between calculated acrotelm storage coefficients, from daily and automated dipwell readings, distance from drain of dipwell and total peat depth at dipwell location.

Storage coefficients	Distance from drain		Total peat depth	
Daily readings	0.423	0.000	0.269	0.012
Automated dipwell	0.938	0.000	0.754	0.012
	<i>Correlation coefficient</i>	<i>P-value</i>	<i>Correlation coefficient</i>	<i>P-value</i>

Figure 26 indicates a clear trend of increasing storage potential at increasing distances from drain channels. This is also apparent in figure 27, although not given as an axis, distance from the drain increases with dipwell number so that 5.1 is 2m from the main drain channel and 5.7 is 190m from the same channel in an undisturbed area of the southern lobe. This relationship is confirmed by the Pearson correlation coefficients and P-values (table 8), which indicate a very strong linear trend between increasing distance from drain and increasing storage potential.

Figure 26. Acrotelm storage coefficients calculated from daily rainfall totals and watertable fluctuations in all 90 dipwells (dimensionless).

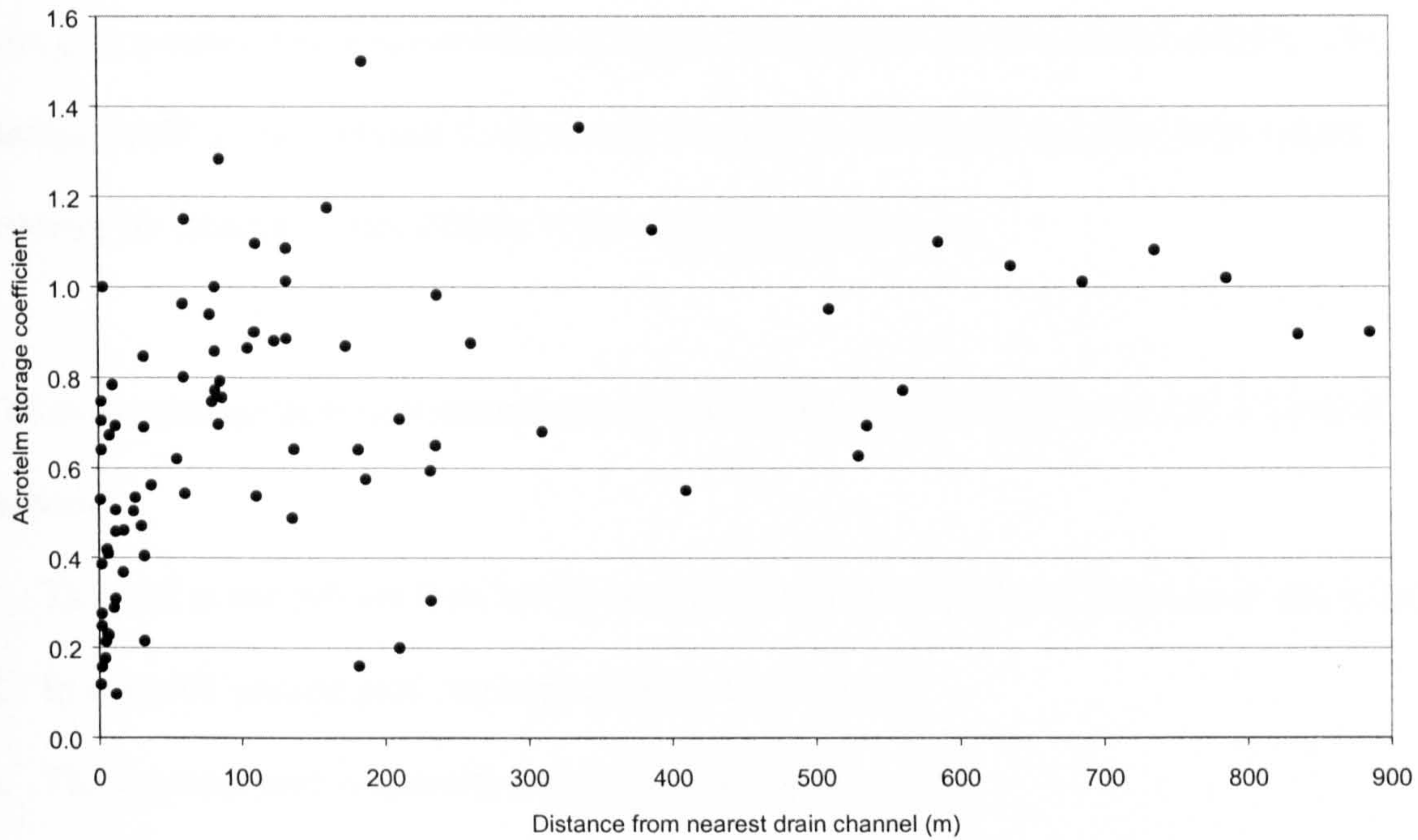
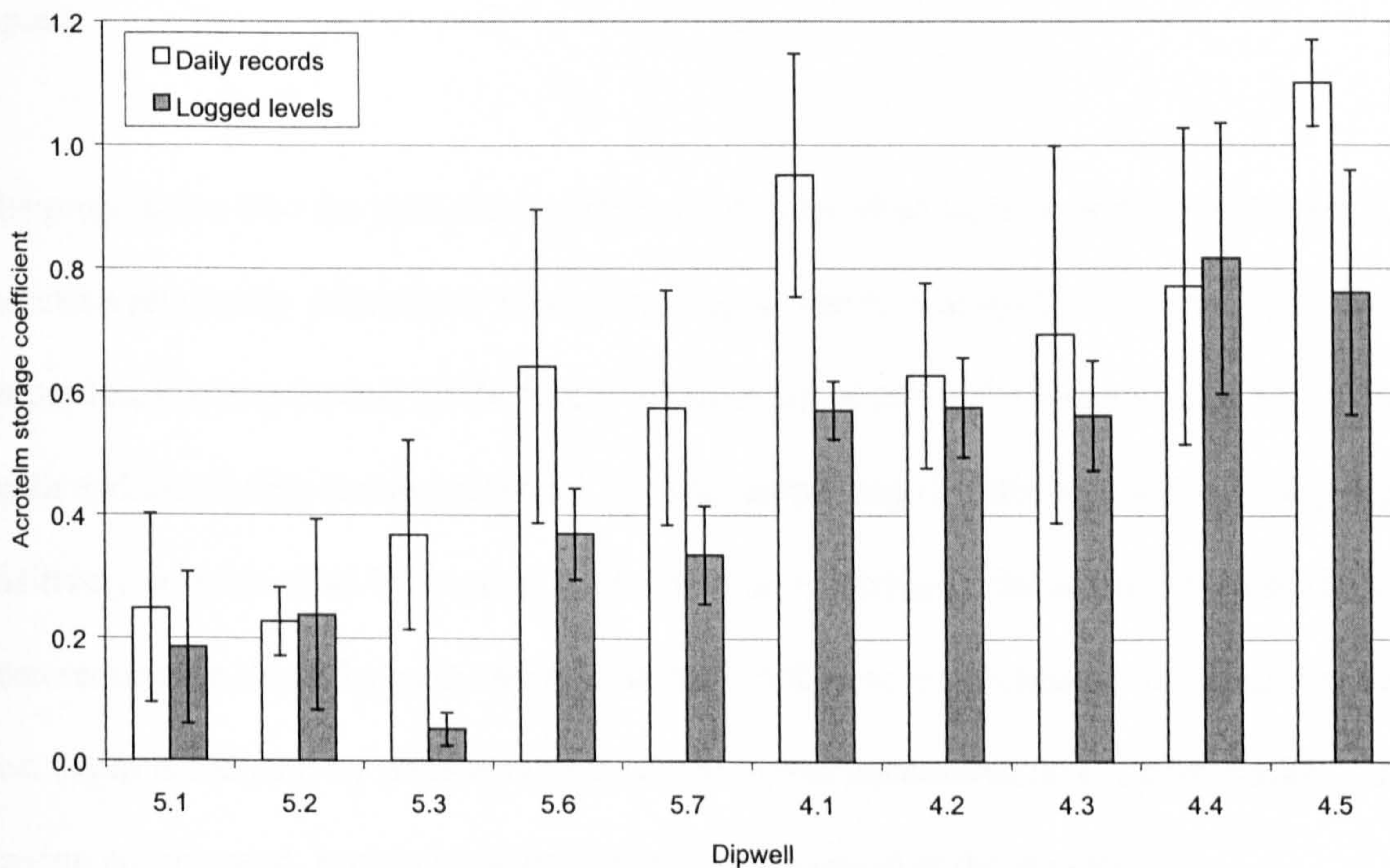


Figure 27. Comparative chart of mean acrotelm storage coefficients for dipwells 5.1-3, 5.5-6 and 4.1-5: calculated from daily rainfall and watertable fluctuations (clear bars) and 20-minute data logger records (filled bars) - error bars represent standard deviation from mean value in sample.



Discussion

Calculating the storage coefficients from both daily and short-term automatically logged data give similar results as indicated in figure 27, and both are considered reliable. The storage coefficients calculated in this way are very similar to the specific yield values reported by Boelter (1965) (Table 7) for undecomposed moss.

The lower storage potential recorded in the disturbed sites is likely to be due to several reasons:

1. The peat at the surface here has an increased bulk density being from lower catotelm;
2. In exposed aerated peat decomposition is accelerated;
3. The exposed peat is sparsely vegetated and easily eroded;
4. The eroded peat becomes easily dehydrated in dry periods and subsequent rewetting results in accelerated flows in the newly created macro pores.

As a result the watertable may rise rapidly in this degraded zone but it is likely to fall as rapidly.

The proposition that the peat at the surface of the disturbed mire is from the catotelm, and therefore physically different to newly forming acrotelm peat in structure and hydraulic properties, is compounded by the linear relationship observed between accumulated peat depth and increasing storage potential. It is not surprising that these factors are very highly positively correlated, as by its nature, the intact mire surface with active acrotelm has not been reduced in depth by peat removal. If this is taken to a conclusion, the accumulated peat depth is reduced by removal of the acrotelm and successive layers of catotelm peat, leaving compressed, poorly structured deep peat exposed at the surface.

The intact acrotelm clearly plays a critical role in the storage potential of the mire and the buffering of through flow during rainfall events.

7. Ground level change and potential subsidence at Wedholme

During the most recent hydrological investigation at Wedholme (Section 5.3), ground surface and well-top levels were surveyed and previous levels were resurveyed across the site. English Nature had surveyed the Newton Arlosh Awards area previously in 1990, with levels taken from a false datum at the edge of the mire (4.3.1).

Figure 28 shows the ground surface surveyed in 1990, with the peat dome to the north of the then active main drain and the newly abandoned cutting face with a ridge-cutting pattern to the south.

Figure 29 illustrates the 2000 survey ground level across transect 1. The vertical scale of both the y-axes exaggerate the surface gradient. Despite this, the 2000 survey shows a distinct slope to the south toward the cutting face, over land made relatively flat during previous peat removal activities.

It was considered useful to try to relate watertables and mire surface in the early 1990's to current levels, given that peat cutting has continued over the last decade in the adjacent area. This required levels to be related to a common datum. Unfortunately the temporary benchmark used in the original 1990 survey could not be relocated, and so it was necessary to find a fixed feature within the Awards that could be resurveyed. During the early monitoring scheme, peat anchors¹ were installed across the northern area and were levelled to the false datum. These were re-levelled in the 2000 manual survey, and the difference calculated. With a small error, the differences between the two sets of levels were

¹ Chapter 2, Section 3.1.1

considered an acceptable correction factor, and the 1990 levels were converted to metres above ordnance datum.

Figure 30 combines the corrected 1990 levels with the surveyed 2000 surface. If the survey is accurate, the dome of the 'intact' region of the Newton Arlosh Awards has subsided considerably. Some reduction in surface elevation may be due to summer dehydration (*mooratamung* or mire breathing, Ingram, 1983), but the apparent change in shape of the dome, particularly between 80 and 210m from the drain, is consistent with slumping in a low watertable zone. In figure 23k, the watertable recorded during the period 6/10/00-3/11/00 was plotted relative to ordnance datum. In the area where slumping is apparent, between 150-220m from the drain channel, the watertable is consistently up to 0.1m below the ground surface. To the south of this point and to the north beyond 220m from the drain, the watertable remains at or above ground surface throughout the monitoring period. Slumping also appears to have occurred on the 'shoulder' of the dome, up to 80m from the drain channel. Along the 'intact' transect subsidence of up to 0.3m, or nearly 5% of the 1990 surveyed peat depth appears to have occurred. Figure 23l shows that although the drain had been blocked for almost a decade, it is still exerting a draw-down influence on the adjacent watertable. This may have a very limited zone of influence, and does not explain apparent slumping beyond the watershed of the central dome, but it is still clearly a sink.

Beyond the drain to the south, slumping is also apparent. The lateral extent of corrected transect levels is limited by the position of accessible peat anchors, however within the 110m of transect which have been adjusted to ordnance datum there appears to be a maximum fall of 0.2m in the surface level. It is not inconceivable that continued peat

removal in the active cutting area 460m to the south, over the last decade, could have resulted in slumping of this magnitude. There are no available data on the 1990 and 2000 surface levels in the active peat cutting area, but it is likely that the continued removal of peat from the surface will have been accelerated by improved milling techniques and therefore the surface will have been lowered over the last 10 years.

Figure 31 illustrates the current surface level and the recorded peat base across the Newton Arlosh Awards and adjacent abandoned cuttings using the 2000 survey data only. This indicates a fall of more than 3m from the dome to the active cutting face. The depth of the peat across the transect also reduces from 7m at the peak of the dome to 1.2m at 1m from the boundary drain of the cutting face. If peat-cutting operations continue to the south of Newton Arlosh Awards then it is likely that this gradient will increase, further contributing to water loss and dehydration of the area.

Further investigation into apparent subsidence of the mire surface is necessary to validate the survey data, with more detailed re-survey and confirmation of the 1990 levels. Some natural re-establishment of surface gradients will occur where over-steepening of mire areas has resulted from peat removal. However, the implications of ground level change of this magnitude are extremely serious for both the remaining intact mire and regenerating areas, and for flow processes within the entire mire catchment.

Figure 28. Surveyed Ground Surface, 1990, Transect 1, dipwells N13-S13 (m above false datum).

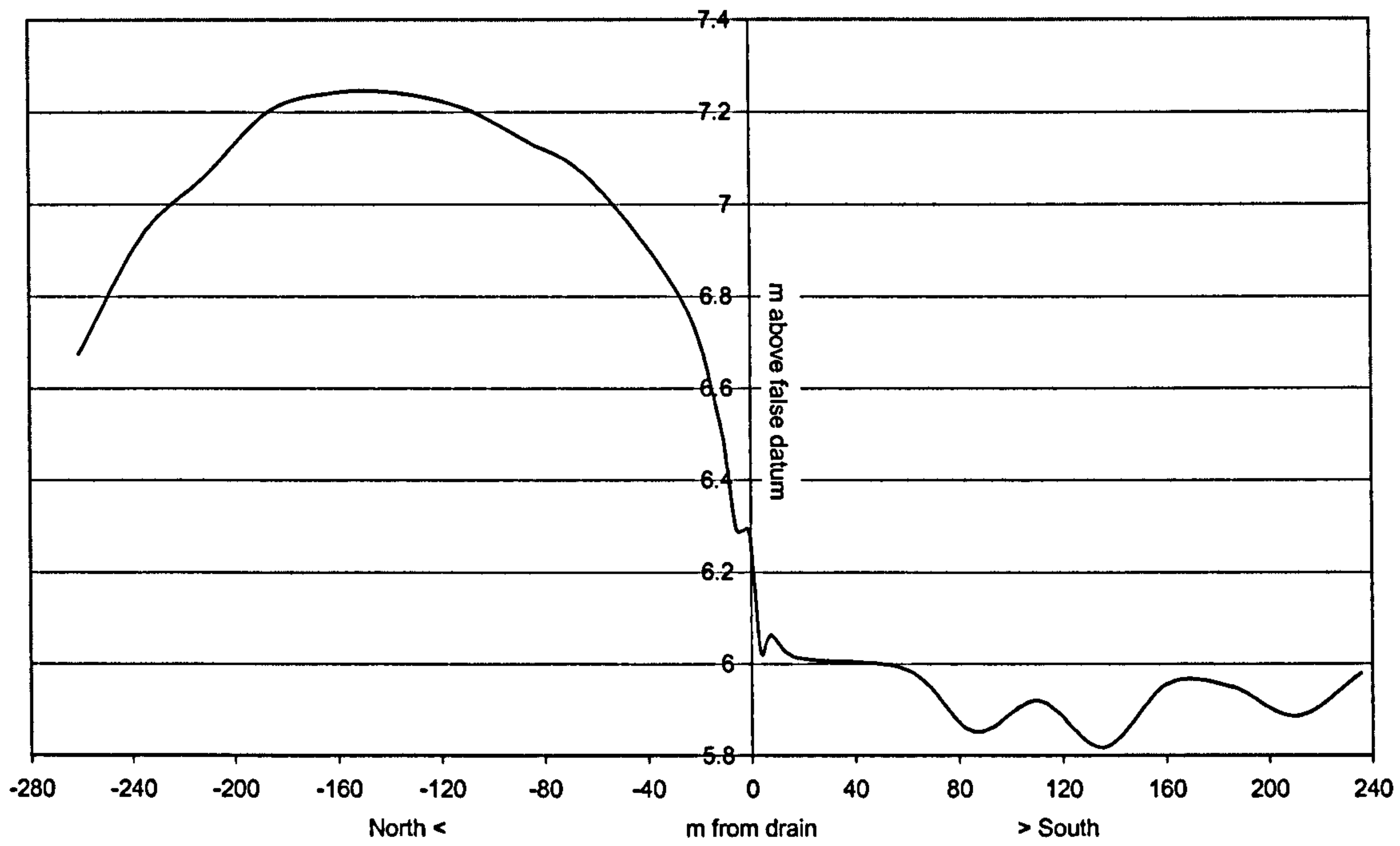


Figure 29. Surveyed Ground Surface, 2000, Transect 1, dipwells N13-S13 (m above ordnance datum).

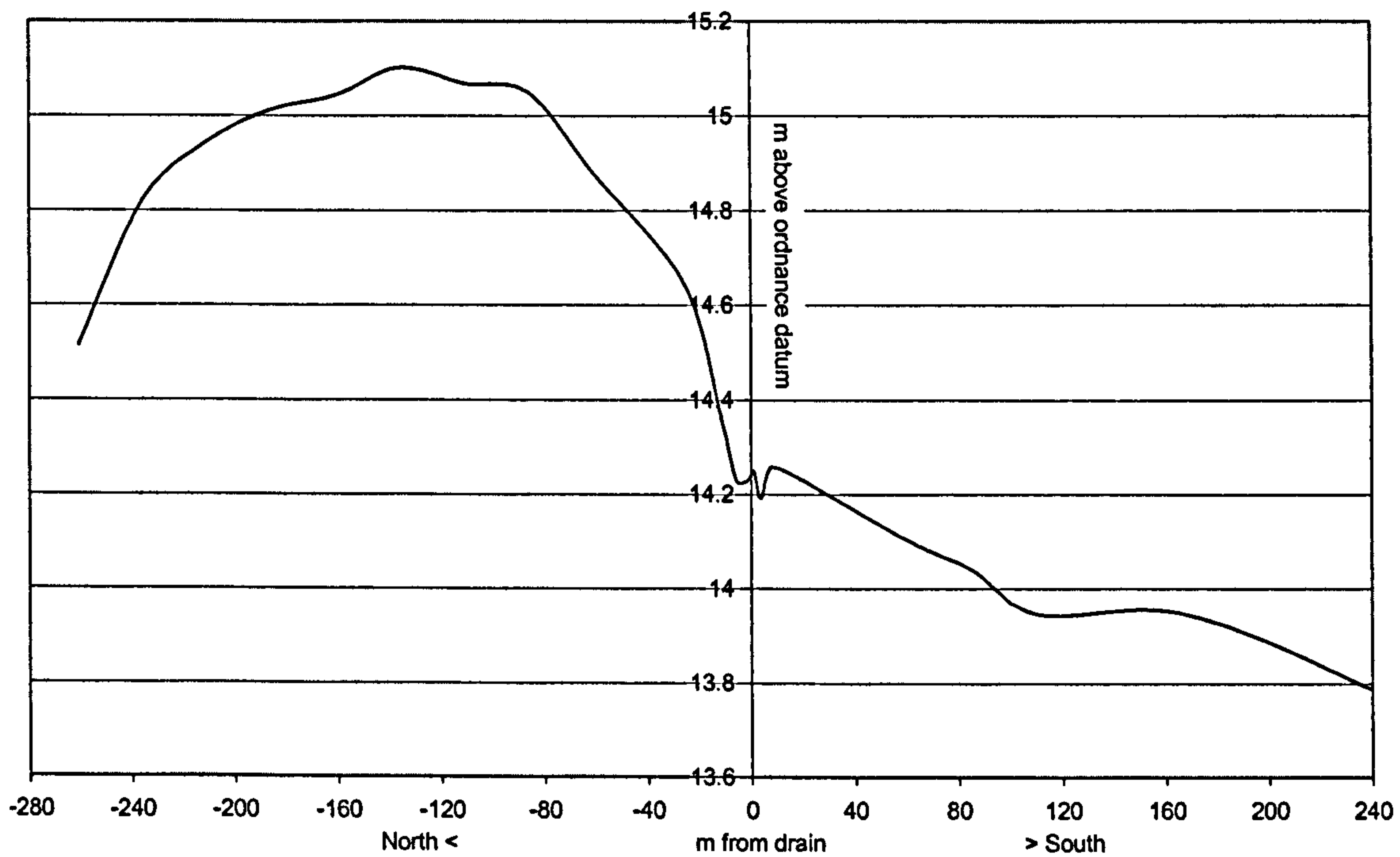


Figure 30. Newton Arlosh Awards surveyed ground surface levels, 2000, and adjusted 1990 ground surface levels (m above ordnance datum).

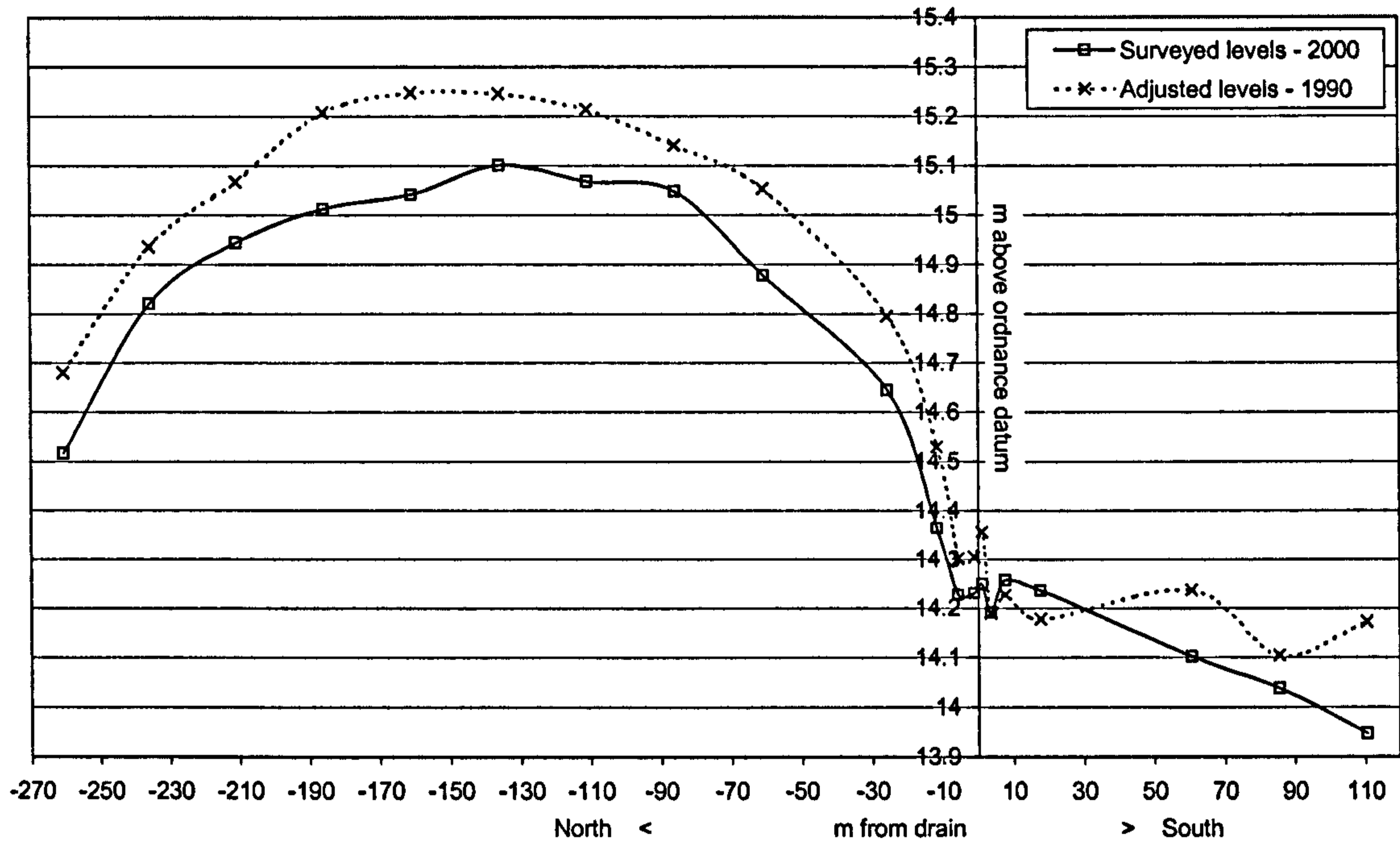
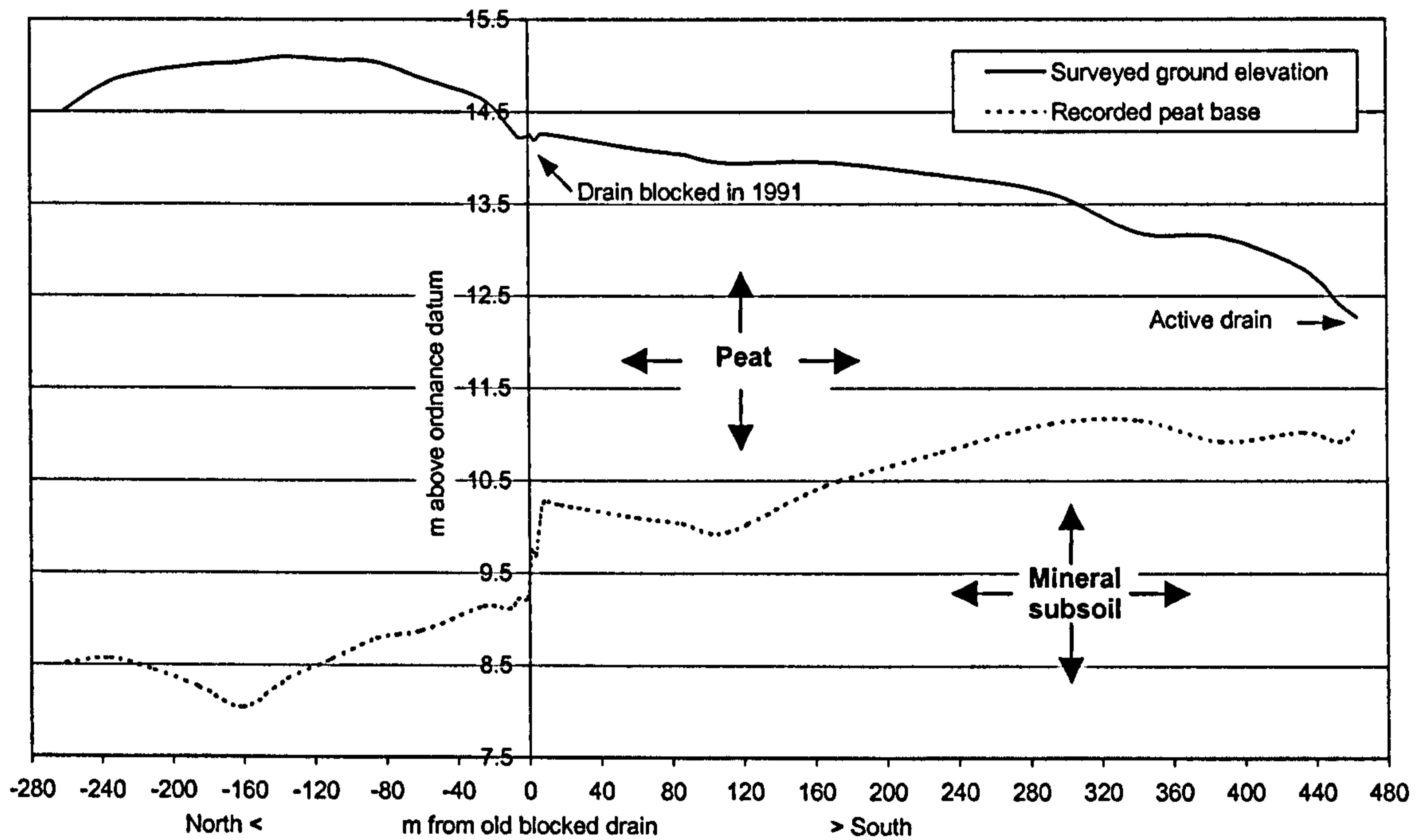


Figure 31. Transect 1 and A1, 2000 surface level and recorded peat base (m above ordnance datum).



8. Discussion and Conclusions

This study was introduced with the observation made by Verry *et al* (1988), that intact mires respond to recharge in a similar way to unregulated reservoirs. It was not feasible to test this assumption at Wedholme by recording streamflow, however from examination of watertable fluctuation, recorded in both intact and disturbed zones, the mire appears to act much like a reservoir at or close to capacity. Long-term dipwell records (Section 5.1) reveal a watertable at or close to the surface of the intact Newton Arlosh peat dome over a six-year period, including the 10-year drought of 1995 (figure 9). The same can be said for the adjacent abandoned cuttings in the post-drain blocking period. Given that the peat hydraulic conductivity recorded at this intact site was so low (0.01-0.1m/d from surface to 1m deep) (Section 6.1), it is likely that a significant proportion of recharge will not enter the peat to instigate sub-surface exchange in storage and form the delayed flow portion of the storm hydrograph. Instead it will remain above ground forcing rapid surface run-off and near-surface exchange, forming a quick-flow response from the site. Fojt's (1983) investigation of the ecohydrology of Gors Goch, Mid Wales, discriminated between two types of hydrograph response: *true peaks* 'represent a maximum watertable maintained for a short period' during which rapid 'near surface saturated exchange divert further groundwater increases towards the runoff stream'; *flattened peaks* were observed when the hydrograph formed an extended plateau which 'most often occurs when the watertable emerges at the surface' and 'inputs equal outputs'. The falling limb of the hydrograph is governed by 'the propensity of the peat to release moisture'.

Where local topography confines potential run-off, surface water will accumulate. This process is observed in the abandoned cutting intersected by transect 1. The generally low

surface gradient and locally uneven topography created by past peat cutting practices, results in the impounding of surface water following the prevention of artificial drainage by blocking and damming the channels. This cutover area has effectively become a reservoir.

The abandoned cutting area of transect 1 corresponds to area A (figure 8), of the intensive study area described in Section 5.3. Comparison of transects installed in area A with those in area B, to the west of the active cutting fields, reveals a much more irregular surface pattern at B, with some obvious pool features. However, with the exception of the immediate area of these pools, area B is both drier in general, and has a more rapidly fluctuating watertable. Both areas have locally steep surface gradients adjacent to the boundary drain and active cutting face ($A = 1:66$, $B = 1:80$), while the extended A transects cover a slightly steeper surface than those at B ($A = 1:110-1:130$, $B = 1:120-1:385$). The hydraulic gradients across both areas are clearly orientated towards the cutting area. Peat removal in area A has been more extensive than at B, so that it may be anticipated the deeper and more intact mire at B would have remained wetter than the heavily exploited A. However monitoring in both areas (Section 5.3) confirmed anecdotal evidence that area A is actually much wetter. Alternative explanations for the dehydration of area B include subsurface factors that cannot be easily observed such as contiguous subsurface weaknesses allowing preferential discharge – the ‘peat-pipes’ observed by Holden (2000) in North Pennine blanket peat - and differences in the pattern of disturbance. The dry ridge–wet cutting surface pattern and similarities in the regularity of watertable fluctuations compared to the other areas, do not point specifically to preferential subsurface flow at B. Therefore it is more likely that the pattern of disturbance, in particular the orientation of the abandoned cuttings down slope towards the active cutting

area, which explains the apparent dehydration at B. There is no doubt that this will increase runoff in the low-lying areas where surface water has been seen to accumulate (figure 23), and where erosion features have been observed in the field. Fojt (1983) also observed erosion features at Gors Goch, and identified such erosion and subsidence due to dehydration as the main threats to the upland mire.

The hydrology of the abandoned cutting areas are in stark contrast to the stability of the intact mire, which barely fluctuates throughout the year, the exception of extreme storm events that produce surface water and must result in overland flow. This response was examined in detail in the intensive monitoring program described in Section 5.2, where the watertable response to rainfall was recorded on weekly basis in transect bisecting the southern lobe and a 20-minute basis in selected wells, over a three-year period. The weekly dipwell readings from the intersecting transects 4 and 5, crossing the intact southern lobe indicate very little seasonal fluctuation. Watertable readings show that all wells more than 50m from the boundary drain fluctuated less than 11cm during the entire monitoring period (figure 17). The records also indicate that during this period the watertable was at or above the mire surface for the majority of transect 4 and a large portion of transect 5. The wells within 50m of the boundary drain channel have a deeper watertable (up to 0.7m below ground) and fluctuate more in response to rainfall (up to 0.5m annually), reflecting both greater through-flow and draw-down influence of the drain itself (figure 16). This corresponds to the fluctuation observed by van de Schaaf (1999) at Raheenmore and Clara Bog, where the watertable in the central areas had a maximum fluctuation of 0.2m rising to 0.5m in marginal and disturbed areas. The almost instantaneous response of the watertable recorded using pressure transducers at Wedholme confirms this pattern and indicates that dipwell water levels in the southern lobe influenced by drainage can be clearly identified

(figure 18). Again, away from the drain, the combination of low hydraulic conductivity (Section 6.1), lack of fluctuation and a watertable position at the surface indicates near surface processes and runoff must account for the redistribution of recharge (Section 6.2). Fojt (1983) observed a similar response to recharge in areas of differential disturbance at Gors Goch. The maximum watertable response to rainfall was recorded in the disturbed areas (specifically the areas 'eroded' and 'front') with a hydrograph characterised by 'peaks', whilst the watertable fluctuation in intact areas (referred to as 'back acid' and 'back carex') was much reduced and produced 'plateau' hydrographs. This was explained by wetter antecedent conditions and a lower available storage capacity that was 'quickly exhausted' during recharge, producing prolonged near surface and overland flow.

Once the watertable has reached the surface and effective 'overflow' has been instigated, further rise cannot be easily recorded, and although water may continue to pond at the surface, runoff will be instigated but not recorded. This was a feature of acrotelm monitoring at Trough End (Chapters 5 and 6). In the disturbed location dipwells of Wedholme, especially those in dry ridge features, the antecedent watertable is likely to be so low that it is possible to record continuous rise in responses to rainfall for some time before storage potential is exceeded.

Fine temporal scale monitoring of water levels also highlights the contribution of evapotranspiration to the water balance. The diurnal fluctuations observed during dry periods (figures 20 & 21) indicate a watertable fall of up to 1cm in 24 hours (similar to that recorded by Fojt, (1983)). Potential evapotranspiration estimates for the mire, calculated for early summer, range from approximately 0.15cm to 0.25 cm per day and so could not account for the entire observed fall in water table for such a period. The fall may also be

due to redistribution of water stored in the peat matrix. Hydraulic conductivities recorded in the intact mire below 0.5m (figure 25f) are around ten times smaller than this fall, so that any redistribution is likely to occur above this depth where conductivities of up to 70cm per day were recorded.

Redistribution of recharge at the site, whether as surface water flow or subsurface exchange is certainly influenced by the mire form and slope of the existing surface. The surface gradient is much steeper in the abandoned cuttings (1:110-1:385 in A & B) than in the intact mire (1:2500 in the southern lobe). As the watertable remains close to the surface along the transects observed, it follows that the hydraulic gradient will be of a similar order, so that according to the Darcy equation, potential discharge will be greatly increased in the abandoned cuttings. This difference in water holding capacity of intact versus disturbed mire goes some way to accounting for the disparity in wetness of sites receiving equivalent recharge.

The aim of restoration is to return abandoned peat cuttings and drained areas to a similar condition to that of the intact mire. In most simple terms this is achieved by attempting to make the disturbed area as continuously wet as is possible to halt the general trend of dehydration of the mire instigated by drainage and peat removal. If this can be reversed it is supposed that vegetation communities approaching those of the intact mire will become established, and eventually peat formation will recommence. The initial exploratory survey of Wedholme vegetation assemblages, carried out to identify different levels of disturbance and regeneration revealed distinct zones. These were confirmed when species were grouped according to the National Vegetation Classification (NVC) of mire communities described by Rodwell (1991). The almost flat intact area of the southern lobe emerged

effectively as a mire plateau, in the form described by van der Molen (1992), as found in Irish raised mires. In this area the hummock-hollow complexes (M18) with clear microtopographical differentiation of *Sphagnum* species were interspersed with wet hollows (M2b) where the microtopographical range was less well defined. These assemblages can be identified as the 'target' vegetation communities for mire restoration. They are found at Wedholme in a typically stable hydrological environment, with a permanently high watertable, limited fluctuation and low hydraulic gradient. Similar communities were found to be characteristic of intact mire areas of Raheenmore and Clara Bog by van der Schaaf (1999) The contrast in hydrology of the abandoned cutting areas produces two distinct vegetation types. Firstly dry heath communities (H1, H9) typical of free draining sites and distinguished by the extent of the *Calluna* canopy and diversity of additional ericoid shrubs, occasional grasses and sedges. Van der Schaaf (1999) also describes '*Calluna vulgaris* dominated margin sites with deep phreatic levels and large fluctuations'. At Wedholme, the other extreme of the disturbed site hydrology, the deep pools created in the blocked drainage channels have been colonised by *Sphagnum cuspidatum*, in some cases by propagation, creating M2 bog pools.

The communities surveyed in the 'regenerating' cutover mire, whilst sharing some species, are quite different to those found at the intact sites. Whilst a great deal has been achieved in the colonisation of large abandoned cutting areas, it is doubtful given the existing hydrological differences, that many of the regenerating areas can form the target communities. The intermediate zones between abandoned peat cuttings and intact mire, where only preliminary drainage was instigated show more promise, and have largely returned to the target communities, as observed in the upper region of transect C. Some isolated areas within the extensive abandoned cuttings have maintained poor raised mire

(M19) and blanket bog (M20) communities, in many cases occurring on the ridges between cuttings. These areas offer hope for the improvement of the surrounding cuttings if wetness can be maintained through the dry periods, which otherwise benefit heath communities. The key differences between these areas have to be the speed of water removal and the potential for removal created by both structural weakness in the remnant peats, and the relatively high surface and hydraulic gradients. In the remaining bare peat areas there is clear evidence of surface water flow with obvious erosion features. The combination of exposed low conductivity catotelm peat and locally high surface gradients must exacerbate runoff and will prevent the establishment of all but the least desirable vegetation species (such as *Molinia caerulea*). These factors must be controlled or removed if the chances of mire regeneration in these most disturbed areas are to improve. In many cases, such as the reversal of subsidence, this is likely to involve considerable input and expense.

Topographical survey data suggests that the 'intact' surface of the Newton Arlosh Awards has subsided by up to 0.3m over the last decade, equivalent to nearly 5% of the 1991-surveyed peat depth. It has been stated that confirmation of the survey data is critical to future management of this area, however according to data presented by van der Molen (1975), Egglesmann (in van der Schaaf, 1999) and van der Schaaf (1999), this is not an unprecedented fall. In 'thick peat layers' van der Molen (1975), observed subsidence due to mire drainage of 0.5-1m within 10 years. Although the drain bounding the Awards and adjacent abandoned cutting was blocked in 1992, watertable records show it is still effectively acting as a sink. (Section 5.1). Schothorst (1982) reported high levels of shrinkage in the upper layer of cultivated Dutch peatlands, with watertable lowering by drainage of around 0.5m resulting in subsidence of 1.4m over ten years. In grazed fen peats with watertables at 0.2m below ground, Schothorst reported a subsidence rate of 0.002m a

year and 0.005m/year where the watertable was between 0.05-1m below ground.

Eggesmann (cited in van der Schaaf, 1999) gives subsidence values of 20-35% of the original peat thickness from a range of German sites. Recent levelling data (1982-1991) reported by van der Schaaf (1999) for Clara bog, in the Irish Midlands, a site with many similarities to Wedholme Flow, indicates a differential rate of subsidence between central mire (Clara West) and marginal areas (Clara East) of 0.015m/year and 0.04m/year respectively. At a maximum of 0.3m in areas of lowest watertable, the apparent subsidence of the Newton Arlosh Awards falls well within the reported range for similar sites. This must not be dismissed as a survey error and should be prioritised in any further research program at the site.

In conclusion:

- ♦ The intact areas of Wedholme react to recharge in a similar manner to an overflowing reservoir, produced by a moderated quick-flow process within the mire acrotelm. This was confirmed by dipwell records.
- ♦ The role of the acrotelm is critical to both storage and quick-flow in the intact mire.
- ♦ The acrotelm is largely absent from the disturbed zone and flow processes here are much more localised.
- ♦ Some form of acrotelm, either natural or artificial must be established before mire function can begin, with peat formation and the associated vegetation.
- ♦ Shrinkage and cracking features are present in the disturbed areas adjacent to current peat cutting face and indicate structural weakness in the peat.
- ♦ Exposure of low conductivity catotelm peat and artificially high gradients have resulted in erosive overland flow in the abandoned cutting areas, particularly close to the boundary

drain. Regeneration of these highly disturbed areas can only be successful with reversal of these processes. This would entail intervention to reduce the gradient and limit overland flow, potentially by re-profiling and bunding.

- ♦ Water loss to the cutting area must be reduced in order for desirable vegetation communities to establish.
- ♦ Continued peat extraction and associated intensive drainage of adjacent areas can only exacerbate water loss and mire dehydration.
- ♦ The observed potential subsidence of the mire surface, both intact and disturbed, has serious consequences for both restoration and catchment management.

The data collected throughout this monitoring program have been employed in a hydrological model for the site. Chapter 4 describes this process.

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List of Vegetation Surveyed at Wedholme Flow.**Sub-shrubs/trees/other:**

Andromeda polifolia
Betula nana
Calluna vulgaris
Chamaenerion angustifolium
Drosera anglica
Drosera rotundifolia
Erica tetralix
Lotus pedunculatus
Myrica gale
Narthecium ossifragum
Potentilla erecta
Pteridium aquilinum
Rubus fruticosus
Rumex acetosa
Stellaria holostea
Vaccinium oxycoccus

Grasses:

Agrostis capillaris
Anthoxanthum odoratum
Holcus mollis
Molinia caerulea

Bryophytes:

Atrichum crispum
Cladonia ciliata
Cladonia coccifera
Cladonia fimbriata
Cladonia furcata
Cladonia portentosa
Cladonia - other
Hypnum jutlanticum
Liverwort Spp.
Sphagnum capillifolium
Sphagnum cuspidatum
Sphagnum magellanicum
Sphagnum palustre
Sphagnum papillosum
Sphagnum recurvum
Sphagnum rubellum
Sphagnum tenellum

Sedges/Rushes:

Eriophorum angustifolium
Eriophorum vaginatum
Juncus effusus
Rhynchospora alba

Table A.1. Goodness-of-fit (%) to predetermined NVC communities calculated using TABLEFIT

Quadrat number	NVC community															
	H1b	H1e	H9c	H9e	M2	M2b	M18	M18a	M18b	M19	M20	M20a	M20b	M25	M25a	M25b
5.1														60	44	64
5.2														69	63	67
5.3														80	70	77
5.4	60	83	64	60												
5.5					55	58		52								
5.6					58	56		73								
5.7					59	63		52								
5.8					62	70		62								
5.9					56	51		71								
5.10							70	79	59							
5.11					63		71	75	63							
4.1							50	65	43							
4.2							52	64		57						
4.3					64		60	74	47							
4.4					61	61	85	92	69							
4.5							72	70	61							
4.6					65	65		61								
4.7					73	75	78	83	66							
4.8						61	73	76	64							
4.9						59	75	82	63							
A	48	59	51	62	54											
B		70	60	74												
C	51	57	53							54	55	49	45			
D		54	49								50		47			
E	39						60	73	52	52						
F							76	83	60	51						
G					72		73	86	63							

Table A.2. Mean acrotelm storage coefficients calculated from daily data of dipwell water level fluctuations following rainfall.

Dipwell	Storage coefficient	Dipwell	Storage coefficient	Dipwell	Storage coefficient	Dipwell	Storage coefficient	Dipwell	Storage coefficient	Dipwell	Storage coefficient	Dipwell	Storage coefficient
N13	0.876	A1.1	0.157	B1.0	0.409	C1	0.276	5.1	0.248				
N12	0.650	A1.2	0.096	B1.1	0.747	C2	0.783	5.2	0.227				
N11	0.708	A1.3	0.214	B1.2	0.505	C3	0.800	5.3	0.367				
N10	1.500	A1.4	0.938	B1.3	0.846	C4	0.900	5.4	0.561				
N9	1.176	A1.5	0.880	B1.4	0.857	C5	0.199	5.5	0.755				
N8	0.487	A1.6	0.868	B1.5	1.013	C6	0.680	5.6	0.641				
N7	0.537	A2.1	0.176	B1.6	0.641	C7	0.550	5.7	0.574				
N6	0.791	A2.2	0.289	B1.7	0.305	4.1	0.951	5.8	0.981				
N5	0.542	A2.3	0.503	B2.0	0.230	4.2	0.627	5.10	1.353				
N4	0.533	A2.4	0.962	B2.1	0.385	4.3	0.693	5.11	1.127				
N3	0.309	A2.5	0.696	B2.2	0.692	4.4	0.771						
N2	0.418	A2.6	0.900	B2.3	0.403	4.5	1.100						
N1	0.529	A3.1	0.640	B2.4	0.770	4.6	1.047						
S1	0.118	A3.3	0.470	B2.5	0.886	4.7	1.012						
S2	1.000	A3.4	0.620	B2.7	0.593	4.8	1.082						
S3	0.672	A3.5	0.746	B3.0	0.213	4.9	1.019						
S4	0.460	A3.6	0.864	B3.1	0.705	4.10	0.894						
S6	1.150			B3.2	0.457	4.11	0.900						
S7	1.283			B3.3	0.690								
S8	1.096			B3.4	1.000								
				B3.5	1.086								
				B3.6	0.160								

Table A 3. Comparison of mean acrotelm storage coefficients calculated from both daily manual records and logged dipwell water level fluctuations with rainfall and water level recorded at 20-minute intervals. A minimum of ten periods was used to obtain the each mean value.

Dipwell	Daily records	Logged levels
5.1	0.248	0.184252
5.2	0.227	0.238164
5.3	0.367	0.05177
5.6	0.641	0.369747
5.7	0.574	0.335588
4.1	0.951	0.570404
4.2	0.627	0.575421
4.3	0.693	0.561984
4.4	0.771	0.816317
4.5	1.100	0.761355

**Chapter 4. Modelling hydrological processes in a lowland raised mire:
implications for restoration management.**

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Modelling hydrological processes in a lowland raised mire: implications for restoration management.

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Abstract

Mire restoration management relies largely on the manipulation of groundwater levels - in practice drain blocking. In many cases understanding of hydrological fluxes within the system may be limited and so the outcome of water level management both for acrotelm (near surface) hydrology and adjacent land use may be uncertain. Clearly the ability to predict the potential impacts of hydrological manipulation, not apparent in the short term, would be an advantage to site managers particularly where adjacent sites are subject to conflicting management practices such as conservation and peat cutting. This requires site data at a range of temporal and spatial scales, and a model capable of reproducing site hydrological behaviour to a good degree of accuracy.

The hydrological practices generally applied in mire restoration management are outlined and several hydrological models previously applied to mire systems are considered, including the 3-D groundwater model, MODFLOW (USGS). The applicability of MODFLOW to raised mire hydrology is tested using hydrological, meteorological and topographical data collected from the field site, Wedholme Flow (SSSI, NNR, cSAC), a lowland raised mire nature reserve in NW Cumbria, subject to both restoration management and peat mining. It is established that the model outputs provide a good fit (>95%) to observed hydraulic heads from both intact and cut over mire areas. The model is then applied to two areas of mire, both adjacent to an active peat cutting face but each exhibiting a different response to re-wetting practices. The implications of model simulations for mire restoration of different cutting regimes and management scenarios are examined.

1. Introduction

Within the UK peatlands cover more than 1.5 million hectares or 6.5% of the total area, of which raised mires represent a small portion (Taylor, 1983). Despite their proportionally small surface area within the UK, mires influence flow patterns in the catchments of most major British rivers (Burt et al., 1990). Raised mires are largely terrestrial ecosystems (although they may contain areas of open water) in which high watertables maintain an anaerobic environment close to the surface allowing partially decomposed plant material to accumulate. As this material (peat) accumulates over time the surface of the mire is raised following the convex watertable. The gradient of the watertable steepens towards the edge of the mire as recharge to the high porosity, low conductivity peat continues over time. The large volumes of peat contained in mires provide an easily extractable and extensively exploited carbon source utilised as a fuel and a horticultural substrate. Estimates of the remaining UK mire area vary widely though all indicate a severe decline in functional mires. Joosten and Clarke (2001) estimate that in the UK existing mires represent only 10% of their former extent. The National Peat Resource Inventory (NPRI) states that 6% of near natural, primary raised bog remains of an original 70,000ha (Lindsay & Immirzi, 1996). The Royal Society for Nature Conservation estimate that only 5% of the 1850 total of 85,000 ha remain intact (RNSC, 1990). Whilst raised mires are now widely recognised as a valued habitat for many threatened species of flora and fauna, they are themselves in severe decline.

The recognition of the ecological value of wetlands around the world, along with the designation and protection of 1060 sites under the Ramsar Convention, of which 35% are peatlands (current to April 2001), has led to extensive 'restoration programs'. Raised mire restoration management practices have relied largely on the crude manipulation of ground water levels. The imposition of a high ground water level by drain blocking, effectively impounding water in some areas whilst reducing inputs to others, is in many cases undertaken with inadequate understanding of hydrological fluxes within the system. In most cases the frequency and depth of open water features increases with drain blocking (MacAlister & Parkin, 1998)¹. Primary data collection may include periodic monitoring of groundwater levels (within the *catotelm*) but in most cases very little is known about near surface hydrology within the ecologically active, periodically aerobic zone or (the *acrotelm*). The

¹ Chapter 1

recharge-discharge function of the system is rarely investigated. Whilst many intensive and often expensive 'wetland restoration' programs are motivated by ecological concerns they may result in widespread and potentially unforeseen consequences for wetland ecosystem dynamics.

In many cases, mire sites managed for conservation purposes are also adjacent to actively drained areas such as peat cutting faces, which are essentially peat quarries. The continued existence and hydrological function of mires depend on the maintenance of a positive water balance. The foremost hydrological features and contributing functions of both ombrotrophic mires in a natural state and mires that have been disturbed by peat mining are summarised in Table 1. An extensive review of the hydrological processes of intact mires is provided by Ingram (1983) and by van der Schaaf (1999), and the hydrological impacts of peat mining are described by Brooks (1988). Ombrotrophic mires differ from minerotrophic peatlands, such as fens, by virtue of their isolation from regional aquifers, receiving only atmospheric inputs. The hydrological features of other types of peatland have been described by previous studies, for example forested swamps (Devito *et al*, 1996).

Table 1. Hydrological features of intact and cut-over mires.

Feature:	Intact mires:	Actively mined mires:
Watertable	High watertable with flooding of topographical lows	Watertable shallow but lowered by drainage – no flooding
Interception	Densely vegetated surface layer – high interception	All vegetation removed – zero interception
Stream length	Highly variable micro-topography created by living vegetation and its accumulating remains – short and irregular stream length in tortuous but extensive temporary networks	Extensive drainage channel network with long stream length intersecting bare peat surfaces
Surface gradient	Lack of macro-topographic relief – low surface gradients	Surface gradients increased with peat surface re-profiled to increase hydraulic efficiency of water removal to drainage network
Evapo-transpiration	Annual evapotranspiration totals greater than stream-flow discharge	Evapotranspiration much reduced by lack of vegetation and lowered watertable
Surface flow	Flow limited in low conductivity, low hydraulic gradient peat mass (catotelm) – discharge routed via aerobic surface layer (acrotelm)	Surface layer removed and catotelm flow induced by increased hydraulic gradients within intensive drainage network
Low flow	Low flow virtually absent when watertable reduced by evapotranspiration	Low flow maintained by pumping if necessary
Storm flow	Storm flow determined by watertable depth with overland flow in microtopographical network when watertable high – time to storm peak increased by depressional storage	Storm flow determined by watertable depth and overland flow increased by profiling of the soil surface to facilitate runoff

A third class of mire hydrology can be identified where peat removal at a previously mined mire surface has ceased and the drainage network is no longer maintained. In the case that site management aims to re-establish the hydrological functions of an intact mire for conservation purposes, it must first overcome the hydrological features developed by peat cutting practices. A rejuvenating site will inherit hydrological functions designed to desiccate peat and without the intervention in the mechanisms of these processes, for example re-profiling to reduce the gradient of a previously steepened surface, rewetting of the peat and re-establishment of a functioning acrotelm will prove difficult. The principals of restoration of damaged mires are reviewed Section 2.

The ability to predict the potential impacts of hydrological manipulation of a mire zoned for restoration would certainly increase the likelihood of success of rewetting programs and may also reduce site management costs. This requires a model capable of reproducing site hydrological behaviour within the heterogeneous, anisotropic peat, to a good degree of accuracy. Along with model formulation, the accuracy of model outputs will depend on the quality of real site data input into the model. Validation of the spatial and temporal model predictions requires site data of equivalent scales. It should also be noted that the scale on which hydrological phenomena are reported is often quite different to ecological 'behaviour'. Therefore where attempts to draw functional links between hydrology and ecology are anticipated, scale issues should be considered closely.

This paper outlines the principals of hydrological restoration of damaged mires. The models currently available for use as predictive tools by mire managers are reviewed. The numerical model MODFLOW (McDonald and Harbaugh, 1988) is selected and tested at the field site Wedholme Flow. The validated model is applied to two areas of the mire previously subject to peat extraction and currently under restoration management, largely in the form of drain blocking. The disparity in recovery rate between the sites is explained in terms of groundwater discharge from the two areas to the adjacent cutting area. The model is also used to examine the potential impact on the mire reserve of continued peat extraction from the current cutting area.

2. Principals of mire restoration management

The designation of Wedholme Flow as a Special Area of Conservation (SAC) under the European Habitats Directive requires English Nature, as the conservation body of the UK government, to maintain the ecological integrity of the site and to prevent adjacent activities from jeopardising this aim. The maintenance of the raised mire complex includes areas previously utilised for peat extraction and now abandoned. These *cut-over* areas must be managed to prevent both their own further degradation and that of the surrounding *intact* mire.

Hydrologically, cut-over mires more closely resemble active peat cutting areas (Table 1). Management intervention must reverse the trend of dehydration to prevent its inevitable spread to surrounding intact areas. This applies especially to the degenerate vegetation communities that colonise the abandoned cuttings. These invasive species often have higher water use than ombotrophic mire species and represent a threat to the both the ecological and hydrological integrity of the intact mire. Restoration management attempts to reverse these trends by rewetting the peat body, by the establishment of raised mire vegetation communities, and by essentially recreating a regenerating acrotelm in which peat can accumulate. As with any severely damaged habitat, it is rarely possible to return it to its original condition. Wheeler and Shaw (1995) state 'in the case of a bog damaged by peat extraction, it may be possible to repair or regenerate a bog by restoring conditions similar to those under which it originally developed and hence to encourage the return of typical raised-bog species'. This is the aim of restoration management.

Restoration of degraded raised mires requires management action to:

1. improve the retention of acidic, nutrient poor precipitation;
2. encourage water-logging;
3. stabilise water levels and reduce watertable fluctuation;
4. reduce erosion by surface runoff;
5. prevent contamination by inputs of potentially mineral enriched water;
6. aid establishment of desirable bog plants particularly *Sphagnum* moss species.

This paper uses numerical modelling to examine the processes that determine the success of points 1-4. The practices generally employed to achieve these aims include:

- ♦ *ditch blocking* and damming to elevate watertables
- ♦ *bunding* to reduce runoff, inundate the surface and elevate the watertable
- ♦ designation of *buffer zones*, within or external to the mire, in which the watertable is managed
- ♦ redistribution of water within the site
- ♦ mechanical re-profiling of the peat surface to reduce the surface and hydraulic gradients and discourage structural failure of the peat body

The last two practices listed are less common. Redistribution of water around the site, or the provision of a supplementary water source may be expensive and non-sustainable often involving the use of diesel pumps. This practice has been employed at degenerate raised mire in the UK (for example at Thorne and Hatfield Moores Reserve), to force rewetting and allow preferred vegetation communities to establish. Where this process is necessary to initiate rewetting, fossil fuel energy sources can be substituted with non-consumptive methods such as wind pumps. Re-profiling is increasingly recognised as a valuable way to establish good starting conditions for restoration (MacAlister & Mawby, 2001), although removing vegetation and moving large volumes of peat may be seen as controversial within nature reserves already subject to widespread disturbance. It also raises concerns over the disturbance of the paleoarchive, even in highly disturbed areas. The wetting of buffer zones and the potential for flooding of adjacent land may also cause conflict and must be carefully managed.

3. Review of existing models

Several attempts have been made to model mire hydrology in the past. These have included (though not exclusively) the Groundwater Mound Model developed by Ingram (1982); the application by Schouwenaars (1990) of the one-dimensional agrohydrological model SWATRE (Belmans et al, 1983) to wetlands and the later addition of a surface inundation component (Spieksma & Schouwenaars, 1997); and the application of MODFLOW (Bromley & Robinson, 1995).

The Groundwater Mound Model (Ingram, 1982) makes steady state predictions using an analytical solution. It equates the geometry of the groundwater mound (described by the equation for an ellipse) to the ratio of net recharge to hydraulic conductivity, effectively giving a solution to the Laplace equation (Freeze & Cherry, 1979, Bear & Verruijt, 1990). It was validated by approximating the surface dimensions of Dun Moss, Tayside, where the 'surface' was taken to be the upper limit of the watertable, and makes several simplifying assumptions:

1. The mire boundaries must conform to predetermined geometric dimensions, where boundary conditions are continuous fixed heads.
2. The mire must be entirely independent of regional ground and surface hydrology.
3. Vertical and horizontal hydraulic conductivity must be homogenous.

As the model provides a steady state simulation all inputs must equal outputs, not allowing for any depression or surface storage. The upper limit of the model is the groundwater table, effectively modelling only the catotelm, so that surface water and evapotranspiration must be accounted for by adjusting the net recharge (MacAlister & Parkin, 1998).

The numerical transient state, agrohydrological model SWATRE (Belmans et al, 1983) calculates interception, evaporation and transpiration using crop factors and outputs the distribution of soil water within a soil profile calculated using the equations for saturated and unsaturated groundwater flow. In the application of SWATRE to wetlands Schouwenaars (1990) noted that open water, particularly ditch levels, could not be included and that once the storage capacity of each cell had been reached, surplus was lost immediately over estimating discharge. Consequently Spieksma and Schouwenaars (1996) developed a 'quasi two-

dimensional' surface inundation component allowing horizontal flux between the soil profile and open water, so that water can accumulate in drainage channels. They conclude that the quasi 2-D approach improves upon SWATRE outputs, with the inclusion of the capacity of areas of surface inundation to buffer of groundwater fluctuations, whilst the estimation of discharge still remains a problem.

The US Geological Survey modular finite-difference groundwater flow model, MODFLOW-88 (McDonald & Harbaugh, 1988), was applied to Thorne Moors (NNR), Yorkshire, by Bromley and Robinson (1995) in an attempt to predict the effect of peat cutting on the hydrology of the adjacent nature reserve. The model, written in Fortran code, simulates three-dimensional groundwater flow through heterogeneous, anisotropic material. As the model applies a finite difference solution, the principal axis of hydraulic gradient must be aligned with the co-ordinate axis (Bear & Verruijt, 1990), whilst the geometry of the model region itself can be irregular in all three dimensions. The accuracy of the model representation of irregular geometry will depend on the grid dimensions and the constraints of numerical stability. Bromley and Robinson (1995) used MODFLOW to produce a range of head distributions at different distances from a peat cutting face, but they did not evaluate the modelled heads in relation to observed heads at the site. It is therefore difficult to assess the accuracy of the model predictions. MODFLOW-88 was also applied to an area of Wedholme Flow (MacAlister, 1996), using the pre- and post-processor graphical user interface (GUI), Processing MODFLOW (Chaing & Kinzelbach, 1993). However transient model convergence proved troublesome and heads produced during steady state simulations were unrealistic.

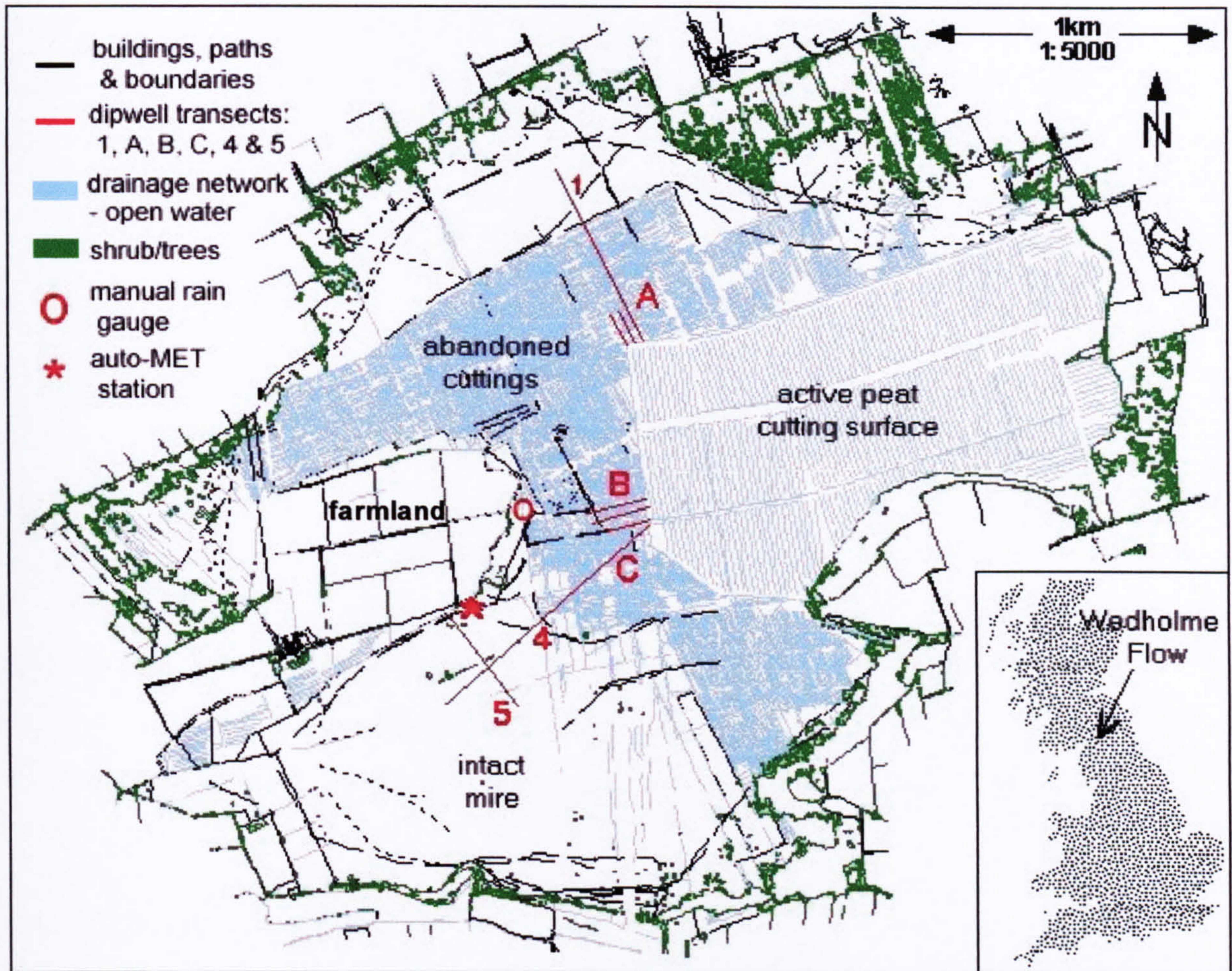
In 1996 the USGS released an upgraded version, MODFLOW-96, with additional numerical flexibility, and software manufacturers subsequently released several extended GUI's. Given a degree of past success, and a greatly extended data set, it was decided to persevere with the application of MODFLOW to Wedholme Flow using the Waterloo Hydrogeologic interface, Visual MODFLOW (Waterloo Hydrogeologic, 1999). This package includes an additional numerical solution, and integrates easily with several GIS packages.

4. The field site

A designated Site of Special Scientific Interest (SSSI), Wedholme Flow (NY220530) (Figure 1), is the largest of the lowland raised mires which comprise the South Solway Mosses National Nature Reserve (NNR - UK), and recently designated as a Special Area of Conservation (SAC) hence requiring in statute, proactive restorative management. The area has a long history of peat cutting and parts of the 780ha site are still referred to as 'Awards', made to local parishes for peat-fuel which and utilised until the middle of the twentieth century (Mawby, 1995). During the nineteenth century landowners used drains to define boundaries within the bog. The current extent of today's site boundary is largely the result of drainage at the periphery during agricultural development. The current mire can be divided into primary, undisturbed mire (16.5%), regenerating, abandoned peat cuttings (39.7%), active peat workings, operated by Levington Horticulture, a subsidiary of the US based Scotts (20.5%), and marginal habitats including wet grassland and wooded fen (23.7%). In addition open water occupies large areas of the site, in the form of both seasonal pools (in the intact mire) and flooded, old drainage networks (abandoned peat workings). The site ranges from 10 – 18m above ordnance datum. The 10year mean precipitation for the site is 896mm, with considerable variation including 567mm in 1996 and 1003mm in 1999.

Figure 1 was produced using digital data from photogrammetric maps of 1:5000 aerial photographs. The differences in mire surface conditions and drainage regimes are clearly revealed by aerial photography (though clarity is lost in reduction of maps). At the end of September 1994 when photographs were taken, the abandoned cutting areas appear largely as open water. This reveals the extent of the deep pools produced by drain blocking and the subsequent inundation of lower lying areas between peat ridges, created by the screw levelling machine, which clears vegetation in preparation for mechanised sod-cutting (Cooper & McCann, 1995). The maintained drainage network of the peat cutting (by milling) area appears in distinct contrast to the largely intact mire areas to the north and south-west and the farmland occupying the high ground north-west of the weather station. The farmland is isolated hydrologically from the mire reserve by boundary interceptor drains.

Figure 1. Inset: Location of Wedholme Flow (NY220530). Main: Three main surface conditions, hydrological transects, and automatic MET station.



The conservation site managers, English Nature, have observed that flooded, abandoned cuttings in area A to the north of the active peat milling face, appear to be rewetting more successfully than those in area B, between the farmland and western cutting boundary drain. Peat cutting in area A was far more extensive and continued until 1990, leaving approximately 1.5 to 2m of peat above the mineral sub-soil, whilst intensive drainage of peat in area B occurred between 1976 and 1985, with peat removal leaving broadly 7m of peat above the drift. A program of drain-blocking in order to re-establish high watertables has been ongoing at both sites over the last decade. An aim of this study was to employ a numerical model of mire hydrology using real site data to investigate potential water loss in both of these areas and to examine the potential impacts on the mire reserve of continued peat removal across the adjacent milling fields.

5. Data collection at Wedholme Flow

The application of MODFLOW, the model selected to recreate hydrological processes at Wedholme, and validation of model outputs requires an extensive range of site hydrological, meteorological and geophysical data. Ideally a hydrological budget for the site should be completed and the physical properties, hence transmissivity of the peat substrate, should be characterised.

5.1 Hydrological monitoring

The assumption that the mire is ombotrophic relies on its isolation from hydrological exchanges with the regional ground and surface water systems. Peat cores removed during dipwell installation confirmed the mire is underlain by dense boulder clay of unknown depth. In some areas a thin layer of alluvial deposit was observed to overlay the glacial deposits that form the main extent of the subsoil. It was considered that any seepage across this layer would be negligible. Regional topography isolates the mire from any input of surface waters. Therefore monitoring of the mire hydrology has focused on internal exchanges and out flow from the site.

Groundwater levels have been monitored since 1990 in a dipwell transect crossing the northern intact mire (area 1) and extending into the abandoned cuttings to the south. Twenty of the original twenty-six wells in transect 1 are still operational. In July 1998 two new dipwell transects (numbers 4 & 5) were installed in the south-west lobe, (figure 1). This is the largest undisturbed area and is bordered to the north, south and west by main drainage channels and to the east by the abandoned cutting area. Twenty-one dipwells were installed in two perpendicular transects, with a total length of just under 1km. In October 2000, an additional 48 dipwells were installed in seven new transects in areas A, B and C, with transects 1 and 4 extended across the adjacent cutover areas up to the active cutting face. All areas were surveyed using both automatic levels and GPS instruments, as a base station and rover (*Trimble GPS Pathfinder Pro XRS*). Data were subject to post-processed differential correction (DGPS) for further accuracy (Trimble, 1997). Dipwell co-ordinates, in the x, y, and z dimensions, were recorded so that well levels could be recorded relative to ordnance datum.

Perforated, 40mm dipwell tubes were installed to the full depth of the peat and anchored in the underlying misdeal subsoil, which could also be related to ordnance datum. Dipwell water levels were read manually on a weekly basis from their installation until November 2000, when recording ceased. Pressure transducers with data loggers were also installed in dipwells at different locations across transects 4 and 5 from July 1999. Pressure transducers (model *Druck PTX530*) were employed with multi-channel data loggers (model *Technolog Newlog Universal logging Module and 2 Channel Interface Unit*). Five transducers and 3 loggers were available. These were moved between wells in an attempt to characterise short-term fluctuations across the area under different rainfall intensities. Moving the equipment was both difficult and labour intensive, and so moves had to be limited. The strategy most likely to yield useful results was judged to be spacing the transducers along one of the transects. The outputs could then be applied easily to model transects.

No records are available for ditch water levels or flow rates.

5.2 Meteorological Monitoring

Precipitation has been recorded on-site (figure 1) in a manual rain gauge since 1990. In order to estimate evapotranspiration (ET), precipitation, net solar radiation, air temperature, humidity, and wind speed were recorded from March 1999, using an automatic weather station (*Environmental Measurements*) installed close to transect 5. The program, Ref-ET (Allen, 1999), was then employed to calculate Penman-Monteith values for potential evapotranspiration calculated according to the methodology outlined by Allen *et al* (1998). In an additional study, the ET values calculated using the program were compared with those produced using mini-lysimeters¹ and examination of watertable fluctuations (Panda, 2000). Recorded precipitation and Ref-ET calculated as net recharge for two periods are plotted in Figure 5a-b.

During monitoring periods of short-term water level fluctuation, all data loggers recorded on 20-minute intervals.

¹ Chapter 3, Section 4.2

5.3 Geophysical properties

For the purpose of this study the mineral sub-soil that underlays the peat was considered to be impermeable. The hydraulic conductivity of peat within the catotelm was measured in the field at the main transect locations, by the Piezometer Method (Luthin and Kirham, 1949, Reeve and Kirkham, 1951, Dielman & Trafford, 1984), at depths of 0.5m, 1m, 1.5m, and 2m. Below 2m, catotelm peat appeared homogenous. These depths were used to determine initial model layers and peat morphology within each layer was compared to the von Post scale of humification. The effective porosity of layers below 0.25m was estimated by the Kozeny-Carman Equation (Ahuja *et al*, 1985) for calculating soil hydraulic properties from limited data sets. The calculated values were comparable to values presented in associated literature (Boelter, 1965, Päivänen, 1973, Ingram, 1983). Given the similarity of the humification observations and the hydraulic conductivities, the literature values of total porosity were considered a likely approximation of the field situation. Approximations and estimated values were then examined and adjusted using sensitivity analysis during model calibration. Conductivity and storage coefficients applied during the model application are listed in Table 2.

The specific yield of the uppermost layer, the acrotelm, was estimated from the ratio of rise in watertable to net precipitation per rainfall event (Gilman, 1994, van der Schaaf, 1999). The storage values for the surface layer at various distances from the nearest drain channel are listed in Table 3. Within the model transect the (saturated) infiltration capacity of the acrotelm, defined as surface to -0.25m, and was measured in the field using a double ring infiltrometer.

6. The model transects and MODFLOW parameterisation

Due to the intensive nature of data input required by MODFLOW and the need to characterise hydrological boundary conditions, three model zones were identified:

1. Model transect 5 (Figure 2), encompasses the intact mire around dipwell transect 5 and the interceptor drain bounding and farmland. This stable area of active mire was selected for the purpose of model testing and as a control to which disturbed mire hydrology could be compared. A model transect with dimensions 30m in 8 cells in the x-axis and 400m in 46 cells in the y-axis was delineated, making a total hydrologically active model surface area of 11610m². The z-axis has a minimum of zero representing ordnance datum, and a maximum of 14.5m AOD, divided into 7 model layers. Layers 1-5 are of fixed dimensions determined by the levels at which soil properties were measured (Table 2). A sixth layer of equivalent properties to those from -2m was added to represent peat from -2m to the underlying mineral material. Layer 7, made up entirely of 'inactive' cells, representing the 'impermeable' layer of drift underlying the peat. No-flow boundaries were assigned to the south, east and west, of the model region. The drain bounding transect 5 to the north with the purpose of isolating it from the farmland, is roughly 1.5m deep and 0.5m wide and largely vegetated. The Neumann boundary conditions imposed by the drain were best represented within the model as 'river' cells, where the riverbed and river stage elevation are specified along the full reach of the river. The thickness and hydraulic conductivity of the riverbed, and the width and reach of the river channel within each cell are represented by the conductance (leakage) of the riverbed. The eleven dipwells (5.1-5.11) within the transect area were included in the model as observation wells, with minimum screen depth at 0.5m below ground level (within the unconfined aquifer).
2. Model transect A-1S (figure 3) extends from the blocked drain intersecting transect 1 (figure 1) over 460m of flooded abandoned cuttings of area A, across the arterial drain and over 400m of the active milling face, with 87 cells in the x-axis. The transect is 30m wide, with 3 cells in the y-axis. Five layers were determined in the Z-dimension, with relatively shallow peat in the central region. No-flow boundaries were assigned around the entire model region, and with a river boundary representing the arterial drain separating the abandoned cuttings from the active milling surface. Given the

shallow peat at this point, the 2m arterial drain must intercept the mineral drift layer. The dipwells of transect 1 south and transect A1 were included in the model transect as observation wells. Again, no data were available for the active peat cutting face and 1994 topographic data were substituted, with observation wells assigned across the cutting face.

3. Model zone B (Figure 4) was defined as the area of relatively dry, abandoned peat cuttings intersected by dipwell transects B1-3, and extending beyond the arterial drainage channel over 100m of active cutting face. No current data were available for the active cutting area but topographical data could be determined from 1994 photogrammetric maps. The total hydrologically active area of the model was 70000m², with dimensions delineated as 350m in 41 cells in the x-axis and 200m in 20 cells in the y-axis was delineated. Six layers were determined in the Z-dimension, from the 'inactive' drift layer to the acrotelm, of 0-0.25m depth. The 23 dipwells of transects B1-3, were included in the model as observation wells and 3 additional wells were added to the active cutting area in order to observe potential heads created by the model. No-flow boundaries were assigned around the entire model region, with 'river' cells representing the maintained interceptor or arterial drains between the active and abandoned peat cuttings, which are approximately 1m wide and 2m deep, with a bare peat surface.

Figure 2. Model transect 5 within the intact southern lobe of the mire reserve. The dimensions shown are the model sub-region, with 0.1m contours. Dipwell transect 4 is also included, along with the location of the automatic weather station.

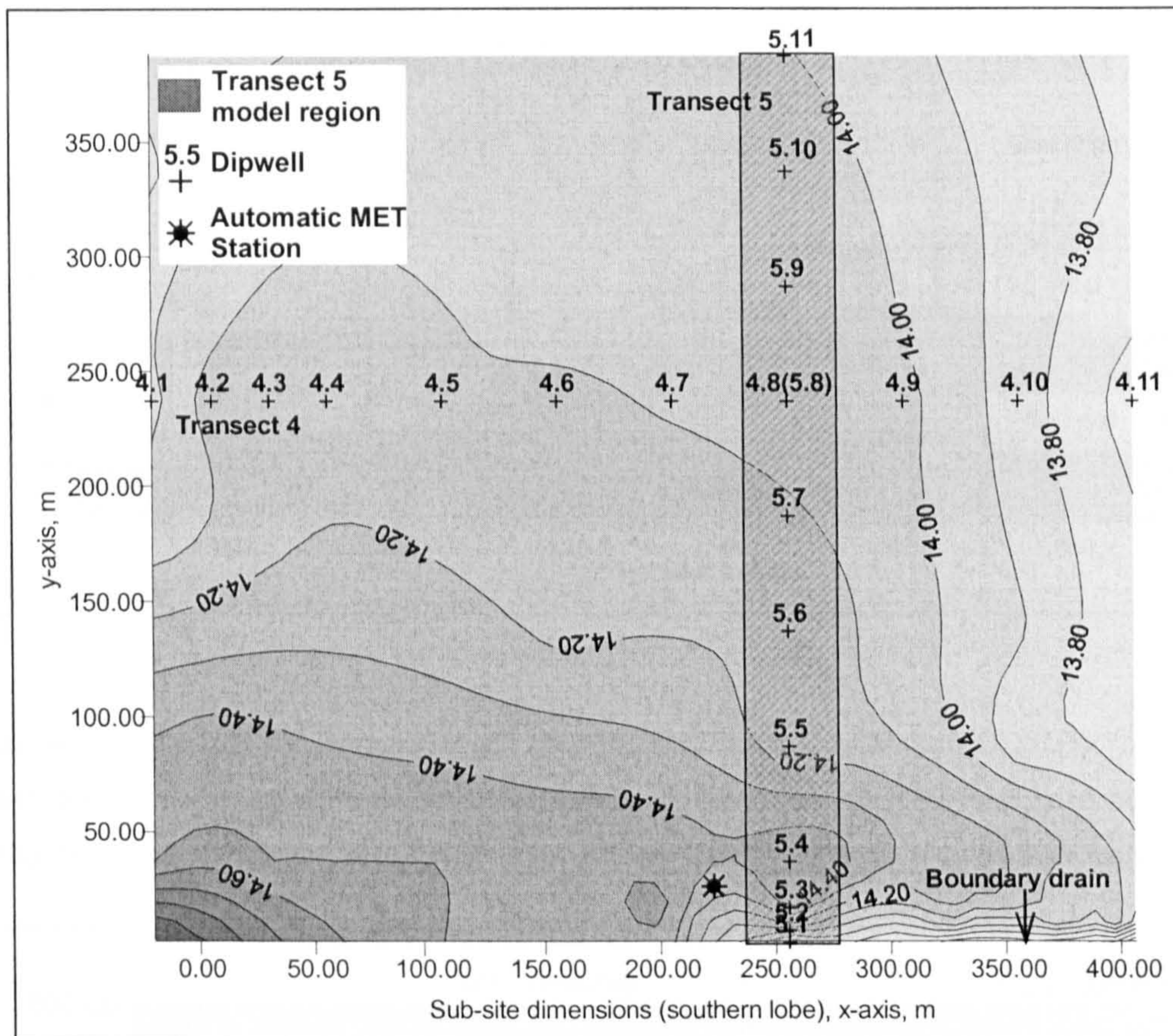


Figure 3. Model transect A in cross-section showing column 3 of the MODFLOW model region with a vertical exaggeration of x20 in the Z-dimension. The individual cells of the model transect are shown along with the 'observation wells' which represent the field dipwells. The model region extends across the regenerating mire reserve into the simulated cutting face delineated from 1994 photogrammetric maps.

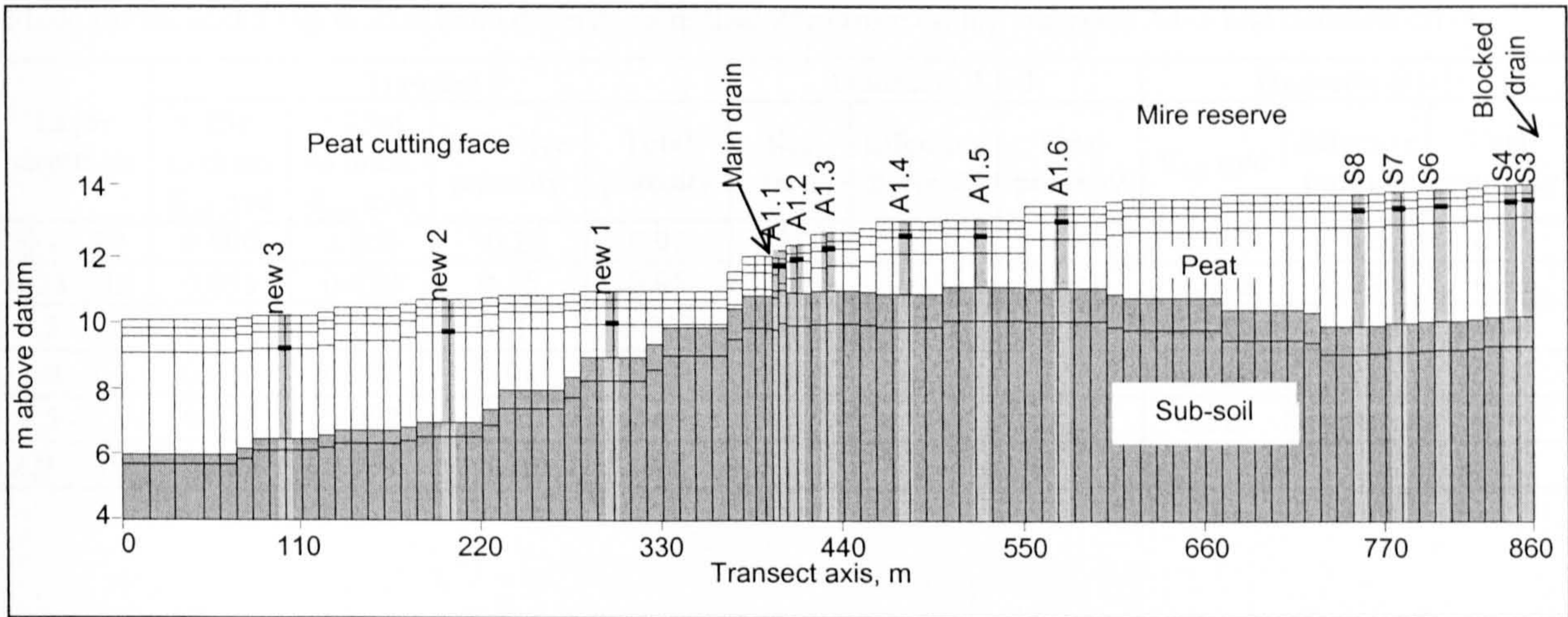
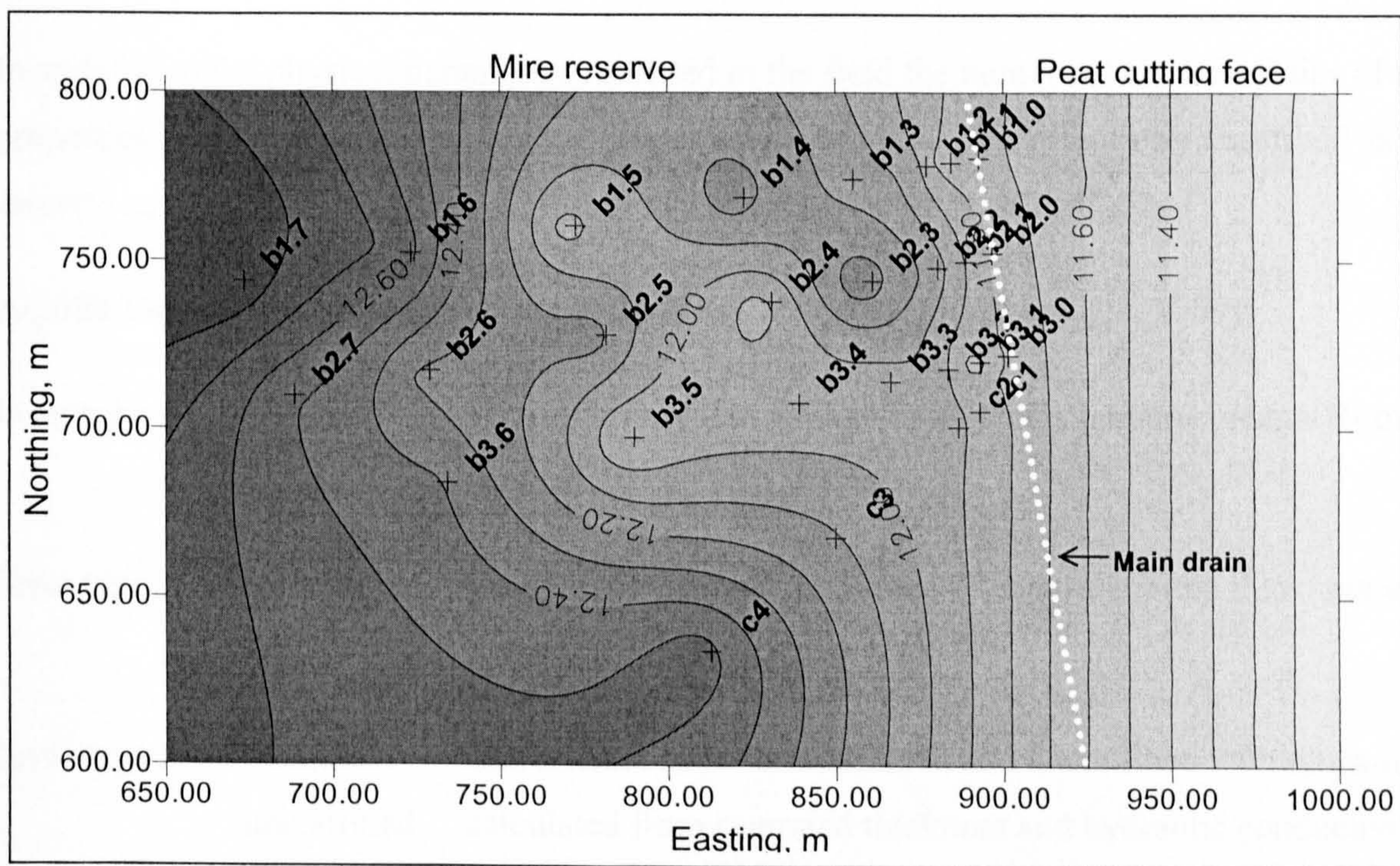


Figure 4. Model area B with boundaries and dimensions corresponding to the MODFLOW model region. The 'observation wells' which represent the field dipwells are shown including the 'simulated wells' within the cutting face delineated from 1994 photogrammetric maps, and the arterial drain which bounds the mire reserve.



The field recorded peat properties and estimated values assigned to each appropriate model cell are given in Tables 2 and 3.

Table 2. Peat properties including saturated hydraulic conductivity, effective and total porosity at Wedholme Flow, for transect 5 (up to 25m from drain & more than 25m from drain); transects A1-3 and transects B1-3.

Layer depth, m	Transect 5:				Transects A1-3:			Transects B1-3:		
	< 25m to drain K _{sat} m/d	> 25m to drain K _{sat} m/d	Effective porosity	Total porosity	K _{sat} m/d	Effective porosity	Total porosity	K _{sat} m/d	Effective porosity	Total porosity
0 - 0.25	0.800	0.600	*0.24	0.97	0.300	*0.170	0.95	0.150	*0.3	0.95
0.25 - 0.5	0.055	0.020	0.15	0.95	0.090	0.053	0.94	0.070	0.047	0.94
0.5 - 1.0	0.045	0.010	0.1	0.925	0.004	0.022	0.94	0.020	0.036	0.94
1.0 - 1.5	0.030	0.002	0.08	0.9	0.004	0.022	0.94	0.020	0.036	0.94
1.5 - 2.0	0.030	0.002	0.07	0.87				0.020	0.036	0.94
2.0 - drift	0.030	0.002	0.06	0.85						

Table 3. Specific yield or storage coefficient of the acrotelm estimated from watertable response to rainfall.

Distance > drain, m	5	10	15	30	60	90	130	180	230	290	330	390
Transect 5	0.248	0.227	0.367	0.561		0.755	0.641	0.574	0.981	1.167	1.353	1.127
Area B		0.30		0.60		0.80	0.90	0.70	0.40			
Area A	0.17		0.30		0.40	0.80	0.90					

In addition to the physical parameters recorded in the field the numerical characteristics of the properties must be specified within the model. Each model layer is effectively described as a discrete aquifer by the model, therefore status of each aquifer must be defined.

Aquifer transmissivity categories are defined as (Waterloo Hydrogeologic, 1999):

layer type 0: Confined Transmissivity and storage coefficients remain constant throughout simulation.

layer type 1: Unconfined Variable transmissivity calculated from saturated thickness and hydraulic conductivity.

layer type 3: Confined/
unconfined Can alternate between confined and unconfined with transmissivity calculated from saturated thickness and hydraulic conductivity.

During model simulations, particularly of low flow periods, it is possible for the surface cells to become dry when the watertable effectively falls below the bottom cell boundary. This results in the problem of zero-division and introduces numerical instability into head

calculation. Modflow-96 includes a 're-wetting' of dry cells, enabled with the WHS - Preconditioned Conjugate-Gradient Package solver. This numerical solution was employed in model simulations with 100 maximum outer iterations, 100 maximum inner iterations, head change and residual criterion of 0.001m for convergence. Enabling cell re-wetting may also introduce mathematical instability into simulations (Waterloo Hydrogeologic, 1999) but its omission was considered to reduce the accuracy of predictions. Discussion of iterative solution procedures can be found in McDonald & Harbaugh, (1988), Hill (1990), Anderson & Woessner (1992).

In addition to head equipotentials and velocity distribution, MODFLOW also included mass transport or water balance exchanges between user specified zones within the model dimensions. In the three models, all layers of the intact mire prescribed *zone 1*, whilst the drain cells and all layers of the simulated cutting area were delineated *zone 2*. The zone budget facility of MODFLOW was then implemented to examine any potential simulated flow from the intact mire into the peat cutting and vice versa.

6.1 Selected simulation periods and model testing

Before MODFLOW could be applied to simulate potential flow scenarios within the model areas, it was necessary to establish the validity of the numerical model to recreate mire hydrological conditions. Two test periods were selected: one dry, low flow condition and one wet, storm flow period. The low flow period selected was July 1999, having a total rainfall of 10.2mm with a mean daily potential evapotranspiration of 2mm/d. During this period weekly well readings were available for transect 5. Hydrological data for areas A and B were only available for October 2000, which coincidentally, had the highest recorded rainfall of the 11 year record with a total rainfall of 130.4mm, well above the October 10-year mean of 71.9mm. Daily watertable readings were collected from all dipwells from 6th October until the 3rd November 2000, and therefore this period provided the storm flow example. The daily precipitation and potential evapotranspiration were then prescribed for each model time step.

The net recharge ($P_{\text{total}} - ET$) and watertable in two dipwells (one adjacent to a boundary drain and the other in undisturbed mire) during the low flow and storm flow periods are plotted in figures 5a & b. As only weekly watertable data were available for the dry period weekly totals are illustrated, while daily records are shown for the wet period. Negative recharge indicates net evapotranspiration. Where evapotranspiration continues to exceed precipitation a

watertable ET extinction depth can be assigned within the model to prevent, uncontrolled water loss. In the field ET is seen to fall considerably and even cease when the watertable falls below the acrotelm. In all three mire transects, the extinction depth was prescribed as -0.5m. The watertable recorded in two dipwells in the intact transect 5 is also illustrated in figures 5a & b. Dipwell 5.1 is 2m from the arterial drain channel and dipwell 5.8 is 237m away, in the central area of the southern lobe at the intersection of transects 4 and 5 (figure 1). The groundwater level is considerably lower in the low flow period being below ground in both wells, whilst during the storm flow period at the beginning of the autumn season, the watertable is above ground in the central area having also risen by a minimum of 0.2m adjacent to the drain. The groundwater level close to the drain can be seen to fluctuate much more rapidly in response to recharge.

The observed dipwell levels on the first day of each simulation period were input to MODFLOW as initial head values in all three model areas. Recorded precipitation and calculated potential evapotranspiration were then applied on a daily basis. The recorded daily precipitation was applied to the highest active cell in the column throughout the simulation, and with the prescribed evapotranspiration extinction depth of 0.5m below the surface, preventing further ET if the watertable fell below that depth. Model calibration was performed and the two estimated variables of porosity and 'river' stage were adjusted accordingly.

The simulated heads could then be compared with observed water levels throughout the simulation period.

Figure 5a. Observed weekly watertable readings in transect 5 dipwells 5.1 & 5.8 and cumulative weekly net precipitation, July 1999.

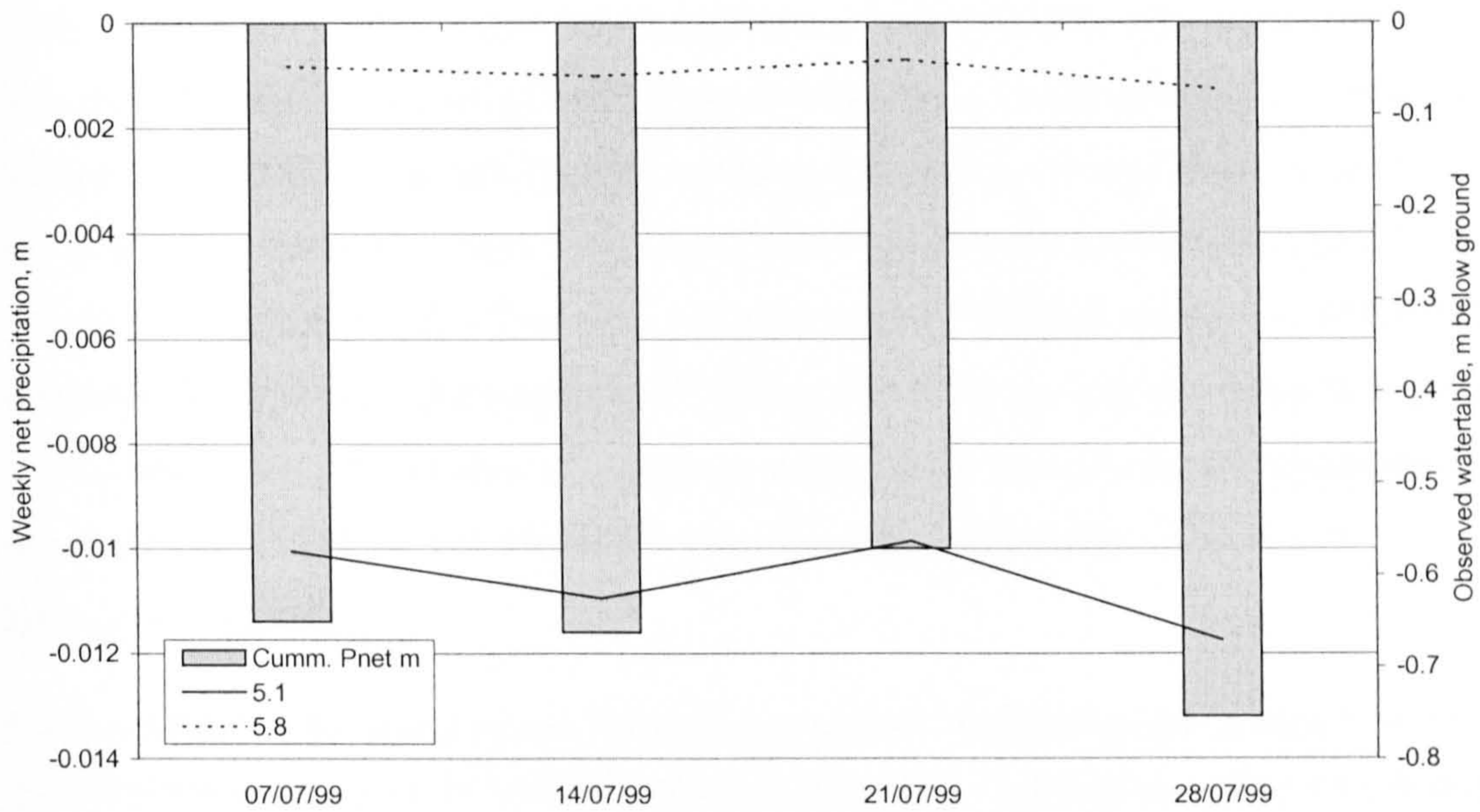
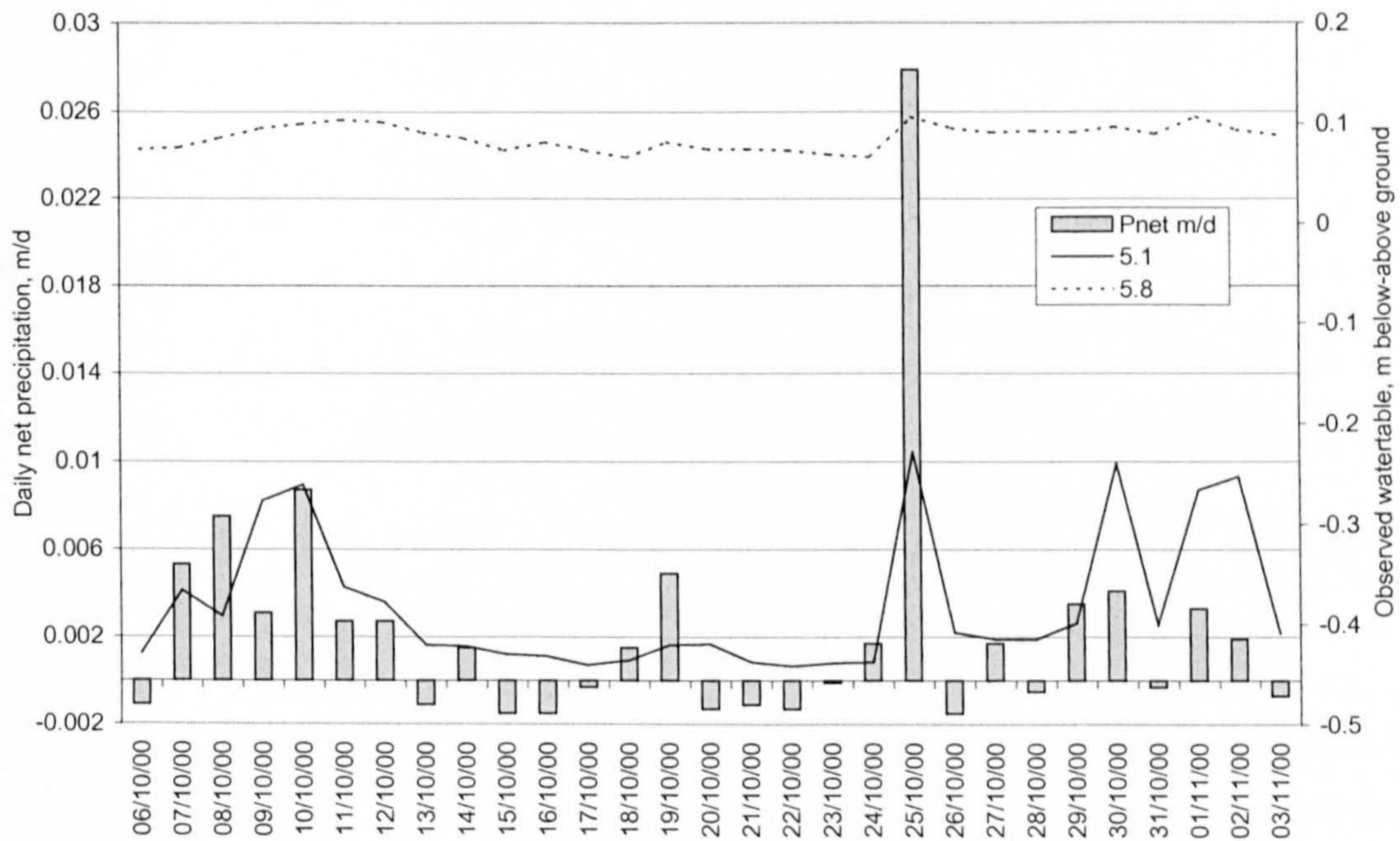


Figure 5b. Observed daily watertable in transect 5 dipwells 5.1 & 5.8 and daily net precipitation, 6th October – 3rd November 2000.



6.2 MODFLOW test period outputs

MODFLOW was applied to transect 5, in the intact mire for a 30-day low flow simulation (July 1999) and a 29-day storm flow simulation (October 2000). The initial groundwater head was provided and the model generated groundwater heads were compared to field recorded values. MODFLOW was then applied to transect A and model area B in the cut-over mire for the storm flow simulation only as no watertable records were available for the low flow period. Figures 6 and 7 plot the actual head recorded in the field versus the MODFLOW simulated head in each observation well of Transect 5 for the low and flood flow periods respectively. The straight line represents an exact match between model results and the recorded groundwater level. Deviation from this line is a measure of model or parameterisation error.

Figure 6. MODFLOW simulated versus observed watertable in Transect 5 dipwells on days 7, 14, 21, & 28 of the low flow simulation (1/07/99-31/07/99). Boundary drain stage = 0.1m and mean daily ET 0.002m/d.

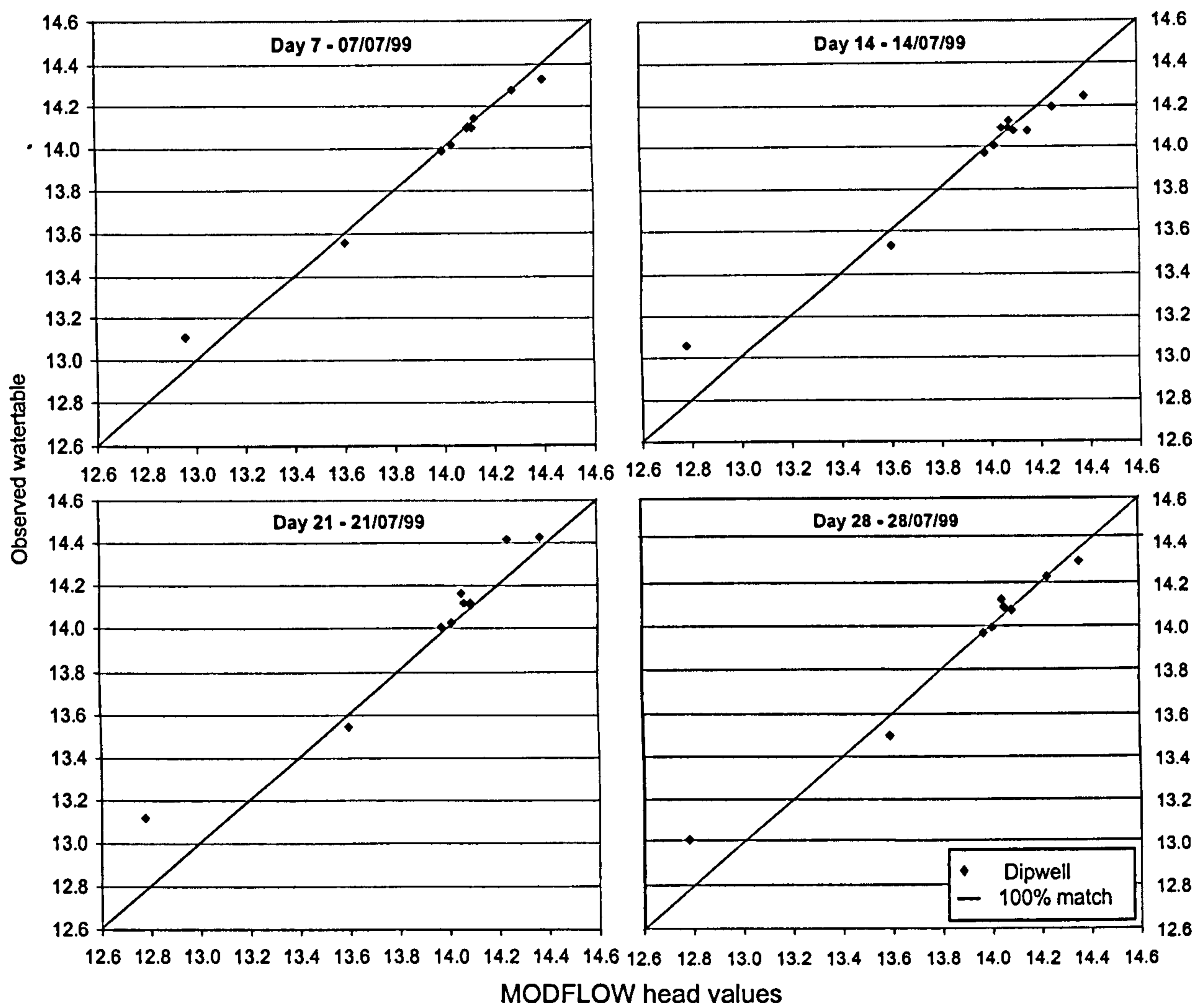
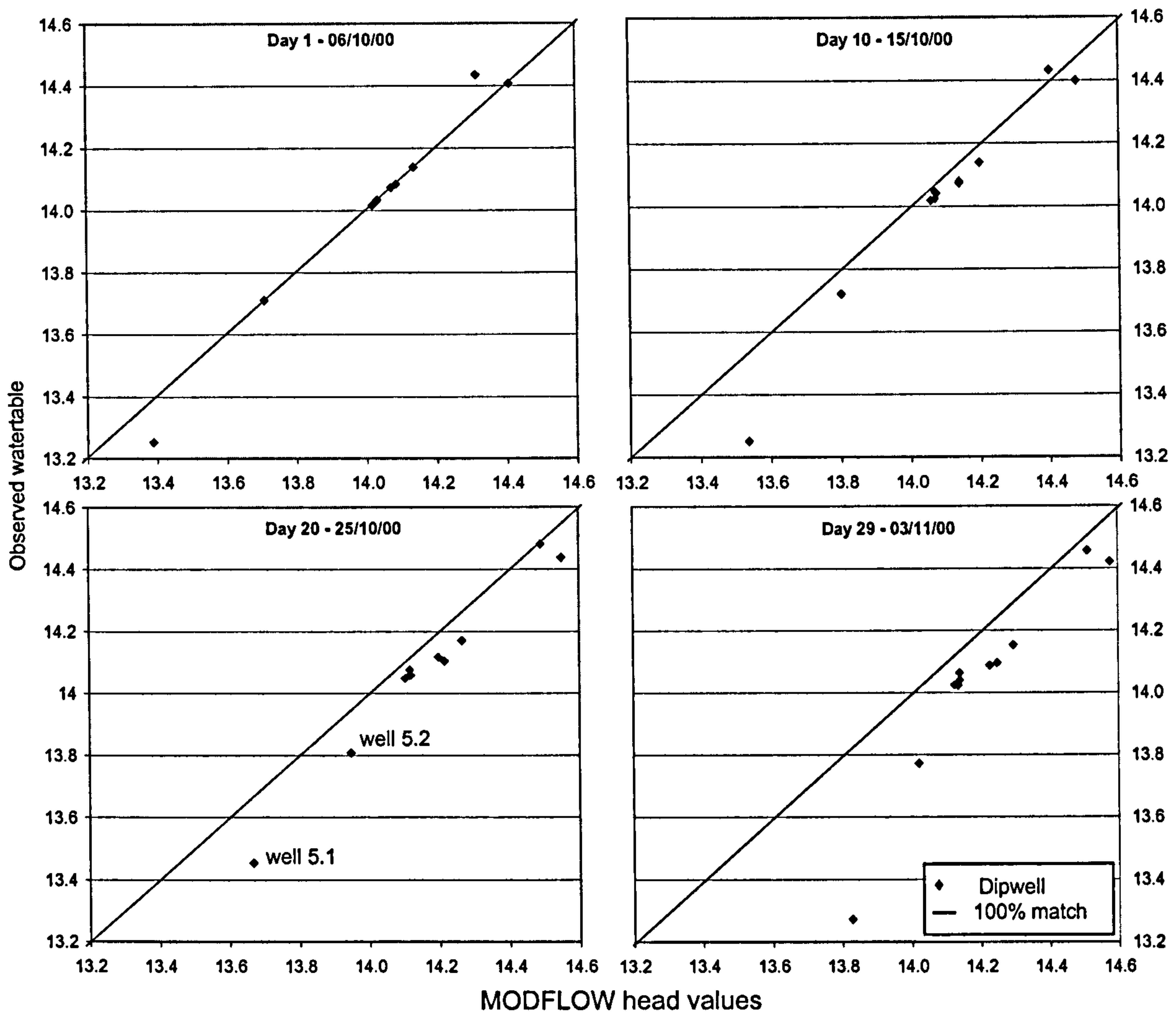


Figure 7. MODFLOW simulated versus observed watertable in Transect 5 dipwells on days 1, 10, 20, & 29 of the storm flow simulation (6/10/00-3/11/00). Boundary drain stage = 0.1m and mean daily ET 0.0015m/d.



During the low flow period (1-31/07/99) the MODFLOW produced head values remain very close to the actual watertable records from dipwells 5.2 –5.11. There is clearly a small amount of deviation from the actual head value for dipwell 5.1, which is 2m from the boundary drain. It is certain that the level in this well, and hence the watertable at this point results from the draw-down influence of the adjacent 2m deep, arterial channel. The water level (stage) at this point was unknown and so fixed drain water levels were maintained throughout model simulations. During this simulation the stage was fixed as 0.1m along the reach of the channel. This is clearly an unlikely scenario and will certainly introduce a source of error into the model calculation. The error observed for well 5.1 remains fairly constant throughout the simulation of the low flow period, as do the small observable errors of the other ten dipwells.

Simulation of the storm flow period (6/10/00-3/11/00) produced slightly different results: dipwell 5.1 continued to exhibit a higher degree of error than all other wells, whilst dipwell 5.2, 7m from the drain channel, exhibited increased deviation from the observed watertable. Unlike the simulation of low flow, the deviation of model head values from observed watertable increases as the simulation progresses, implying that the error is repeated and compounded in each model time step.

Many model runs were completed during sensitivity analysis while the estimated model parameters or drain water stage and porosity were varied. All storm flow simulations predicted a head above the ground level at a distance of 30m or more from the drain of transect 5, for all drain water depths. This is concurrent with observed dipwell levels also reading a water level above ground, effectively indicated surface water flow. The model did not appear sensitive to changes in porosity.

The predicted heads for intact mire transect 5 and recorded levels did not coincide on two counts:

1. The predicted heads were consistently greater than the recorded water levels and remained at a relatively constant height above ground, increasing as the simulations progressed.
2. The recorded water levels fluctuated across the transect being both above and below ground at different points whilst the simulated heads remained relatively constant, at or above the ground level.

Both differences were small and are likely to be artefacts of the inability of MODFLOW to simulate surface water flow and of the microtopography of the site. All of the simulations indicate that the potential head is above the ground surface therefore indicating the presence of surface water. However the model does not include any calculation of surface water flow, so that changes in the level of water at the surface can only occur via flow in the near surface through layer 1. Observation of surface water processes on the site, reveals a complex pool and channel network on a sub-cell scale. The smallest cell included within the simulation is 1x5m, whilst there is considerable microtopographical variation at the mire surface within 1m². With the watertable at or near the surface for a large part of the year, flow within hummock-hollow sequence becomes critical.

Figures 8 and 9 plot the goodness of fit of each 'model day' prediction to the observed processes within the mire, exhibited as groundwater heads within each dipwell. Results for the low and storm flow periods are given for transect 5 on one plot (figure 8).

The storm flow period outputs for model transect A and model area B are plotted for comparison along with daily precipitation totals (figures 9a & b).

Figure 8. Goodness of fit of MODFLOW predictions of transect 5 watertables to the observed groundwater heads: days 7, 14, 21& 28 low flow (July 1999) and days 1-29 storm flow (Oct/Nov 2000) periods.

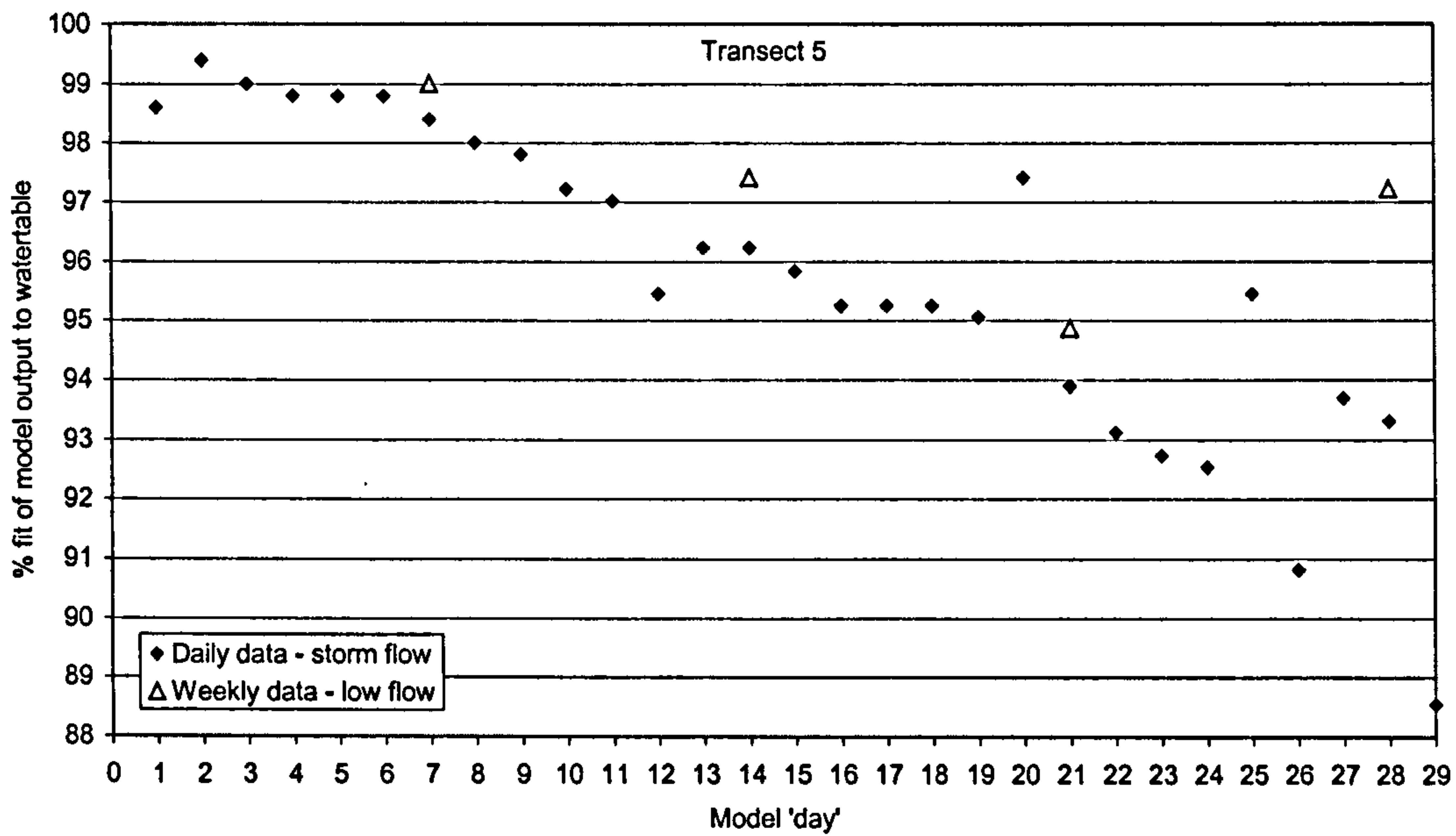
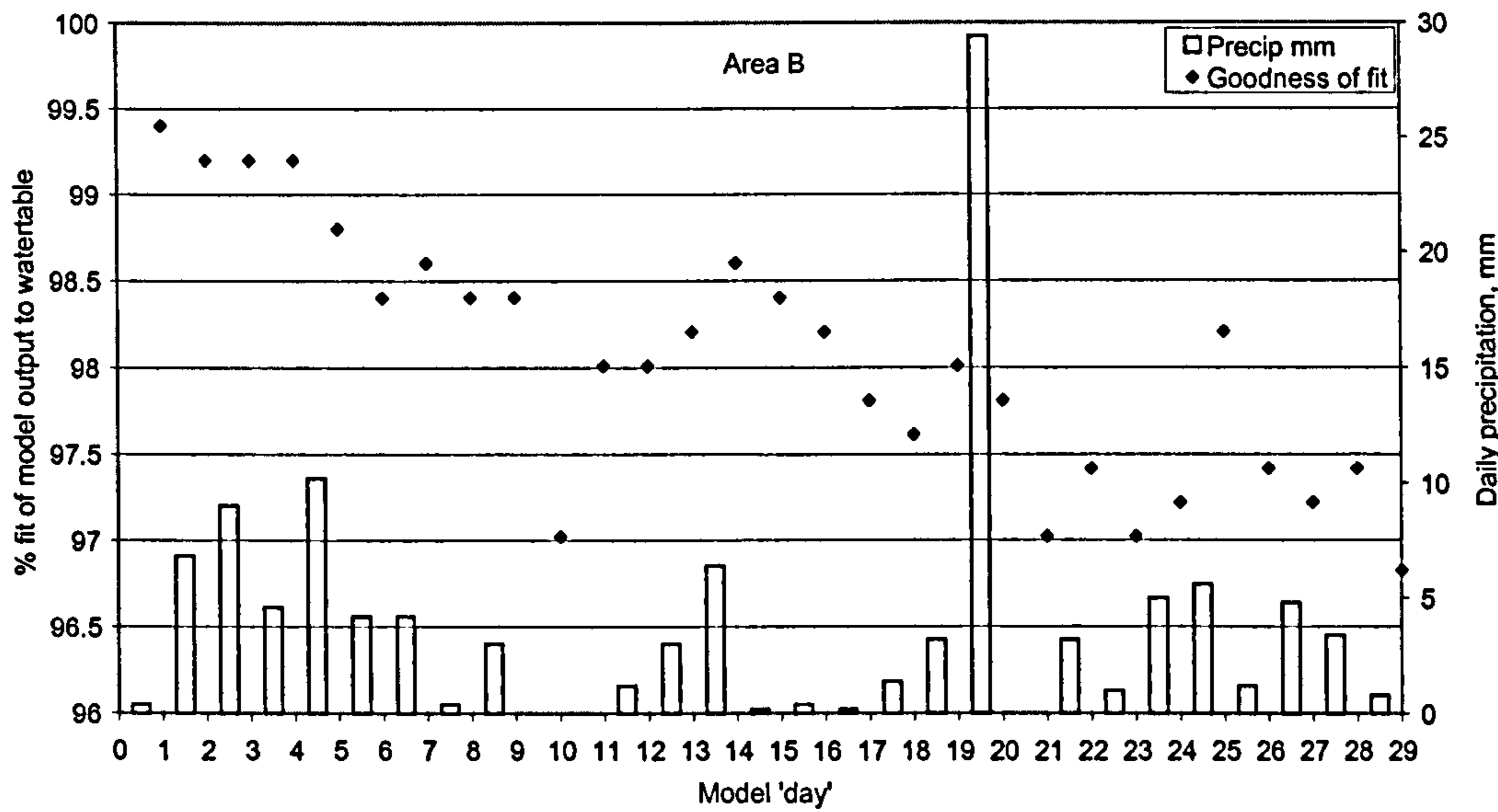
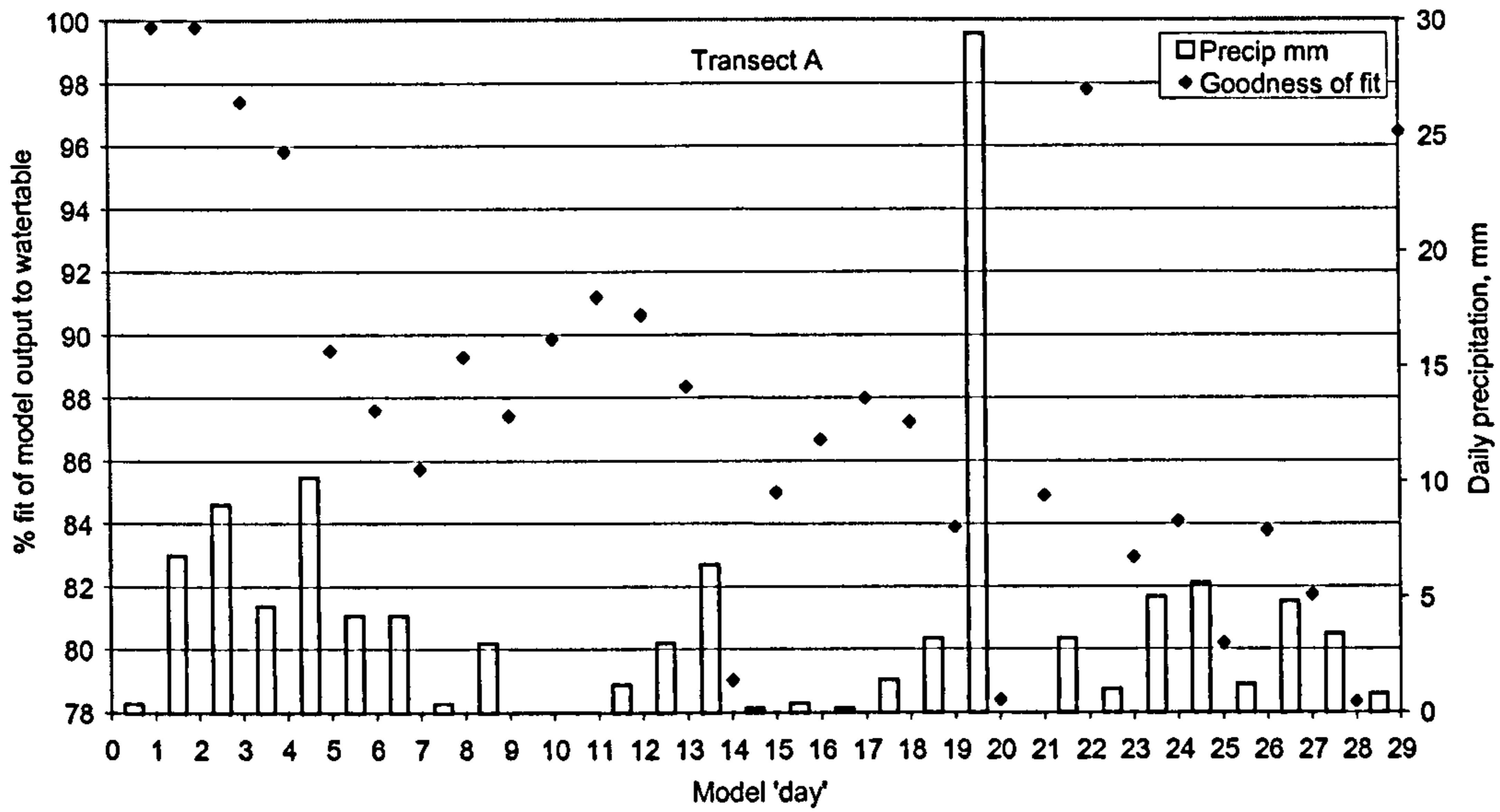


Figure 9a & b. Goodness of fit of MODFLOW predictions of groundwater heads to the observed watertables for days 1-29, storm flow (Oct/Nov 2000) periods: (9a) transect A; (9b) model area B. Total daily precipitation is included as columns (mm/day).



The model predictions of low flow conditions can be compared within transect 5 on four occasions throughout the month long model period. During this period the fit of the model results to observed watertable elevation ranged from a best fit of 99% after one week to a 94.87% match after 21 days. The accuracy of the prediction was fairly constant, rising after 21 days to a 97.22% match after 28 days. The range in goodness of fit of the model was greater for the storm flow period the best fit being 99.4% after 2 days, and the worst fit being an 88.55% match after 29 days – the only occasion on which the model predictions fell below the 90% threshold. Twenty-one out of the twenty-nine day storm flow period head outputs for the whole of transect 5 had a minimum of 95% fit to observed watertable. In general whilst remaining high, the accuracy of the model appears to decline as the model period progresses. Again this suggests an error in the model calculation, which is compounded by repetition. The goodness of fit of MODFLOW predictions of transect A and Area B groundwater heads to the observed watertables show a similar trend of declining match as the 29-day simulation continues. The fit of the model to area B conditions appears by far the best of all three model zones, with the worst fit of the model being a modest 96.83% match on day 29 of the simulation, with all other days providing a 97% fit or better. Comparison of recorded versus simulated water levels reveals that differences are due to a trend of increasing watertable particularly in topographic lows. This is similar to the process observed in the intact mire simulation, and may be attributed to the absence of surface water flow simulation within the model, resulting in retention of potential ‘surface water’ within a modelled region. A conclusive trend cannot be delineated between precipitation and good fit of the model, though the dependency of the variables is apparent.

On the whole it can be concluded that the model provides a good approximation of observations in the field though care should be taken when it is applied over longer periods, particularly within the intact mire. Simulations in the intact mire during the low flow conditions provided a good representation of field observed conditions. The decline in fit of the model to the observed hydrology as the storm flow simulation progressed suggests that the model has difficulties representing flow when the watertable is above ground and surface flow processes dominate.

7. Application of MODFLOW to potential site management scenarios

The model is now applied to changes in mire management, particularly the management of the peat cutting, to determine potential effects on the adjacent regenerating mire within the protected area. Several potential scenarios have been identified and the resultant hydrophysical and structural changes have been applied to both transect A and area B within the dimensions of the model regions. The surface of the peat cutting area included in model regions A and B was derived from a 1994 photogrammetric map, and it is likely that even without active peat removal, the bare peat surface will have fallen subsequently due to humification and surface erosion. Continued peat removal from the site and the necessary regime of maintained watertable draw-down to allow vehicle access, would result in progressive reduction in the peat cutting surface. MODFLOW has been applied to examine the hydrological implications of such conditions.

In order to maintain the established validity of the simulations the storm flow model period used previously in model testing was maintained for meteorological inputs to the model along with the *in situ* hydrophysical peat properties recorded in the field, whilst the actual depth of peat at the cutting face was progressively reduced. Over this short model period it would not be possible to observe a response in the watertable of the intact mire, however peat removal resulting in a reduction of the cutting face also increases the surface gradient at the reserve-cutting boundary. The maintenance of draw-down by the drainage network of the new cutting area surface will subsequently increase the hydraulic gradient at the boundary whilst all simulations assume a minimum draw-down of 0.5m. According to the Darcy law (Freeze and Cherry, 1979, Kruseman and Ridder, 1990), the steepening of the hydraulic gradient will result in increased groundwater discharge from the mire reserve. It is likely that both water yield and the timing of stream flow from both the mire reserve and cutting will change as a result of peat removal (Brooks, 1988). In the absence of stream flow data, MODFLOW produced head gradients can be used to calculate specific discharge and the model groundwater discharge outputs from delineated zones (using the zone budget facility) can be examined.

Initially discharge and head gradients from the model validation tests were recorded without any control over the drainage regime of the cutting. Field recorded heads at 50m from the drain channel were selected, as these appear to indicate its maximum influence. A constant

head of 0.5m below the cutting surface was then imposed. In addition, the peat cutting surface was reduced progressively, in steps of 1m, within the model region, whilst the imposed constant head was maintained at 0.5m below the cutting surface. The peat of the cutting face intersected by transect A was already shallow in 1994, so that the surface level could only be reduced by 1m. Therefore results from simulations in which the drain stage was adjusted are also presented. In practice this may be due to increased pumping in other areas for example. The peat of the cutting face adjacent to area B was approximately 7m deep in 1994 and has been modelled at five progressively lower levels.

The storm flow simulation was repeated for each new mire model whilst head gradients and discharge were recorded.

7.1 Model Outputs

Table 4 lists the changing hydraulic conditions for the model regions, calculated both manually and by MODFLOW, for the storm flow period under the different levels of imposed draw-down from 1994-survey cutting surface elevation, and gradual reduction of the face by simulated peat removal. The hydraulic gradient (dH/dx) in the 50m zone adjacent to the boundary drain is calculated from the MODFLOW produced groundwater heads. The specific discharge (m/d) is calculated for each scenario using (a) the head gradient estimated from MODFLOW produced heads and the mean hydraulic conductivity over the peat depth, and (b) the MODFLOW maximum daily discharge from each of the intact zones. The discharge rates of both regions can then be compared directly. An estimate of total daily groundwater discharge (m^3/d) through the cutting-reserve interface is given, multiplying the head calculated specific discharge by cross-sectional area for both model regions. The maximum daily MODFLOW groundwater outputs from each model region to the cutting area are presented for each model scenario. The total groundwater discharge is presented as a percentage of total precipitation (Q/P) for the twenty-nine day period, along with the MODFLOW calculated evaporation as a percentage of total precipitation (E/P).

Table 4. Model regions A and B, 29-day storm-flow simulations: hydraulic gradient (dH/dx); specific discharge (m/d); maximum daily groundwater discharge (m³/d); total groundwater discharge and total evaporation as a percentage of total precipitation for the period.

Simulated peat surface and drain water level (m)		Draw-down from 1994	Estimated from MODFLOW heads:			MODFLOW calculated discharge:			
			dH/dx	Specific discharge (m/d)	Max daily discharge (m ³ /d)	Specific discharge (m/d)	Max daily discharge (m ³ /d)	29 day Q/P _{total} (%)	29 day E/P _{total} (%)
Transect A									
1994	1.5	0	0.050	0.007	0.236	0.010	0.38	0.71	38.35
1994	0.5	0	0.067	0.009	0.318	0.011	0.40	0.74	37.26
1994	0.5	0.5	0.067	0.009	0.318	0.011	0.40	0.74	37.26
1994-1m	0.5	1.5	0.097	0.013	0.457	0.011	0.41	0.76	37.26
Area B									
1994	0.1	0	0.013	0.001	1.620	0.005	6.95	3.70	4.85
1994	0.1	0.5	0.066	0.006	7.990	0.007	10.29	5.49	4.29
1994-1m	0.1	1.5	0.160	0.014	19.379	0.011	15.42	8.18	4.65
1994-2m	0.1	2.5	0.247	0.021	29.840	0.014	19.56	10.39	4.68
1994-3m	0.1	3.5	0.346	0.029	41.827	0.014	19.98	10.60	4.67
1994-4m	0.1	4.5	0.446	0.038	53.847	0.015	20.92	11.10	4.68

Estimated groundwater discharge from MODFLOW simulated heads and groundwater output from the intact zone of transect A are closely correlated. A 1m reduction in drain water level results in a small but significant increase in estimated hydraulic gradient and subsequent specific discharge rate. The additional imposition of head reduction of 0.5m, in the cutting area has no apparent effect, as it is equivalent to the specified drain water level. The same effect is observed in the MODFLOW outputs, although the actual increase in specific discharge (0.001 m/d) is half the estimated value (0.002), resulting in small differences in the maximum daily discharge. A 1m reduction in the simulated peat cutting face produces the more significant increase in estimated discharge, and a small increase in the MODFLOW value. Examining the proportion of total groundwater discharge to total precipitation (Q/P) in model region A for the 29-day stormflow simulation, there is little apparent effect of increased draw-down. At less than 1%, the proportion of P_{total} apparently translated to discharge in the model simulation is insignificant when compared to evaporation, which accounts for 38% of the water balance. The MODFLOW simulated evaporation is fifty times the groundwater discharge from A, for the same period.

In comparison to area A, changes in the B model region, in both estimated and simulated specific discharge are much greater. A 1.5m increase in draw-down, by the imposition of a constant head 0.5m below the 1m reduced adjacent peat cutting surface, results in an

estimated increase of 0.006m/d and a simulated increase of 0.001m/d from A, and respective increases of 0.013m/d and 0.006m/d from B. However the actual discharge rate for this same simulation period was equal at A and B. When the peat cutting face at B is reduced further to 2m below the 1994 surface, the simulated specific discharge rate is doubled. Further reductions of the face beyond this depth have less apparent efficacy.

The reason for the over estimation using the estimated head gradients is likely to arise from the assumption of a linear gradient between the two observed heads, when applying the Darcy law over the 50m drain boundary region. In reality the head does not follow a constant gradient between two points but is in profile, a curved if not irregular surface. It is also subject to surface and subsurface anisotropy. These factors are included in the MODFLOW simulation and this may be one reason for the lower predicted discharge. This effect is more pronounced as the watertable in the cutting falls and the head gradient becomes potentially steeper. In the field the increase in gradient may be counteracted, at least in the short term, by the low hydraulic conductivity of the peat. In the long term, the extreme gradient imposed is likely to produce cracking and subsidence at the boundary (processes not included in the model) resulting in the creation of accelerated flow routes.

Comparison of the water balance of model regions for all simulation periods reveals the most significant differences between the areas. During area A simulations, evaporation accounts for nearly 40% of total precipitation, whilst total groundwater discharge is less than 1%. This varies very little with changing head conditions. In area B, evaporation accounts for less than 5% of total precipitation, whilst groundwater discharge ranges from 3.7% to 11.1%, at the maximum drawn-down. A 1m reduction in the 1994 peat cutting surface at B, results in an increase of the proportion of precipitation translated to groundwater discharge to twice that leaving the region as evaporation. Whilst the same simulation conditions at A result in very little change with the proportion of evaporation to precipitation remaining approximately fifty times that of groundwater discharge.

Disparity in the evaporation/precipitation proportions are probably due to differences in watertables during the simulations. Evaporation is calculated in MODFLOW according to availability of groundwater, and when the water level falls below the specified 'extinction depth' evaporation ceases until the level is exceeded by subsequent recharge. The generally wetter condition observed in area A, suggests more water available for evaporation, at or near

the surface. Compared to evaporation, groundwater discharge is insignificant at A, but represents a considerable drying effect at B.

The MODFLOW daily discharge rates reported in Table 4 are the maximum daily rate produced during the storm flow period and are therefore 'extreme' values. However, when presented as a total volume for the 29 day period and compared to the total precipitation, even as an extreme storm event forecast, the percentage of total rainfall discharged from the model area represents a drying of the mire under all of the scenarios presented for area B. It should also be recognised that the model may under-estimate the total evaporation from any simulation as it is a very simplified calculation, based only on the user specified daily evapotranspiration. If vegetation physiological factors, such as rooting depth and water availability to plants, are not included in the user-specified evapotranspiration, they are omitted from subsequent MODFLOW simulations. This has increasingly serious implications when it is considered that the total rainfall for this storm period is nearly double the 10-year mean for the same month. All of these factors point to inevitable dehydration of the mire reserve.

The minimum peat level reduction of 1m from the 1994 cutting surface and associated fall in watertable results in an equivalent increase in hydraulic gradient at both the transect A boundary and the area B boundary. However the resultant increase in modelled maximum daily discharge is much smaller for A. The potential for increasing groundwater discharge is limited at boundary A by the remaining depth of peat left above the uneven sub-peat topography (figure 3). The underlying, effectively impermeable subsoil of this interface zone is likely to constrain subsurface flow at this point, forcing any discharge through a shallow layer of peat or over the mire surface. In reality this area is observed to be much wetter than its surroundings and exhibits a high degree of overland flow. The wetter conditions observed in the field, accompanied by higher groundwater levels in the dipwells, may be explained to some extent by this limitation in groundwater discharge to the cutting area. The remaining portion of the model water balance not included in Table 4 is accounted for by MODFLOW as storage exchanges. Surface flow is not included within MODFLOW and may account for both 'storage exchanges' and some overestimation of heads by the model. Longer-term data collection and modelling is needed to consider the implication of these factors.

8. Conclusions

The validation tests performed on low-flow and storm-flow data collected at Wedholme indicated a good level of model fit to observed processes. The success of the model in simulating observed behaviour increased considerably during the low-flow period.

Unfortunately data for this period were only available for the intact mire region. This area demonstrates a high degree of surface water flow and depressional storage within the hummock-hollow microtopography of the mire surface during storm-flow conditions. This has been confirmed by dipwell data, which indicates a water level near the surface for the majority of the year and a rapid response to rainfall, with water levels above ground during storm events. MODFLOW is not able to reproduce this behaviour and this may explain the improved fit of the model during low flow conditions.

The scale at which data are collected, both temporally and spatially should also be recognised as a possible source of error. Water level data used in this modelling process were collected on a daily basis whilst meteorological data were recorded continuously. The disparity in scale means that quick-flow or the immediate response to storm events were not registered in watertable data sets. The spatial scale of the topographic survey also tends to generalise the surface features that make the hydrology of both the intact and cut-over the mire unique. Both surfaces are uneven and capable of considerable depressional storage. The intensity of surface irregularities, whether anthropogenic or natural, are not easily represented within a large-scale model. Survey and mapping of topography on the scale used, and in fact of any practical scale, means that certain features are omitted. This applies to the pattern of abandoned cuttings, which are approximately 10m wide and separated by a ridge roughly 0.3-0.5m high and 5m wide. The cutting-ridge features at site A are orientated parallel to the boundary drain and hydraulic gradient, whilst at B they are orientated towards the cutting. This exacerbates the problem of water loss, effectively channelling any surface water flow towards the active cutting. This could not reasonably be included in the model. Issues of model form, in terms of transect (area A) or grid (area B), may also effect the accurate characterisation of the site as hydrological boundaries must be strictly defined in the model whilst they may be less permanent in the field.

Some useful implications of the modelling process and outputs can be clearly identified. The lower hydraulic and surface gradients at area A go some way to explaining the better recovery

rate and increased success in re-wetting observed by site managers. Given the higher predicted discharge rates in area B, even a small adjacent reduction in groundwater level has the potential to greatly increase groundwater discharge and accelerate dehydration, making re-wetting impossible. Devito *et al*, (1996) reported head gradients of 0.002-0.005 in forested peatlands in the Canadian Shield, producing specific discharge rates of $8.64 \times 10^{-6} - 10^{-5} \text{ md}^{-1}$, and whilst the gradients are only one order of magnitude lower, the velocities are two orders lower. They still report however, 'a rapid storm response and a predominance of saturated overland flow'. Better simulation of area A to include the surface water portion may enforce these findings and could be used to investigate potential re-wetting strategies for area B.

Given that the surface gradient is higher in the drier regeneration zone B, further investigation of the issue of re-profiling the abandoned surface and the form that any buffer zone may take is advisable. Re-profiling of the cutting-ridge pattern should also be considered in further, in a more detailed modelling scheme.

The main concluding points of this exercise are:

- The high level of model head output fit for low flow simulation (above 94%), suggests potential application of the model to predict the sustainability of restoration measures under summer drought conditions.
- Low gradients, the restricted potential groundwater flow region of the minimum remaining peat depth, combined with restrictive sub-peat geology adjacent to the cutting boundary have contributed to the successful rewetting of area A.
- Higher discharge potential from area B, compared to A, explains to some extent dryer condition of this area.
- Continued high discharge and an increased gradient resulting from further peat removal is likely to result in accelerated dehydration of area B.
- Simulation of subsidence is not a feature of MODFLOW, however the mechanical failure of peat adjacent to the cutting boundary and area B would appear to be due to these factors.
- Extended simulation of all areas for extended storm and low flow periods, with the inclusion a surface water model component should confirm these findings.

The application of modelling techniques to the hydrological investigative processes has filled gaps in the available data, including discharge potential or estimated water loss from the reserve. It has also indicated constraints in the hydrological concept with which the system may be viewed, for example the role of surface water processes. Most valuable of all, the modelling process makes possible predictive assessments of the impact of potential site management strategies, concerning for example, drainage and peat removal. Whilst such predictions are tentative, they provide a baseline from which alternative programs can be developed.

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Monitoring and modelling shallow surface and groundwater flow in mires.

PART A: Monitoring Flow Processes

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Abstract

An ecohydrological study was undertaken to determine influential hydrological processes of an upland valley mire in the North of England, scheduled for restoration. The ground and surface water monitoring programme described focuses on hydrological exchanges and runoff processes within the near surface region of the mire known as the acrotelm. The design of a closed boundary Surface Water Monitoring Plot (SWaMP) is described and precipitation, runoff and groundwater fluctuations recorded within the plot are presented. Vegetation, micro- and macro-topographical data were collected at the site using standard and experimental techniques. These data provide the ecohydrological linkage used in the construction of a numerical model, described in Part B, in which hummock-hollow vegetation sequences determine friction coefficients and microtopographical slopes, depicting the complex, rapidly varying flow type. Such flows are moderated by submerged and emergent vegetation species, occurring at characteristic locations within the microtopographical sequence. It is suggested that these linkages require further investigation.

The data collected support field experience of surface water activity during and after storm events at the site.

Quickflow is well represented in runoff recorded in the SWaMP. It is concluded that enlargement of the plot in a nested-type scheme may better represent the field situation, including both interflow and surface flow within the acrotelm. Unknown storage potential in soil and vegetation make it difficult to establish an analytical rainfall-runoff relationship, and it is suggested that the modelling approach presented in Part B may provide a suitable alternative. Mire restoration management based on the re-imposition of high groundwater levels by drain blocking could result in flooding if the quickflow and interflow observed in this study are detained. The implications for favoured ecological processes should be considered in management plans.

Keywords: mire, peatland, runoff, surface water, groundwater, microtopography, retardance, acrotelm

1. Introduction

In recent years appreciation of the ecological value and importance for catchment hydrology of mires has grown consistently. A mire is a peatland in which peat is being formed and is accumulating (Sjörs, 1948). Throughout Northern Europe extensive areas of upland peatlands have been artificially drained to improve the quality of the sward for grazing livestock and to encourage forest growth, with varying degrees of success. In the lowlands, drainage has also been employed to enable the removal of peat for fuel and as a horticultural substrate, and to increase the potential productivity of agriculture and forestry. It is estimated that only 10% of the former UK mire area remains (Joosten, 1999). In response, many previously disturbed wetlands are now managed for reclamation and conservation objectives, the main aim being restoration of peat forming vegetation and associated animal communities. Understanding of the hydrological processes of naturally and artificially drained peatlands is a prerequisite to effective management of these habitats.

In this paper we are largely concerned with low gradient ombrotrophic peatlands such as lowland raised mires, oligotrophic valley mires and fens having *Ericoid-Sphagnum* dominated communities typically found within blanket bog complexes. According to the diplotelmic model of these peat bodies (Ingram, 1978), we can differentiate between two hydromorphic zones. The surface layer, or acrotelm, of living vegetation and partially decayed vegetation, is saturated periodically when the phreatic level reaches the ground surface. It is highly porous with recognisable plant remains having relatively high hydraulic conductivity and specific yield. Boelter (1965) quotes field measured hydraulic conductivity values of $381 \times 10^{-6} \text{ms}^{-1}$ at 0.15-0.25m depth, $10.4 \times 10^{-6} \text{ms}^{-1}$ at 0.45-0.55m depth, and specific yields of 0.52 and 0.33 respectively, for 'undecomposed mosses'. Below the watertable (Ivanov, 1953, cited in Ingram, 1978) the catotelm consists of permanently saturated, anaerobic peat in various degrees of humification and compaction, hence much reduced hydraulic conductivity. These properties have been discussed at length in the past (Boelter, 1965, Romanov, 1968, Rycroft et al, 1975, Ingram, 1978). A recent and extensive review of the properties of mire peat is provided by van der Schaaf (1999).

By these definitions, there is a partitioning of flow between the acrotelm (extending to approximately 0.5m below the surface) and the catotelm (usually beyond 0.5m depth and up to 15m of peat depth in biologically productive zones). Hammer and Kadlec, (1986), state 'lateral subsurface flows in peatlands are generally insignificant compared to vertical movement of water in response to evapotranspiration demands or to recharge'.

Given that the watertable remains close to the surface throughout the year and responds rapidly to rainfall, the importance of the contribution of near surface flow, flow over the vegetated surface and through the characteristic microtopography of mini pool-channel networks or the hummock-hollow sequence, (Sjörs, 1948, Masing, 1982, Lindsay *et al.*, 1985, Lindsay, 1995) is critical to understanding of mire hydrology.

Verry *et al.* (1988), examined the streamflow response from an ombrotrophic mire and found the 'watertable:discharge relation...closely parallel to the stage:discharge of a level reservoir'. Burt *et al.* (1990) comment that the 'low gradient and near saturated state [of peatlands] make it likely that extensive saturation-excess overland flow may be produced'. Tension infiltrometer experiments carried out by Holden (Holden, 2000) on similar peat soils in the North Pennines, UK, indicated that infiltration-excess overland flow is infrequent, and that in *Sphagnum* covered areas, macro-porosity within the upper 5-10cm make this unlikely. Fitzgibbon (1982) documented saturated overland flow in a bog-fen complex, observing that discharge was greatest when the watertable was at or above the surface. Klove and Bengtsson (1999) identified three peatland runoff mechanisms:

1. rain falling directly onto channels (frequent small runoff peaks);
2. rain falling onto wet soil – antecedent surface saturation and rapid groundwater response (intermediate sized runoff peaks);
3. flooding of the upper catchment due to prolonged rainfall (largest runoff peaks).

Rain falling directly onto channels could also refer to shallow surface water networks within a hummock-hollow complex. Verry *et al.* (1988) conclude by suggesting the use of well-defined hydrological functional models to quantify these effects. Whilst many predictive numerical, three dimensional groundwater models of highly acceptable levels of accuracy exist, and some have been applied to the hydrology of mires (MacAlister and Parkin, 1998), none are capable of reproducing both the groundwater and complex surface water processes observed in wetlands. A spatially distributed numerical model of mire hydrology must incorporate near surface and overland flow at a resolution of sufficient detail to exclude the manifold simplifying assumptions regularly employed in hydrological modelling, such as large scale Darcian flow processes (Hemmond and Goldman, 1985). Not only do assumptions introduce inaccuracies, they also cause numerical instability in solution schemes (MacAlister, 1996). Spatial scale must necessarily include microtopographical variation, bed roughness and

vegetation imposed friction. A suitable model should be capable of reproducing the rapidly varying and potentially discontinuous flow conditions likely with locally steep surface gradients, shallow flow depths and hence high velocity flow (Zhang and Cundy, 1989).

The overall aim of this project has been to achieve better understanding of mire hydrological processes through investigation and numerical simulation, or modelling. These two objectives are represented in parts A and B of this paper. In part A, field processes are examined and discussed. In part B, the numerical model GSHAW5 (Ground and SHallow Water equations solved by FInite Volume Equations) is described and tested using data from the field plot outlined in part A.

A field site in the British uplands, likely to exhibit surface flow processes was selected and a programme of hydrological monitoring was undertaken to characterise the site hydrology. Having established the prevalence of near surface and surface water processes at the site, monitoring was intensified to include small scale, acrotelm processes. This paper describes the field site (Section 2) and the installation of its hydrometric network, using both established and experimental techniques (Section 4). The need to parameterise the key hydrological functions at field scale in order to reproduce them numerically was prevalent in monitoring strategy and is discussed in the methodology (Section 3). The design and operation of an experimental Surface Water Monitoring Plot (SWaMP) (Section 4) and the development of survey techniques for the vegetation and microtopography of a hummock-hollow complex (Section 5) are described. Outputs from the whole site monitoring regime and the SWaMP are presented (Section 6), field data and monitoring methodology are discussed (Section 7) and conclusions on the estimation of runoff in a mire environment are drawn (Section 8).

2. The Field Site

Trough End Bog (grid. ref. NY383592), is a small upland valley mire (2ha) in the catchment of the Potter Burn (upper R. Rede catchment) within the Northumberland National Park in Northern England (Figure 1). Up to 3.5m of peat have accumulated over fell-sandstone and the site supports a wide range of flora and fauna, including extensive *Sphagnum* hummock-hollow complexes and *Drosera rotundifolia* (Round-leaf Sundew) (UK National Vegetation Communities primarily M15, with M17 and M18) in addition to *Dactylorhiza maculata* (Heath Spotted Orchids). The site is currently subject to shallow drainage via a system of peat-grips (shallow plough drains) and some 0.5m drains. There is evidence of high flows and erosion of the boundary drain channels. Sheep, which are allowed to graze freely across the site, contribute to erosion of both drains and of the mire surface, creating trails across the bog. The landowners wish to manage the site for conservation value and remediate past damage.

The main body of the site is largely ombrotrophic, with inputs from adjacent uplands intercepted by 0.5-1m boundary drains. Piezometers installed close to the uppermost margin of the mire suggest a weak potential for groundwater inputs at this point, but this was not confirmed or observed elsewhere. Changes in vegetation communities close to boundary drains, from *Erica tetralix-Sphagnum papillosum* to *Juncus effusus-Sphagnum recurvum* dominated assemblages suggest enriched nutrient content. However, this does not extend more than 1m beyond the boundary drain. Anecdotal evidence suggests that storm events at the site are characterised by a rapid succession to saturated overland flow. This corresponds with consistently high watertables observed throughout the year in dipwell readings (Figure 2), low recorded saturated hydraulic conductivity (piezometer method) and low recorded infiltration (double-ring infiltrometer) (Section 6, Table 2). The climate of the site can be described as cold-humid, as would be expected in a temperate region at an altitude of 276-283m above sea level (Figure 1). High rainfall (10-year mean 1030mm) is distributed fairly evenly throughout the year, with potentially inflated evapotranspiration occurring during the months of May to September (Figure 3).

The macro-topography of the site was surveyed manually using a Pentax Automatic Level and the dipwells were levelled to ordnance datum (Figure 1). Vegetation across the site was surveyed in March 1997 (Gough, 1997) and again in July 1999. Canonical Correspondence Analysis (CCA) (ter Braak and Smilauer, 1998) of the July 1999 vegetation data suggested that watertable fluctuation (range) and microtopographical range were defining environmental variables (axis one and two) in community composition (MacAlister, 1999).

Figure 1. Surveyed monitoring and drainage network at Trough End Bog, Northumberland, UK (NY383592). Plot dimensions based on 0.5m contour interval (z-axis) and 10x10m grid cells (x - y-axis). Inset: location of Trough End in North of England.

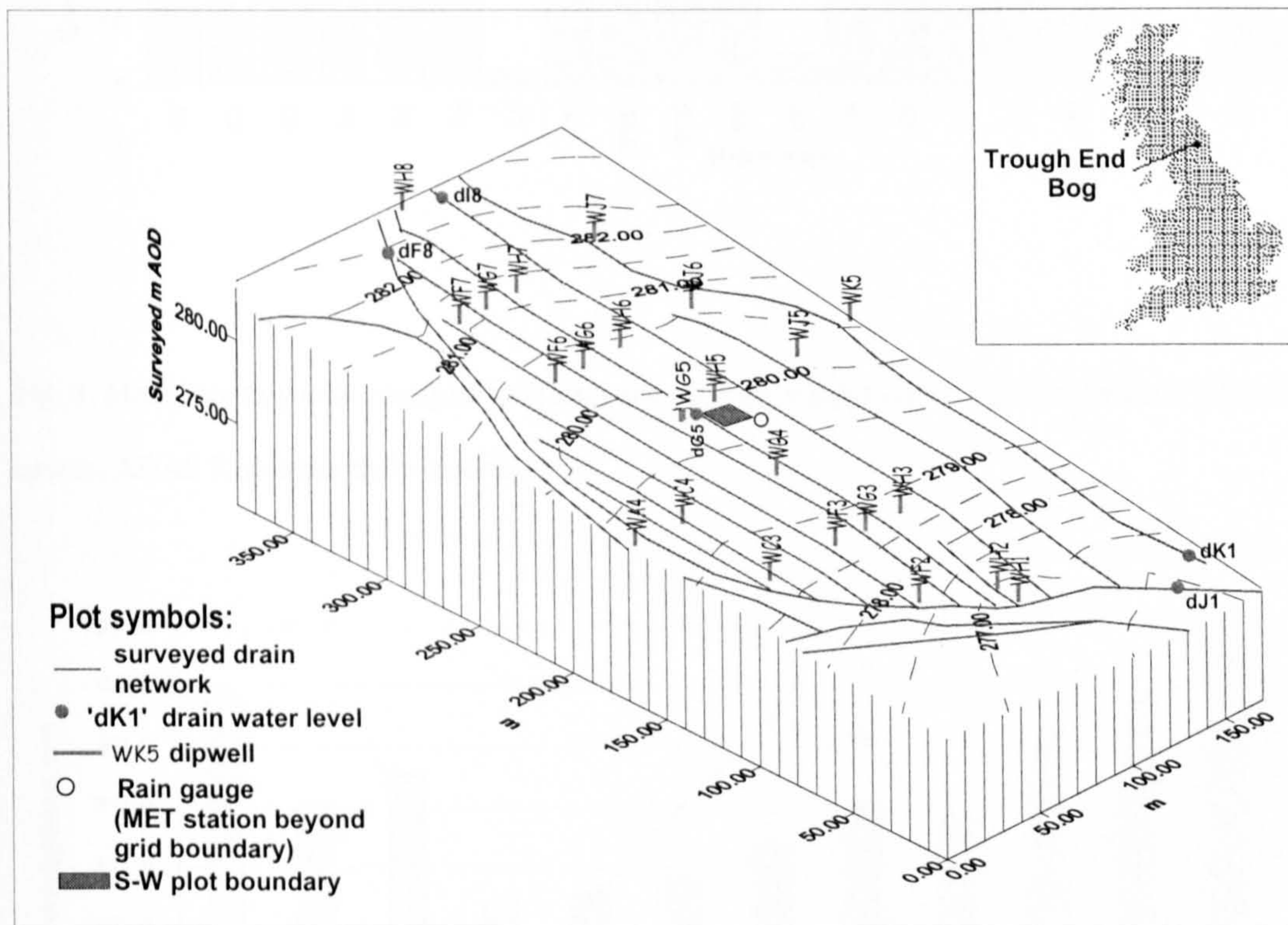


Figure 2. Percentage of total weekly dipwell records when the watertable was at or above the ground surface, (May 1998-February 2000) – one bar represents one dipwell.

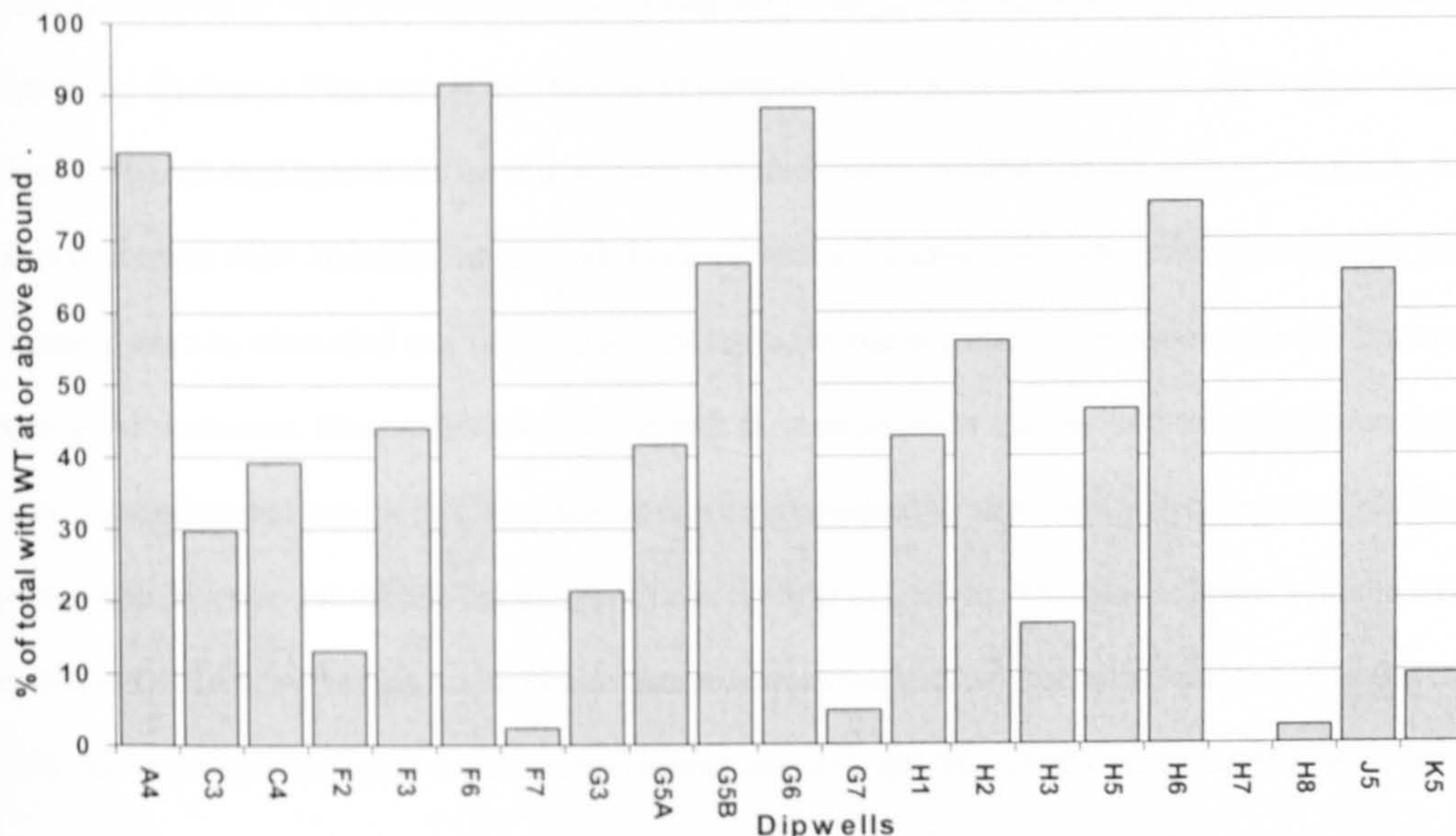
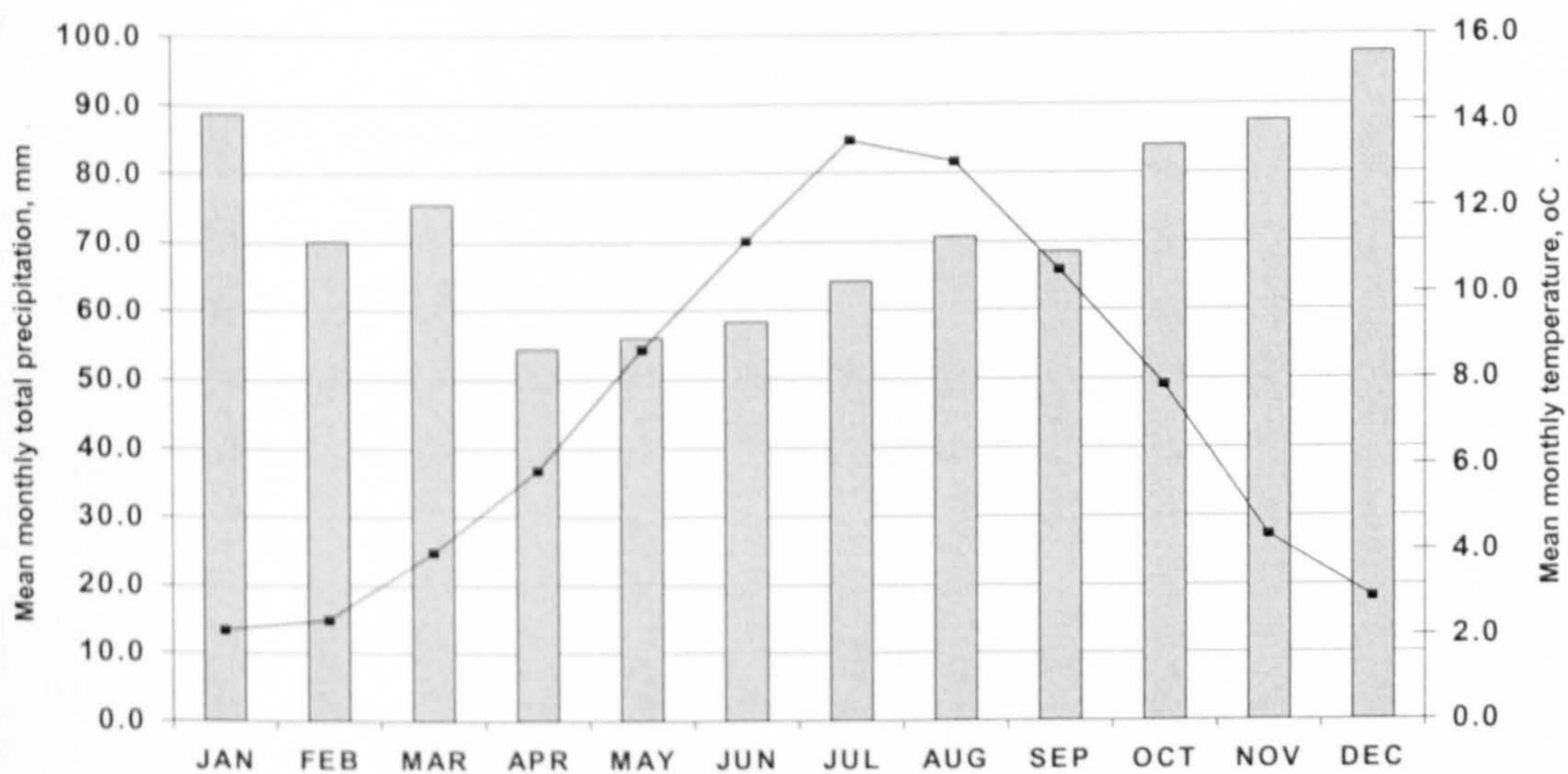


Fig. 3. Mean monthly total precipitation (mm) and daytime temperature (°C), Trough End, 1985-1998. Data source: ADAS Redesdale daily records.



3. Identification of key hydrological components and model parameterisation

The first priority of hydrological characterisation of the site must be the establishment of a basic water balance and the monitoring of its key components including net recharge, sub-surface seepage (input) and leakage (output) and discharge. Past review and testing of complex hydrological models for mires (MacAlister and Parkin, 1999) has highlighted the need to include a surface water equation along with groundwater flow where surface processes were identified as integral. In cases where a numerical model will be employed, further parameters must be identified and satisfied according to the mathematical expressions used to represent real hydrological processes. The model described in part B, is required to operate in three dimensions, but maintain a realistic computational time. The Darcy law within a representative grid scale was considered most suitable expression to describe subsurface exchanges (Yakirevich *et al.*, 1998). This was coupled with the shallow water equation in GSHAW5 (Part B), so that basic data requirements to solve the numerical schemes were identified as aquifer thickness and hydraulic conductivity (transmissivity), specific yield (storage coefficient), head gradient (ground part); water depth, friction coefficient and bed slope (surface part) all within a three dimensional co-ordinate system. In addition to fixed model parameters it was necessary to collect areal groundwater head and surface water discharge to validate model outputs. In order to relate the vegetation of the site to hydrological function, it is also necessary to survey the vegetation assemblages on an equivalent scale. This relates directly the fixed components of the model environment in terms of friction or flow retardance and physical structure of the microtopography. It is intended that these relationships will be investigated further at a later stage.

4. Hydrometric methodology

Watertable and drain stage have been recorded weekly since May 1998, when 21 dipwells and 5 ditch gauge boards were installed across the site (Figure 1). Dipwells were constructed from perforated plastic tubing, 40mm in diameter. Water level in each well was recorded manually using a purpose built sensor consisting of an open circuit and buzzer, wired to a float switch. The tubing was installed into a cavity prepared with an auger to the full depth of the peat, and anchored in the underlying weathered sandstone and sediment where possible. The peat depth at each well location was recorded. The dipwells had loosely fitting caps to prevent insects from becoming trapped. The dipwell network was designed to include the differing vegetation zones identified across the site. Wells were distributed in an irregular grid according to ditch spacing and numbered A to K from south to north, and 1 to 8 from east to west, where all transects were not the same length. Gauge boards were fixed into intact sections of drain channel by inserting angle iron into the substrate and attaching rules. Large sections of drain have been eroded by water and collapsed due to crossing sheep and drain channels have not been maintained for several years.

Meteorological data are collected daily at a manual weather station nearby, and more recently, rainfall data have been collected on site.

The minimum recorded summer watertable was identified as the range of the acrotelm, indicating aquifer thickness within the zone of the dipwell, with hydraulic conductivity and saturated infiltration closely related in this upper layer (Table 2).

The saturated surface infiltration (F_{sat}) was recorded in the field using a double-ring infiltrometer, previously employed in a bog by Galvin (1976) and Stunell (1996). Although the method was designed for bare soil, it was the only practical way of recording the rapid conductivity in the surface region. The method measures the rate of saturated infiltration and this was not considered a problem given that much of the natural infiltration was occurring under saturated conditions. If the watertable is high throughout the extended recording period, the process recorded is effectively the saturated hydraulic conductivity of the surface layer.

The saturated hydraulic conductivity (K_{sat}) was recorded in the field at depths 0.4-0.5m, 0.9-1m, 1.4-1.5m, and 1.9-2m using a modified piezometer method with rising head, or seepage tube (Kirkham, 1946, Luthin and Kirkham, 1949). This method whilst not ideal, has been applied widely to peatland situations. A review of past applications is provided by Rycroft *et al.* (1975). Problems in the application of this method arise as the peat substrate is not rigid and so the cavity tends to collapse when inserting the piezometer, and small fibres from the peat clog the inlet. These problems were avoided by inserting a slightly wider pipe into the augered cavity, removing peat from this sleeve using suction, and then inserting the piezometer whose inlet had been covered with nylon mesh to prevent infilling. Results of conductivity and infiltration tests are presented in table 2.

Specific yield values were estimated using the Kozeny-Carman Equation for effective porosity values as described by Ahuja *et al.* (1985), which calculates soil water characteristics from limited data.

The components of the water balance had to be recorded continuously in a discrete region, with accurately defined boundary conditions. A region of relatively constant vegetation assemblage, with good hummock-hollow features and small macro-surface gradient was identified in the central ombrotrophic region of the bog (Figure 1). A 150m² plot was fenced to prevent disturbance and a central 10m x 10m area marked out. Within this area it was determined that acrotelm features including vegetation composition, microtopography, recharge, groundwater fluctuation and surface water discharge would be recorded. The basic design of the Surface Water Monitoring Plot (SWaMP) is represented in plan view in Figure 4. Groundwater fluctuations within the plot were monitored using two dipwells containing pressure transducers, Druck model PTX530 (4-20mA, 1mH₂Og) and a multi-channel data logger (Technolog Newlog Universal logging Module and 2 Channel Interface Unit). The groundwater head was recorded continuously, with a logging frequency of 20 minutes. The logger recorded changes of 1mm, which were accepted as accurate within the small range of fluctuation. It was assumed that the only recharge entering the plot was precipitation and this was recorded by an automated tipping-bucket rain gauge (Environmental Measurements, model ARG100, 1LX Data Logger). Rainfall was recorded continuously with a logging frequency of 20 minutes, so that the records are effectively cumulative rainfall over the logging interval.

The plot was positioned adjacent to a shallow main drainage channel (peat grip) and the small hydraulic gradient was determined to be towards the drain. The nearest edge of the 100m² plot was 3.5m from the grip. Flow barriers were then inserted into the substrate (peat) around three sides of the plot, to a depth beyond the influence of the drain and the lowest recorded watertable at this point (0.35m). In this way, all lateral flows both surface and subsurface, were excluded so that the only flow occurring within the plot resulted from precipitation. Corrugated plastic roofing material was found most suitable to form the no-flow barriers, being rigid, inert and reusable.

At the 'bottom' of the plot, next to the drain, a collecting channel was fixed into a shallow depression below the level taken as the surface (in this case, the living zone of the non-vascular plants), to collect surface water runoff. Standard plastic domestic guttering forms an adequate collecting channel. This was fixed in place using more corrugated plastic inserted approximately 0.2m into the ground to allow groundwater leakage from the plot and to prevent it entering the channel. The flow was directed into a 1.2 litre tipping-bucket gauge fixed into a submerged sump, from which it was then pumped out of the plot into the nearby drain. The gauge followed a design developed by the Institute of Hydrology, Wallingford, UK, and previously employed in similar sized plots (Calder, 1976, Calder and Rosier, 1976). The buckets were calibrated *in situ*, and attached to a 'Squirrel' multi-channel continuous data logger (Grant Instruments 1200 series). The logging interval was 20 minutes, so that the recorded flow rate is a 20-minute-mean discharge calculated from 20-minute-cumulative volume. A 12-watt 'Lalisaz' marine bilge-pump (2270 litres per hour), powered by rechargeable 12-volt batteries, was employed to remove runoff from the sump, as it could not be drained by gravity.

Figure 4. The SWaMP design in plan view – not to scale.

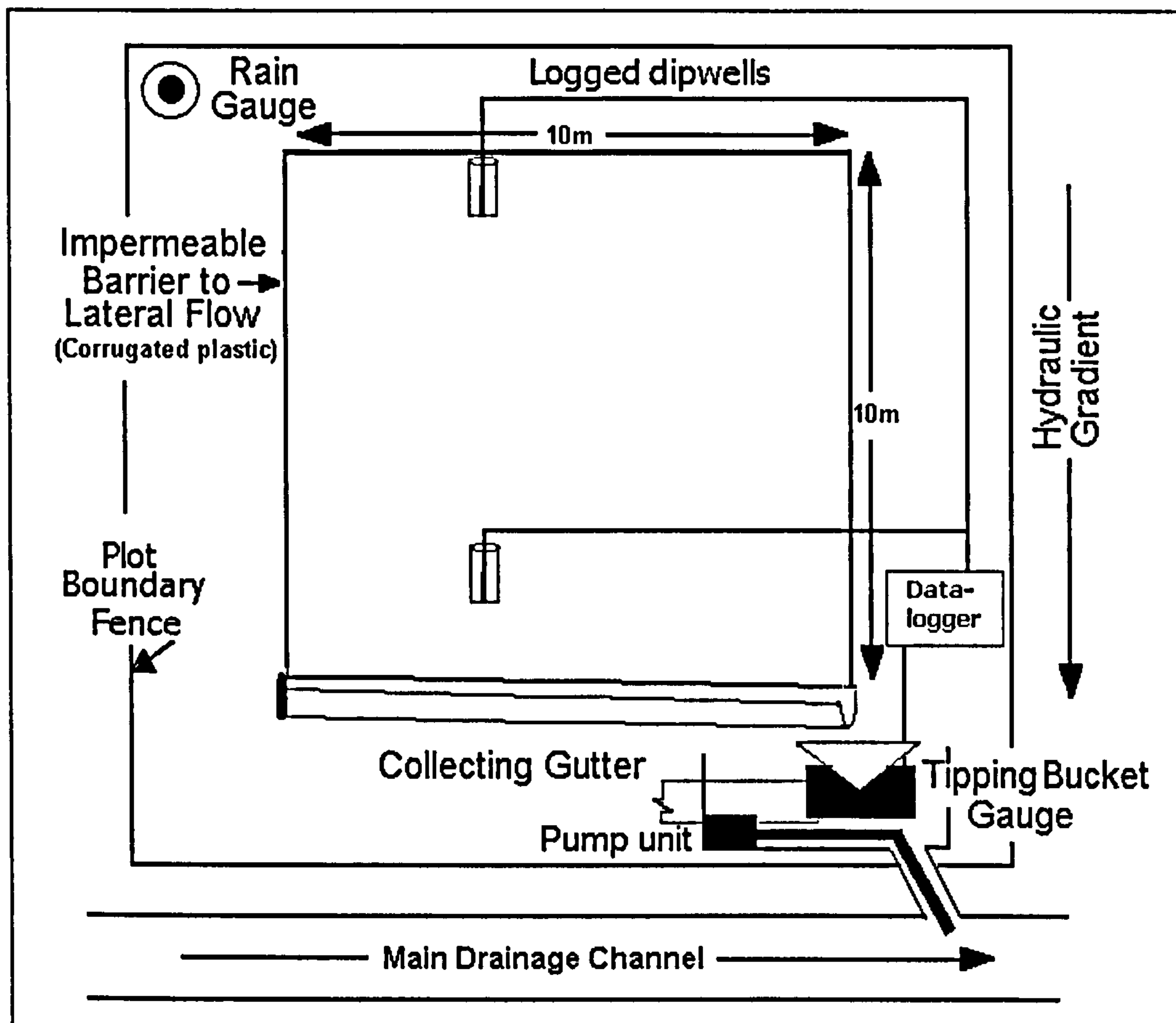
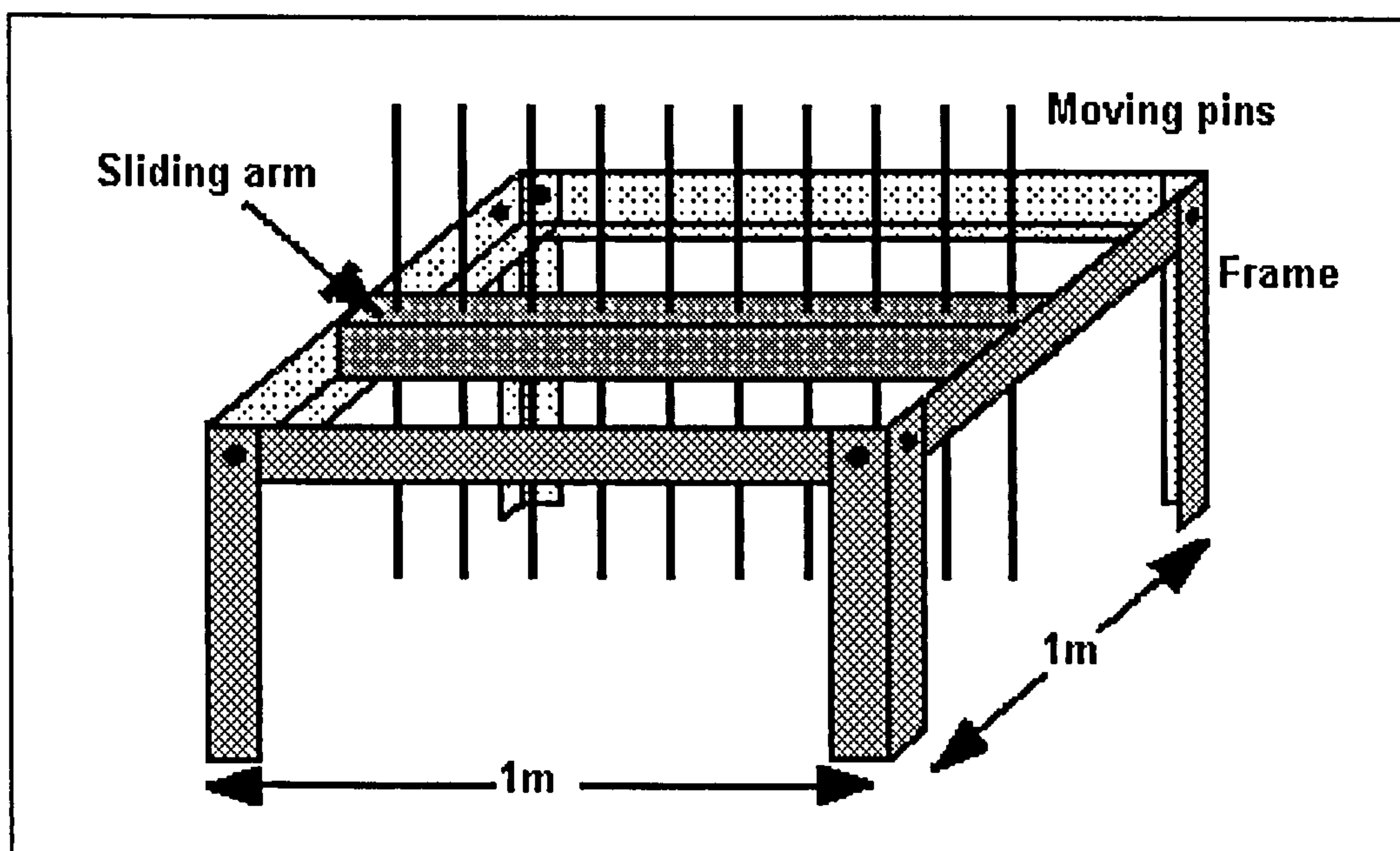


Figure 5. Plan of the purpose built 1m² vegetation and microtopography pin-frame.



5. Vegetation and Microtopographical Survey Methodology

The 100m² of the plot were divided into 1m² cells and assigned x and y co-ordinates 0 to 10 on both axes. The addition of the gutter, external to the original plot with dimensions 10x0.1m, increased the x-axis maximum to 10.1. The z co-ordinate (elevation) of the origin of each cell was surveyed to the nearest benchmark using a Pentax Automatic Level, and the base of the collecting gutter was surveyed in the same way. The likelihood of discontinuous, supercritical flow in a shallow surface water condition has already been identified and accepting this the model cell size was selected as 0.01 m². This scale was also considered representative of microtopographical variation within the vegetation complex (Lindsay, 1995). The 1m² cell co-ordinates were then decimalised accordingly with the addition of the row of 0.1 m² cells forming the collecting gutter, making a total of 10100 cells.

In order to calculate bed slope and friction coefficients, a method was developed to record plant species and micro-elevation simultaneously. Vertical measurements from a horizontal datum frame have been used previously to survey vegetation within a microtopographical sequence in an Irish bog (Guinan *et al*, 1998). This method was expanded so that freely moving vertical pins were supported on a sliding horizontal arm within a 1m² horizontal frame with adjustable legs (Figure 5). The frame was placed over the pre-marked 1m² cell and levelled using a portable spirit level. The distance between the cell origin and the frame height at that corner were recorded and taken as datum for that cell. The vertical range in microtopography was then recorded, relative to the horizontal datum bar, at each corner of the 0.1m² cells using the 0.5m aluminium pins. The bar could then slide across the frame and hence the quadrat, with measurements repeated at 0.1m intervals. Plant species were recorded at the same point, so that for each 0.1m² square, four elevation and four vegetation records were taken, revealing the surface features in three dimensions.

The Manning's friction coefficient for each cell was estimated from the surveyed vegetation species. A large body of literature exists concerned with resistance values of submerged and non-submerged vegetation (Ven Te Chow, 1959, Kouwen *et al* , 1981, Turner and Chanmeesri, 1982, Jensen, 1983, Walker and Skogerboe, 1987, Abdelsalam, *et al*, 1992, Bakry, *et al*, 1992), however this is largely focused on cultivated crops and weed growth in irrigation channels. No published values could be found for mire vegetation and so these were estimated for each species according to similarities in its physical structure to plants having published coefficients and by the likelihood of submergence during model flows. In this way, recorded species were assigned friction coefficients (Table 1).

Table 1. Submerged and emergent vegetation species and surface material recorded within the SWaMP, and their assigned Manning's coefficients¹.

Submerged plant species / surface material	Manning's coefficient	Emergent plant species	Manning's coefficient
Plastic gutter	0.01	<i>Vaccinium myrtilus</i>	0.08
Bare peat	0.02	<i>Erica tetralix</i>	0.08
<i>Drosera rotundifolia</i>	0.06	<i>Potentilla erecta</i>	0.08
<i>Vaccinium oxycoccus</i>	0.06	<i>Narthecium ossifragum</i>	0.1
<i>Empetrum nigrum</i>	0.06	<i>Eriophorum angustifolium</i>	0.12
<i>Sphagnum capillifolium</i>	0.06	<i>Eriophorum vaginatum</i>	0.12
<i>Sphagnum capillifolium (rubellum)</i>	0.06	<i>Molinia caerulea</i>	0.12
<i>Sphagnum magellanicum</i>	0.06	<i>Carex nigra</i>	0.12
<i>Sphagnum palustre</i>	0.06		
<i>Sphagnum papillosum</i>	0.06	Submerged / emergent plant species	Manning's coefficient
<i>Sphagnum recurvum</i>	0.06		
<i>Sphagnum tenellum</i>	0.06	<i>Aulacomnium palustre</i>	0.1
<i>Polytrichum commune</i>	0.1	<i>Dicranum scoparium</i>	0.1

¹ In this form the Manning's coefficient is not usually assigned a unit. According to the formulation, when the contributing parameters have SI units, the units of the coefficient would be $m^{-1/3}s^{-1}$ (Ven Te Chow, 1959).

6. Observed hydrological characteristics and SWaMP hydrographs

Figure 2 illustrates the occurrence of surface water at the site during the 22 months, from May 1998 – February 2000, in which weekly records were taken. The columns represent the percentage of total weekly readings for each individual well, in which the watertable was recorded at or above the ground surface. The watertable in dipwells in the central area of the mire, numbered 4, 5 and 6 (Figure 1) was recorded at or near the surface for a minimum 40% of the monitoring period (Figure 2). The same is true for wells to the middle and south of the plot. The watertable in wells to the west of the bog with numbers above 6, and outside of the mire boundary at well K5, remains low throughout.

Figure 3 represents the mean monthly precipitation and temperature for the site, based on daily records collected between 1985 and 1998. Rainfall is fairly high throughout the year never falling below 55mm per month, with April the driest month from whence rainfall rises steadily, peaking in December and January close to 100mm per month. Daytime temperature follows a clear unimodal trend, peaking in July at 14°C and lowest in January at 2°C, although it is likely to be much lower during the long winter evenings.

The mean recorded saturated infiltration capacity (ms^{-1}) of the surface layer (approximately 0-0.2m), the saturated hydraulic conductivity (ms^{-1}) up to 2m in depth, and estimated specific yield values (dimensionless) are presented in Table 2.

Table 2. Field measured mean saturated infiltration (F_{sat}), hydraulic conductivity (K_{sat}) (ms^{-1}), and estimated specific yield (S_y) (dimensionless) at Trough End Bog.

	Surface	0.4-0.5m	0.9-1.0m	1.4-1.5m	1.9-2.0m
$F_{\text{sat}} \& K_{\text{sat}} (\text{ms}^{-1})$	70.9×10^{-8}	2.45×10^{-8}	1.5×10^{-8}	2.69×10^{-8}	2.55×10^{-8}
S_y	0.006	0.003	0.002	0.003	0.003

Figure 6a illustrates the microtopography of the SWaMP using the surveyed elevation of the cell 'corners' within the horizontal plane co-ordinates and the estimated central elevation (from the geometric mean of the four surrounding points), so that slope is represented in all directions.

The Manning's friction coefficients assigned to each surveyed vegetation species are presented in Table 1.

Figure 6b illustrates the distribution of assigned friction coefficients across the plot.

Recharge as precipitation and the resulting fluctuations in groundwater level and surface runoff were recorded simultaneously in the SWaMP. The recorded 20-minute cumulative rainfall and runoff totals were examined and periods suitable for modelling were selected. Despite the operation of the SWaMP over a four-month period, many data were unusable due to equipment failure or low battery problems in the harsh environment conditions of the mire.

Recorded recharge and runoff for two 24 hour periods from midday 9th June and 10am 14th June 2000, are represented as overlapping columns in the Figure 7. Runoff in m³ and recharge as total precipitation in mm are given as the cumulative totals logged during a 20-minute interval. In both plots runoff values have been multiplied by 10⁻² in order to share the y-axis with precipitation. The fluctuating watertable records in dipwells 3,2 at the 'gutter end' and 3,9 at the upper end of the SWaMP, are represented by line plots of water level in m below ground.

Fig. 6a . Microtopography surveyed across the SWaMP using the pin frame: 0.02m contour interval.

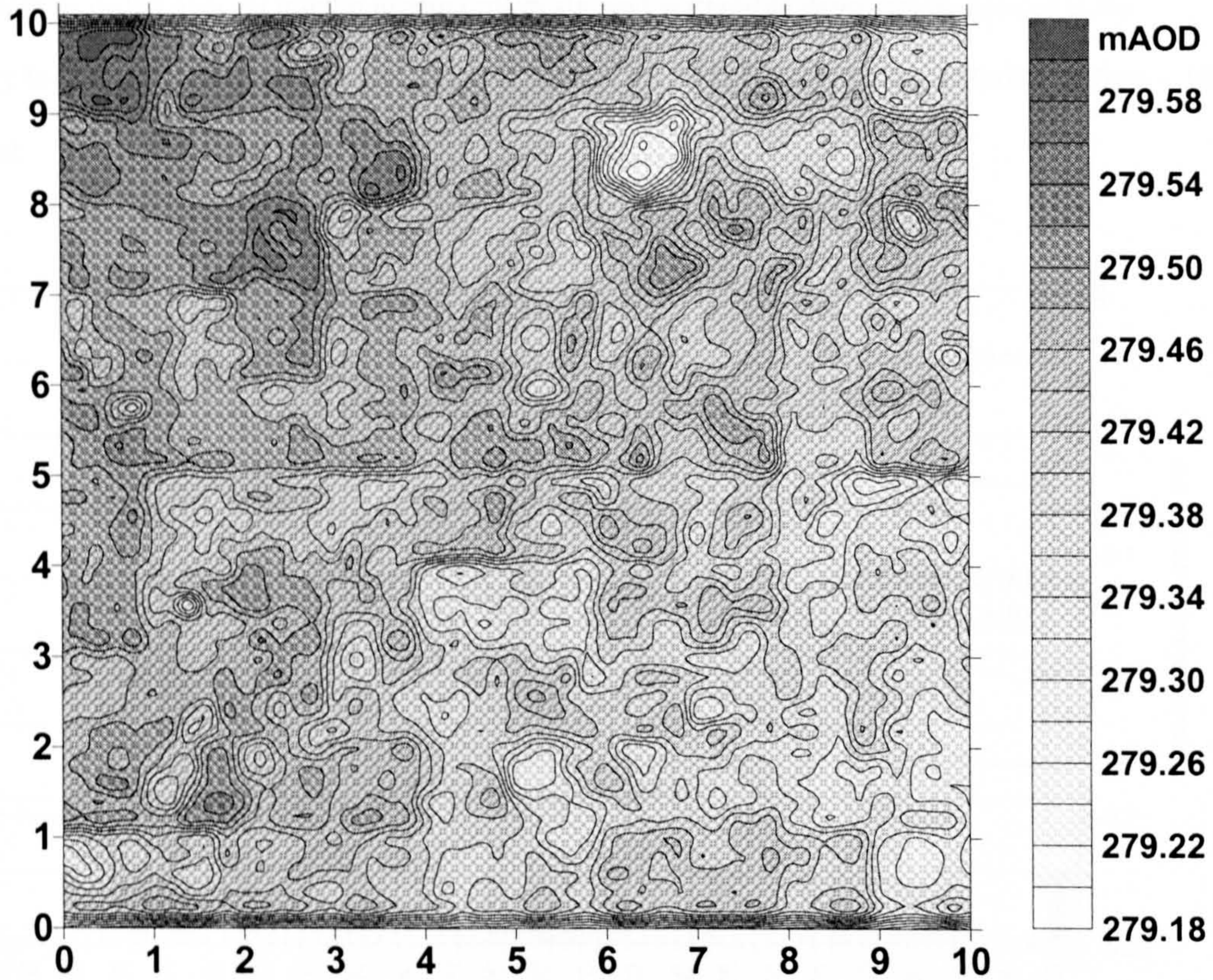


Fig. 6b. Manning's friction coefficients (n) assigned to vegetation surveyed across the SWaMP using the pin frame.

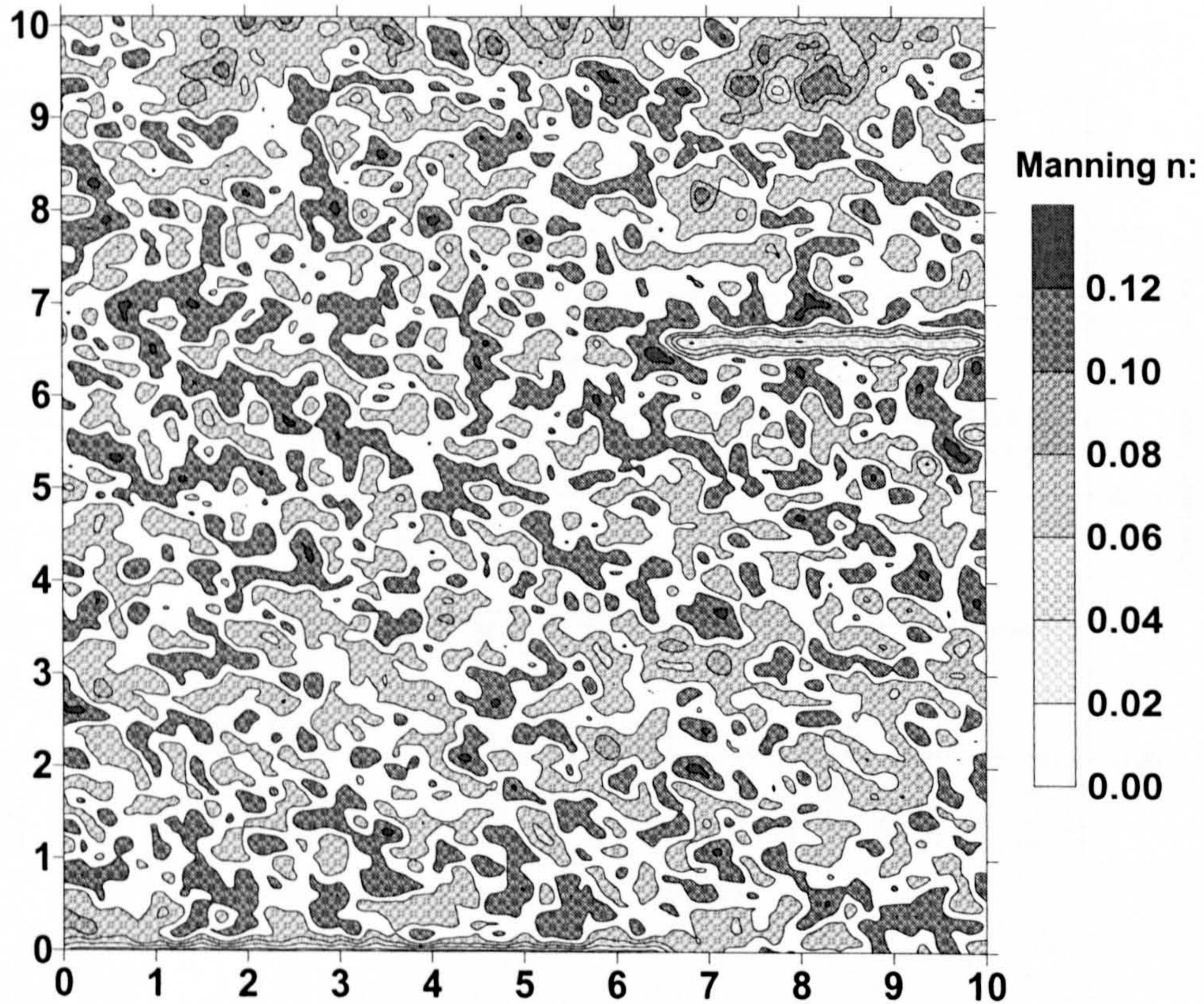


Figure 7a & b. SWaMP water balance components, where precipitation (mm) and runoff ($\times 10^{-2} \text{ m}^3$) are cumulative totals recorded over 20 minute logging intervals, and watertable depth below ground is the simultaneously logged dipwell water level. a) 12:00 9th June – 12:00 10th June, 2000; b) 10:00 14th June – 10:00 15th June, 2000.

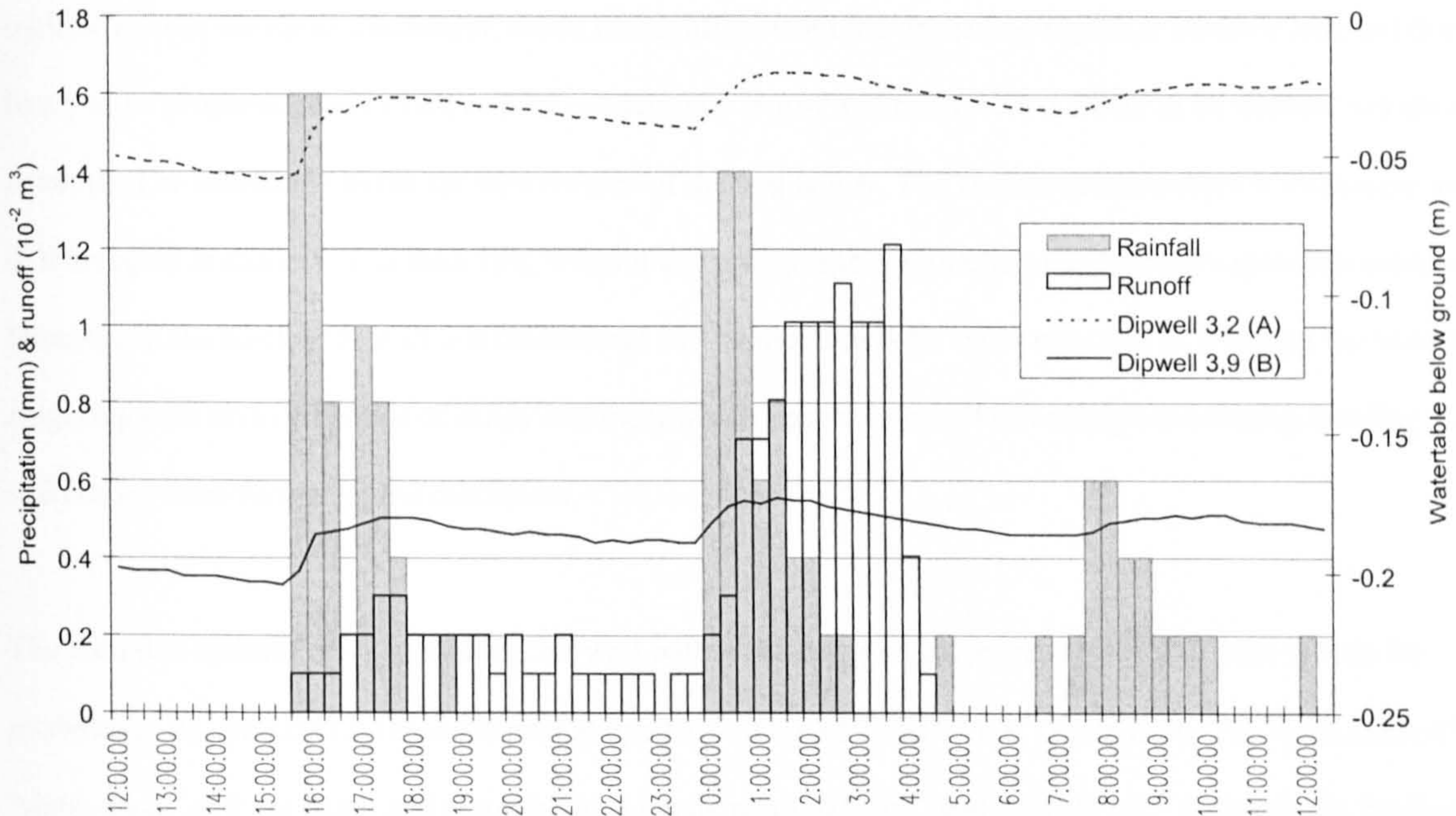


Fig. 7a. 12:00 9 June - 12:00 10 June 2000

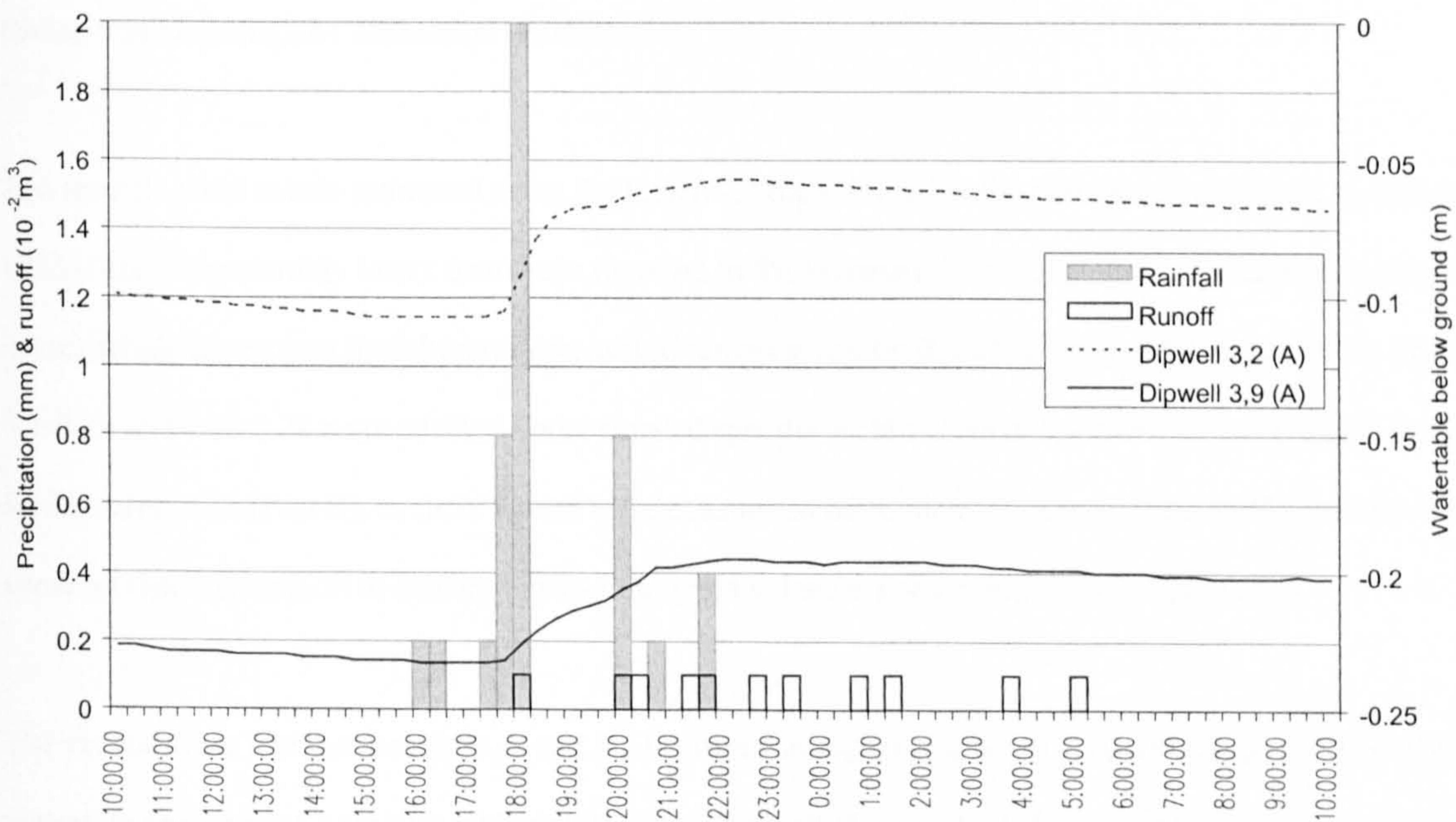


Fig. 7b. 10:00 14 June -10:00 15 June 2000

7. Discussion

The watertable was observed to be high in the mid-southern part of the bog, where vegetation and yearlong ponding (Figure 2) suggest that this area receives inputs for the adjacent upland area. The watertable in wells in the central ombrotrophic area, which remain at or above the surface at least 50% of the time, are not supported by inflow from the upper catchment. Some throughflow from the upper bog region is possible here but this is likely to be proportionately small as peat conductivity is low and most flow is likely to be directed via the drain network. The watertable in the far western part of the bog is low. The surface gradient here is increasing and peat in this region is shallow (less than 1m), without any recognisable acrotelm or associated vegetation communities. Drainage in the shallow peat of this transitional part of the mire is far more effective in lowering the watertable. Augering here revealed bands of sandy sediment which appear to have been transported during flooding with soil eroded from further up the catchment.

The recorded hydraulic conductivities fall well within the range of values reported by Boelter (1965) for moderately decomposed herbaceous peat at depth 0.7-0.8m of $7.7 \times 10^{-8} \text{ ms}^{-1}$, by Ingram (1967) for blanket bog 'water-track' at 0.5m depth and amorphous at 1m depth of 0.2×10^{-8} and $0.3 \times 10^{-8} \text{ ms}^{-1}$ respectively, by Sturges (1968, cited in Rycroft et al. 1975) for well decomposed peat at 0.46m and 0.91m depth of $0.28 \times 10^{-8} \text{ ms}^{-1}$ and $0.18 \times 10^{-8} \text{ ms}^{-1}$, and Galvin's values for blanket peat of $6.94 \times 10^{-8} \text{ ms}^{-1}$ (1976). A range of K values were applied during model testing and calibration (Part B).

The specific yield values estimated using the Kozeny-Carman Equation for effective porosity values (Ahuja *et al.*, 1985), were considerably lower than those reported in the literature. The calculated values are up to two orders of magnitude lower than the laboratory measured ranges given by Boelter (1965) and Galvin (1976) which were 0.1-0.79 and 0.08-0.38 respectively. Approximated specific yield values of 0.05 and 0.1 were applied during model calibration (Part B), as these values were considered more likely to represent the field situation. It is apparent that this method of calculating specific yield values is not suitable for mire peat soils.

The groundwater levels at positions A and B, illustrated in Figure 7a&b, indicate that the watertable response to rainfall is similar across the plot, although less rapid in well B. In both of the selected monitoring periods, the watertable is higher at point A, with rising levels following rain synchronised in wells A and B. The watertable

is higher in both wells in the earlier selected monitoring session (9-10 June), and runoff is clearly greatest in this period. The antecedent watertable appears to influence the instance of runoff, indicating a saturated overland flow process. Once this process is initiated additional rainfall is rapidly transformed to runoff, as can be observed in Figure 7a. The instance of runoff at point A suggests a watertable of 0.05m below the 'ground surface' is the threshold for overland flow. The intensity of fluctuation in microtopography, being as much 0.1m height gain-loss in 0.1m laterally (Figure 6a), makes identification of a 'true' ground surface a subjective process. So that 0.5m below ground at point A, may be 0.5m above ground 0.2m distant.

The rainfall-runoff relationship exhibited from 9-10 June and 14-15 June are typical of observed behaviour in the plot: initial rainfall results in a small amount of runoff whilst interception and depression storage account for a larger proportion. As rainfall continues and the plot wets up runoff increases, peaking one to two hours after the storm peak. The large storage capacity of the intercepting vegetation is likely to be considerable (although not currently represented within the GSHAW5 formulation - Part B). Water stored at the surface within the vegetation hummock-hollow sequence will contribute considerably to evaporation.

Runoff in the latter part of plot in Figure 7a does not appear to follow the same trend as the previous 14 hours: it would be expected to increase again following the third substantial rainfall event. The reason that no runoff was recorded is most probably due to equipment failure in the form of flat pump-batteries. This was a common problem in operation of the plot, causing the sump to fill with runoff and so that the tipping bucket was overcome. It is suggested that in a low surface gradient situation such as this, isolated from mains power supply, that an alternative and sustainable power supply would be most useful. A small wind turbine or solar cell should be adequate to maintain the battery charge. In general, the design of the plot proved very successful. The plastic roofing sheet provided an adequate barrier to isolate the acrotelm, its corrugations over-lapping in an inter-linking fashion to prevent leaks. Leakage between plastic sheets and increased infiltration immediately next to the barrier were identified as potential sources of experimental error but were not observed. Such potential perimeter errors would be reduced proportionally in larger plots. It should also be noted that if the barriers are left in place in droughty locations for long periods, dehydration within the plot might be accelerated without the buffer of the surrounding water table. The survey method developed for vegetation and microtopography within the SWaMP proved extremely accurate but time consuming, with a maximum survey rate of ten quadrats per day (10m²).

8. Conclusions

Periods of surface runoff within the one hundred square metres SWaMP were recorded successfully and it has been demonstrated that overland flow accounts for a significant proportion of the mire water balance. The proportion of the water balance accounted for by runoff cannot be described by a predetermined analytical relationship as it is dependent on antecedent conditions not easily recorded at this time, such as storage within the vegetation and unsaturated soil zone. The establishment of a good match between field and numerically modelled behaviour using GSHAW5, presented in Part B of this paper, may replace a conventional analytical approach.

The runoff recorded within the SWaMP represents a portion of the total acrotelm flow, effectively the quickflow component of a flood hydrograph, and is determined largely by the height of the collecting gutter. To estimate the runoff for the entire mire area it would be necessary to include both the quickflow in the immediate vicinity of the SWaMP and interflow component, which becomes runoff and surface water in the lower catchment. This would require nesting of the SWaMP within a larger recording catchment.

The role of acrotelm flow should be considered when intervening in the drainage network during mire restoration. Such management action normally aims to stabilise groundwater levels by blocking drainage channels. The observations made during this study are that drain channels are likely to be most effective in the removal of quickflow and interflow from the acrotelm. Damming of channels will slow down water removal by reducing the quickflow component of the flood hydrograph, potentially resulting in surface flooding. This may not be desirable to conservation management aims and the favoured ecological conditions, but should not be overlooked.

The difference in groundwater level within the plot is significant. The two dipwells are 7m apart but the recorded water level is consistently lower further up the hydraulic gradient, moving away from the collecting gutter.

Within monitoring networks in peatlands dipwells are regularly considered to represent the watertable over much larger areas, but monitoring within the SWaMP reveals the need to increase well density to truly characterise the groundwater condition in one hundred square metres.

Flow retardance and potentially high storage capacity within the vegetation of the hummock-hollow complex requires further investigation if it is to be better represented. Friction coefficients applied in this study were estimated as extensive literature review revealed little previous study of flow retardance within similar vegetation types. Determining more appropriate friction coefficient empirically demands an extensive and lengthy study, but is necessary to improve the suitability of estimated values. The micro-scale of topographical and vegetation data collection within the plot would not be replicable on a whole-site scale, and therefore future initiatives will focus on up-scaling issues and the relationship between species assemblages, microtopography and runoff production.

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**Chapter 6. Monitoring and Modelling Shallow Surface and Groundwater
Flow in Mires. PART B: Modelling Flow Processes**

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Monitoring and Modelling Shallow Surface and Groundwater Flow in Mires.

PART B: Modelling Flow Processes

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Abstract

An integrated shallow surface and ground water model, GSHAW5 (Ground and SHallow Water equations solved by Finite VolumE method), has been developed to simulate acrotelm flow in mires. The surface water flux is estimated using the Osher shock-capturing scheme, making the model suitable for simulation of steady and unsteady, continuous and discontinuous, subcritical and supercritical surface water flow conditions. The scheme proves highly successful in the simulation of micro-scale flow in complex mire microtopography with extremely variable flow conditions. The groundwater fluxes are computed by application of Darcy's law. Ground and surface water interaction is achieved by the introduction of source-sink terms for rainfall and leakage into the continuity equations. The numerical scheme of the model is explained and test scenarios presented. The model is then applied to an experimental plot area (described in Part A of this paper) and outputs are compared to real data collected in the field plot. The model simulations provide a very close representation of field observed processes and discrepancies are small.

Keywords: shallow water equations, groundwater equation, finite volume, shock-capturing scheme, surface and groundwater coupling, micro-scale application.

1. Introduction

Many integrated groundwater (GW) and surface water (SW) models have been developed. The following can be given as examples: SHETRAN (Parkin, 1996) uses a complicated groundwater module and simplified open channel flow module; ISISMOD (Aradas, 2001) is developed by coupling ISIS, an unsteady surface water model, with MODFLOW, a 3-D GW model (McDonald and Harbaugh, 1988); the MIKE SHE - MIKE 11 integrated model (Sorensen & Refsgaard, 2001) couples the MIKE SHE GW model with the MIKE 11 1-D hydrodynamic SW model.

GSHAW5 (Groundwater and SHallow Water equations solved by FInite VolumE method) is an integrated 2-D ground and surface water model. Solution of the 2-D shallow water equations and 2-D groundwater equation is achieved by Finite Volume Method (FVM). The method is more recent than the Finite Difference (FD) or Finite Element Method (FE). The key element in FVM is to estimate the fluxes at cell interfaces. In the surface water calculation, fluxes through the cell interfaces are computed using the Osher Scheme, one of five available shock-capturing schemes within the model. In the groundwater calculation they are computed according to Darcy's Law. Integration is achieved by the introduction of source-sink terms in the continuity equations of both ground and surface water solutions. These source-sink terms include leakage from surface to subsurface and a flow from the subsurface to surface. The solution to surface water equations is suitable for many types of flow including continuous to discontinuous flow, subcritical to supercritical and steady to unsteady flow. It is also capable of simulating drying and wetting flow conditions, commonly occurring in mire hydrology. The FVM with the Osher Scheme has been applied to severe flow conditions such as simulation of dam break problems (Zhao *et al.*, 1994), simulation of an oblique shock wave (Erduran *et al.*, 2000), and simulation of hydraulic jump (Erduran and Kutija, 1999). Many other widely used methods based on FD schemes have difficulty simulating these types of flow to a reasonable degree of accuracy. Rapidly varying flow can also be seen in the simulation of flow in a microtopographical environment (the plot area described in Part A). It occurs due to the local large slope gradient of microtopography and the high bed shear stress. Zhang and Cundy (1989) apply their model using the MacCormack scheme (which is able to reproduce rapidly varying flow) to a microtopographical complex. They discuss the problem of flow simulation in this complex microtopography, caused by a large local slope and bed shear stress.

Solution of the 2-D groundwater equation is described in Section 2 and the solution to 2-D shallow water equations is given in Section 3. The coupling processes are explained in Section 4. The features of the model are given in Section 5. Section 6 illustrates test scenarios carried out during the development of the model. The model is then applied to a field plot area (SWaMP), from which hydrological data have been collected. Data collection methodology is described in detail in Part A of this paper. Some modification of the data-set, including grid size and aquifer thickness, were necessary and are explained in Section 7. The model results are presented and compared to field recorded data in Section 8. The difficulties resulting from a micro-scale flow simulation in a microtopographical environment are discussed in Section 9. Finally conclusions are drawn in Section 10.

2. Solution to Ground Water Equations

The 2-D groundwater flow equation for homogeneous fluid with constant density can be given as,

$$S_y \frac{\partial H}{\partial t} = \nabla \cdot (\mathbf{K} \nabla H) \text{ or more explicitly } S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left(K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial H}{\partial y} \right) \quad [1]$$

where S_y is the specific storage or yield (for an unconfined aquifer) - “volume of water that can be released from a unit volume of a saturated aquifer by a unit reduction in hydraulic head” (Shaw, 1996). H is the groundwater head, K_x and K_y are the hydraulic conductivity in x and y directions respectively.

Equation [1] is known as continuity (mass balance equation) for 2D ground water flow in porous medium. The groundwater equation can also be written as,

$$S_y \frac{\partial H}{\partial t} = \frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} = \nabla \cdot \mathbf{F} \quad [2]$$

where f_x and f_y are the fluxes (specific discharge) in x and y direction respectively and they can be represented as,

$$f_x = K_x \frac{\partial H}{\partial x} \quad f_y = K_y \frac{\partial H}{\partial y}, \quad \nabla \cdot \mathbf{F} = \frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} \quad [3]$$

The FVM is based on the integration of equation over a cell. Application of divergence theorem and integration of Equation [2] over a control volume V results in:

$$\iiint_V S_y \frac{\partial H}{\partial t} \partial V = \iiint_V \text{div} \mathbf{F} \partial V = \iint_S \mathbf{F} \mathbf{n} \partial s = \oint_L f_x \partial y - f_y \partial x \quad [4]$$

where \mathbf{n} is an outward normal vector, and S denotes the surface integral, L represents the line integral. Referring to Figure 1 (2D rectangular cell), the discrete form of the above relation can be written as follows:

$$AS_y \frac{\partial H}{\partial t} = f_{x1}(y_B - y_A) - f_{y1}(x_B - x_A) + f_{x2}(y_C - y_B) - f_{y2}(x_C - x_B) + f_{x3}(y_D - y_C) - f_{y3}(x_D - x_C) + f_{x4}(y_A - y_D) - f_{y4}(x_A - x_D)$$

where x_A, x_B, x_C, x_D are x co-ordinate of points A, B, C, D respectively, similarly y_A, y_B, y_C, y_D are y co-ordinate of points A, B, C, D respectively, subscript 1,2,3,4 refers to the side of a cell as shown in Figure 1. Finally, Equation [2] may be rewritten as,

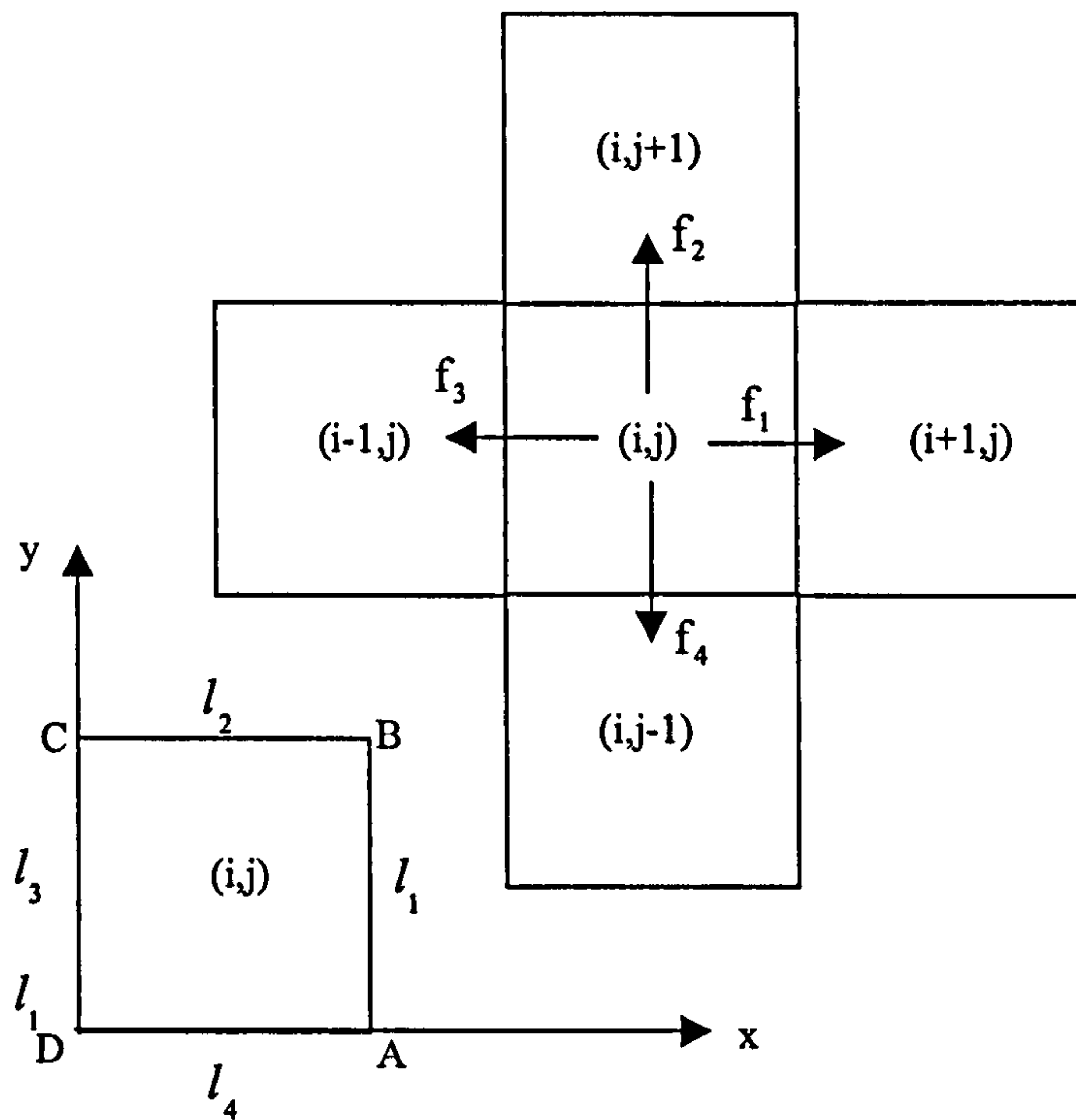
$$AS_y \frac{\partial H}{\partial t} = \sum_{j=1}^k f_j L_j \quad [5]$$

where k is the number of side of the cell.

2.1 Estimation of the Fluxes by Darcy's Law

The key element in the finite volume method (FVM) is the computation of the fluxes through cell interfaces. They can be computed by Darcy's Law for each direction (Figure 1).

Figure 1. 2D rectangular grid and corresponding fluxes through cell interfaces.



For instance, flux through the interface $(i+\frac{1}{2},j)$ can be given in discretised form as,

$$f_1 = K_{x(i+1/2,j)} \frac{(H_{i,j} - H_{i+1,j})}{\text{abs}(x_{i,j} - x_{i+1,j})} E \quad [6]$$

where,

$$E = \left(\frac{H_{i,j} + H_{i+1,j}}{2} \right) \text{ if Groundwater head, } H \text{ is less than ground level } Z.$$

$$E = \left(\frac{Z_{i,j} + Z_{i+1,j}}{2} \right) \text{ if Groundwater head, } H \text{ is greater than ground level } Z.$$

Z is the vertical elevation at the centre of a cell, similarly, x is x co-ordinate of the centre of the cell. In the same way, remaining fluxes for the other interfaces can be computed.

Finally, the solution for H can be obtained by Euler time integration:

$$H^{up} = H^n + \frac{\Delta t}{AS_y} \sum_{j=1}^k \mathbf{f}_j L_j \quad [7]$$

where H^{up} is a solution for H over a time step Δt .

However, solution of Equation [7] may not be the final solution for H as it will be explained at the end of Section 4.

Hence the notation H^{up} instead of H^{n+1} is used.

3. Solution to Shallow Water Equations

The two-dimensional form of the shallow water equations can be written as,

$$\left. \begin{aligned} \frac{\partial h}{\partial t} + \frac{\partial(hv_x)}{\partial x} + \frac{\partial(hv_y)}{\partial y} &= 0 \\ \frac{\partial(hv_x)}{\partial t} + \frac{\partial(hv_x^2 + gh^2/2)}{\partial x} + \frac{\partial(hv_x v_y)}{\partial y} &= gh(So_x - Sf_x) \\ \frac{\partial(hv_y)}{\partial t} + \frac{\partial(hv_x v_y)}{\partial x} + \frac{\partial(hv_y^2 + gh^2/2)}{\partial y} &= gh(So_y - Sf_y) \end{aligned} \right\} \quad [8]$$

where h is the water depth, v_x , v_y represent the depth-averaged velocity components in the x and y directions, g is the acceleration due to gravity, So_x and Sf_x are the bed slopes and friction terms respectively in the x direction and similarly for So_y and Sf_y .

Denoting $p_1 = h$, $p_2 = hv_x$, $p_3 = hv_y$ and defining the conserved physical vector $\mathbf{p} = [p_1, p_2, p_3]^T$, the conservative vector form of the shallow water equations can be written in vector notation as,

$$\frac{\partial \mathbf{p}}{\partial t} + \frac{\partial \mathbf{f}(\mathbf{p})}{\partial x} + \frac{\partial \mathbf{g}(\mathbf{p})}{\partial y} = \mathbf{b}(\mathbf{p}) \quad [9]$$

where $\mathbf{f}(\mathbf{p})$, $\mathbf{g}(\mathbf{p})$ are the flux vectors in the x , y directions respectively and $\mathbf{b}(\mathbf{p})$ denotes source/sink terms.

Equation [9] can also be written in the compact-conservative form given below by denoting:

$$\mathbf{F}(\mathbf{p}) = [\mathbf{f}(\mathbf{p}) \quad \mathbf{g}(\mathbf{p})]^T$$

$$\frac{\partial \mathbf{p}}{\partial t} + (\nabla \cdot \mathbf{F})^T = \mathbf{b}(\mathbf{p}) \quad [10]$$

The FVM is based on integration of the equations of interest over each finite volume (cell) covering the computational domain. Thus,

$$\int_V \left(\frac{\partial \mathbf{p}}{\partial t} + (\nabla \cdot \mathbf{F})^T \right) dV = \int_V \mathbf{b}(\mathbf{p}) dV \quad [11]$$

where V represents the volume over which integration is performed.

Zhao *et al.*(1994) shows that assuming that \mathbf{p} varies with time but is constant over the cell, applying the divergence theorem to the second term on the left hand side of Equation [11], using the rotational invariance property between $\mathbf{f}(\mathbf{p})$ and $\mathbf{g}(\mathbf{p})$ on each side of the cell and resolving $\mathbf{F}(\mathbf{p})$ in the direction of the normal vector \mathbf{n} , the 2D equations are reduced to a number of 1D local problems which are solved separately; one across each cell boundary. In discretised form these are given by:

$$A \frac{d\mathbf{p}}{dt} = - \sum_{k=1}^m \mathbf{T}^{-1}(\theta) \mathbf{f}(\mathbf{q}) L^k + A \mathbf{b}(\mathbf{p}) \quad [12]$$

where A is the area of the cell, m is the number of sides of the cell, $\mathbf{T}(\theta)$ is the transformation matrix which can be obtained by rotating the co-ordinate axes, L^k is the length of the k^{th} cell side, k is an index that represents the side, θ is the angle between the outward normal vector \mathbf{n} and the x axis, \mathbf{q} is the transformed conserved physical vector obtained by multiplying \mathbf{p} by the transformation matrix and $\mathbf{f}(\mathbf{q})$ is the transformed numerical flux vector. We have

$$\mathbf{q} = \mathbf{T}(\theta) \mathbf{p} = [h, hu, hv]^T \quad \text{and} \quad \mathbf{f}(\mathbf{q}) = [hu, hu^2 + gh^2/2, huv]^T$$

where u, v are local components of velocity in the normal and tangential directions respectively given by

$$u = v_x \cos\theta + v_y \sin\theta, \quad v = -v_x \sin\theta + v_y \cos\theta$$

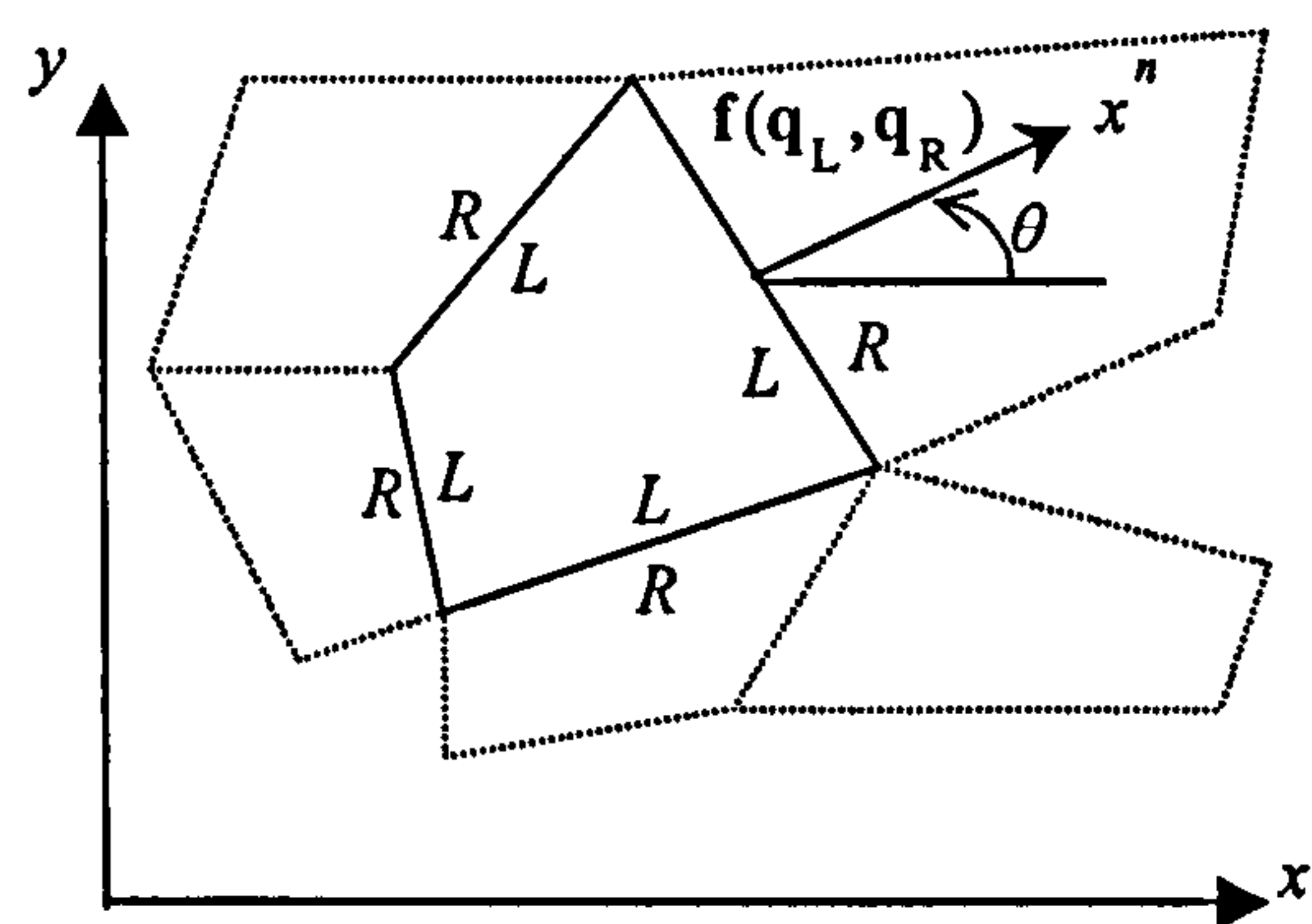
Toro (1997) states that each of these 1-D local problems is a Riemann problem defined to be an initial value problem that exhibits an abrupt change in the flow variables. The Riemann problem is characterised by two states, for which the conservative variables have known values at the beginning of a time step, separated by a line called the Riemann interface. If we let x^n be a local co-ordinate, normal to the cell side the Riemann problem can be written,

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial [\mathbf{f}(\mathbf{q})]}{\partial x^n} = 0 \quad [13]$$

The initial state is given by
$$\mathbf{q}(x^n, 0) = \begin{cases} \mathbf{q}_L; & x^n < 0 \\ \mathbf{q}_R; & x^n > 0 \end{cases}$$

where \mathbf{q}_L and \mathbf{q}_R denote the values of the transformed conserved physical vector to the left and right of the cell interface respectively. The inside of the cell under consideration always corresponds to the left hand side of the Riemann interface, and the neighbouring cell to the right hand side as shown in Figure 2.

Figure 2. Typical Finite Volume Cell and Riemann Interface



Equation [14] is solved by Osher Scheme, giving the normal flux through each cell boundary, denoted $\mathbf{f}(\mathbf{q}_L, \mathbf{q}_R)$ in Figure 2. For more detailed information about the solution presented so far, see Zhao *et al.* (1994), Tan (1992), Hirsch (1990) and Toro (1997).

The solution to equation [13] is based on the conservation law and the solution is achieved in the absence of source-sink terms. Hence, they are treated separately. In this study, so called splitting technique is used. The shallow water equations given in Equation [9] are split into two parts; the homogeneous part, which consists of only the terms on the left-hand side of the equation, and the inhomogeneous part, which is of the form:

$$\frac{\partial \mathbf{p}}{\partial t} = \mathbf{b}(\mathbf{p}) \quad [14]$$

The homogeneous part is solved using Euler's method, giving the following expression:

$$\mathbf{p}^{n+1} = \mathbf{p}^n - \frac{\Delta t}{A} \sum_{k=1}^m \mathbf{T}^{-1}(\theta) \mathbf{f}(\mathbf{q}) L^k \quad [15]$$

where \mathbf{p}^{n+1} shows values at the next time step and Δt is the length of the time step.

This equation shows that, in order to find the conservative variables h , $h v_x$, and $h v_y$ at the next time step, first the numerical fluxes for each cell side are computed. They are then multiplied by the inverse transformation matrix and the length of the corresponding cell side and summed.

The inhomogeneous part, which is the set of Ordinary Differential Equations (ODEs) given in Equation [14], can be solved by any suitable method. Here a fourth order Runge Kutta method is adopted.

Note that the solution to these ODEs uses as initial values the conservative variables obtained from Equation [15]. Hence, the solution of Equation [14] gives the corrected values at the next time step. It may be worth mentioning that, although the fourth order Runge Kutta method is used for the solution of ODEs, the solution of the system is still first order accurate as shown in Equation [16].

$$\mathbf{p}^{n+1} = \mathbf{S}^{(\Delta t)} \left[\mathbf{H}^{(\Delta t)} \left[\mathbf{p}^n \right] \right] \quad [16]$$

where $S^{(\Delta t)}$ and $H^{(\Delta t)}$ are operators which correspond to solutions to the inhomogeneous (source/sink terms) and the homogeneous parts respectively.

3.1 Estimation of flux by the Osher scheme

Each 1D problem can be written in the form of Equation [11], where the transformed numerical flux vector $\mathbf{f}(\mathbf{q})$ has the form:

$$\mathbf{f}(\mathbf{q}) = [hu, hu^2 + gh^2/2, huv]^T$$

Equation [13] can be represented by the quasi – linear equation:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{J} \frac{\partial \mathbf{q}}{\partial x} = \mathbf{0} \quad [17]$$

where \mathbf{J} is the Jacobian matrix (also known as the coefficient matrix):

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial q_1} & \frac{\partial f_1}{\partial q_2} & \frac{\partial f_1}{\partial q_3} \\ \frac{\partial f_2}{\partial q_1} & \frac{\partial f_2}{\partial q_2} & \frac{\partial f_2}{\partial q_3} \\ \frac{\partial f_3}{\partial q_1} & \frac{\partial f_3}{\partial q_2} & \frac{\partial f_3}{\partial q_3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -u^2 + c^2 & 2u & 0 \\ -uv & v & u \end{bmatrix}$$

Solution of the Riemann problem requires knowledge of the slope of the characteristic lines (eigenvalues). These are found by solving the characteristic equation, $|\mathbf{J} - \lambda \mathbf{I}| = 0$. The solution yields three eigenvalues;

$\lambda_1 = u - c$, $\lambda_2 = u$, $\lambda_3 = u + c$ given in order of ascending magnitude, where $c = \sqrt{gh}$. Note that the

Jacobian matrix \mathbf{J} is diagonalizable and the hyperbolic Equation [13] can thus be written as a system with real

eigenvalues and the diagonalizable coefficient matrix given above (Toro, 1997). The Osher-Riemann solver requires

the Riemann invariants to be known, which means that the eigenvectors are also required. The eigenvectors, γ , are obtained from the equation $\mathbf{J} \gamma = \lambda \gamma$ and the solutions for corresponding eigenvalues $\lambda_1, \lambda_2, \lambda_3$ are $\gamma_1 = [1, u - c, v]^T$, $\gamma_2 = [0, 0, 1]^T$, $\gamma_3 = [1, u + c, v]^T$ respectively. The Riemann invariants are constant along the characteristics. They can be found by solving the following ordinary differential equations for each eigenvector:

$$\frac{dq_1}{\gamma_{j1}} = \frac{dq_2}{\gamma_{j2}} = \frac{dq_3}{\gamma_{j3}}$$

where j is the number of the eigenvector, γ_{jk} denotes the k^{th} component of γ_j .

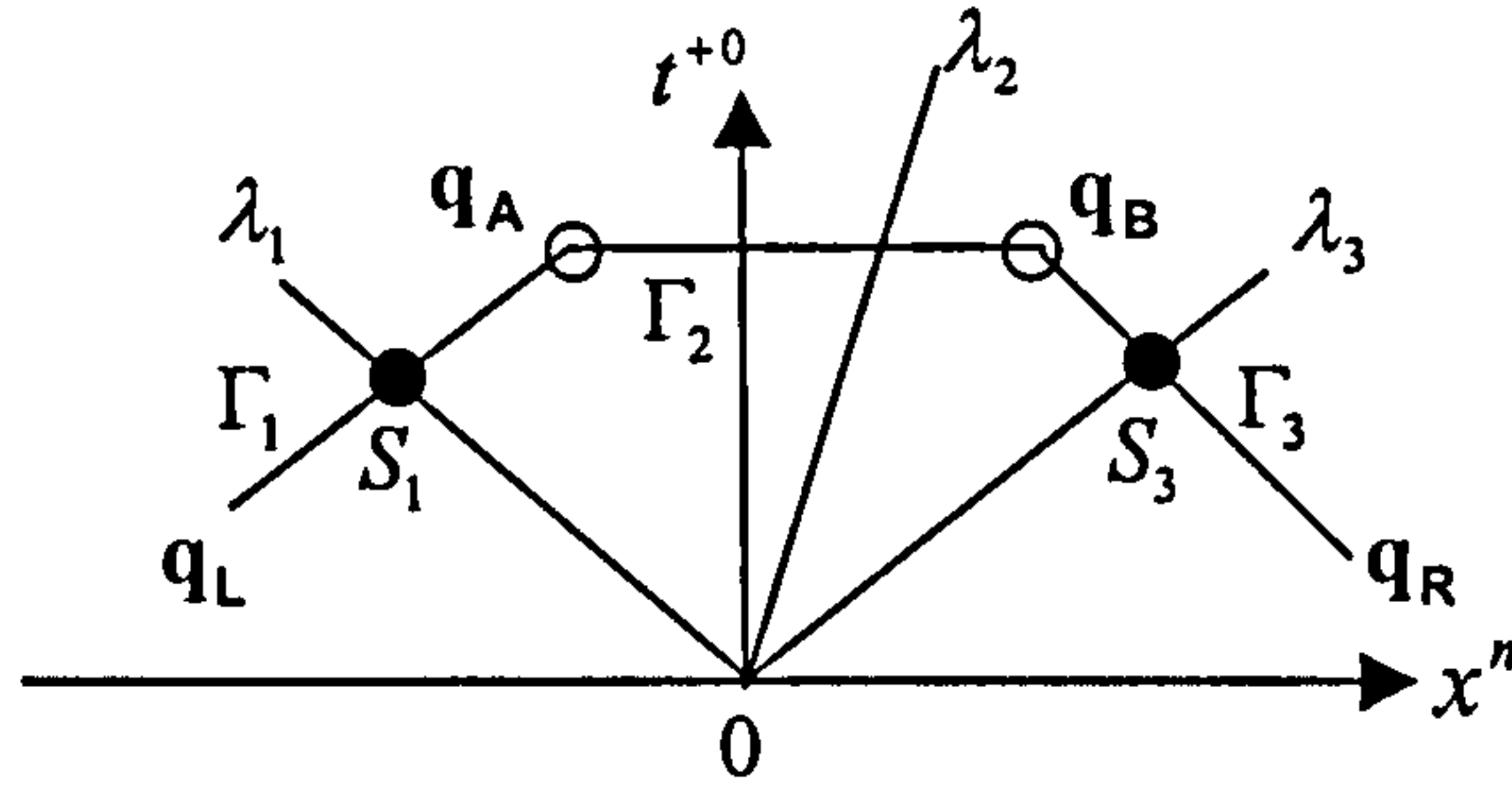
The above equations produce two Riemann invariants for each eigenvector, denoted $\psi_j^i, i = 1, 2$. We have:

$$\psi_1^1 = u - 2c, \quad \psi_1^2 = v, \quad \psi_2^1 = u, \quad \psi_2^2 = h, \quad \psi_3^1 = u + 2c, \quad \psi_3^2 = v$$

The aim of solving the Riemann problem is to find the solution in the wedge between the first and third characteristic lines (Toro, 2001). The Riemann problem must be constructed and solved at each cell interface, thus the number of solutions for each cell equals to the number of sides of the cell.

There are two ways to follow Osher's method. One is the original Osher scheme (sometimes called O-ordering) and the other is known as a physical ordering or P-Ordering (Toro, 1997). In this paper only P- Ordering is presented.

Figure 3. Osher integration paths ($\Gamma_1, \Gamma_2, \Gamma_3$), intersection points (q_A, q_B), sonic points (S_1, S_3) and slope of characteristics.



In Figure 3, the sonic point (critical point) represents a point where the characteristic speed becomes zero and occurs when the wave is crossed (the sign of the characteristic speed changes). A point where two characteristics intersect is called an intersection point. In order to find these points, the Riemann invariants are used. Zhao *et al.* (1994) gives the velocities and water depths at points A and B as follows:

$$u_A = u_B = \frac{\psi_L + \psi_R}{2}, \quad h_A = h_B = \frac{1}{g} \left(\frac{\psi_L - \psi_R}{4} \right)^2$$

and at points S_1, S_3 they can be given as:

$$u_{S_1} = \frac{1}{3}\psi_L, \quad h_{S_1} = \frac{(u_{S_1})^2}{g}, \quad u_{S_3} = \frac{1}{3}\psi_R, \quad h_{S_3} = \frac{(u_{S_3})^2}{g}, \quad v_L = v_A = v_{S_1}, \quad v_R = v_B = v_{S_3}$$

where $\psi_L = u_L + 2\sqrt{gh_L}$, $\psi_R = u_R - 2\sqrt{gh_R}$ are constant across λ_1 and λ_3 respectively.

Each integration path is drawn tangential to the corresponding eigenvector. The solution begins with splitting the Jacobian matrix of the shallow water equations into two as one part has only positive eigenvalues and the other has only negative eigenvalues. Similarly, the flux vector can be split. Then, by choosing the direction of integration (left

to right or right to left), the integration is completed according to the sign of the eigenvalues. By considering only the negative eigenvalues, the integral equation from left to right for the general case can be given as:

$$\begin{aligned} \mathbf{f}(\mathbf{q}_L, \mathbf{q}_R) = & \mathbf{f}(\mathbf{q}_L) + \int_{\mathbf{q}_L}^{\mathbf{q}_{S_1}} \mathbf{J}^-(\mathbf{q})d\mathbf{q} + \int_{\mathbf{q}_{S_1}}^{\mathbf{q}_A} \mathbf{J}^-(\mathbf{q})d\mathbf{q} + \int_{\mathbf{q}_A}^{\mathbf{q}_B} \mathbf{J}^-(\mathbf{q})d\mathbf{q} \\ & + \int_{\mathbf{q}_B}^{\mathbf{q}_{S_3}} \mathbf{J}^-(\mathbf{q})d\mathbf{q} + \int_{\mathbf{q}_{S_3}}^{\mathbf{q}_R} \mathbf{J}^-(\mathbf{q})d\mathbf{q} \end{aligned} \quad [18]$$

where \mathbf{J}^- is a Jacobian matrix, which has only negative or zero eigenvalues, $\mathbf{f}(\mathbf{q}_L, \mathbf{q}_R)$ denotes the normal flux through the cell interface from left to right.

The integration results in the 16 different cases shown in Table 1 and each one determines the numerical flux through each cell interface. Each case represents a hydraulic condition (Zhao *et al.*, 1994).

The steps required to solve the Riemann problem using the Osher scheme are:

- (a) Prepare the left and right initial data for the initial value Riemann problem for each cell interface by computing u_L, v_L and h_L for the left interface and u_R, v_R and h_R for the right interface.
- (b) Compute wave speeds for both interfaces c_L, c_R and the Riemann invariants ψ_L, ψ_R .
- (c) Compute $u_A, u_B, h_A, h_B, v_A, v_B, c_A, c_B, u_{S_1}, h_{S_1}, u_{S_3}, h_{S_3}, v_{S_1}, v_{S_3}$
- (d) Estimate the normal flux at each cell interface by taking the appropriate normal flux definition given in Table 1.

Table 1. Estimation of the normal flux using Osher Schemes (Zhao et al., 1994)

Hydraulic Conditions	$u_L - c_L \geq 0$ $u_R + c_R \geq 0$	$u_L - c_L \geq 0$ $u_R + c_R \leq 0$	$u_L - c_L \leq 0$ $u_R + c_R \geq 0$	$u_L - c_L \leq 0$ $u_R + c_R \leq 0$
$u_A \geq 0$ $u_A - c_A \geq 0$	$f(q_L)$	$f(q_L) + f(q_R)$ $- f(q_{S_3})$	$f(q_{S_1})$	$f(q_{S_1}) - f(q_{S_3})$ $+ f(q_R)$
$u_A \geq 0$ $u_A - c_A \leq 0$	$f(q_L) - f(q_{S_1})$ $+ f(q_A)$	$f(q_L) - f(q_{S_1})$ $+ f(q_A) + f(q_R)$ $- f(q_{S_3})$	$f(q_A)$	$f(q_R) + f(q_A)$ $- f(q_{S_3})$
$u_B \leq 0$ $u_B + c_B \geq 0$	$f(q_L) - f(q_{S_1})$ $+ f(q_B)$	$f(q_L) - f(q_{S_1}) + f(q_B)$ $- f(q_{S_3}) + f(q_R)$	$f(q_B)$	$f(q_B) - f(q_{S_3})$ $+ f(q_R)$
$u_B \leq 0$ $u_B + c_B \leq 0$	$f(q_L) - f(q_{S_1})$ $+ f(q_{S_3})$	$f(q_L) - f(q_{S_1})$ $+ f(q_R)$	$f(q_{S_3})$	$f(q_R)$

Note that although the solution to shallow water equations introduced here can be used for structured, unstructured, uniform or non-uniform grid. Due to the limitation on the solution to groundwater equations, the overall solution is only applicable structured uniform rectangular grid.

3.2 Inclusion of Rainfall

Rainfall can also be simulated in GSHAW5 by introducing flow resulting from rainfall as a source term in the continuity equation of the shallow water equations. Again, the solution is achieved using splitting technique.

$$\frac{\partial h}{\partial t} + \frac{\partial(hv_x)}{\partial x} + \frac{\partial(hv_y)}{\partial y} = q_R$$

where q_R is rainfall intensity (m/s). Splitting the continuity equations as:

$$\frac{\partial h}{\partial t} = q_R \quad [19]$$

$$\text{and} \quad \frac{\partial h}{\partial t} + \frac{\partial(hv_x)}{\partial x} + \frac{\partial(hv_y)}{\partial y} = 0$$

Equation [19] is an ODE and can be solved by Euler method given below.

$$h^{up} = h + \Delta t q_R \quad [20]$$

where h^{up} illustrates the solution to h over a time step Δt .

Since solution of Equation [20] is not the final solution for h , the notation h^{up} (for h updated) instead of h^{n+1} is used (see Section 4 for more detail).

Finally overall solution including the rainfall effect can be achieved in two steps:

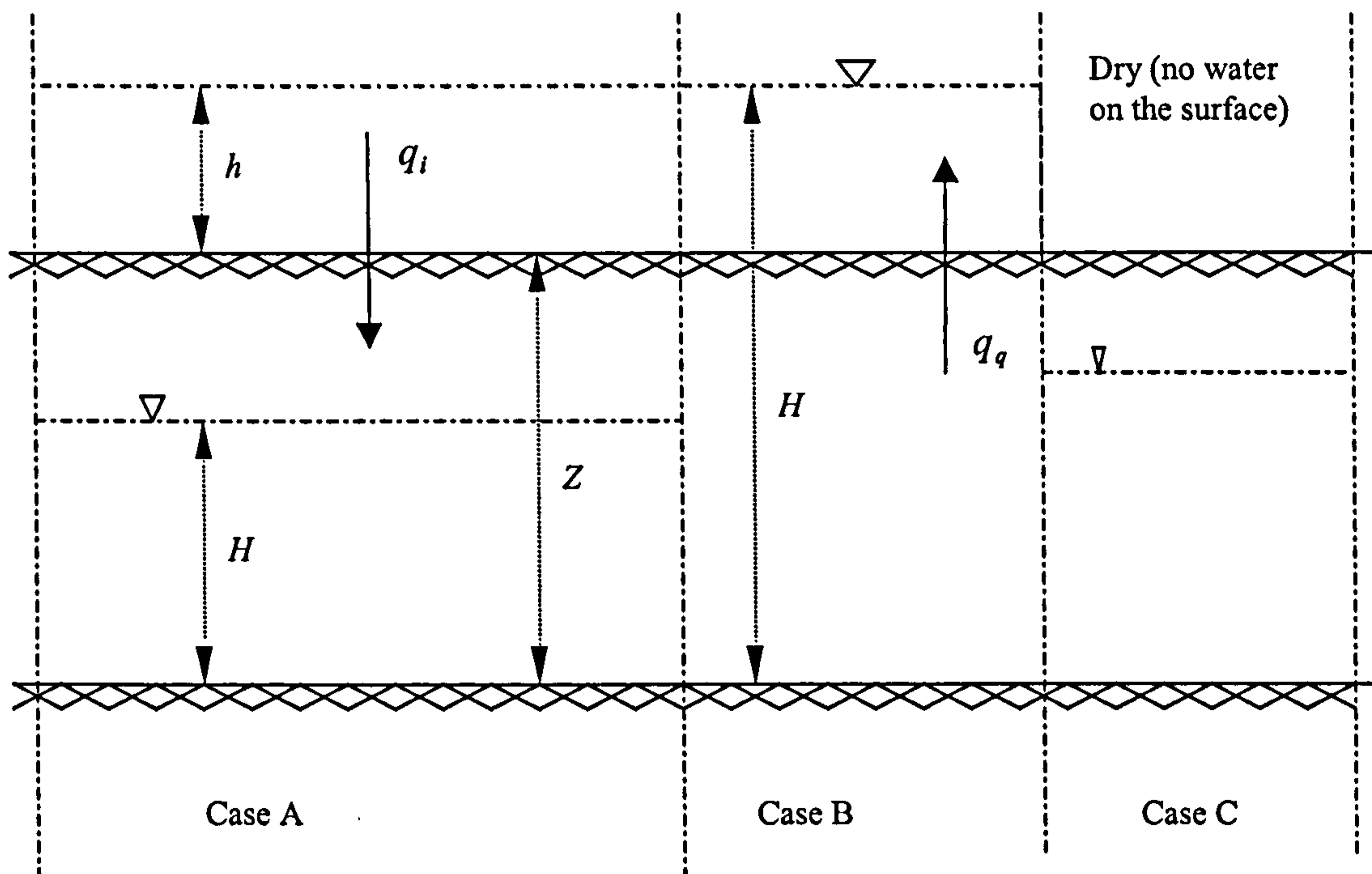
Step 1: Use Equation [20] to update the first component of \mathbf{P} , h .

Step 2: Use Equation [16] to find the next time step values for all three components of \mathbf{P} .

4. Coupling surface water with groundwater

Ground and surface processes are linked in three different scenarios in GSHAW5. Figure 4 illustrates the coupling procedures used in GSHAW5.

Figure 4. The coupling processes used in GSHAW5: Cases A, B and C.



Case A: the surface is wet and the water depth is prescribed, but the groundwater head is below the ground level elevation for that cell. In this case, there will be a flow from surface to ground due to leakage, computed by Darcy's Law in the Z direction:

$$q_i = K_z (h + Z - H) / Z \quad [21]$$

where q_i is the flow due to infiltration, K_z is a hydraulic conductivity in Z direction, and Z is an elevation in the centre of a cell (thickness of the aquifer). The same expression for the computation of leakage can be found in

Wilson and Akande (1995), and Haagsma and Johanns (2001). An alternative technique would be to solve the Richards Equation, which includes unsaturated and saturated zones (Yakirevich *et al.* (1998), Singh and Bhallamudi (1998).

Infiltration results in decreasing surface water depth and increasing groundwater head, computed as:

$$h^{up} = h^n - \Delta t q_i \quad \text{the surface water depth is updated.} \quad [22]$$

$$H^{up} = H^n + \frac{\Delta t q_i}{S_y} \quad \text{the groundwater head is updated.} \quad [23]$$

Equations [22] and [23] are obtained by first introducing q_i in each continuity equation of surface and ground water as a source-sink term, then applying the splitting technique. For instance, Equation [23] can be obtained after introducing q_i as source term, rewriting Equation [1]:

$$S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} (K_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y} (K_y \frac{\partial H}{\partial y}) + q_i \quad [24]$$

Application of the splitting technique to Equation [24] yields two equations. The first is an ODE given in Equation [25]. The second is Equation [1] given earlier.

$$S_y \frac{\partial H}{\partial t} = q_i \quad [25]$$

By using the first order Euler method, Equation [23] is obtained. Note that the lateral flow computation in the groundwater is also carried out.

Case B: The groundwater head is above the ground level and is equal to $h+Z$. The surface is wet and there is no infiltration. In this case, an interaction between GW and SW occurs because of the change in storage in groundwater caused by the lateral flow. Again, the surface water depth and groundwater head is recomputed by:

- a) Equation [7], which takes into account of the change in storage and gives a solution to H over a time step, Δt .
- b) introducing another source term into the continuity equation of the shallow water equations, which can again be solved by splitting technique. Then, the solution reads:

$$h^{up} = h^n + \frac{\Delta t}{A} \sum_{j=1}^k \mathbf{f}_j L_j \quad [26]$$

A further coupling is considered in Case B: when the surface water computation is complete and shallow water depth has changed, the groundwater head, given by the sum of h and Z , must be updated.

Case C: There is no water on the surface and cells are effectively dry. To avoid the zero-division problem, water depth is the prescribed value 0.00001m. There is no integration between ground and surface. However, the Equations [7] and [16] are still applied in order to compute the changes due to the horizontal water movements in both ground and surface water.

Finally, the following steps can be carried out during the computation in GSHAW5:

- 1- Flow due to rainfall: Equation [20] is used.
- 2- Infiltration: Equations [22] and [23] are used.
- 3- Groundwater flow computation: Equation [7] is used. If Case B occurs then Equation [26] is used.
- 4- Surface water computation: Equation [16] is used. If Case B occurs then the groundwater head is recalculated.

The updated value of depth, h^{up} , is obtained from equations [20], [22] and [26]. The updated value of groundwater head, H^{up} , is obtained from equations [7] and [23]. If those equations are the final equations used according to the steps described above, then h^{up} and H^{up} become h^{n+1} and H^{n+1} respectively. Otherwise, h^{up} and H^{up} are used as intermediate values, denoted h and H respectively in the following equations. For instance, in Case A when some rain occurs, the next time step value (h^{n+1}) for h is obtained from the solution to Equation [16] not the solution to Equations [20] or [22]. In other words, for this particular case, the final solution for h is obtained by taking step 1 first, then step 2 (using h^{up} resulted from Equation [20] as h in Equation [22]) and finally step 4 (using h^{up} resulted from Equation [22] as h in Equation [16] for final solution, h^{n+1}).

5. GSHAW5

The programme used throughout is GSHAW5, developed by the first author. The code is written in the object-oriented programming language DELPHI 5 and is user friendly. Previously, the programme was suitable only to simulate shallow water flows and has been applied as such in several previous studies (Erduran and Kutija, 1999, Jeong, 1999, Erduran *et al.*, 2000). The main features of the model are:

- (a) Five Riemann solvers: HLL Scheme (Harten, Lax and van Leer), HLLC (Modified HLL scheme which includes a Contact wave, it is named after Toro *et al.*, 1994), Osher Scheme, Roe Scheme and Flux Vector Splitting Scheme (FVS).
- (b) Suitability for different types of flow including continuous and discontinuous flow, steady and unsteady flow, subcritical and supercritical flow.
- (c) Suitability for both first and second order accuracy computations.
- (d) Two alternative time integration methods for second order accuracy in time are included: Predictor-Corrector and van Leer to Hancock.
- (e) Four 'limiters' are available: Superbee, Minmod, van Leer and van Albada,
- (f) Ability to handle complex topography i.e. use of a variety of cell shapes. In particular, any grid type, such as unstructured and non-uniform can be used if first order accuracy is chosen. Second order accurate solutions are restricted to structured grids but these can be non-uniform. For the slope computations, a surface slope is defined. As long as the co-ordinates (x, y, z) of the corner of the cells are known, the model can compute the slope in the x and y directions.
- (g) The model has the ability to handle different boundary conditions. The boundary conditions available in the programme include rating curves, time dependent discharge boundaries, given discharge and or water depth and closed or open boundaries.
- (h) Suitability for flow in initially dry areas and drying and wetting flow conditions.

The model was modified by adding the groundwater module. This addition provides simulation of integration between GW and any types of 2D shallow water flow on the surface. However, since the solution to the groundwater equation is restricted to use structured, uniform rectangular grids, GSHAW5 becomes suitable for only structured uniform rectangular grids.

Rainfall effect is also included in the model. These features make the model most suitable for ground and surface water flow integration, especially processes occurring in complex natural flow situations such as wetlands.

6. Test cases

The integrated model has been tested for a number of hypothetical cases. Here, one example for 1D case is introduced. The computational domain is divided into two regions from the middle of the domain, namely the left and the right (Figure 5a). On the left side the water depth is taken to be 2m, on the right side it is taken to be as 1m, providing a rapidly varying flow on the surface. On the right side the groundwater head is above the ground and is equal to $h + Z = 4\text{m}$. On the left side, it is below the ground level and equal to 1.5m. Boundary conditions are selected as closed for both surface and groundwater, so that the head is taken to be equal to the head in the boundary, providing zero fluxes. Specific yield is taken to be unity in order to check the mass balance at the end of computation. Under these conditions, it is expected that the mass will be redistributed. The water depth on the surface will reduce to 1.25m and will remain constant. There will be no empty space within the ground and the groundwater head is expected to be equal to 3.25m (2+1.25m).

As seen in Figures 5b and 5c, there is a rapid change on the surface water at time 2s and 4s due to the large water depth differences set up initially. The surface water has fluctuated between the closed boundaries at both ends of the domain. However, there is no movement of the groundwater head as the leakage rate is very low and in such a short period, there is no lateral flow. When the simulation time reaches 60s, the water surface almost reaches a steady state condition, whilst there is still no significant change in the groundwater head. At a time, 10000s, there is a considerable drop on the surface due to infiltration on the left-hand side of the domain. The groundwater head increases due to the infiltration and the lateral flow caused by the head differences particularly in the middle of the domain. Similar but more significant changes are seen at times, 20000s and 40000s. Finally, the expected equilibrium condition is obtained at 60000s.

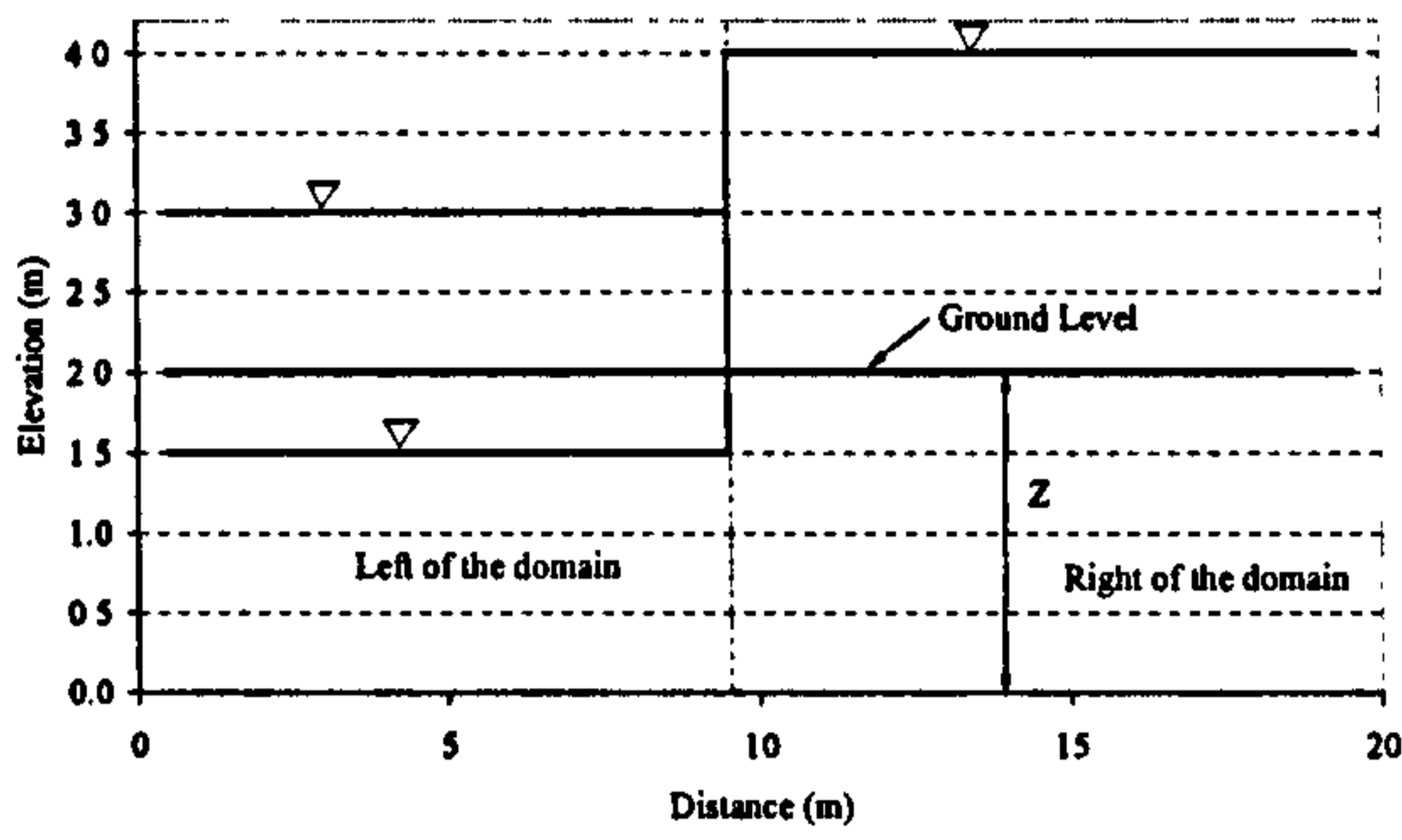
This test is used to demonstrate groundwater flow, due to the head differences and infiltration, surface flux due to water depth differences. The results show that the expected flux occurred and that total mass was preserved. The test also demonstrates that the splitting technique and time coupling of surface and groundwater computation have not produced significant inaccuracies. This may be because the selected time step is so small. The use of the explicit

algorithm requires a time step small enough to fulfil stability condition defined by Courant, Friedrichs and Lewy (1928). The condition is given by $CFL < 1$ where CFL is known as the Courant number and given below:

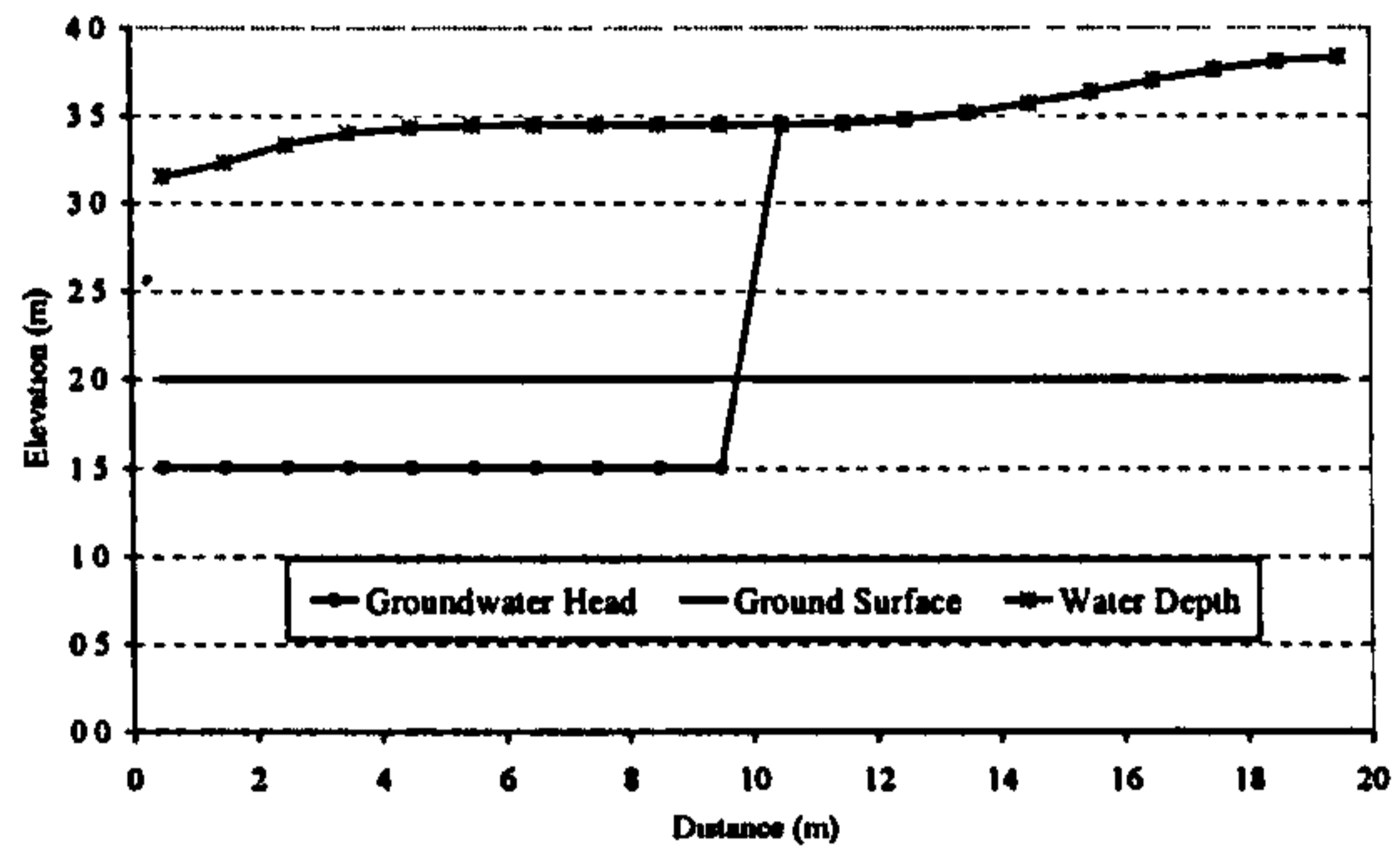
$$CFL = \frac{\Delta t}{\Delta x} (\lambda_{\max}) \leq 1 \quad [27]$$

where λ_{\max} is the maximum propagation speed of the wave.

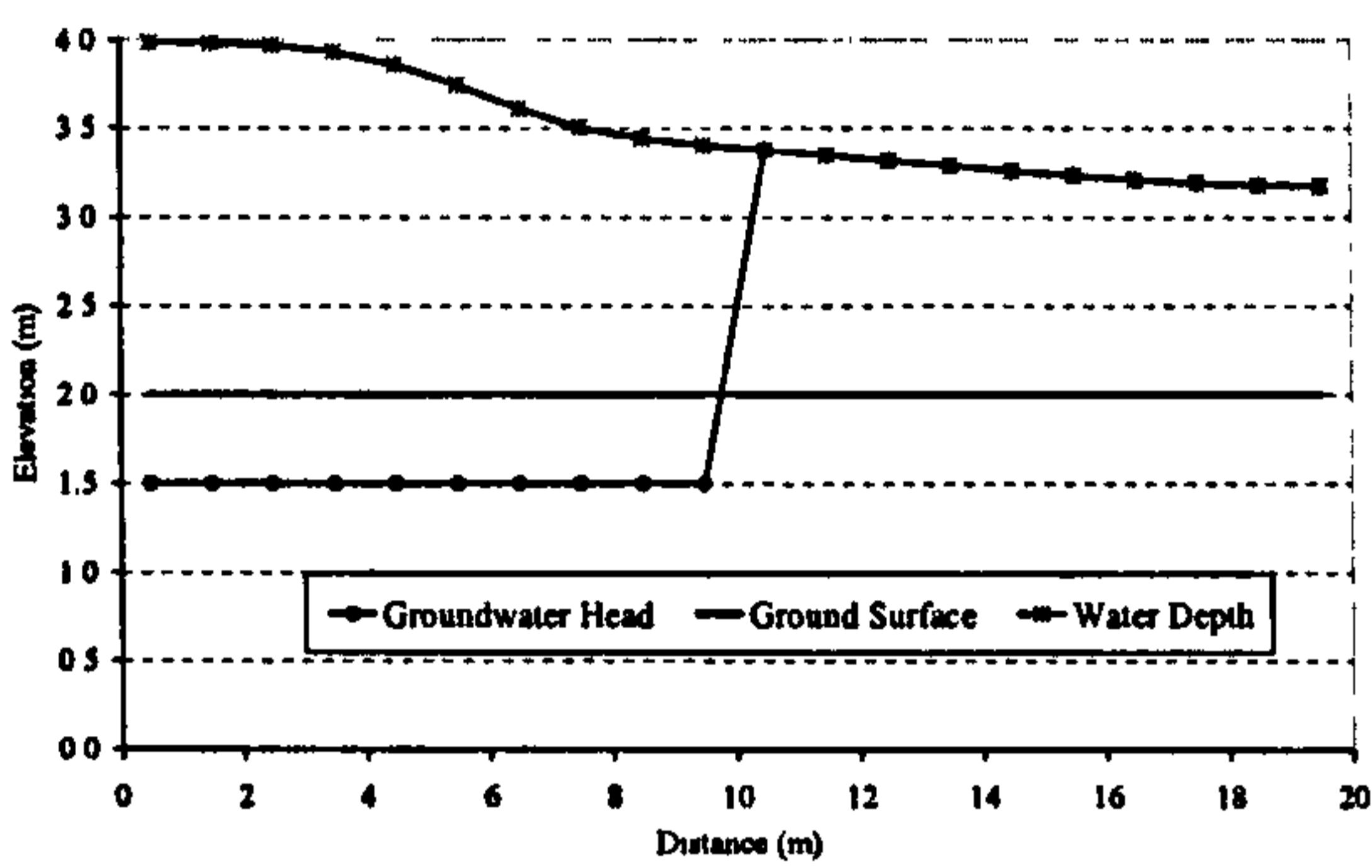
Figure 5. Groundwater and Surface Water integration Processes for the test over 60000s.



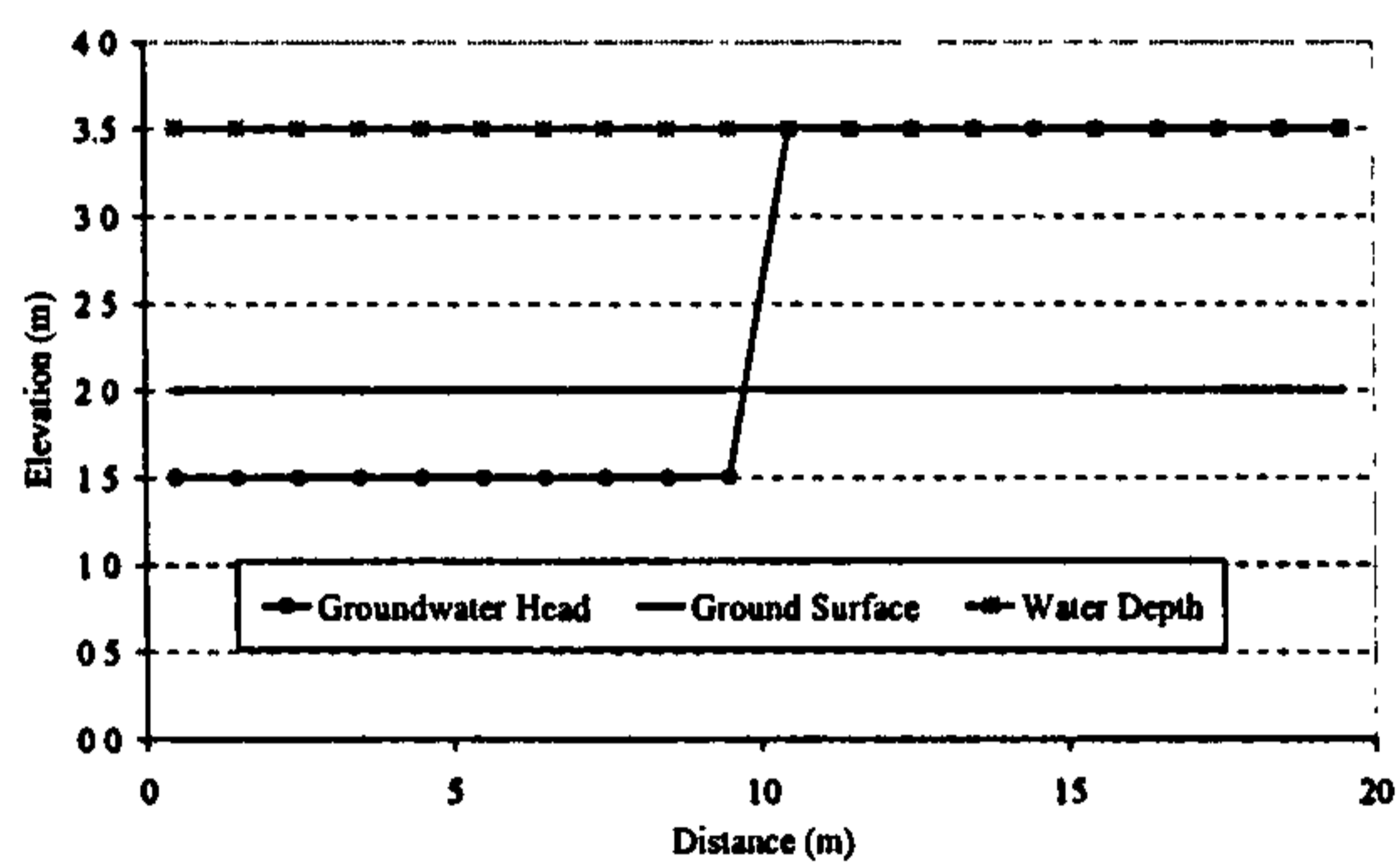
(a) Initial



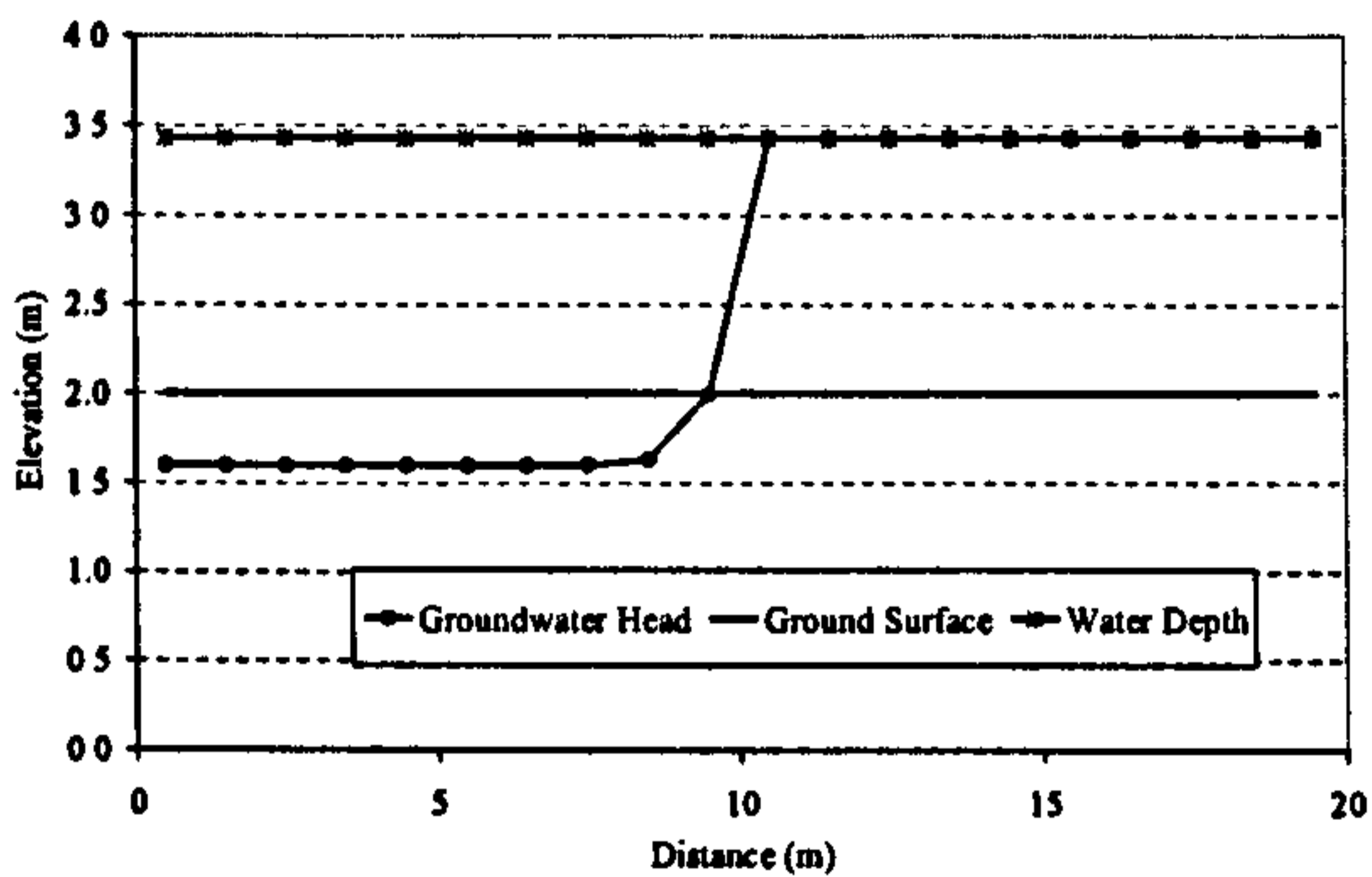
(b) 2s



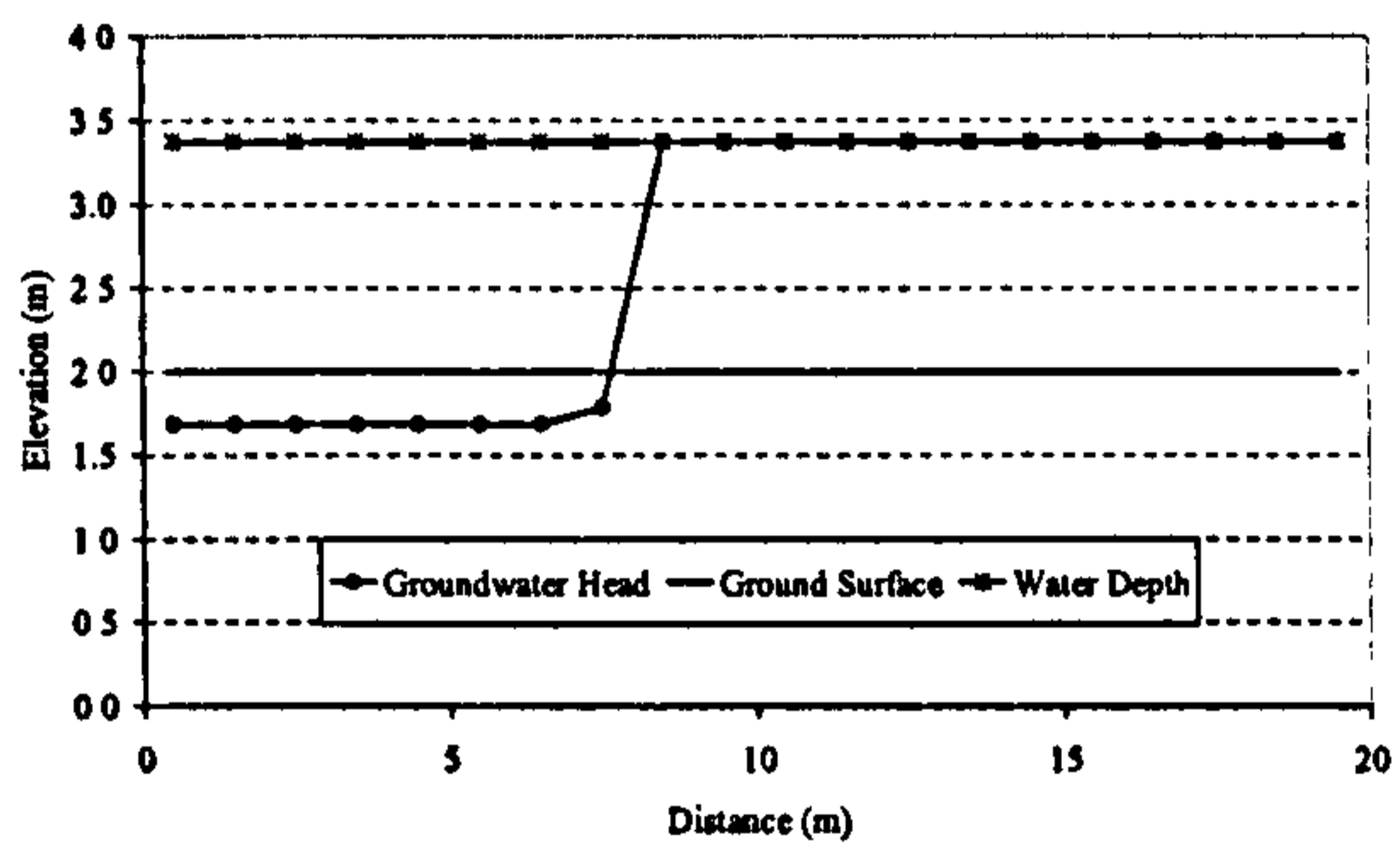
(c) 4s



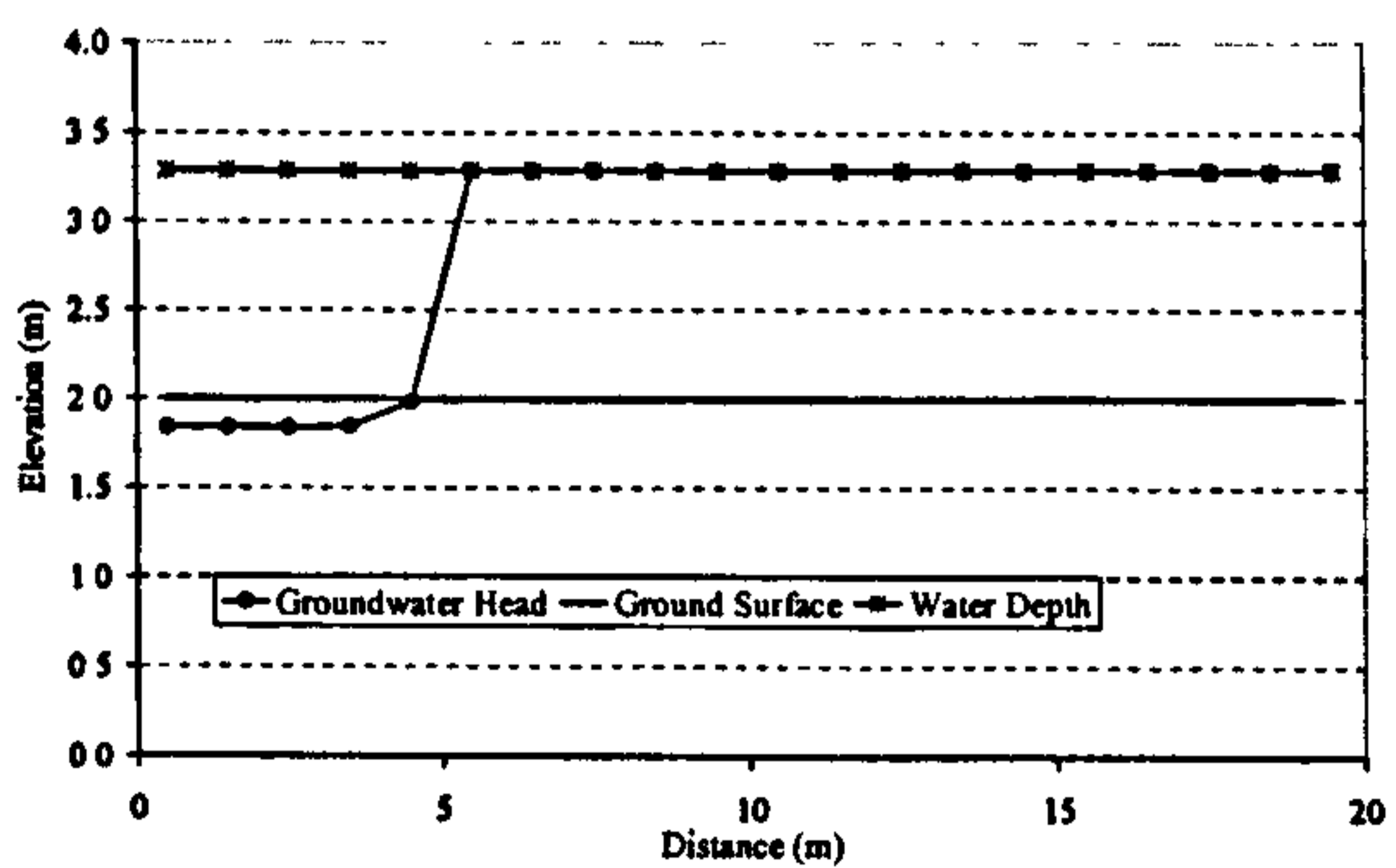
(d) 60s



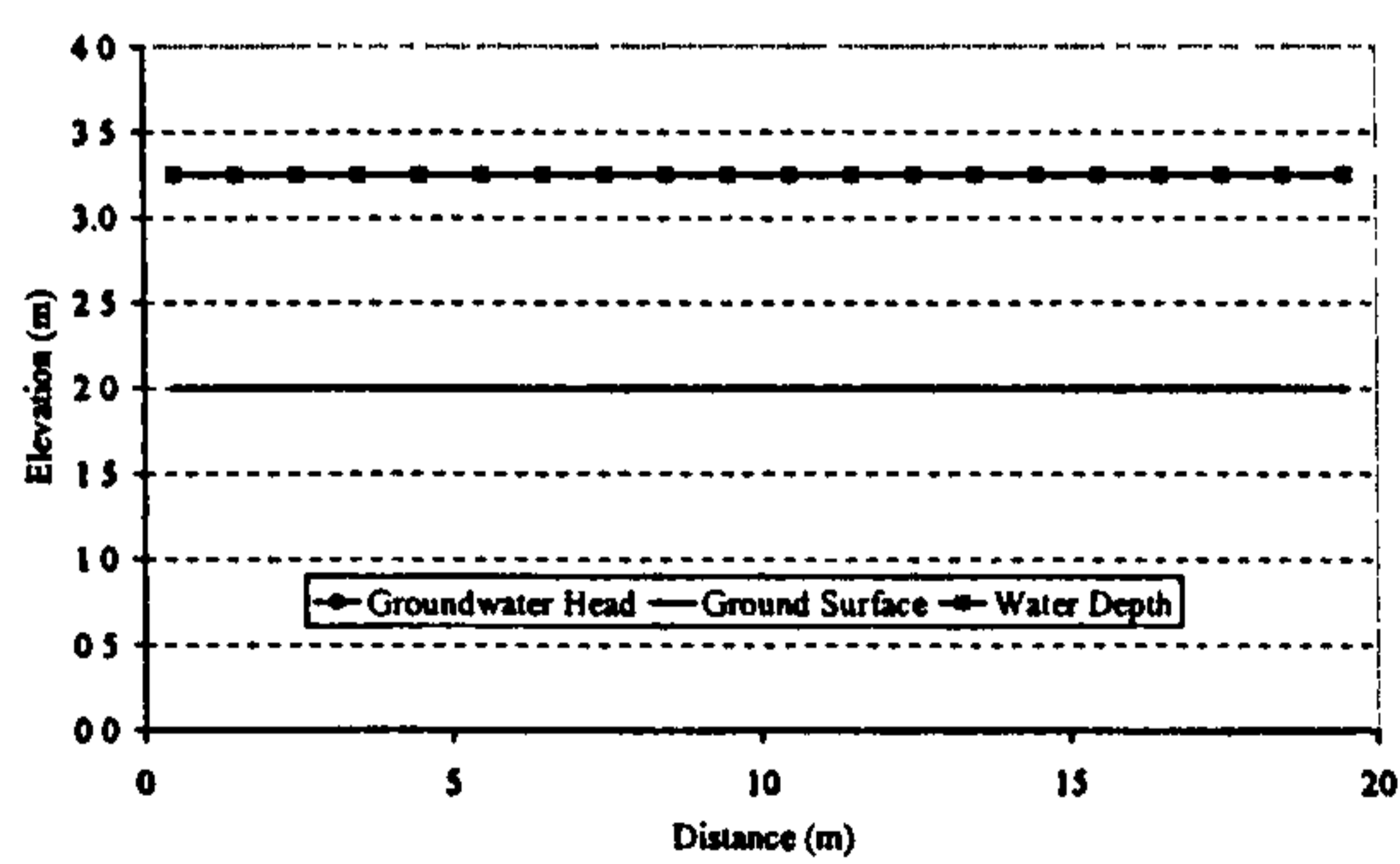
(e) 10000s



(f) 20000s



(g) 40000s

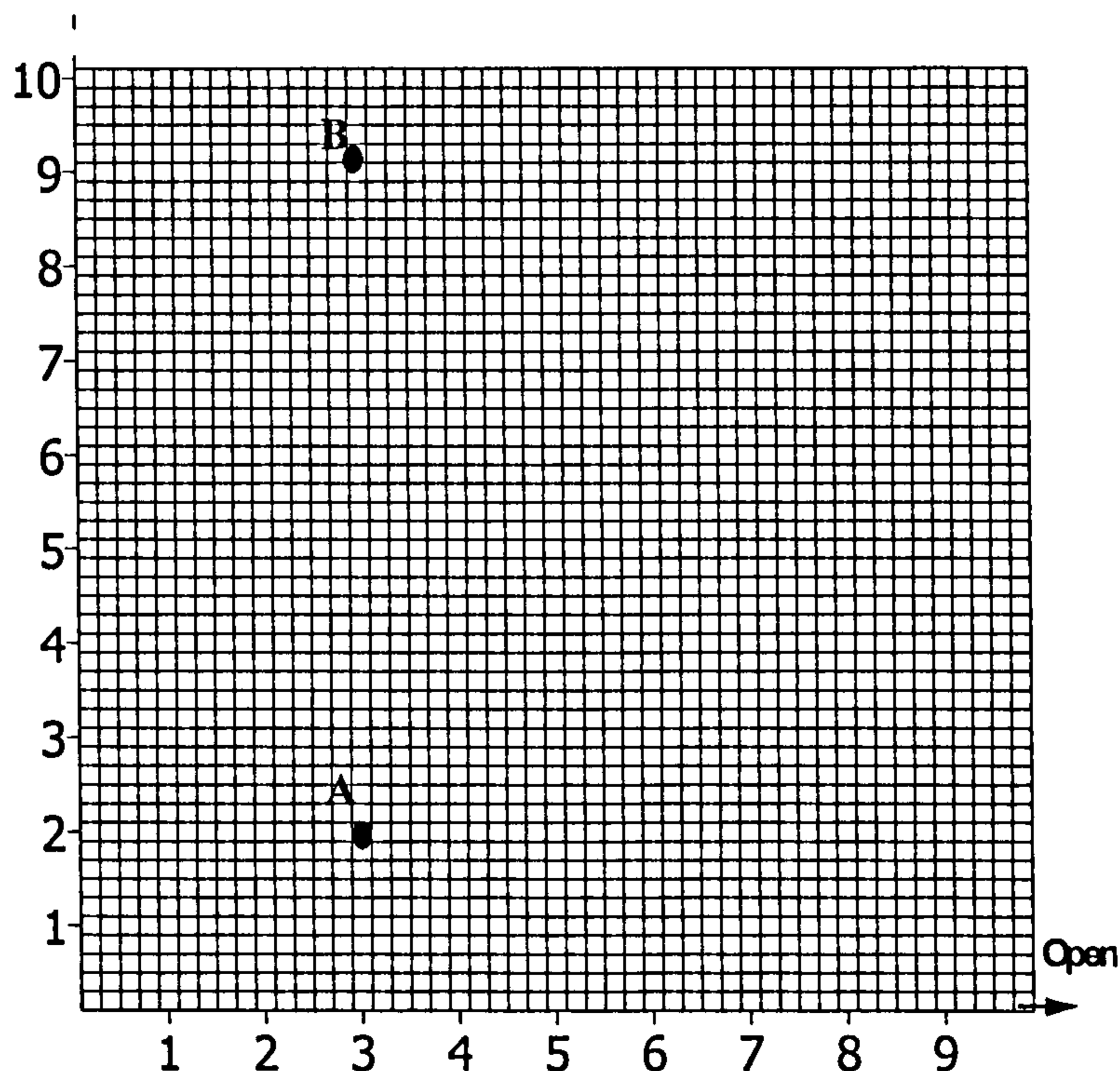


(h) 60000s

7. Application to the field plot

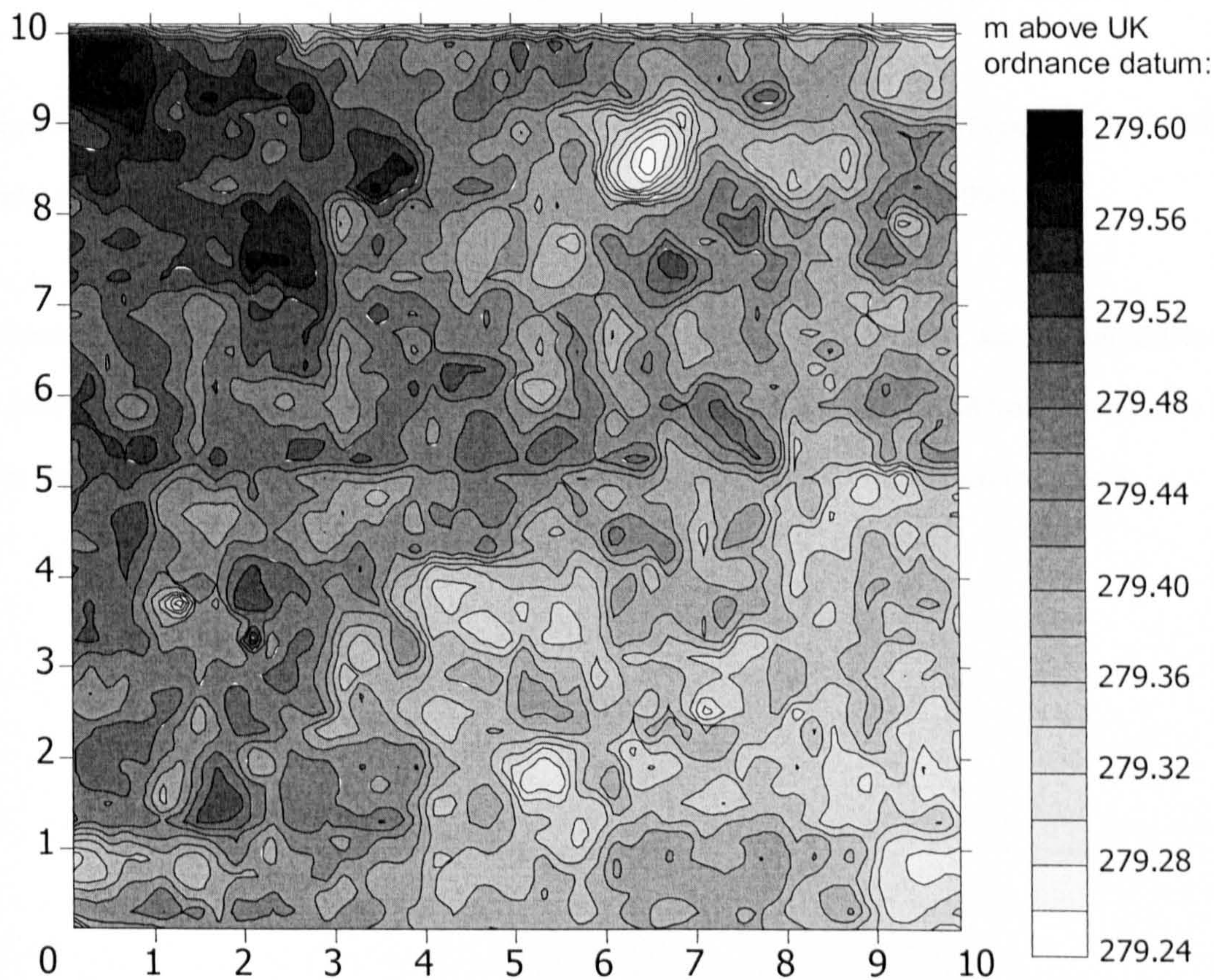
The monitoring plot area, SWaMP, described in Part A, has been divided into 51x50 rectangular cells, (Figure 6), each cell having 0.2m length in x and y directions. As the model describes the hydrology of only the acrotelm, or vegetatively active top layer of the mire, the thickness of the region to be modelled was reduced by subtracting 278.8m from all ordnance datum z -co-ordinates. The model scheme was flexible so that layer thickness varied from 0.4m to 0.8m, in which ground water fluctuations were calculated. The area was originally surveyed (as described in Part A) and initially modelled at cell size 0.01m^2 . After initial model testing cell area was increased to 0.04m^2 , by merging four original cells. The centre elevation (z -co-ordinate) of each new 0.04m^2 cell was taken as the z -co-ordinate at the intersection of the four original 0.01m^2 cells. The Manning's coefficient for each new cell was given by the geometric mean of the original four cells. This was necessary to increase the stability region and reduce computational time.

Figure 6. Grid representation of the study area: A, B observation wells.



As described in Part A, there are two observation wells in the field at co-ordinates 3,2 (A) and 3,9 (B) shown in Figure 6. Groundwater head values were measured continuously and recorded at 20-minute intervals in these wells. External plot boundary conditions are set as closed, reflecting the field condition, except for the right bottom corner (0,10) of the plot, which was open to a sump, into which runoff was directed by a gutter. In the model, this boundary is also set as an open boundary so that discharge at this point can be obtained. In the field discharge is recorded via a tipping bucket gauge (Part A, Section 4). Hydraulic conductivity values in the Z direction were set to zero along the gutter (0,0-0,10) as it was impermeable. The contour map of the surface elevation of the model domain with cell size 0.04m^2 is shown in Figure 7.

Figure 7. Contour map of the plot microtopography, contour interval 0.02m.



8. Results

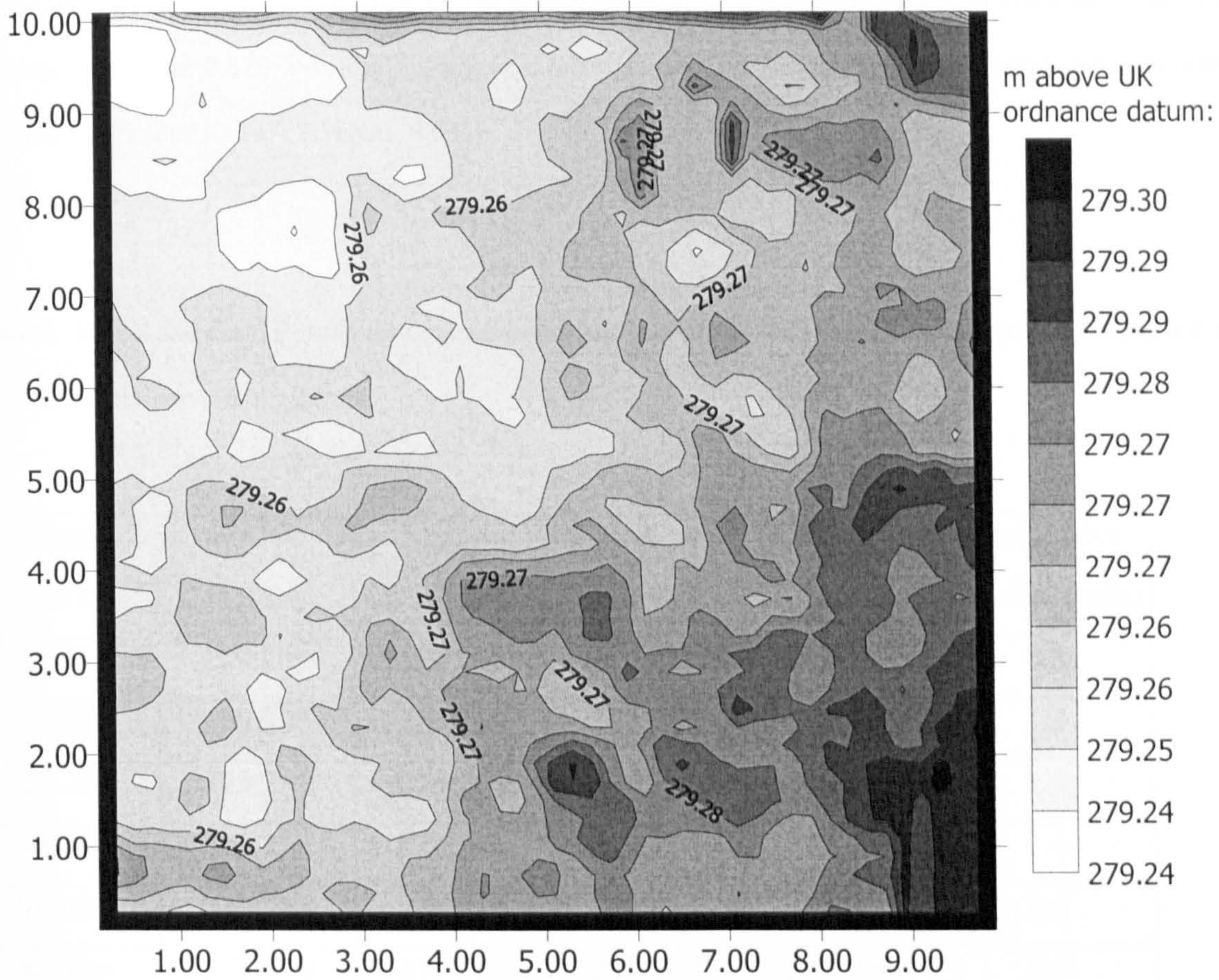
The model case study occurred on the 10th July, 2000, in the early hours of the morning between 00:00 and 03:20. Physical input data required to run the model including topography, roughness and hydraulic conductivity were determined previously. Measurement and calculation procedures are described in Part A. Hydrological data including rainfall, groundwater head fluctuations and runoff were measured at 20-minute intervals in the SWaMP using the raingauge, tipping bucket and automated dipwells A and B (Figure 6) (Part A Section 4). The storage coefficient was estimated from literature values (Part A Section 5 & 6) and taken as 0.05 throughout the model domain.

Initial groundwater condition or head was known only in the two dipwells A and B. As the model requires a groundwater head values for the entire domain, an initial value must be prescribed for each cell. This was achieved by pre-running the model with an estimated initial head. When the modelled head approached the observed groundwater head at the model period start time, the domain head values were accepted as a 'good' initial groundwater condition. A contour map of the initial groundwater head obtained by this process is shown in Figure 8.

At the beginning of the model run, the ground surface is assumed to be 'dry' - no water is ponding in hollows. The initial water depth at each grid point is prescribed as the minimum allowable value, 0.00001m.

The run is completed after 220 minutes. The recorded and modelled head for each well, and the cumulative rainfall for each interval, are included in Table 2 and illustrated by Figure 9. The change in head from one result to the next ($t_n - t_1$) for individual wells, calculated from field recorded and model values, is contained in Table 3.

Figure 8. The contour map of the groundwater head obtained from the model.



The model results are taken from the nearest grid point since location of dipwells A and B are not at the centre of a grid point. The results obtained from the field and the model shows some small differences. Numerically plots of field A and model A groundwater levels appear quite different in Figure 9 though they follow a similar trend. Field B and model B appear relatively similar, though they do not appear to follow the same trend in Figure 9. When fluctuations in groundwater level (Table 3) are compared with each other, model and field results in both A and B are quite strongly correlated (Pearson coefficient: 0.602 & 0.611; P-value: 0.05 & 0.046 respectively). When fluctuations in groundwater levels are compared to rainfall, both field results for A and B are very strongly correlated (Pearson coefficient: 0.961 & 0.843; P-value: 0.00 & 0.001 respectively) and model A is weakly correlated (Pearson coefficient: 0.551; P-value: 0.079). Fluctuations in model B groundwater levels are not correlated with rainfall.

Surface water runoff recorded in the plot and computed by the model are shown in Figure 10, along with the 20-minute cumulative rainfall for the same intervals. Modelled runoff is extremely positively correlated with rainfall (Pearson coefficient: 0.879; P-value: 0.000); field recorded runoff is strongly negatively correlated with rainfall (Pearson coefficient: -0.847; P-value: 0.001).

Table 2. Model and Field Results for Groundwater Head in wells A & B (in m above ordnance datum) and recorded 20-minute cumulative rainfall (mm).

Time Interval	Field A	Model A	Field B	Model B	Cumulative Rainfall (mm)
Initial	279.269	279.262	279.241	279.251	0.0
0-20	279.275	279.263	279.248	279.253	1.2
20-40	279.281	279.266	279.254	279.253	1.4
40-60	279.286	279.266	279.256	279.254	1.4
60-80	279.288	279.266	279.255	279.255	0.6
80-100	279.289	279.266	279.257	279.256	0.8
100-120	279.289	279.267	279.256	279.257	0.4
120-140	279.289	279.267	279.256	279.258	0.4
140-160	279.288	279.267	279.254	279.259	0.2
160-180	279.288	279.268	279.253	279.259	0.2
180-200	279.287	279.268	279.252	279.260	0.0
200-220	279.285	279.268	279.251	279.261	0.0

Table 3. Changes in the groundwater head for Model and Field Results, (m).

Time Interval	Field A	Model A	Field B	Model B
0-20	0.00600	0.00171	0.00700	0.00066
20-40	0.00600	0.00080	0.00600	0.00267
40-60	0.00500	0.00086	0.00200	0.00018
60-80	0.00200	0.00084	-0.00100	0.00024
80-100	0.00100	0.00084	0.00200	0.00029
100-120	0.00000	0.00084	-0.00100	0.00033
120-140	0.00000	0.00085	0.00000	0.00036
140-160	-0.00100	0.00085	-0.00200	0.00039
160-180	0.00000	0.00085	-0.00100	0.00042
180-200	-0.00100	0.00093	-0.00100	0.00044
200-220	-0.00200	0.00085	-0.00100	-0.00030

Figure 9. Model calculated and field observed groundwater level (m above datum) 00:00-03:20, 10/07/00.

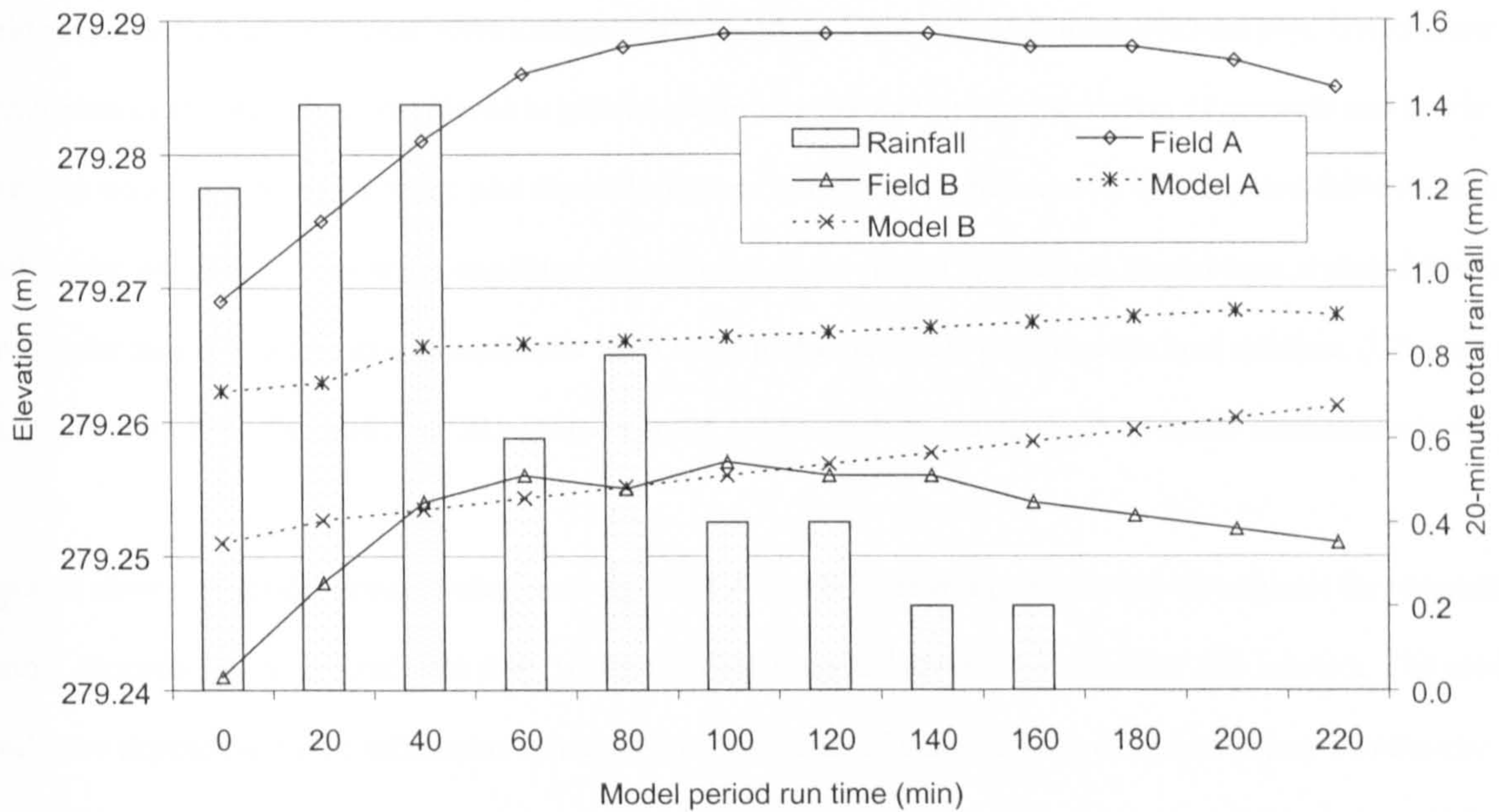
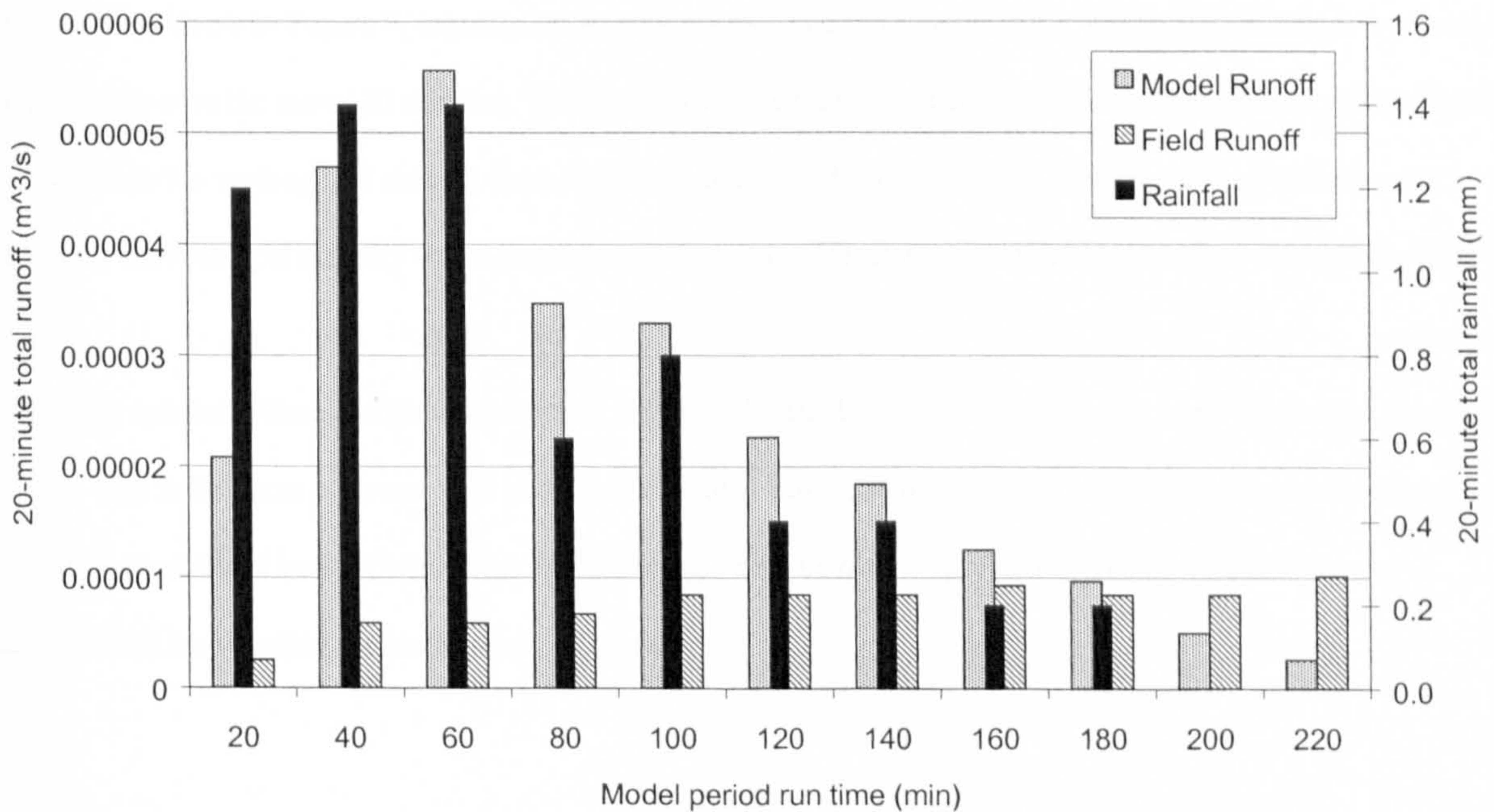


Figure 10. Cumulative rainfall (mm), model calculated and field recorded surface water runoff (m^3/s) for 20-minute intervals.



9. Discussion

Field values of groundwater head were known at two locations 7m apart, within the 10x10m plot. Under most circumstances this would be considered to give an extremely favourable representation of groundwater levels. However watertable recorded in the plot dipwells showed considerable differences. This created difficulties in establishing an initial groundwater condition for each cell in the model simulation. Model tests revealed that pre-running the model to arrive at a groundwater level close to the field data provided the best solution. Although many runs were completed the model initial condition could not be made to match the field initial condition exactly.

Figure 9 shows the model groundwater level for wells A and B increases continuously throughout the simulation period, excepting A in the final time step, whilst the field recorded levels decrease after 100 minutes. The model results are dependent on the infiltration relationship which is continuous and the closed boundary conditions, therefore no water loss. The apparently linear increase in the model groundwater level, particularly in well B, is a result of the leakage computation (Section 4), effectively head difference times by layer transmissivity. At point A the groundwater level during the first 40 minutes shows fluctuations caused by greater lateral flow, having a greater contributing area (Figure 8). The rate of increase in the groundwater level at point A is less than that of B, as water level at A is closer to the ground surface having a smaller head difference in the leakage relationship. The field groundwater levels in Figure 9, increase up to 100 minutes due to recharge, after which they decrease by 4 and 5 mm respectively over the next 120 minutes. The falling recorded levels could be due to several reasons: redistribution of water within the wetting soil matrix; there could be some loss from the SWaMP either through or below the boundary material, particularly when groundwater heads are greatest; vertical and lateral loss through the mire body.

Generally speaking there is a good agreement between the field recorded groundwater head values and the model results. The differences between field and model are less than 0.02m and in many applications, such differences would be considered insignificant. This agreement can also be observed when correlating fluctuations of groundwater head values for model and field results.

Very little was known about surface water within plot at the beginning of the simulation period, and surface water was recorded as runoff only. The recording dipwells were perforated both below and above ground, and so could not be considered to give an accurate representation of any open water at that point. The initial surface water depth within the model simulation was prescribed as 0.00001m, the dry cell value.

Model runoff shown in Figure 10, was very strongly correlated with recorded rainfall, in fact the model responds immediately to rainfall. As rainfall increases, model runoff increases proportionately; as rainfall decreases so does model runoff. Field recorded values respond in a very differently and are strongly negatively correlated to rainfall. The field values increase steadily throughout the period. This condition reflects the field conditions in which interception and potential surface storage within dense vegetation cover is likely to be high, and which saturation of the imperfectly defined subsurface zone is also likely to delay overland flow. No account is taken of the lag in which the field becomes 'wet-up' before runoff occurs in the model scheme. The prescribed initial surface water depth (0.00001m) may have also caused high runoff during the first 40 minutes. If the model could be made to produce less runoff, more water would remain at the surface resulting in higher infiltration and producing a groundwater fluctuation closer to field conditions.

Discrepancies between the field recorded and modelled runoff may be due to the cumulative nature of field measurements versus 'distributed' runoff production by the model. Field values of runoff and rainfall are based on a cumulative record given by a 20-minute data logging interval, whilst of the model input parameters determine that rainfall must be distributed evenly throughout the small time-steps of each 20 minute model period. Model runoff values are output as a 20-minute cumulative totals (calculated for each 0.001s time-step) but may not be based on the actual distribution of rainfall which is unknown. If precipitation was unevenly distributed, occurring for example in the first or final minute of the logging period, this could not be determined and hence would be misrepresented by the model input parameter.

Agreement between the model result and field observed values could be improved if the field conditions were better represented. Up-scaling of the model grid from 0.01m^2 to 0.04m^2 was necessary to increase the stability region and reduce computational time. This increase in cell dimensions may reduce the accuracy of representation of the plot

topographical and friction characteristics. High discharge values obtained from the model may be attributed to the estimated Manning's coefficient values (Part A, Sections 5 & 6). Any increase in the Manning's coefficient values will result in a decrease in the discharge rate. The friction coefficient applied was the only way in which flow control by vegetation was represented. In reality the retardance imposed by vegetation is in the form of flow obstruction (the main effect) and bed friction (the lesser effect). Some calibration was carried out, however the Manning coefficient does not adequately represent this effect.

Rainfall inputs applied were gross precipitation values and evapotranspiration was not accounted for. However, as the model run was reproducing an event which occurred during the night, these factors were not considered important.

10. Conclusions

The following conclusions can be drawn from this study:

- 1- The groundwater head values obtained from GSHAW5 were in good agreement with field observed results from the SWaMP, with differences between field and simulated heads of no more than 0.02m.
- 2- Runoff values obtained from the model show small differences to the field measured results, simulated values for the field case described being a maximum of $5 \times 10^{-5} \text{ m}^3/\text{s}$ more than recorded values. It is understood from this study that the simulation of flow in a micro-scale environment (micro-topography, micro-water depth) requires a very close representation of physical parameters within a mathematical model. In particular, retardance associated with flow through and storage within submerged and emergent vegetation must be more accurately represented by an appropriate mathematical expression.
- 3- The present model accurately represents the test cases (A-C) and can be considered highly suitable for river-aquifer interaction, where the ground is saturated, there are no vegetative effects on the behaviour of flow, and evapotranspiration can be neglected. Ongoing development of the model includes a new module for the computation of flow through vegetation. Future developments will include additional modules for better representation of flux in the unsaturated zone and evapotranspiration, and the facility for additional sub-surface layers allowing vertical distribution of conductivity and storage potential.
- 4- Numerical observations included surface flow as rapidly varying flow with Froude number changes between $\bar{F} 0.1$ and $\bar{F} 4$ due to the large local slope and the large changes in the bed roughness values (vegetated surface and the roughness values between 0.018-0.12). In order to represent the rapidly varying flow condition as accurately as possible, a small grid size and explicit scheme were used with an initial time step of 0.001s. The use of such small time steps requires a relatively long simulation model run-time. When a stable initial condition is established during pre-running of the model, time steps can be increased and model run-time is reduced considerably.

Acknowledgements:

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Chapter 7. Conclusions and Recommendations

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7.1 Achieving the stated aims: mires and models.

This thesis began by stressing the need for better understanding of functional hydrology in mire systems. In fact, the thesis and the literature cited herein are evidence of the breadth of knowledge of the internal hydrological processes of mires. Such understanding is however limited to a narrow community of wetland scientists. This highlights the real challenges facing mire conservation: to integrate existing extensive knowledge within a framework that can be implemented at a practical site management level and to include this understanding in mire conservation strategies at a legislative level. It is essential that conservation planning and management satisfy the practical demands of each site and that this requirement forms the basis of legislative protection. If nature conservation policy is not informed by the practicalities of habitat management then it cannot protect the ecological resource it seeks to maintain.

The monitoring programmes illustrated by the two mire case studies presented in this thesis, demonstrate how the linkages between hydrophysical properties, and combined with both internal and external management options, determine the overall ecological 'condition' of mires. For example, continued peat extraction adjacent to the mire reserve at Wedholme Flow alters more than the hydrophysical properties of the peat cutting area. It clearly determines the hydrology and hence influences the ecology of the nature reserve, so that restoration management is shaped by external practices over which English Nature has no control.

Without a suitable framework it is virtually impossible to integrate wide ranging and often conflicting factors in a quantitative way. Numerical models provide a quantitative framework on which to base or to inform a decision making process.

The aim of this thesis has been to demonstrate potential ways in which hydrological models can be used, in conjunction with high quality monitoring programmes, as management tools providing a framework to integrate the hydrophysical characteristics of mire complexes. It is not suggested that such models provide exact replicas of individual mires, but they represent the system by defined properties and processes, and as such provide a quantitative insight into ongoing and potential exchanges. This was demonstrated on two different scales: firstly, on a mire-complex scale with the application of the 3-D groundwater model MODFLOW at Wedholme Flow; secondly, on a micro scale with the development of the shallow surface and ground water model GSHAW5 at Trough End.

At Wedholme Flow the mire complex was divided into zones according to disturbance indicated by vegetation communities. Hydrological processes were then monitored within each zone. This allowed both characterisation of intra-site hydrological zones and comparison of hydrological characteristics based on observations only. The monitoring programme identified a differential response to recharge during wet and dry periods, and in disturbed versus intact zones. These differences appeared largely due to storage potential in the near surface zone due to both antecedent conditions and level of disturbance. The low gradient, high watertable intact mire appeared to act much like a reservoir close to full capacity (as observed at other sites, e.g. Fojt, 1983, Verry et al, 1988,), with surface and near-surface pathways within the acrotelm critical in maintaining a hydrologically steady state. This was also reflected in the vegetation communities of this zone at a broad scale. Near-surface watertables and surface water were found to be much more localised in the drier, higher gradient disturbed mire, within a surface layer still dominated by previous peat mining activity.

Validation and application of MODFLOW in both mire types at Wedholme confirmed observed behaviour and offered potential explanations. Groundwater heads produced by the model for simulations of the intact mire in wet periods are slightly (but consistently) higher than the observed watertable, with the above ground phreatic level indicating a degree of surface water activity. Simulation of the disturbed zones revealed significant groundwater discharge from the mire reserve to the area of mire currently exploited for peat extraction. This explains the relative dehydration of some zones, and particular problems experienced by conservation managers in rewetting certain areas. MODFLOW was also used to simulate the effect of ongoing peat removal and associated drainage in cuttings adjacent to the mire reserve. The simulations highlighted the importance of increasing gradients in the post-mining mire surface and the threat of prolonged dehydration with increasing discharge from the mire reserve if adjacent drainage continues. This has consequences not only for the restoration and conservation of Wedholme Flow reserve, but also for the efficacy of legislative protection of mire nature reserves in general.

Observations of the critical role of surface/near-surface processes made in the Wedholme intact site monitoring programme were developed and tested in the micro-scale investigation of Trough End acrotelm hydrology. Significant overland flow was recorded within the microtopographical environment of the mire acrotelm enclosed in the SWaMP unit. However, comparison with model-simulated discharge revealed that GSHAW5 overestimated the response of the acrotelm to precipitation, with rainfall events resulting in almost instantaneous run-off, whilst the recorded groundwater levels and discharge from the SWaMP indicate a more gradual response. The model response could be interpreted as an infiltration excess overland flow regime whilst the field data are indicative of a saturation excess process, so that lag between actual recharge and recorded discharge is due to the replenishment of water

storage capacity within acrotelm vegetation and peat, not adequately represented in the current model.

Ingram (1983) stated that, 'it is hydrologically meaningless to maintain any distinction between the living surface layer of *Sphagnum* and the dead material below'. Following this concept, the ground surface within the SWaMP was defined as the uppermost surface of the *Sphagnum*, whether hummock or hollow, and surveyed across the plot. Within GSHAW5 this surface represents the boundary between calculation of the shallow open water layer and calculation of acrotelm exchanges to an arbitrary depth of -0.5m . In the simulation of the SWaMP, the factors governing open water flow within the microtopography, such as bed slope and friction coefficient, were assigned across the plot according to surveyed data. However, within the subsurface acrotelm, storage and conductivity were assigned constant values in the x, y, and z-dimensions, and whilst the model grid of the subsurface layer is capable of representing lateral heterogeneity, this requires the appropriate values at a representative scale. Considering the z or vertical dimension, a single homogeneous layer is clearly an over-simplification of the heterogeneous transition from living vegetation to peat. Within a *Sphagnum* layer Clymo (1978, 1983), distinguishes several zones: uppermost are the vertical stems of living *Sphagnum*; as depth and age increases and light decreases, stems bend and plant cells die; eventually over-burden results in the collapse of individual stems, which in turn are subject to decay in this periodically aerobic, biologically active zone; continued growth at the surface increases over-burden contributing to further structural failure and consolidation of now humified material. This process occurs differentially across the mire surface depending on localised watertable fluctuation, resulting eventually in heterogeneity of peat density and hence hydrophysical properties throughout the mire body. In order to truly represent this variability with GSHAW5, it would be necessary to introduce depth dependent

density into the acrotelm, so that storage and conductivity are variable on a sub-hummock scale. The most simple way to do this would be to divide the acrotelm into several layers linked using the numerical coupling procedure currently used to compute leakage from surface to ground (described in Chapter 6, Section 4), hence allowing different values to be represented in the z-dimension. A second possibility would be to introduce a density dependant relationship into the groundwater flow equation by making hydraulic conductivity a function of depth. Both possible solutions have the disadvantage of implying an empirical relationship between depth and density throughout the acrotelm, and would require significant validation, not to mention extensive data sets.

The development of the model GSHAW5 in order to simulate acrotelm flow, exemplifies some of the advantages and problems inherent in numerical modelling of natural systems. The model simulations provided good approximations of the observed hydrological behaviour, and could be used in the same way to simulate acrotelm flow at other sites. However, the extensive field survey programme and intensive scale of data collection required are prohibitive to its application in most practical situations. Application of the model at this scale also requires long computing time with some of the best processors currently available. This is likely to increase if the suggested developments of the model are completed. It is not suggested then, that the SWaMP or GSHAW5 should be applied at other sites at this scale, and in their current stage of development. Despite these doubts, the GSHAW5 framework and the SWaMP concept, with their integration of hummock-hollow vegetation with hydraulic principals provide a very promising starting point for larger scale applications.

The confirmation of the role of surface water and acrotelm exchanges, quantified in the SWaMP and reproduced by GSHAW5, are important to mire regeneration at Trough End and

other similar sites. The potential for surface flooding where quickflow is retained has implications for vegetation succession and should be considered where ditch blocking is planned.

The application of both models has demonstrated their suitability to both investigation and problem solving in the hydrological management of mires.

7.2 Application in the ‘real world’: monitoring, models and management.

It has been stated that it is virtually impossible to integrate the hydrophysical processes of a mire complex with potential management strategies in a quantitative way without a suitable framework. The framework recommended in this thesis has been a numerical modelling scheme. However, conservation managers regularly make judgements and take decisions about site management based on qualitative assumptions of hydro-ecological mechanisms. The value of such a decision making process is limited and becoming increasingly so as the conservation of more and more critical mire sites come under the scrutiny of both legislative process and profit making industry. As the habitat resource becomes increasingly scarce, pressure to prevent its over exploitation grows, and as with any scarce resource its value, both ecological and financial, also increases. This issue is brought into sharp focus at Wedholme Flow.

Wedholme forms a large portion of the Solway Mosses National Nature Reserve. The entire site was notified a Site of Special Scientific Interest (SSSI) in 1986, under the UK ‘Wildlife and Countryside Act’ of 1981. Previously, 270ha of the southern lobe were protected under the 1949 Act, following a survey in 1957 by Rose who acknowledged the degraded condition

of large areas of the site but described the south west area as, 'the best remaining example of active raised mire vegetation left in the English Lowlands' (EN, 1995). The 1986 notification states that the peat body should be regarded as a 'single hydrological unit' and that the whole remaining area of 780ha is required to maintain the existing intact mire and rehabilitate the cut-over areas. This area includes the peat cutting area then operated by 'Fisons' and still in current use today by 'Levingtons', a subsidiary of the US based multinational corporation 'Scotts'. The notification prescribes twenty-eight 'operations likely to damage the Special Interest'. These include all forms of drain maintenance, earthworks, and the extraction of minerals including peat, all of which are performed to date in the active peat cutting area within the boundary of the SSSI.

Most recently Wedholme has been further notified as a candidate Special Area of Conservation (cSAC) within the NATURA 2000 ecological network, developed to satisfy the requirements of the European Habitats Directive throughout the European Union. Under EU law 'Directives' must be implemented by all member states. The Habitats Directive (92/409/EEC), adopted in 1992, specifically aims to protect 'all forms of wildlife' and requires that 'positive measures are taken [for the] maintenance of ecological processes and life support systems' (EC, 2001). The purpose of the directive is to include specified habitats and species (having a natural range within the EU territory) in the NATURA 2000 European ecological network of SACs. Member states are not only required to designate SACs. They are obliged to establish all conservation measures necessary to prevent deterioration of such habitats listed in Annex I of the directive, and to protect the species listed in Annex II. The most basic requirements of protection are the need to specify how sites will be conserved (with the creation of management plans), and to monitor habitats and species.

Around 25% of the habitats listed for protection in the directive are further notified as 'priority habitats'. More than 10% of these habitats are peatlands including raised mires. Member states are obliged to provide stricter and earlier protection to priority sites and in addition to taking all necessary conservation measures to maintain the sites, they are required to restore the conservation value of degraded sites. Any action within or external to the protected area, likely to have negative implications for its conservation, must be prevented and the state is required to take compensatory measures to ensure this. In addition to the habitats and species listed in Annex I and II, Annex V of the directive is concerned with the conservation of exploited species and these include *Sphagnum* moss.

Despite all of the protective measures outlined under both UK and EU legislation and applicable to Wedholme Flow, the site continues to be exploited for peat removal under a UK local authority planning consent, and is continually degraded as an ecological resource. The problems experienced by conservation managers in rewetting areas with increased gradients and a post-mining mire surface (as they are obliged to do under the Habitats Directive) have been outlined, as have MODFLOW simulations of the disturbed zones revealing significant groundwater discharge from the mire reserve into peat cutting zone. The model simulations indicated that continued drainage of the cuttings from ongoing peat removal would cause increased discharge from the mire and prolonged dehydration of the cSAC. Whilst this is common sense to a conservation manager, it is necessary to quantify the scale of the problem. Considering the issue of continued and clearly conflicting management of this ecological reserve in terms of the protection it is afforded within the framework of official designation, has consequences not only for the restoration and conservation of Wedholme Flow, but also for the efficacy of legislative protection of mire nature reserves throughout the European Union. At this time, despite the best efforts of the conservation managers and the highest level

of legislative protection possible, Wedholme Flow is not adequately protected from continued ecological degradation.

In contrast to the situation at Wedholme, Trough End Bog is neither notified nor especially protected beyond its location within a National Park. In conservation terms this provides a 'flexible' approach to land management, as the park includes military operations, wind farms, agriculture of various scales of intensity, mining and forestry, so that it can hardly be seen as restrictive. However, the only identified threats to this small (2ha), isolated mire site, are the occasional grazing sheep and potential maintenance of the currently unmanaged drainage network. The National Park authorities place particular value on the conservation and restoration of damaged bogs, and 'mires' are listed as a 'key habitat' in the Northumberland Biodiversity Action Plan (BAP), published by the local authority and the Biodiversity Steering Group representing local interests, NGOs and government agencies (Feige, 2000). The plan refers to the inclusion of blanket bog in Annex I of the Habitats Directive, and represents the most local level of implementation of this legislation. The BAP emphasises that as over 17,000ha of mire in Northumberland represent 8% of the UK resource, including SPAs, SSSIs and SACs, they should be considered of highest priority. The plan lists nine 'Issues of Concern' including overgrazing and drainage, whilst the restoration and conservation of bogs by grip (shallow drain) blocking is amongst the stated objectives. In addition the benefits to the larger catchment of 'restoration of the hydrological function' of mires are clearly identified. Both the Park authorities and land owners have expressed a desire to restore this function to Trough End Bog, and this clearly positive approach encompassing both sound ecohydrological aims and international policy at a local level is extremely promising.

7.3 Recommendations and future work.

Outside of the official lines of legislative procedure, improvements in the communication of better conservation practices and of shared knowledge between conservation managers and scientists are growing. An appendix to this thesis, the report on the 58th Eurosite workshop is concerned specifically with collaboration between managers and scientist throughout the community, and is evidence of the formalisation of such communication within Europe by organisations such as Eurosite. In this same spirit, a document of historical importance is currently being produced as a joint venture between the International Mire Conservation Group and the International Peat Society, representing the scientific, conservation and industrial communities with one common interest: peat. The venture is supported by the bureau of the Ramsar Convention and by Wetlands International, and has increased the profile of mires within the wider wetland lobby. The document represents collaboration previously unknown at such a contentious level. When complete, it will represent a true framework within the spirit of the Ramsar Convention, for the 'Wise Use of Peatlands' (Joosten and Clarke, 2001). This represents the combination of both mire level best management practice and international level legislation, and it is hoped that it will fill the gaps between the two in the future.

The future of numerical modelling of mires is that of extensification whilst maintaining the accuracy demonstrated at intensive scales. The two very different scales of numerical modelling presented in this thesis both have their merits and would both benefit from combination, possibly in some form of nested model. MODFLOW simulations of groundwater processes within mires were accurate to the degree at which such processes were found to dominate local hydrology. Where surface processes were more influential, such as

during storm periods in the intact mire, the model performed less well. Although it produced effective surface water depths in the form of above ground phreatic levels, overland flow could not be simulated and this led to a compounding error as the simulation proceeded. Given that groundwater processes are increasingly accepted as less influential in intact ombrotrophic mires, the two layer model developed as GSHAW5 may present a more suitable way forward. The model effectively represents the overflowing reservoir described by Verry *et al* (1988), with calculation of shallow surface water flow instigated by above ground phreatic levels.

The GSHAW5 model scenario presented included open water and a single acrotelm layer only but could be extended without difficulty, using the linkage procedure outlined, to relate deeper groundwater heads to the near surface region. The accuracy of the hydrological simulation may be improved by the inclusion of an unsaturated subsurface flux module, possibly in the form of a Richards type equation. Additional modules could be included in the surface part as leakage coefficient, such as a conditional evapotranspiration calculation with open water and extinction depths, and a depth-dependant friction relationship in place of the arbitrary Manning coefficient, to better represent flow through submerged and non-submerged vegetation. The immediate development of the model should focus on the inclusion of a depth dependent peat density relationship in the subsurface and the up-scaling of the processes observed to a large scale model application.

Future investigations should focus on potential relationships between individual plant species recorded during the SWaMP survey, and hydrological factors including open water, interflow within the unsaturated zone (effectively within hummocks), and both seasonal and short-term water table fluctuations.

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EUROSITE

58ème Atelier EUROSITE
English Nature - EUROSITE Workshop



ENGLISH
NATURE

10-14 October 2000

Le restauration des tourbières:
Vers le retour Sphaignes?

*Sphagnum or not?
Variations in peat forming
vegetation in relation to
restored water levels*

Foreword

The View From The Bogs

Baroness Young of Old Scone: Chairman English Nature

L'optique des tourbières

I love peat bogs. They have a character all of their own. But everyone at this workshop shares the view that they are in danger of disappearing unless we take action to restore them. Ireland is almost synonymous with peat bogs and if they disappear - which is a real threat - then the nature of the country would be changed.

English Nature is charged with the stewardship of a similar acreage as Ireland, but their disappearance in this country would be no less of a catastrophe.

France, Belgium and the Netherlands are all faced with the same problem which individual countries have solved in many ways. This workshop has been an opportunity to share our views on how the problem of dehydration of peatland might be solved.

But what we need now is for a greater public awareness of the problem. How often have I heard the cliché that peat is a renewable resource? Yet many people continue to perpetrate this myth. Clearly our experience shows that peat is not a renewable resource - at least in the short term - and if we continue to drain our peatlands and extract peat in the volume we are now doing, the peatlands may be lost forever.

What we need is for the public to switch to non-peat growing media; but this is difficult. Firstly because peat itself is an excellent growing medium and secondly because it is relatively cheap. Other forms of compost require more processing which makes them more expensive. There seems little incentive for the peat industry to change. Yet with a modest amount of Research and Development they could produce a product that is equal to peat in quality and price.

In the meantime, we must take measures to preserve our peat bogs. This workshop, by sharing the views of peatland managers from several countries has been a positive means to that end.

J'adore les tourbières. Elles ont un caractère qui leur est propre. Mais toutes les personnes présentes à cet atelier s'accordent à reconnaître qu'elles risquent fort de disparaître à moins que nous ne prenions des mesures pour les restaurer. L'Irlande est presque synonyme de tourbières et si celles-ci disparaissent - ce qui est une réelle menace -, le caractère du pays sera alors modifié.

English Nature est chargé de l'intendance d'une superficie analogue à celle qui existe en Irlande, et la disparition de ces tourbières serait tout aussi catastrophique.

La France, la Belgique et les Pays-Bas sont tous confrontés au même problème que les pays individuels ont résolu de nombreuses façons. Cet atelier a été l'occasion de partager nos vues sur les moyens de résoudre le problème de la déshydratation des tourbières.

Ce qui est maintenant nécessaire, c'est une sensibilisation accrue du public au problème. Combien de fois ai-je entendu le cliché selon lequel la tourbe est une ressource renouvelable? Cependant, de nombreuses personnes continuent à perpétuer ce mythe. De toute évidence, notre expérience montre que la tourbe n'est pas une ressource renouvelable - tout au moins à court terme - et si nous continuons à drainer nos tourbières et à extraire la tourbe au rythme actuel, les tourbières pourraient disparaître à jamais.

Il faut amener le public à utiliser des milieux de culture non tourbeux, mais cela est difficile. Premièrement, parce que la tourbe elle-même est un excellent milieu de culture et, deuxièmement, parce qu'elle est relativement bon marché. Les autres formes de compost nécessitent un plus grand traitement, d'où leur coût plus élevé. Il semble que pratiquement rien n'incite l'industrie de la tourbe à changer. Pourtant, avec de modestes travaux de recherche et de développement, elle pourrait mettre au point un produit égal à la tourbe en termes de qualité et de prix.

En attendant, nous devons prendre des mesures pour préserver nos tourbières. En stimulant le partage des vues entre des gestionnaires de tourbières de plusieurs pays, cet atelier a été un moyen positif d'œuvrer à cette fin.

Baroness Young



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Introduction

The purpose of the workshop was to facilitate collaboration between peatland site managers and scientists across Europe in the practical context of real site restoration issues. This is a primary aim of *Eurosite*. The workshop was attended by site managers, conservation officers, scientists, and representatives of concerned NGO and government agencies from England, Wales, Scotland, Northern Ireland, the Republic of Ireland, France, Belgium and the Netherlands.

The focus of discussion was the relationship between 'restored' water levels in peatlands, with both cut-over and intact surfaces, and the establishment of pre-disturbance type vegetation assemblages, in particular *Sphagnum* moss species. A wide range of factors pertaining to the restoration and management of bogs were considered ranging from the most suitable material with which to construct dams and the most reliable vehicles to use on wet peat surfaces, to algal inhibition of *Sphagnum cuspidatum* establishment in pools and drainage conflicts with neighbouring land owners.

Whilst in many cases the wetlands concerned were specifically raised mire complexes, the management practices discussed are pertinent to most peatland forms in both upland and lowland situations.

Three sites were visited, with an optional fourth site on the last morning. All of the sites visited are National Nature Reserves managed by English Nature.

Issues discussed and questions arising throughout the workshop are grouped thematically, along with appropriate site visit reports. Contributors and site managers provided notes and abstracts that have been combined with workshop and site discussion points. Issues on which the group agreed as good management practice, are contained in boxes entitled *Management Precepts*. Those issues on which no agreement was reached, or which were posed as 'open ended', are included in boxes entitled *Discussion Points*, and may be considered by future workshops. A list of pictures from each site, which do not necessarily relate directly to the text are given as an appendix.

Frank Mawby : Co-editor (rédacteur)
Charlotte MacAlister: Co-editor (rédacteur)
Geoffrey Lindop: Co-ordinator (coordinateur)

Le but de l'atelier a été de faciliter la collaboration entre les gestionnaires de tourbières et les scientifiques de toute l'Europe dans le contexte pratique de questions réelles de restauration des sites. Cela constitue l'un des principaux objectifs d'*Eurosite*. L'atelier a rassemblé des gestionnaires de sites, des spécialistes de la conservation, des scientifiques et des représentants des ONG et des organismes gouvernementaux concernés de l'Angleterre, du pays de Galles, de l'Ecosse, de l'Irlande du Nord, de l'Irlande, de la France, de la Belgique et des Pays-Bas.

Les débats ont été axés principalement sur les relations entre les niveaux phréatiques « rétablis » dans les tourbières, ayant à la fois des surfaces exploitées et intactes, et sur l'établissement d'assemblages de végétation du type qui existait avant les perturbations, en particulier les espèces de sphaignes. Les participants ont examiné un large éventail de facteurs se rapportant à la restauration et à la gestion des tourbières, allant des matériaux convenant le mieux à la construction de barrages et des véhicules les plus fiables à utiliser sur les surfaces humides des tourbières jusqu'à l'inhibition algale de *Sphagnum cuspidatum* dans les mares et les conflits en matière de drainage avec les propriétaires fonciers voisins.

Dans de nombreux cas, les zones humides concernées étaient spécifiquement des tourbières hautes, mais les pratiques de gestion débattues sont pertinentes pour la plupart des formes de tourbières, qu'elles soient situées sur des terres d'altitude ou dans des plaines.

Trois sites ont été visités, une visite optionnelle d'un quatrième site ayant été prévue pour le dernier matin. Tous les sites visités sont des Réserves naturelles nationales gérées par English Nature.

Les points débattus et les questions soulevées tout au long de l'atelier sont réunis par thème, avec les rapports appropriés des visites de sites. Les collaborateurs et les gestionnaires de sites ont fourni des notes et des résumés qui ont été associés avec les points de discussion s'inscrivant dans le cadre de l'atelier et des visites de sites. Les questions sur lesquelles le groupe a marqué son accord comme constituant de bonnes pratiques en matière de gestion figurent dans des encadrés intitulés *Préceptes de gestion*. Les questions au sujet desquelles aucun accord n'a pu être dégagé ou qui ont été posées comme étant ouvertes figurent dans des encadrés intitulés *Points de discussion* et pourraient être abordées par de futurs ateliers. Une liste des photographies de chaque site, qui ne se rapportent pas nécessairement directement au texte, est donnée en annexe.



Thorne, Crowle and Goole Moors NNR

1.0

The National Nature Reserve which totals 1380 ha is part of the huge area of peatland found in South Yorkshire and North Lincolnshire. This peatland comprises of two units, Thorne, Goole and Crowle Moors and, 10 Kilometres to the South, Hatfield Moors. They represent the largest area of lowland raised bog in Britain totalling an area of 3318 ha. This site has been extensively cut for peat over many decades and cutting continues over a large area to within 0.5 metres of the mineral soil. Over the past 8 years work to restore water levels to the NNR has been undertaken whilst cutting continues on the remainder. The whole site will eventually be returned to nature conservation. There are many interesting and complex issues on this site not the least that the site is host to many invertebrates and birds some of which are rare and endangered. The local community also have a considerable interest in the site.



La réserve naturelle, qui couvre au total 1380 ha, fait partie d'une très grande zone de tourbière du Sud Yorkshire et nord Lincolnshire. Cette tourbière se compose de deux unités qui représentent la plus grande tourbière active de Grande-Bretagne (3318 ha). Ce site est exploité de manière extensive depuis de nombreuses années et l'exploitation continue sur une large zone jusqu'à 0,5m du substrat. Depuis 8 ans les travaux de restauration des niveaux d'eau ont été entrepris dans la réserve tandis que l'exploitation continue alentour. Tout le site à terme sera consacré à la conservation de la nature. Les enjeux sur ce site sont complexes et intéressants : le site accueille de nombreux invertébrés et oiseaux dont certains sont rares et menacés. La population locale est très intéressée par le site de plusieurs manières.



Introduction to Thorne, Crowle and Goole Moors NNR

Peter Roworth
Site Manager, *English Nature*

1.1

The Thorne Moors complex comprises the degraded remnants of a flood plain raised mire (Gaunt, 1987). The Moors lie below the high tide level of the surrounding rivers (1-3.5 m above mean sea level). The peat, which reached its greatest depth of 7m in the 'Yorkshire Triangle' on Crowle Moor, overlays Lake Humber lacustrine silt and clay. This mantles rocks of the Sherwood Sandstone Group in the west and Mercia Mudstones to the east.

The whole of the site has been cut over for peat at some time and the majority of the southern, western and eastern parts of the Moors form a mosaic of abandoned peat workings, cut in a variety of ways and in various stages of recolonisation by vegetation. The remainder of the site, about half of Thorne Moors west of Swinefleet Warping Drain, is now managed for commercial peat extraction by The Scotts Company (UK) Ltd (hereafter 'Scotts'; formerly Levington Horticulture and previously Fisons plc), with the peat being processed and marketed as compost. The modern technique of surface milling currently employed has created an almost featureless plain of bare unvegetated peat subdivided by a system of drains.

The main factors controlling the type of communities that have developed on these various surfaces are:

- ◆ Time elapsed since last worked
- ◆ Type of cutting technique employed
- ◆ Height and stability of the water table
- ◆ Water quality
- ◆ Growing medium
- ◆ Period since last fire damage
- ◆ Subsequent management

This has resulted in a complex pattern of vegetation comprising open water, bog, fen (a continuum from nutrient poor to rich),

wet and dry heath and scrub communities. The Moors also have non-peatland habitats including woodland growing on warp (land deliberately flooded to leave residual layers of silt and clay in order to improve its agricultural potential), poor fen, fen-meadow and tramways with lime-rich ballast supporting nutrient-poor grassland.

Crowle Moor, now separated from the main peat body by the Swinefleet Warping Drain, shares many of the habitats found on Thorne and Goole Moors. Fisons ceased peat extraction here during the 1950s and mire communities and scrub woodland have regenerated over large areas of former peat cuttings. Some peat is still extracted on a small scale by private owners outside the National Nature Reserve.

HATFIELD MOORS

Hatfield Moors also comprise the degraded remnant of a raised mire, which, until the 17th century, was probably separated from Thorne Moors by a complex of river channels. Like Thorne Moors it lies 1-3.5 m above sea level. The peat overlays wind blown sand and Lake Humber deposits and locally reaches a depth of some 3.3 m, although generally less than 1.5 m deep. Until comparatively recently Hatfield Moors was much less degraded than Thorne Moors; although partially drained in the 19th century, most of the Moors were not cut over until the 1960's. Thereafter, Fisons undertook commercial peat winning on the site using increasingly intensive techniques culminating in surface milling. The production area now covers some 80% of the Moors. The peatland here is generally 'drier' than that of Thorne Moors, possibly as a result of the more successful drainage of the Moors and the loss of water into the underlying sands as a result of water abstraction, and/or improved land drainage which has lowered the level of the regional water table.

Only small areas of Hatfield Moors remain vegetated; however it has been suggested that one of these (Packard's South; compartment 24) may never have been cut over (Eversham, 1991). If this suggestion is correct, this is the only sizeable area of original mire surface on either of the sites and is the largest area of uncut-over mire surface in eastern England.

The factors influencing the vegetation development on peat and the communities resulting are generally similar to those described above for Thorne. An additional influence, however, particularly around the Lindholme 'island' and on the western edge of the moors, where the peat is patchy and shallow, is that of the underlying sand. This has increased the extent and importance of heathland species and communities in these areas. Other non-peatland habitats, mainly outside the NNR, include restored gravel workings, dry woodland on warp, and agricultural land on dry warp.

Overall our long-term management objectives are to restore lowland raised mire habitat over the greater part of the NNR; to maintain and develop the full range of wetland habitats currently present on the NNR; and to maintain and enhance the cultural values and uses of the NNR.

Q. Is the current practice of moving large volumes of water around the site (from 'wet' to 'dry' sectors) using diesel pumps sustainable in the long term?

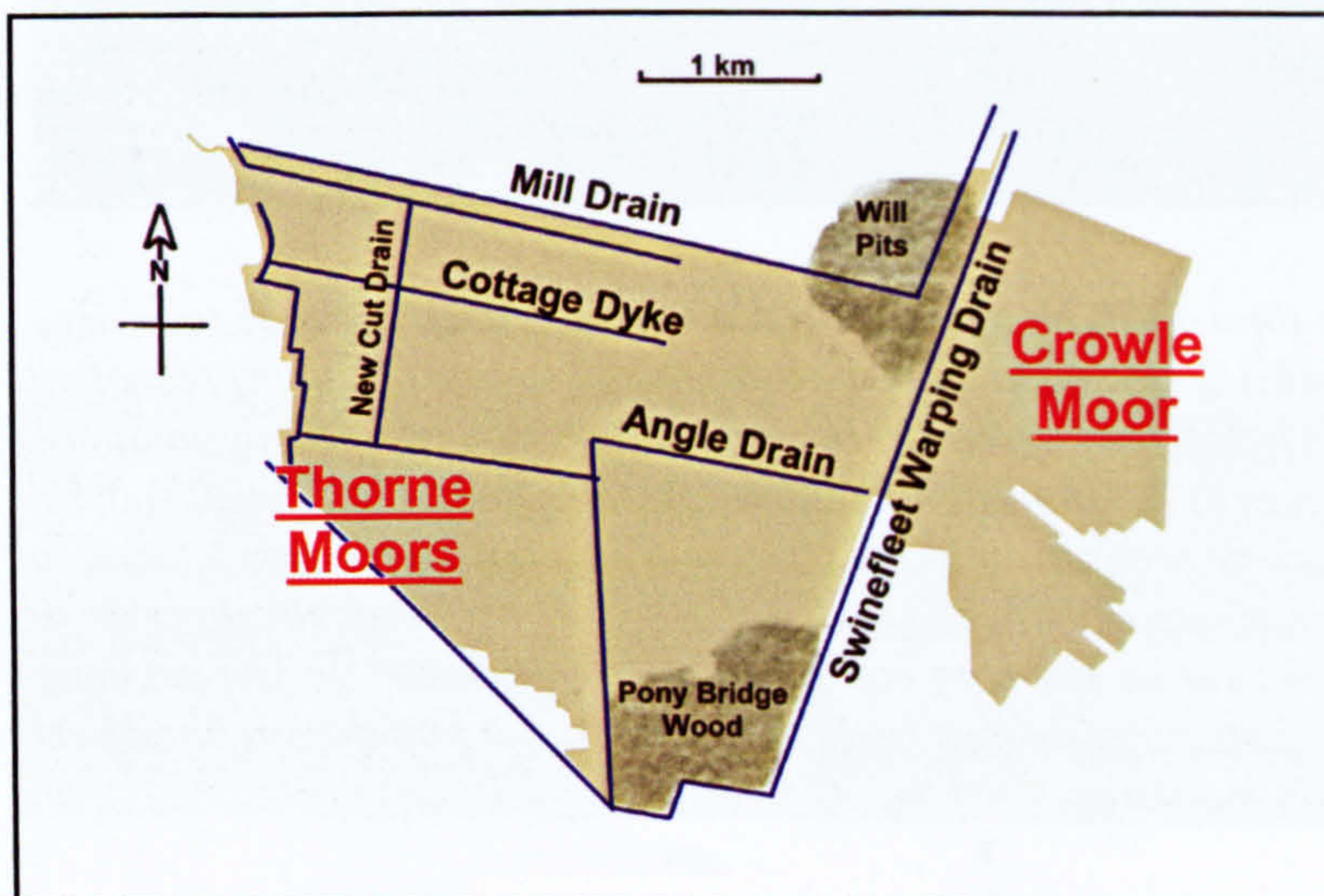
A. No – it is hoped that if pumping continues a more sustainable method such as wind pump, will be introduced.

Q. How were the locations of drain dams determined?

A. The location and spacing of the dams were chosen in the light of existing site knowledge about current open water flow patterns, along with a detailed topographical survey, allowing gradients and positions to be calculated more accurately.

Q. What type of peat was left after milling and cutting was discontinued?

*A. Peat remnants at Thorne consist largely of sedge and wood remains creating problems for re-vegetation, with accelerated water movement and aeration. This is manifested in the different colonising vegetation communities, at locations of differing depths on remnant peat. Where peat removal has been more extensive and shallow fen-type peats are left, scrub invasion can exacerbate problems in re-wetting. Where deep and especially ombrotrophic peat remains successions to a favourable vegetation community appear to be more rapid, with *Juncus* species appearing rapidly and apparently acting as a nurse crop to *Sphagnum cuspidatum* establishment.*



Le complexe de Thorne Moors comprend les vestiges dégradés d'une tourbière haute de plaine d'inondation (Gaunt, 1987). Les Moors sont situés au-dessous du niveau des cours d'eau avoisinants à marée haute (1-3,5 m au-dessus du niveau moyen de la mer). La tourbe, qui a atteint sa plus grande épaisseur, à savoir 7 m, dans le « Triangle du Yorkshire » sur Crowle Moor, recouvre le limon et l'argile lacustres du Lac Humber. Ceci enveloppe les roches du Groupe gréseux de Sherwood, à l'ouest, et de la formation d'argilite de Mercia à l'est.

Le site tout entier a fait l'objet d'activités d'extraction de la tourbe à une époque ou à une autre, et la majorité des parties méridionale, occidentale et orientale des Moors constituent une mosaïque de sièges d'extraction abandonnés, où la tourbe a été prélevée de diverses manières et qui sont à divers stades de recolonisation par la végétation. Le reste du site, environ la moitié de la superficie des Thorne Moors à l'ouest du canal Swinefleet Warming Drain, est désormais géré à des fins d'extraction commerciale de la tourbe par la société The Scotts Company (UK) Ltd (ci-après dénommée « Scotts », anciennement Levington Horticulture et précédemment Fisons plc), la tourbe étant transformée et commercialisée sous forme de compost. La technique moderne de broyage de la surface actuellement utilisée a créé une plaine tourbeuse nue et sans végétation, quasiment dénuée de traits distinctifs et sillonnée par un réseau de canaux.



Les principaux facteurs influençant les types de communautés qui se sont développés sur ces diverses surfaces sont les suivants :

- Temps écoulé depuis les dernières activités d'extraction
- Type de technique de prélèvement utilisé
- Niveau et stabilité de la nappe phréatique
- Qualité de l'eau
- Milieu de culture
- Temps écoulé depuis les derniers dommages causés par les feux
- Gestion subséquente



Cela a entraîné l'apparition d'une structure végétale complexe comprenant des masses d'eau libre, des tourbières, des fagnes (un continuum entre des sols pauvres et des sols riches en éléments nutritifs), des landes humides et sèches et des communautés de fourrés. Les Moors ont également des habitats non tourbeux, dont des zones boisées sur sols colmatés (terres intentionnellement inondées pour provoquer le dépôt de couches résiduelles de limon et d'argile afin d'améliorer leur potentiel agricole), des fagnes pauvres, des prairies-fagnes et des tramways avec des ballasts riches en chaux entretenant des prairies pauvres en éléments nutritifs.

Crowle Moor, qui est désormais séparé de la masse de tourbe principale par le Swinefleet Warming Drain, possède un grand nombre des habitats que l'on trouve sur les Thorne et Goole Moors. Fisons y cessa l'extraction de la tourbe dans les années 50, et les communautés de tourbières et les zones boisées à fourrés se sont régénérées sur de vastes étendues des anciens sites d'extraction. La tourbe fait toujours l'objet de prélèvements sur une petite échelle par des propriétaires privés à l'extérieur de la Réserve naturelle nationale (RNN).

HATFIELD MOORS

Les Hatfield Moors comprennent également les vestiges dégradés d'une tourbière haute qui, jusqu'au XVII^e siècle, était probablement séparée des Thorne Moors par un ensemble de chenaux de rivière. A l'instar des Thorne Moors, ils sont situés à 1-3,5 m au-dessus du niveau moyen de la mer. La tourbe recouvre une étendue de sable fouettée par le vent et les dépôts du Lac Humber et atteint localement une épaisseur de quelque 3,3 m, encore qu'elle ait en général une épaisseur de moins de 1,5 m. Jusqu'à une date relativement récente, les Hatfield Moors étaient beaucoup moins

dégradés que les Thorne Moors ; bien qu'ayant été partiellement drainés au XIX^e siècle, la majeure partie des Moors ne fit l'objet de prélèvements de tourbe que dans les années 1960. Par la suite, Fisons entreprit l'extraction commerciale de la tourbe sur le site en utilisant des techniques toujours plus intensives se terminant par le broyage de la surface. La zone de production couvre maintenant environ 80 % des Moors. Les tourbières y sont généralement plus « sèches » que celles des Thorne Moors, peut-être en raison du drainage plus efficace des Moors et des pertes d'eau par infiltration dans les sables sous-jacents par suite des captages d'eau, et/ou d'un drainage amélioré des terres qui a provoqué l'abaissement du niveau de la nappe phréatique régionale.



Seules de petites étendues des Hatfield Moors sont toujours dotées d'un couvert végétal ; il a toutefois été suggéré que l'une d'entre elles (Packard's South, segment 24) n'a peut-être jamais été exploitée (Eversham, 1991). Si cette suggestion est exacte, c'est l'unique étendue assez grande de surface de tourbière originelle sur l'un ou l'autre site et la plus grande étendue de surface de tourbière non exploitée de l'est de l'Angleterre.

Les facteurs influençant le développement de la végétation sur la tourbe et les communautés qui en résultent sont généralement analogues à ceux décrits-ci dessus pour les Thorne Moors. Une influence supplémentaire, toutefois, en particulier autour de l'« île » de Lindholme et à la lisière occidentale des landes, où la tourbe est inégale et peu épaisse, est celle du sable sous-jacent. Cela a accru l'aire de répartition et l'importance des espèces et des communautés de landes dans ces zones. D'autres habitats non tourbeux, principalement à l'extérieur de la RNN, comprennent des gravières restaurées, des zones boisées sèches sur sols colmatés et des terres agricoles sur sols colmatés secs.



Monitoring vegetation change at Thorne Moors following re-wetting

Tom Dargie,
Consultant

1.2

1.2.1

A monitoring technique recording the extent of re-wetting indicators within the Humberhead Peatlands was applied in 1994 and 1999.

Overall, there have been major changes in the distribution and abundance of most indicators, revealing an unanticipated scale of vegetation changes over a five-year period.

There are strong links between the scale of indicator change, indicator distribution, major habitats and changing environmental conditions.

The most important plant indicators, representing raised bog habitat, are distributed strongly in the south of Thorne, mainly in older traditional peat cuttings and adjacent canals and drains, but with signs of spreading out into some milled peat flats.

There has been an overall strong *Sphagnum* response to re-wetting, with a 13.9% increase in area since 1994.



Some *Sphagnum* species have increased in large quantities but others seem less tolerant of changing water levels and there have been marked declines in some species.

There has been a significant decline in the range and abundance of *Andromeda polifolia* and *Vaccinium oxycoccus*.

There has been a marginal decrease in area (1.6%) for *Eriophorum angustifolium*, mainly made up of a decline in cut flats and baulks counterbalanced by an expansion in milled peat flats.

There has been very large increase (132.6%) in area of *Juncus effusus* and this has occurred mainly in cut flats/baulks and milled peat flats.

The distribution patterns of *Juncus effusus* (occupying swamps in the centre and north of Thorne, and expanding strongly) and *Molinia caerulea* (present in varied habitats in the east of the area) are very different to other indicators.

Major indicator increases have already occurred from moderate increases in water levels as part of the re-wetting programme, but plant responses have been markedly slower in sub-compartments with a major increase in water depth.

Changes resulting from re-wetting are far more important than most other environmental trends. There are important unexplained vegetation patterns which probably represent local plant successions, for example, decline in *Eriophorum angustifolium* within old cuttings due to die-back in areas of increased water-logging due to a slight rise in watertable.

Q. *Eriophorum* species are obviously successful colonisers of re-wet sectors, and

Management Precepts

Water levels should be controlled within a maximum fluctuation of 20cm of the surface.

In re-wet areas tending to suffer from a moisture deficit, control of birch scrub invasion is critical.

could be competing with other invading species. Does *Eriophorum* suppress *Sphagnum* species?

*A. No - large areas of *Sphagnum recurvum* are established amongst stands of *Eriophorum vaginatum*, and during the monitoring period there has been an overall increase in *Sphagnum* species coverage.*

Q. Is there a potential for suppressed *Sphagnum* growth and regeneration by pollution from coal fired power stations, as high sulphur and nitrate concentrations are thought to prevent the production of spores in *Sphagnum* species?

*A. Atmospheric deposition of both nitrates and sulphates has currently reached a historical low in Britain, however there could be a legacy of pollution, the extent of which is not fully understood. Spore suppression is acknowledged as a factor in regeneration, however lab experiments have shown *Sphagnum* survival at NO_2 applications equivalent to 100kg/hectare/year, without signs of phytotoxicity. Transplanting *Sphagna* can accelerate colonisation allowing vegetative reproduction in cases where spores are not being produced.*

1.2.2

Water loss at Thorne Moors through different vegetation communities

Katherine Birdsall, Assistant Levels & Moors Officer, Somerset County Council

<No abstract received>

Removal of birch scrub may reduce evaporative demand in sectors where it has become dominant. However, this alone would not achieve and maintain high groundwater levels in these areas as their recharge is limited by storage potential. Scrub removal cannot increase the storage capacity of peats in these sectors, where it has been lowered previously by aeration and accelerated humification during drainage for peat harvesting.

Q. Was the temperature in the lab experiment similar to that in the field?

A. Yes temperatures were similar, but remained at the higher limit of field conditions in order to ensure sufficient evaporation oc-

curred to carryout comparisons. Air was also circulated in the lab using a fan.

Q. What was the relationship between calculated potential evapotranspiration (PET) and actual evapotranspiration (AET) in the lab experiment?

A. AET was higher than PET at high water tables and lower than PET at low water tables.

Q. Why did none of the lysimeters used in the field contain *Sphagnum* species?

A. This was considered too difficult to maintain and moss contained in the lysimeters became dry and died very quickly.

Q. In the large field plots, where dipwell data were used to estimate AET, where did apparent nocturnal recharge come from?

A. Recharge appeared to come from wetter adjacent areas.



Site Visit: Thorne Moors, Humberhead Peatlands NNR

Kevin Bull,
Site Manager, English Nature

1.3

The site was approached through remnants of the original mire surface now converted to agricultural uses, via an access road constructed for peat removal. The road passed through an area of woodland on mineral soil overlaying the mire peat. This area was created with the aim of improving its agricultural potential by flooding the land, which is close to sea level, and allowing mineral sediments to settle out on top of the peat, in a process referred to as 'warping'. At the disembarking point, active peat cuttings could be observed on an area which, under a current leasing agreement, allows peat removal to a mean depth of 0.5m, at which point its conservation management by English Nature will commence.

The site is divided into a candidate Special Area of Conservation (cSAC) and proposed Special Area of Conservation (pSAC).

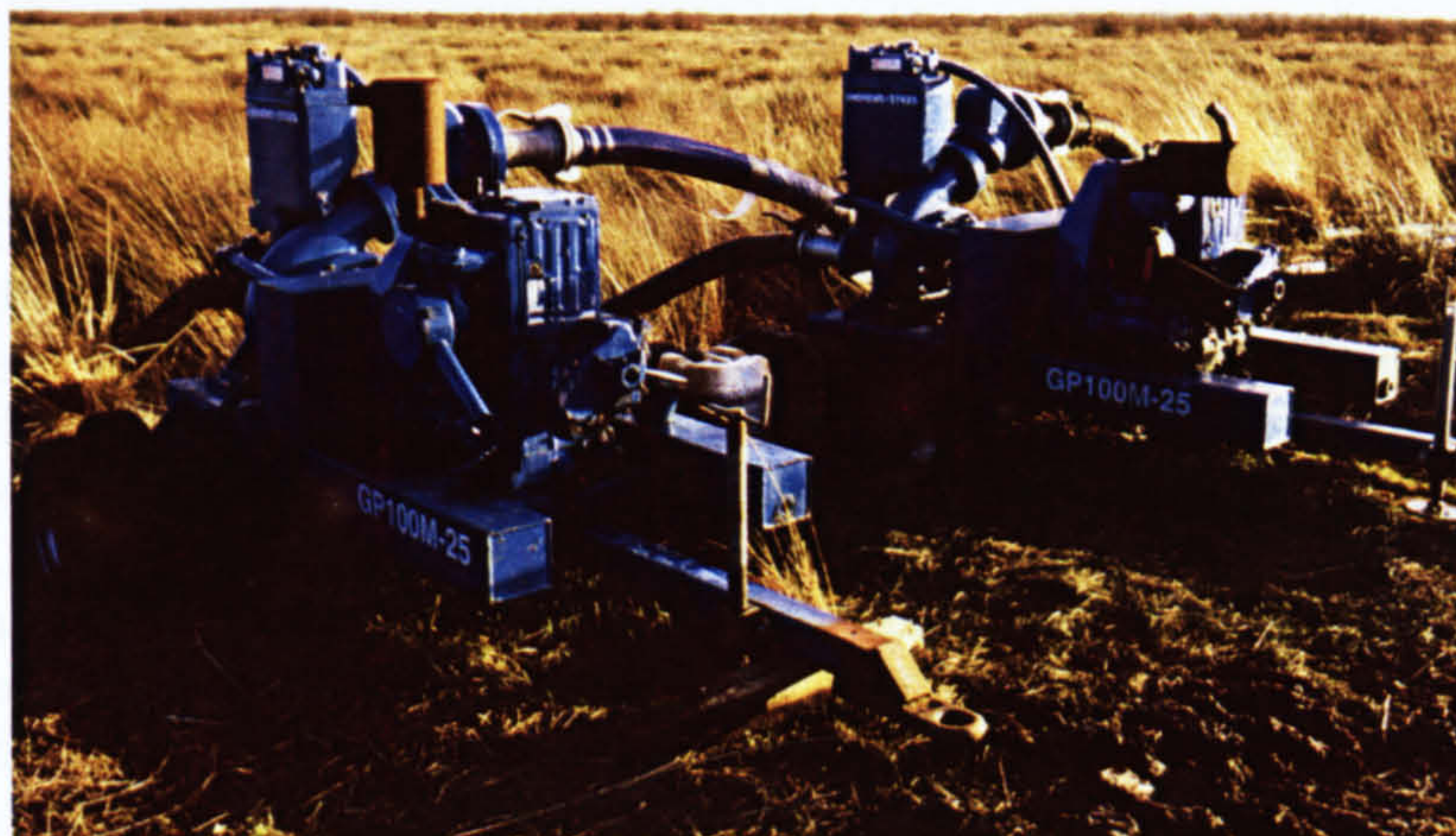
Delegates were taken on a walking tour of different regenerating sectors and at each stop, progress was discussed:



Stop1: Flooded sector, with water levels maintained at 0.7-0.8m to force re-wetting of remnant peat. Area underlain by clay of glacial origin, and known to be a zone of preferential flow. Dominant vegetation, *Juncus* and *Typha* species.

Q. Is this a typical treatment across the rest of the site?

*A. No – strategy in this area was to level the compartments, which were mostly 200m long, then flood them to a depth of 0.3m for 2 years to enforce re-wetting. Pumping was used where necessary to maintain water levels to the specified depth. Transplanting of *Eriophorum angustifolium* was then employed, and after a further two years the water table was raised further and the compartments were 'seeded' with *Sphagnum cuspidatum* propagules. In some large pools, wave action proved a problem for *Sphagnum* establishment. In such cases, *Juncus* species were observed to act as a suitable nurse crop, providing shelter and reducing wave-action.*



Stop2: The site of a constructed dam and a diesel powered pump used to redistribute water. Compartment dominated by *Juncus*.

Q. Do any other countries have experience of large apparently *Juncus* dominated areas and if so, how is it dealt with?

*A. The Dutch experience, especially on re-wet agricultural area, previously subject to extensive agrochemical inputs, is that such *Juncus* dominated conditions can persist for up to 15 years. In such cases, it is considered that the maximum water depth at which photosynthesised CO₂ is produced is critical to the accumulation of peat, and acidification of the system. Hence, the restoration of peat forming vegetation and its water holding may be slowed.*

Stop 3: This successfully regenerating sector was previously dominated by birch scrub and *Calluna vulgaris*. The birch was killed using a topical herbicide (*Krenite*) and the area has subsequently been colonised by *Eriophorum*. No direct flooding was imposed on this sector, and re-wetting has been by recharge from adjacent flooded compartments.

Discussion: 'Swelling' of peat and increased storage potential appears to have occurred as a result of adjacent high water tables.

Stop 4: A metal viewing platform has been constructed for the use of the public, local natural history groups and ornithologists, at a cost of approximately £9,000.

Discussion: Thorne was designated a Specially Protected Area (SPA) because of its nightjar (*Caprimulgus europaeus*) nesting sites. Unfortunately, the drier scrubby areas preferred as nesting sites by the birds are protected by virtue of SPA status and contradicts the mire restoration management agreement. This means that when sectors are re-wet, new dry areas must be provided for the birds. In such cases higher ground with shallow or no peat remnants can be best utilised.

Management Precepts

Levelling or re-contouring is considered to be advantageous to re-wetting and reduces the potential for scrub invasion by removing 'high and dry' zones.

Stop 5: Peat grips (narrow drains often up to 1.5m deep) successfully blocked using plastic pile or sheeting were examined. The interlocking pile is made from recycled plastic, and is made in sections 3m x 0.3m costing approximately £16 per square metre in the UK. It does not photo-degrade and has a lifetime of 150 years. The sheets are inserted directly into the peat, with adjacent sheets following within the lateral interlocking channels.

Discussion: Other methods of drain blocking and suitable materials were discussed including galvanised metal roofing sheets and heather bales as a 'natural' alternative. These can be harvested on site where heather is present.

Stop 6: peat removal in this sector ceased in 1920 and therefore it is the deepest peat on site. It was not levelled at the time when restoration management began, and birch scrub invasion has been a problem on high and therefore drier areas.

Discussion Points

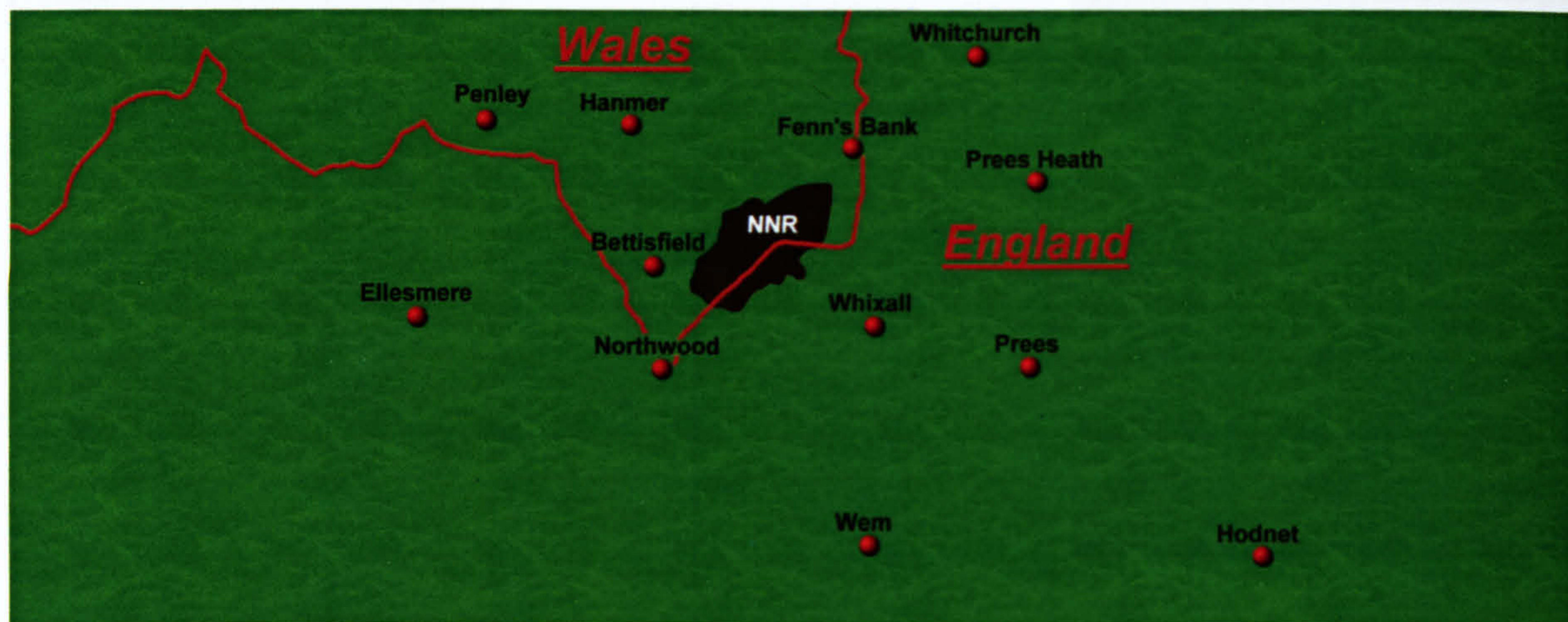
Can birch scrub be controlled by imposing high water tables as opposed to applying herbicides?

What is the minimum depth of peat that can be left before restoration becomes impossible?



2.0 Fenn's, Whixall and Bettisfield Mosses NNR

This mire has a total area designated as SSSI of 948 ha of which 275 ha is in Shropshire (England) and 691 ha in Wrexham (Wales.) Of this area 575 ha is National Nature Reserve and managed by English Nature and the Countryside Council for Wales. This raised bog has been cut over by sod cutting for domestic use since 1550 and for commercial use for fuel since 1850 and more recently has been extensively cut for horticultural purposes. Part of the site has been afforested and other areas have been colonised by dense woodland after abandonment. The site was acquired for nature conservation in 1990 to halt the commercial cutting. Since then extensive tree and scrub removal, damming and re-hydration has been carried out on the NNR. Very little original surface remains. The peat bog surrounding the NNR is a range of semi-improved and improved grassland susceptible to flooding and this together with opposition to timber removal, constrains the management work and strains relationships with neighbours. The local community keenly observes management work and a great deal of public relations work is carried out by the site management staff. The management work has also been complicated by the need to retain many rare and endangered invertebrates which have adapted to the peat cutting.



La tourbière couvre au total 948 ha dont 275 ha sont situés dans le Shropshire (Angleterre) et 691 ha dans le Wrexham (pays de Galles). Sur les 948 ha, 575 ha sont classés en réserve et gérés par English Nature et le Countryside Council for Wales. La tourbe a été exploitée depuis 1550 pour usage domestique, puis pour usage commercial depuis 1850 et récemment plus intensément pour l'horticulture. Une partie du site a été boisé, d'autres zones ont été colonisées par la végétation arbustive après abandon. Le site a été acheté pour la conservation de la nature en 1990 et depuis l'exploitation commerciale a été arrêtée. D'importants travaux ont été entrepris : débroussaillage, arrachage des arbres, construction d'ouvrages de rétention et remise en eau. Il reste très peu de couverture végétale d'origine. La tourbière qui entoure la réserve est constituée de prairies semi-naturelles inondables. Ce facteur, ainsi que le refus par la population de voir des arbres abattus, conditionnent les relations avec les voisins. La population locale observe avec intérêt les activités de gestion, un travail de communication important est engagé par l'équipe de gestion. La gestion est rendue complexe par la nécessité de garder des invertébrés rares et en danger qui se sont adaptés à la tourbe exploitée.

Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Joan Daniels,
Site Manager, English Nature

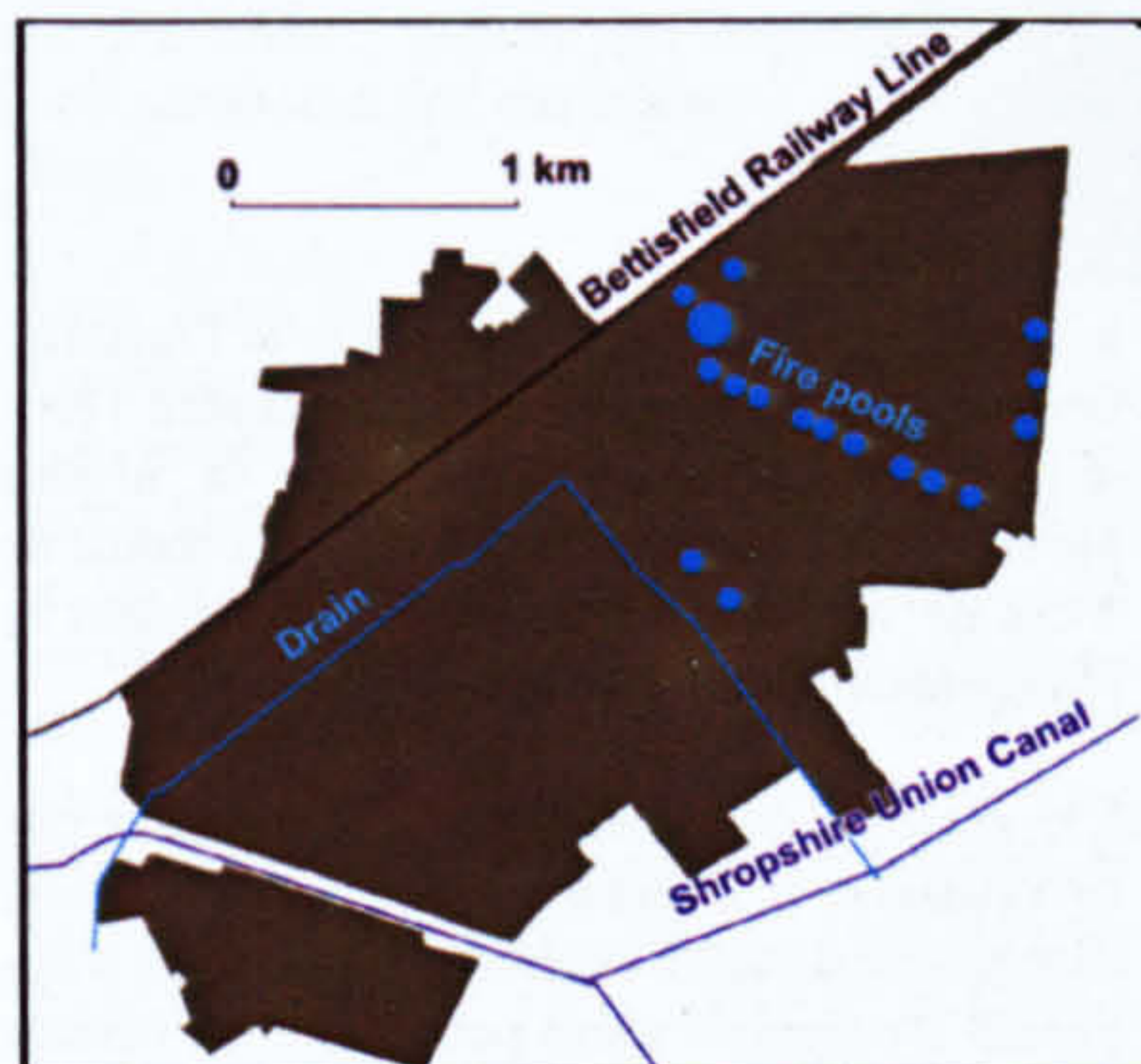
Fenn's, Whixall & Bettisfield Mosses National Nature Reserve (NNR) lies 15 km SW of Wrexham, NE Wales, straddling the English/Welsh border. The raised mire is much the largest wetland site in the Meres and Mosses Natural Area, which is a distinct landscape area of Britain typified by a myriad of meres and mosses nestling in glacial drift deposits.

The NNR forms the central 575 ha of Britain's third largest raised bog, the 948 ha Fenn's, Whixall, Bettisfield, Wem & Cadney Mosses Site of Special Scientific Interest (SSSI) (five names for different parts of one peat body). It is partly owned, partly leased and is managed by both English Nature (EN) and the Countryside Council for Wales (CCW) who are the government agencies responsible for nature conservation. The SSSI is also a candidate Special Area of Conservation and a Ramsar Wetland of International Importance.



The mire lies in the rain shadow of the Welsh hills, with an average annual rainfall of only 706 mm. This can be as low as 552 mm in drought years, such as 1996, when potential evapo-transpiration exceeds rainfall. On the other hand, in 1999 the annual rainfall was 930 mm. The average peat depth left after peat cutting was 3m, varying from 0m-8m.

The outer areas of the mire were first systematically drained around 1800 as a result of Enclosure Awards. The main installation of drainage was carried out in the 1920's when the mire was dissected by drains into 80 m wide peat cutting flats separated by 10 m wide trackways, and an arterial drainage network was installed. The cutting of peat for fuel and litter for animal bedding lapsed in the 1940's and 1950's but then restarted in the late 1950's for horticultural use. At first 10 ha per year were cut of the 400 ha of Fenn's Moss, but when cutting by machine was introduced in 1968 the rate of extraction increased to 30 ha/year. However, this low rate was greatly increased to 140 ha per year from 1989 to 1990. All mechanised cutting stopped in 1990 and restoration work began in 1991 after a public campaign to save the site.



The starting point for restoration of the mire varied with the previous peat cutting history of each area. Seven peat cutting types existed: very little uncut ground, old Whixall hand cuts, old Dutch hand cuts, old commercial cuts, recent commercial cuttings, recent hand cuttings and archaic cuts converted or reverted to fields or forestry. The old hand cuts had some water in the base of old abandoned peat cuttings and acted as refuges for mire flora and fauna. The old commercial areas also were partly re-colonised by mire plants but tended to have more scrub. The modern hand cuts had a lot of bare ground, but were not as severely drained as the desert of the recent commercial cuttings. Bettisfield Moss, the largest uncut area had been colonised by pine trees, but retained a bryophyte carpet below. Other areas such as fields were devoid of mire vegetation.



La Réserve naturelle nationale (RNN) de Fenn's, Whixall & Bettisfield Mosses est située à 15 km au sud-ouest de Wrexham, dans le nord-est du pays de Galles, et est à cheval sur la frontière anglo-galloise. La tourbière haute est la zone humide la plus vaste dans la Zone naturelle de Meres and Mosses, qui constitue un paysage distinct du Royaume-Uni caractérisé par une myriade de lacs et de tourbières nichés dans des dépôts glaciaires.

La RNN constitue le cœur, de 575 ha, de la troisième tourbière haute (par sa superficie) du Royaume-Uni, le Site d'intérêt scientifique spécial (SSSI) de 948 ha de Fenn's, Whixall, Bettisfield, Wem & Cadney Mosses (cinq noms pour les différentes parties d'une masse de tourbe). Elle appartient en partie à et est louée en partie et gérée par English Nature (EN) et le Countryside Council for Wales (CCW - Conseil de la campagne pour le pays de Galles) qui sont les organismes gouvernementaux responsables de la conservation de la nature. Le SSSI est également une zone candidate à la désignation comme Zone spéciale de conservation et est une Zone humide d'importance internationale (site Ramsar).

La tourbière est située dans l'ombre pluviale des collines galloises, la hauteur moyenne des précipitations annuelles n'atteignant que 706 mm. Celle-ci peut tomber à 552 mm au cours des années de sécheresse, comme en 1996, auquel cas l'évapotranspiration potentielle est supérieure aux précipitations. En revanche, la hauteur des pluies en 1999 a été de 930 mm. L'épaisseur moyenne de la tourbe après prélèvements était de 3 m, variant entre 0 et 8 m.

Les zones situées aux extrémités de la tourbière furent initialement drainées de façon systématique vers 1800 sous l'effet du mouvement des enclôtures. Les principaux travaux de drainage furent entrepris dans les années 1920, lorsque la tourbière fut divisée par des canaux en étendues d'extraction de 80 m de large séparées par des voies de 10 m de largeur, et un réseau de drainage artériel fut installé. L'extraction de la tourbe en vue de son utilisation comme combustible et litière pour animaux fut interrompue entre les années 40 et 50, mais reprit à la fin des années 50 à des fins horticoles. Initialement, une superficie de 10 ha par an fut exploitée sur les 400 ha de Fenn's Moss, mais avec l'introduction de machines en 1968, le taux d'extraction passa à 30 ha/an. Ce taux bas fut toutefois accru de manière substantielle pour passer à 140 ha par an de 1989 à 1990. Toutes les opérations de prélèvement mécanisées cessèrent en 1990 et les travaux de restauration commencèrent en 1991 à la suite d'une campagne publique menée pour sauver le site.

Le point de départ de la restauration de la tourbière a été fonction de la nature des prélèvements de tourbe effectués par le passé dans

2.1





chaque zone. Il existait sept types d'extraction : terrains exploités sur la majeure partie de leur surface, terrains ayant fait l'objet de prélèvements manuels anciens de Whixall, terrains ayant fait l'objet de prélèvements manuels anciens de type hollandais, terrains exploités commercialement dans le passé, terrains ayant fait l'objet d'une exploitation commerciale récente, terrains ayant fait l'objet de prélèvements manuels récents et terrains à exploitation archaïque transformés en champs ou forêts ou étant retournés à l'état de champ ou de forêt. Les terrains ayant fait l'objet de prélèvements manuels anciens contenaient une certaine quantité d'eau dans la base des sièges d'extraction abandonnés et servaient de refuges à la flore et à la faune des tourbières. Les terrains exploités commercialement dans le passé étaient eux aussi été recolonisés en partie par des plantes de tourbières, mais avaient tendance à abriter davantage de fourrés. Les terrains ayant fait l'objet de prélèvements manuels récents comprenaient de vastes étendues de sol nu, mais n'étaient pas aussi gravement drainés que le désert laissé par les prélèvements commerciaux récents. Bettisfield Moss, la plus grande étendue non exploitée, avait été colonisée par les pins, mais conservait en dessous un tapis de bryophytes.



Les autres espaces, tels que les champs, étaient dénués de végétation des tourbières..

L'objectif de la gestion de la restauration est de rétablir une tourbière haute active caractérisée par le type de végétation M18a du Système national de classification de la végétation, à savoir la sous-communauté *Andromeda polifolia* -*Sphagnum magellanicum* de la communauté *Erica tetralix*-*Sphagnum papillosum*.

Les travaux de restauration ont fait intervenir l'enlèvement des fourrés de pins et de bouleaux, la construction de barrages pour

maintenir l'eau de pluie sur le site et l'installation de canalisations pour lutter contre l'érosion. L'objectif est de maintenir le niveau phréatique de la tourbière à 5 cm ou à moins de 5 cm de la surface de la tourbière pendant la plus grande partie possible de l'année.

L'hydrologie de la tourbière a été évaluée par surveillance, à intervalles de deux semaines, d'un réseau de tubes immergés, au moyen d'appareils d'enregistrement permanent du niveau phréatique, par des mesures des précipitations et des mesures faisant appel à des bacs évaporatoires et à un lysimètre. Les niveaux d'eau dans les fossés sont également évalués deux fois par an à l'époque la plus humide et à l'époque la plus sèche. Ce système s'est avéré important pour ce qui est d'aider à comprendre les différences de végétation après restauration entre les différentes zones ainsi que la question de l'accroissement récent des niveaux d'inondation des terres agricoles sur les étendues de tourbe à la lisière de la tourbière. Il a également permis d'effectuer une estimation des effets de l'enlèvement des pins de Bettisfield Moss sur les écoulements d'eau projetés en aval.

La végétation est surveillée par le biais de quadrats permanents dans chacun des quatre principaux types d'extraction de la tourbe, ceci étant étayé par des évaluations subjectives de la couverture végétale de l'ensemble du site pour les espèces principales. Une comparaison de la couverture entre 1991 et 1998 met en évidence, par exemple, l'extension spectaculaire de l'aire occupée par la linaigrette commune (*Eriophorum angustifolium*).

La succession après restauration est à un stade très précoce, mais de grandes différences sont d'ores et déjà visibles dans les différentes zones. Sur les étendues ayant fait l'objet d'une exploitation commerciale récente, le terrain nu s'est transformé en des mosaïques de *Sphagnum cuspidatum* et *Molinia* ou en des mosaïques d'*Eriophorum/Sphagnum cuspidatum*. Sur les terrains ayant fait l'objet de prélèvements manuels anciens, il s'est créé une couverture de *Sphagnum cuspidatum* avec *Eriophorum angustifolium* et d'autres espèces du type M18a ou un dense couvert d'*Eriophorum vaginatum* avec *Sphagnum cuspidatum*. Des expansions temporaires d'espèces comme *Utricularia minor* se sont produites.

Le point de départ initial, les espèces restantes, la chimie de l'eau, la profondeur d'eau et le climat au moment de la restauration ont eu des effets sensibles sur la flore après restauration. En conclusion, malgré les variations, la flore et la faune de la tourbière sont en train de retourner à leur état d'origine, à savoir principalement des landes sèches, des fourrés et des zones boisées.

The aim of restoration management is to restore active raised mire, characterised by National Vegetation Classification vegetation type M18a, the *Andromeda polifolia*-*Sphagnum magellanicum* subcommunity of the *Erica tetralix*-*Sphagnum papillosum* community.

Restoration work has involved clearing the pine and birch scrub, damming to keep rain water on the site and installing erosion control pipes. The aim is to keep the peat water level at or within 5 cm of the peat surface, for as much of the year as possible.

Peat hydrology has been assessed by monitoring a network of dipwell tubes at two-week intervals, by constant water level recorders, rainfall, evaporation pan and lysimeter measurements. Ditch water levels are also assessed twice yearly at the wettest and driest time. This has proved to be important in helping to deal with understanding the differences in post-restoration vegetation in different areas, and also the issue of recent greater levels of flooding of agricultural land on the edge peats of the Moss. It has also allowed an estimation of the effect of pine tree removal from Bettisfield Moss on projected water flows down stream.

Vegetation is monitored by permanent quadrats in each of the main four peat cutting types, backed up by total site subjective vegetation cover assessments for key species. A comparison between 1991 and 1998 cover for example showing the dramatic increase in the cover of Common Cotton sedge (*Eriophorum angustifolium*).

It is very early in the post-restoration succession, but major differences are visible in different areas. The recent commercial areas have developed from bare ground into either mosaics of *Sphagnum cuspidatum* and *Molinia*, or *Eriophorum/Sphagnum cuspidatum* mosaics. The old hand cuts have developed either into *Sphagnum cuspidatum* with *Eriophorum angustifolium* and more M18a species, or dense *Eriophorum vaginatum* with *Sphagnum cuspidatum*. Temporary expansions of species such as *Utricularia minor* have occurred.

The initial starting point, residual species, water chemistry, water depth and climate at the time of restoration have had major effects on post - restoration flora. In conclusion, despite the variation, mire flora and fauna are returning to what were mainly dry heath, scrub and woodland.

Q. How are problems on the site associated with water chemistry manifested?

A. Effluent inputs of both agricultural and domestic origin arise within the drain network at several locations around the site. Where this pollution can be detected, it has been observed to increase the pH from 2.8 to 4 and from pH 5 to 6, encouraging the establishment of less desirable mire species such as *Molinia caerulea*. Minerotrophic groundwater is also thought to recharge the mire aquifer through the underlying sand layer and this may provide an unwelcome addition of nutrients, but this has not been confirmed. The bog may also recharge the regional aquifer at some point within its extent.

Hydrological changes due to restoration work

Kevin Gilman
Consultant Hydrologist

On the English/Welsh border, the balance between rainfall and evapotranspiration is very close, and in summer there is a decline in water levels on Fenn's, Whixall and Bettisfield Moss, which varies widely from year to year. In its present state, after generations of peat cutting and drainage, the peat surface of the Moss experiences episodes of drought and water. Management is essential to protect and rehabilitate the mire vegetation.

English Nature and CCW management objectives emphasised the importance of hydrology to the rehabilitation of the moss. A project was commissioned last year to examine the impacts, if any, of the English Nature /CCW management programme on the hydrology of the adjoining land. There has been long-lasting flooding in recent winters on the margins of Whixall Moss, and landowners are concerned that this could be caused by the management

of the Moss, notably the removal of trees and scrub and the rewetting of the peat cuttings.

Data from dipwells, water level recorders, lysimeters, an evaporation pan and a recording rain gauge has been analysed and interpreted, using the techniques of mathematical modelling in an attempt to isolate the effects of management from those of climate. The conclusions are complex. For example, water level data indicate that clear of well-grown pines from Bettisfield Moss will lead to a significant increase in runoff but this increase will be mostly in the early winter and will result from higher water levels in autumn. Runoff rates later in the winter will be unaffected. On the other hand, detention of water in flooded peat cuttings will lead to a delay in runoff from Fenn's and Whixall Mosses and a reduction of the peak but little change in total runoff. However, the report



shows that the events most likely to induce serious flooding in Whixall are high rainfalls extending over a 28-day period and it is doubtful that improvements in the timing or magnitude of flood peaks would have any effect on the off-site flooding problem. The evidence points to climate as the prime cause of over-bank flows and to defects in the drainage network, notably old culverts, which retain the floodwaters for long periods, rather than to the management of the Moss.

Q. Has the possibility for groundwater recharge of the mire aquifer from underlying sands been investigated?

A. Local opinion has been that the 'wetting-up' of the bog has caused flooding of low-lying land adjacent to the site by recharging the local aquifer. However deep well records for the area show that it is more likely that the bog is recharged by the regional sand aquifer. No conclusive data is available to confirm this. Recent local flooding appears to be due to the lack of maintenance of culverted channels carrying ditch flows away from the bog.



Review of main issues on Fenn's, Whixall & Bettisfield Mosses

- It is necessary to quantify the influence of birch-scrub on mire water balance.
- The type of remnant peat, including its depth, constituents (sedge, wood or moss) and subsequent hydrological and chemical properties exerts a strong influence on the success and speed of restoration of a peat forming vegetation at any site.
- The role of carbon evolution in the establishment of peat forming vegetation is poorly understood.
- Atmospheric deposition of SO₂ and NO₂ on mires, both past and present, needs to be investigated further.
- The depth of water in areas flooded for restoration and the area of flooded sectors can influence the vegetation that colonises such areas in ways not previously considered, such as wave action and erosion.
- Re-profiling bog surfaces before re-wetting can speed up regeneration, increasing the effectiveness of high water-table imposition, and reducing the area of 'high and dry' birch-scrub zones.
- A wide range of damming practices have been employed at different sites with varying degrees of success, including several tried and tested materials and different methods of installation and recommended spacing rules. A great deal of experience on this topic is available to draw upon within the Euro-site membership.

2.2

2.2.1



Vegetation change in relation to restored water levels

Karen Horton

Research Student, Wolverhampton University

2.2

2.2.2

Vegetation monitoring has been ongoing at Fenn's, Whixall and Bettisfield Mosses National Nature reserve since 1991. Hydrological monitoring commenced in 1993 Trends of vegetation change and rises in water levels are apparent within each of the four different peat cutting types.

Recent Commercial Cuttings

From the period 1993-1998 winter ditch-water levels were fairly consistent, with values of approximately 7.5 to 15 cm recorded, below the general peat surfaces. Since 1998 levels have been generally higher with open water recorded over the sub-compartment.

Summer ditch-water levels, despite damming in 1993, did not begin to hold water through the summer period in any major way until 1997. Since then summer water levels have been maintained at approximately 0-7.5 cm down from the general peat surface.

These areas began mostly bare with little existing cover of mire species. There appears to be a time lag of approximately six and a half years from the damming to the colonisation of *Sphagnum*. Cover of *Sphagnum cuspidatum* has however reached 16% on sub-compartment 3.9.



Old Hand Cuttings

Restoration management has had to take account of the un-regimented nature of past peat-cutting and has been carried out with consideration of entomological interest.

Winter ditch-water levels since 1993 have shown a consistent increase from 22.5 - 30cm below the general surface of the peat to 0 to 7.5cm this year. The summer ditch-water data shows a rise to approximately 0-7.5cm following damming during 1995-1998.



Old Commercial Cuttings

Since 1993, winter ditch-water levels have changed from being mostly dry, to this year showing a figure of 0-7.5cm below the level of the general peat surface.

Summer ditch-water levels have risen dramatically following damming in 1997, to give a peat surface this summer which is saturated (boggy).

These areas began as a dry heath type vegetation with a very few existing mire species. Approximately three years after damming *Sphagnum* cover is now 30% on sub-compartment 4.4.

These areas began as a wet heath type vegetation with several mire species. *Sphagnum cuspidatum* cover has increased to its current position of 60% on sub-compartment 13.7.

Uncut Sub-compartments

Due to the topography of the uncut areas the ability of peat to retain water is impaired. Limited restoration measures have been undertaken including the damming of old drains and the removal of scrub.

Winter and summer observations of the peat surface indicate dry conditions in the sub-compartment 7.8 up until damming in 1998. After

Management Precept

Re-colonisation of mire species is occurring at various rates across the site in response to the rise in water levels due to restoration management. There is a clear correlation between the increase in cover of mire species and the rise in water levels following damming



this time peat surface conditions are described as mainly dry with some boggy areas.

Five mire species were recorded in 1991 which account for 30% of the vegetation in this area. The area at that time was predominantly a dry heath type vegetation. *Sphagnum* cover this year has reached 5% and other mire species are also very gradually increasing on the sub-compartment.

Q. Was transplanting employed in flooded areas created by drain blocking?

A. No transplanting was used. Vegetation colonised from refugia created by old cutting patterns. Hand-cutting left step-wise cutting faces with vegetation left on the highest step surface. 'Dutch' cutting also left original vegetated surfaces between the lower terraces where peat had been removed.

Q. How was birch-scrub invasion dealt with?

A. Scrub removal is controversial in some areas where it contradicts with invertebrate conservation, in particular of those species that favour the wet-scrub habitat. Scrub has however been removed in several areas by cutting and removing and by spraying with herbicide. In some sectors, *Betula* species have been attacked by a parasite and *Calluna* has suffered from heather beetle infestations assisting scrub removal. In these areas and in some untreated areas, higher watertables have also accelerated scrub die-back.



Site Visit: Fenn's and Whixhall Moss NNR

Joan Daniels,
Site Manager, English Nature

The site was approached through the original lagg zone, more recently converted to farmland. Most of the farmland crossed on this edge of the bog was flooded making an excellent habitat for wading birds, several species of which could be observed. The main source of the current flooding was also observed clearly with the main drainage channel and a culverted section in a state of severe disrepair. This area, previously part of the mire complex, was omitted from the national designation of Site of Special Scientific Interest (SSSI) and subsequent management plan, as it was considered to be isolated from the main bog area by the Shropshire Union Cannel. The canal, a navigable waterway used now mainly by tourists, dissects the site and it is likely that it reduces the conductivity of underlying material in the immediate vicinity. However, it may not isolate the site entirely from the adjacent and previously contiguous mire area.

Recent flooding and a culture of blame, has raised opposition locally to re-wetting within the bog, and this situation is exacerbated by management agreements that guard against interference in neighbouring drainage regimes. If the site were to be reclassified, or the opportunity to reassess SSSI boundaries arose, adjacent farmland and previously contiguous mire would be included.



Stop 1: Agricultural land within the SSSI at the boundary of the NNR purchased by English Nature but leased to a local farmer under a management agreement allowing light grazing. The field is wet with patches of *Juncus* and some larger birch trees. Old subsurface tile drains have fallen into disrepair but further wetting is not currently possible under the management agreement, with the additional complications caused by adjacent domestic properties.

Q. If future management agreements allowed, would it be possible to wet this area further and establish a peat forming vegetation?

*A. The Welsh experience on similar land is that by removing turf and using it to create bunds and 'walkways', *Juncus effusus* and *Molinia caerulea* invade and *Sphagna* are established in deeper scrapes without any planting. These areas also have some grazing by ponies which favour the ecologically less desirable softer herbs when grazing.*

A. Similar result has been achieved by the RSPB at Bowness Common in Cumbria, although planting was used to establish a habitat for waders in the scrapes which were created within the Wet Meadow scheme.

A. In the Netherlands, similar wet meadows have also been created on shallow peats previously utilised for agriculture. Problems can arise where residual agrochemical concentrations, particularly nitrogen fertilisers, are still relatively high. This may be addressed in some cases by removing from the site the turf containing higher nutrient levels.

A. In France there has been very little agricultural utilisation of peatlands so this has not been necessary, however similar schemes have been successful on alluvial sites.

Different recommendations for the field were prescribed as follows:

- Leave the field as it currently is since it appears to act as an important buffer between the bog and the canal.
- Since the water table is near the surface, remove the turf and use it to form bunds to hold water.
- Remove the turf altogether; it is likely to contain added agricultural macronutrients which may encourage undesirable vegetation species.
- Allow the current establishment of *Juncus*, *sphagnum* and other fen meadow plants to continue with minimum grazing.



2.3





Stop 2: Previously scrub dominated area where hand cutting of peat had taken place. A sector that had been successfully dammed and scrub removed was observed adjacent to an area of similar cutting without active re-wetting. Scrub is controlled by cutting and herbicide application. Some re-treatment is carried out using a 'weed-wiping' implement which, when driven over the small scrub applies the chemical to the uppermost plants. This sector could not be actively re-wet due to the risk of flooding neighbouring agricultural land. A clear contrast could be seen between the established peat forming vegetation in the flooded sector and the slower re-wetting in the untreated area separated by an old track-way used for peat removal.

Q. Is it possible to use tracks and tramways as effective hydrological barriers?

A. The effectiveness of such boundaries is dependant on the structure and properties of the underlying peat and the extent of hydraulic gradients imposed. For example, peat likely to fracture due to previous extended periods of drying would be unlikely to support a rapid head change. Steep gradients in such cases may result in structural failure, cracking, collapse and potentially mass movement.

Q. What evidence is there of peat swelling at other sites?



A. Irish experience has been for rises of up to 1m in bog surfaces following a program of re-wetting.

A. Little swelling (up to 5cm) was observed at Wedholme Flow following drain blocking.

A. Experience in the Netherlands has been that the degree of humification of remnant peat influences the degree of swelling.

Q. How has the conflict between invertebrate conservation and mire restoration been accommodated?

A. Suitable invertebrate habitats have been maintained in drier areas and the strategy has been to dislocate invertebrate communities so that they occupy these designated areas.

Stop 3: Active hand cutting sector. In order to come to an amicable agreement with the current leaseholder, it was agreed that hand cutting would continue here until the leaseholder reached retirement (now in two years time). A large number of fossil tree stumps can be observed here within the 'white' *Sphagnum* peat layer currently being hand cut. The peat layer called 'white peat', is a light colour on drying, and is dominated by *Sphagnum cuspidatum*.

Q. Can this woodland layer be used to draw climatic parallels to other sites and in-situ peat forming vegetation deposited during the same period?

*A. It is noted that the woodland phase had an understorey of *Sphagna* and that the survival*

Management Precepts

Several differences in strategic management of birch scrub have been identified:

- management of the site as a mosaic including scrub;
- flooding of scrub areas with eventual die-back resulting;
- cutting and removal of scrub;
- cutting and removal of scrub, stumps treated with herbicide

of the two vegetation types did not seem to be in conflict. Dendrograms could be taken from the tree remains and compared to those taken at other sites to link the growth phases.

Stop 4: Regenerating Dutch hand cuttings, with apparently restored vegetation assemblages including *Andromeda polifolia*.

Q. Does *Eriophorum vaginatum* act as a nurse crop to favourable species?

*A. The Belgian experience is that *Eriophorum vaginatum* does appear to act as a nurse crop, providing shelter and structure that allows *Sphagnum cuspidatum* to become established. *Molinia caerulea* however, has a negative effect smothering *Sphagna* with its litter.*

*A. In the Netherlands the situation is observed to be similar, with the additional disadvantage that *Molinia* appears to have a higher evaporative demand.*



Q. Why is *Utricularia* present in the pools created by flooded cuttings and what does its presence indicate?

A. It is likely that it is an indicator of water movement, and is present in areas receiving water from adjacent pools. This also explains dense patches close to overflow pipes positioned in pools to prevent over-topping.

Discussion Point

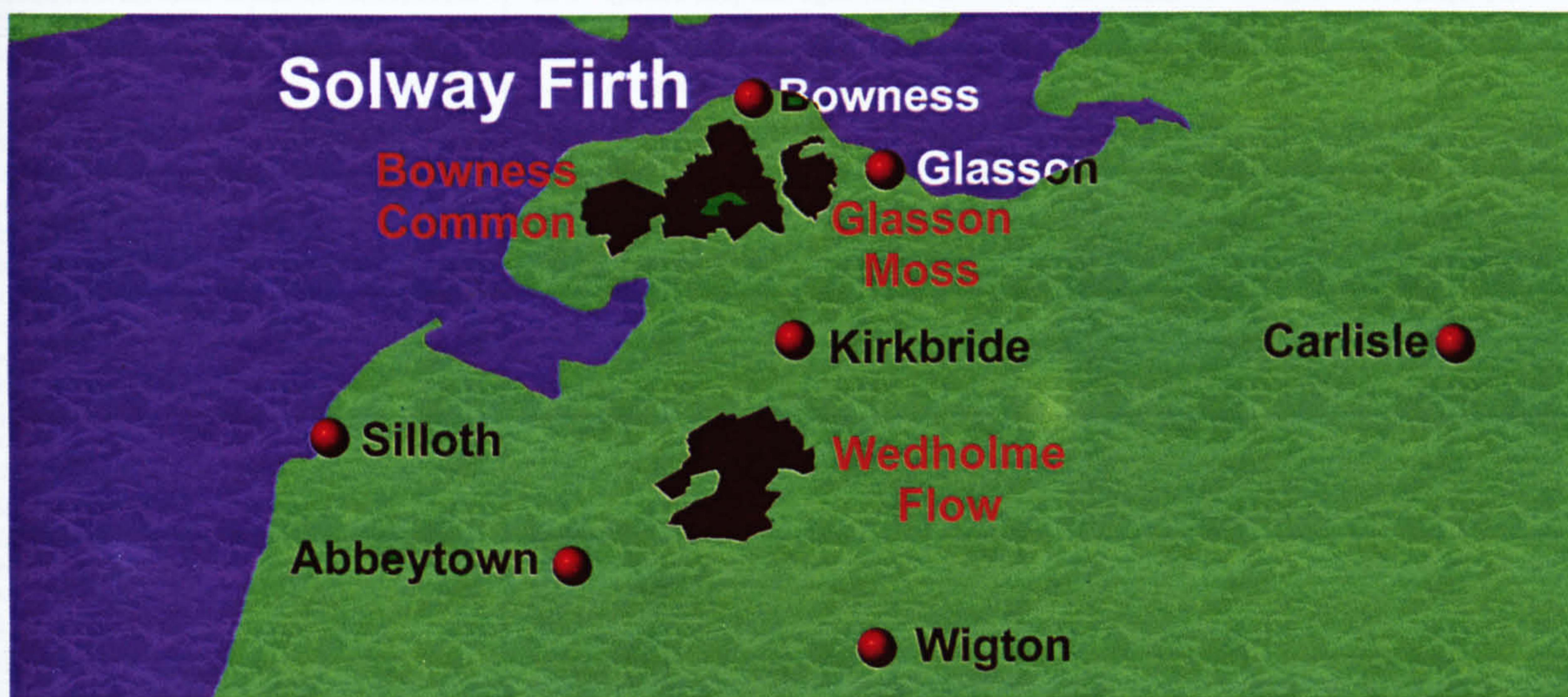
What is 'too much' water; can levels be too high and what is the desirable water level for successful restoration?

III

The South Solway Mosses NNR and Wedholme Flow

3.0

The Solway Mosses comprise of Wedholme Flow, Bowness Common and Glasson Moss. These three sites contain most of the intact active bog surface in England, indeed it is estimated that there are only 450 hectares of original surface with active peat forming vegetation in England and most of this is found on the three sites. Wedholme Flow (790 ha) has been cut almost continuously since the early 1900's but still retains a substantial area of intact surface. Over half the cuttings were taken out of production in 1990 and restored to nature conservation but 160 ha remains in peat production. A wide range of rehabilitation conditions exist on all three sites with the earliest damming occurring on Glasson Moss in 1985. The old sod cuttings on Wedholme were dammed between 1991 to 1993. The mosses are surrounded by intensive arable grassland with only remnants of any form of lagg. Drainage systems around the sites and leading away from them are regularly maintained. Many of these fields are on shallow peat. From a small ownership in 1985 English Nature now owns and manages a substantial area of all three sites. The current aim is to secure the cessation of peat cutting on Wedholme Flow.



Ces trois sites comprennent la plus grande surface intacte de tourbière active d'Angleterre. Sur les trois sites, seul Wedholme a une zone importante de tourbière dont la surface d'origine est intacte. On estime qu'en Angleterre, il y a seulement 450 ha de tourbières actives et elles se trouvent sur ces trois sites. Wedholme a constamment été exploitée depuis le début des années 1990 mais a gardé une surface intacte importante. Plus de la moitié de la surface exploitée a été retirée de la production en 1990 et restaurée pour la conservation de la nature mais il reste 160 ha en exploitation. Les conditions de réhabilitation sont variées sur les trois sites mais les plus anciens ouvrages de rétention des eaux ont été mis en place à Glasson Moss en 1985. Les zones anciennement exploitées à Wedholme ont été remises en eau entre 1991 et 1993. Les sites sont entourés de prairies artificielles avec seulement quelques zones rélictuelles de lagg. Les réseaux de drainage qui entourent les sites sont bien entretenus. Beaucoup de champs sont situés sur de la tourbe peu profonde. En 1985, la maîtrise foncière d'English Nature était faible, elle atteint désormais une surface importante sur les trois sites. L'objectif est d'arrêter l'extraction de la tourbe sur Wedholme Flow.



Solway Mosses cSAC - Wedholme Flow NNR, Cumbria

Frank Mawby
Site Manager, English Nature

3.1

The Solway Mosses Lowland Raised Mire SAC is situated on the lowlands surrounding the Solway Firth Estuary and consists of Wedholme Flow (780 ha.), Bowness Common, (759 ha.) Glasson Moss, (225 ha.) Drumburgh Moss cSAC (189 ha.), plus Solway Moss pSAC (495 ha.), Wedholme Flow pSAC extension.

There is an estimated 475 ha of uncut, original natural surface remaining on bogs in England of which approximately 125 ha. is on Wedholme, 100 ha on Bowness Common, 38 ha on Glasson Moss and 20 ha on Drumburgh. The remaining area of these mires has been damaged by drainage and cutting for domestic fuel, commercial use and conversion to agricultural land.

Cutting for domestic fuel has occurred for many centuries but considerable amounts were removed through the 19th and early 20th century. These mosses survived because they were away from the larger towns and cities. Extensive drainage occurred in the mid nineteenth century followed by conversion of the shallower perimeter peat to agricultural use.



Commercial cutting commenced in the early 1900's. Between the two World Wars there was extensive cutting on Wedholme Flow. Cutting resumed on Wedholme and began on parts of Glasson and Bowness in 1948. Fortunately the peat company withdrew from Glasson and Bowness in 1954 but increased their operations on Wedholme. They intensified their cutting in the 1970's as peat became important to the horticultural industry and home gardeners.

The conservation of these sites became an important issue in the 1980's and between 1984 to 1986 the key sites were notified as Sites of Special Scientific Interest (SSSI's) under the 1981 Wildlife and Countryside Act. From that date their protection became a key nature conservation objective either through acquisition of the land for direct management as a National Nature Reserve (NNR's) or by management agreement with the many owners.

The development, implementation and demonstration of bog rehabilitation management techniques is one of the main roles of the NNR's. The principal management objectives are to maintain the hydrological conditions

essential to sustain the best areas of sphagnum dominated bog and to restore water tables to damaged and cut-over areas to restart the growth of active peat forming vegetation. The most important objective for Wedholme is to stop the damaging peat cutting operations.

The results have been variable ranging from a rapid restarting of *Sphagnum* growth to no *Sphagnum* species at all. Water levels are very critical in this process and only a few centimetres determine whether the community is dominated by *Calluna* or *Sphagnum*. The severity of the damage done to the water retention capacity of peat following drainage and cutting is very difficult to reverse. However, ponding water on cut-over areas greatly increases the chances of regenerating *Sphagnum* and associated plant communities. Slopes greater than 1 in 40 are very difficult to re-wet.

On Wedholme deep vertical structural cracks have developed when the bog has slumped as a result of drainage and peat cutting. These cracks have shown there is deep lateral water movement in the layered structure of the peat, with surface water moving between the cracks.

The best sphagnum regeneration has been observed where water tables have been restored to areas of original acrotelm that had been damaged by drainage.

The vegetation has responded to water level management work in a range of situations. Peat cutting by the milling method still continues on part of the site. When English Nature eventually gain control of this area there will be a new and interesting challenge to re-establish sphagnum.



Q. What management occurred at Glasson Moss in the early years of its notification as a National Nature Reserve?

A. It appears that in the period 1967-1976, very little action was taken to restore degraded areas of the mire. Following a serious fire in 1976, lagoons were dug at intervals around the site, supposedly to act as fire breaks. They appear to have acted more like drains, and although re-vegetating they are still apparent today.



La tourbière haute de basse altitude de Solway Mosses, qui est une ZSC, est située dans la plaine entourant l'estuaire du Firth of Solway et comprend Wedholme Flow (780 ha), Bowness Common (759 ha), Glasson Moss (225 ha), Drumburgh Moss (189 ha), Solway Moss (495 ha).

Selon les estimations, il existe 475 ha de surface naturelle originelle non exploitée subsistant sur les tourbières en Angleterre, dont environ 125 ha sur Wedholme, 100 ha sur Bowness Common, 38 ha sur Glasson Moss et 20 ha sur Drumburgh. La superficie restante de ces tourbières a été dégradée par diverses activités : drainage et extraction de la tourbe comme combustible domestique, utilisation commerciale et transformation en terres agricoles.

L'extraction de la tourbe comme combustible domestique est pratiquée depuis de nombreux siècles, mais des quantités considérables furent enlevées au XIX^e siècle et au début du XX^e. Ces tourbières survécurent parce qu'elles étaient situées à une certaine distance des grandes villes. D'importants travaux de drainage furent entrepris au milieu du XIX^e siècle et furent suivis de la transformation de l'étendue tourbeuse périphérique moins épaisse pour une utilisation agricole.

L'exploitation commerciale commença au début des années 1900. Dans l'entre-deux-guerres, des prélèvements très importants furent effectués sur Wedholme Flow. L'extraction reprit sur Wedholme et commença sur des parties de Glasson et de Bowness en 1948. Heureusement, le producteur de tourbe cessa ses activités sur Glasson et Bowness en 1954, mais il les accrut malheureusement sur Wedholme. Il intensifia ses opérations d'extraction dans les années 70, la tourbe étant devenue importante pour le secteur horticole et les particuliers férus de jardinage.

La conservation de ces sites devint une question importante dans les années 80 et, entre 1984 et 1986, les sites principaux furent noti-



fiés comme Sites d'intérêt scientifique spécial (SSSI) en vertu de la loi de 1981 sur la vie sauvage et la campagne. A partir de cette date, leur protection devint un objectif essentiel au titre de la conservation de la nature, celle-ci étant assurée soit par l'acquisition des terres en vue de leur gestion directe comme Réserves naturelles nationales (RNN), soit par le biais d'accords de gestion conclus avec les nombreux propriétaires fonciers.

Le développement, la mise en œuvre et la démonstration des techniques de gestion de la réhabilitation des tourbières constituent l'un des principaux rôles des RNN. Les objectifs clés de la gestion sont d'assurer le maintien des conditions hydrologiques essentielles pour entretenir les meilleures étendues de tourbières dominées par les sphaignes et rétablir la nappe phréatique dans les zones dégradées et exploitées afin d'encourager la croissance d'une végétation active formant de la tourbe. L'objectif le plus important pour Wedholme est de mettre fin aux opérations d'extraction de tourbe qui sont préjudiciables.

Les résultats ont été variables, allant de la repousse rapide de *Sphagnum* à l'absence totale d'espèces de *Sphagnum*. Les niveaux phréatiques jouent un rôle très critique dans ce processus et une différence de quelques centimètres détermine si la communauté sera dominée par *Calluna* ou par *Sphagnum*. Il est très difficile de remédier aux dommages graves causés à la capacité de rétention d'eau des tourbières à la suite de leur drainage et de leur exploitation. Toutefois, la création d'étangs sur les zones exploitées accroît sensi-



blement les chances de régénération de *Sphagnum* et des communautés de plantes associées. Les pentes de plus de 2,5 % sont très difficiles à réhumidifier.

Sur Wedholme, de profondes fissures structurales verticales se sont formées lorsque la tourbière s'est affaissée par suite du drainage et de l'extraction de la tourbe. Ces fissures ont montré que des mouvements d'eau latéraux et profonds se produisent dans la structure stratifiée de la tourbe, l'eau de surface circulant entre les fissures.

On a observé que les sphaignes se sont le mieux régénérées là où la nappe phréatique a été reconstituée dans les étendues où l'acrotelme d'origine avait été endommagé par le drainage.

La végétation a réagi aux travaux de gestion du niveau phréatique dans un éventail de situations. L'extraction de la tourbe par la méthode de broyage est toujours pratiquée sur une partie du site. Lorsque English Nature prendra finalement le contrôle de cette zone, le rétablissement de la sphaigne constituera pour lui un défi nouveau et intéressant.

3.1

Hydrological regimes following restoration work at Wedholme Flow

Charlotte MacAlister,

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Wedholme Flow has a relatively long history of hydrological monitoring, with a continuing program established over the last decade. Monitoring strategies have been used to track changes across the site and in areas where the hydrological regime has been manipulated manually. The success of management intervention in local systems, such as re-wetting by drain blocking, in previously cut-over areas, can be observed in these records. Groundwater levels recorded in dipwell transects over both cut-over and intact mire surface reveal their different hydrological characteristics and the

subsequent impact of reduced hydraulic gradients following drain blocking.

Concern over peat extraction at the site has led to an increase in monitoring in recent years. With recent candidate SAC notification, efforts are concentrating on the examination of potential impacts of continued extraction close to a re-wet area of old peat cutting. In addition, an ongoing program of continuous monitoring logs groundwater fluctuations and meteorological parameters in the large area of undisturbed mire. This has revealed interesting surface-

groundwater interactions previously thought typical of only cut-over areas. Along with evapo-transpiration measurements by lysimetry, this constitutes the large data set held by the University of Newcastle, and collected in collaboration with English Nature. This data set is being used in the construction and development of several computer modelling techniques. It is expected that computer models tested using Wedholme Flow data will be applied as predictive tools by managers of a wide range of wetland sites.

Q. Did drain blocking in the early 1990's effect the uncut mire surface?

A. Although apparent changes in the hydrological behaviour of the 'intact' mire were very small in comparison to those observed in the adjacent cut-over area, they were significant. The response of the water table close to the drain which was blocked, was to exhibit a much smaller hydraulic gradient within 30m of the drain. The water table indicated in dipwells further from the drain did not appear to respond significantly to the damming and was much more dependent on net recharge values. This is of course an obvious result of the raised open water head in the old drain channel. The consequence for local hydraulic activity was observed anecdotally, in the form of much increased surface water flow and relatively large run-off events close to the drain boundary.



3.2

3.2.1



Monitoring hydrological conditions from macrofossils in the peat

Dr. J. Andy McMullen,
Department of Geography & Environment, University of Aberdeen

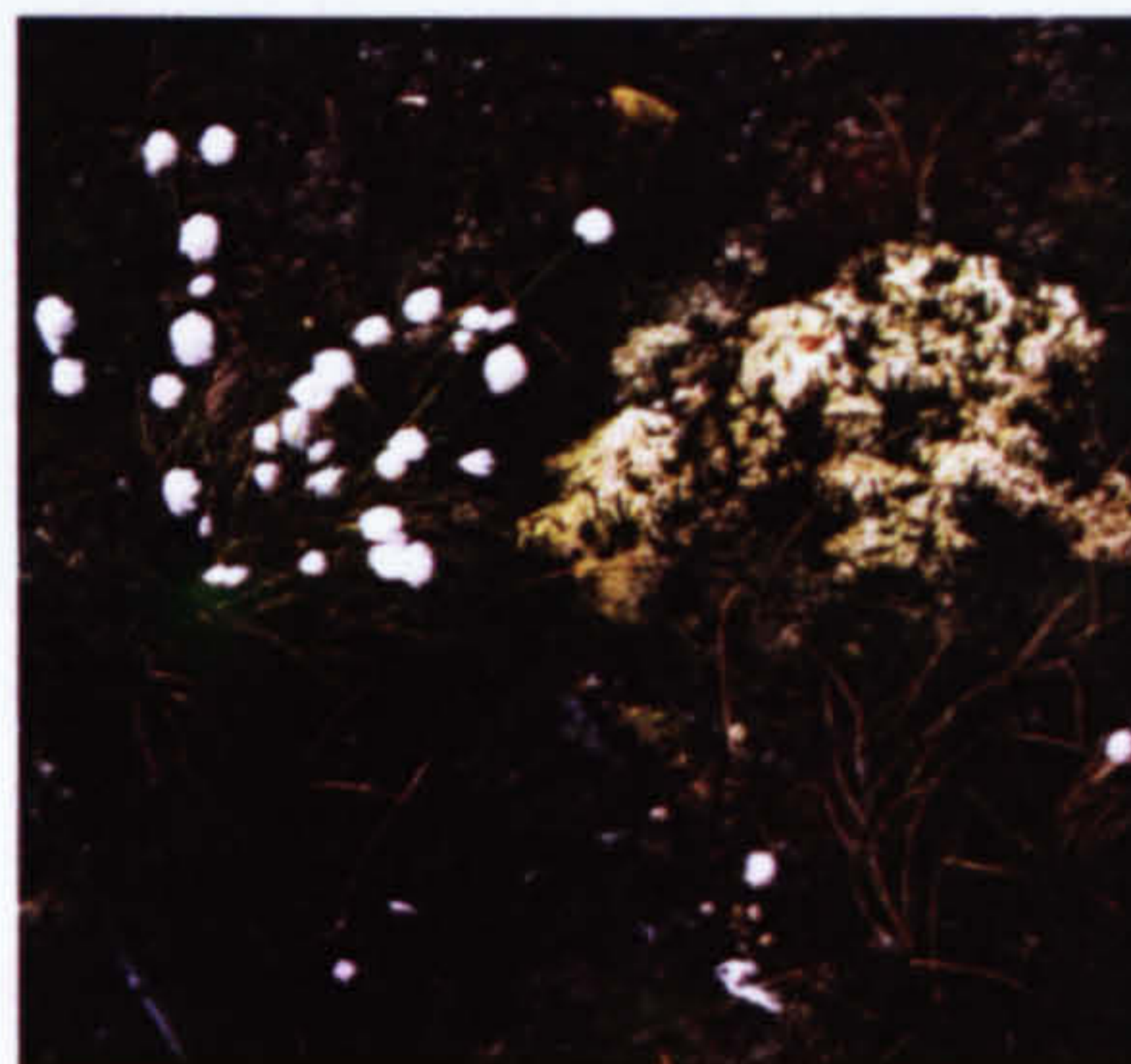
3.2

3.2.2

The past hydrological condition of a raised bog can currently be determined by a number of methods including measurement of humification / decomposition and the reconstruction of plant or testate amoebae communities. In this presentation the main focus was upon reconstructing past hydrological conditions from plant macrofossils such as the leaves, stems or reproductive structures of vascular or bryophyte species. This is because such remains are relatively easy to identify in the field and crude reconstruction may thus be attempted in such a setting. Other techniques presented are more elaborate and require microscopy, but they offer increased accuracy and relation of hydrological conditions within or between sites.



Exposed peat faces offer the greatest scope in reconstructing past hydrological conditions since the spatial scale of changes can be directly determined, albeit in one dimension [i.e. patch dynamics .v. the all over reaction of the vegetation surface to climatic change (Barber, 1981)]. If such exposures are not available then it is necessary to rely upon a coring technique using one of the many types of manually operated corer now available (see Brooks & Stoneman, 1997, for example). Whatever technique is used it will be seen that the peat forms stratigraphic horizons or phases of differing states of decomposition and floristic composition. The decomposition of the peat or floristic composition of each of these phases can be described using one or a number of the techniques outlined below in order to reconstruct past, hydrological conditions.



At the crudest level it is possible to simply determine the approximate, floristic composition of the peat at the familial level e.g. *Ericaceae*, *Cyperaceae* or *Sphagnaceae*, this allowing a qualitative reconstruction along the lines of "dry", "wet", "very wet", etc. according to the ecology of the species present (see Walker & Walker, 1961 or Svensson, 1988, for examples). Alternatively, the von Post scale determines the degree of decomposition that has taken place, this variable being positively correlated with the "dryness" of the peat forming community at its time of deposition (see Brooks and Stoneman, 1997, pg. 77, for a concise summary of this scheme). A more desirable approach that encompasses the state of preservation as well as the floristic compo-

sition is the Troels-Smith scheme (Troels-Smith, 1955). This scheme is a little unwieldy to use at first, but it does allow for field recording in some detail.

More quantitative techniques, such as weighted averaging and the moisture index models derived from Detrended Correspondence Analysis rely on quantification of the peat components under a dissection microscope and preferably, further quantification and identification of *Sphagnum* to section level, under a compound microscope.

Testate amoebae are offering a new way to reconstruct the past hydrological conditions of raised bogs. They may offer some advantage over plant macrofossils since changes in community composition are apparently more continuous than the marked, threshold changes seen in the vegetation communities of raised bogs. Additionally, calibration data sets exist for the testate amoebae and these permit modelling of the average depth to the water table. The accuracy of this remains controversial but it is still early days in the application of this technique (see Warner & Charman, 1994; Warner & Chmielewski, 1992 and Woodland, Charman & Sims, 1998 for examples).

Q. Did you find any evidence of past fires in the peat monolith?

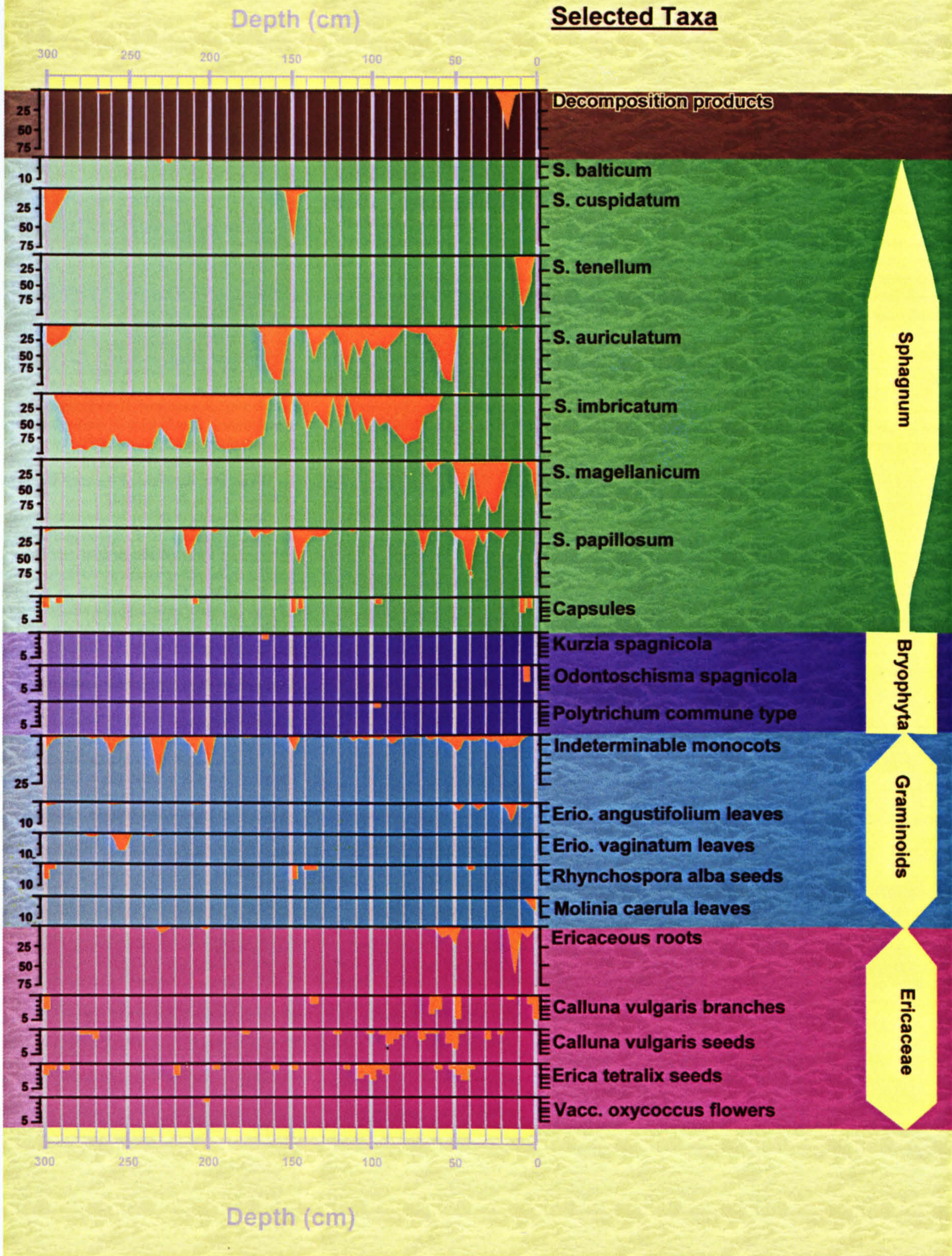
A. No charcoal was found in this particular core, although it would have been expected from natural summer fires.

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Wedholme Flow Macrofossil Diagram

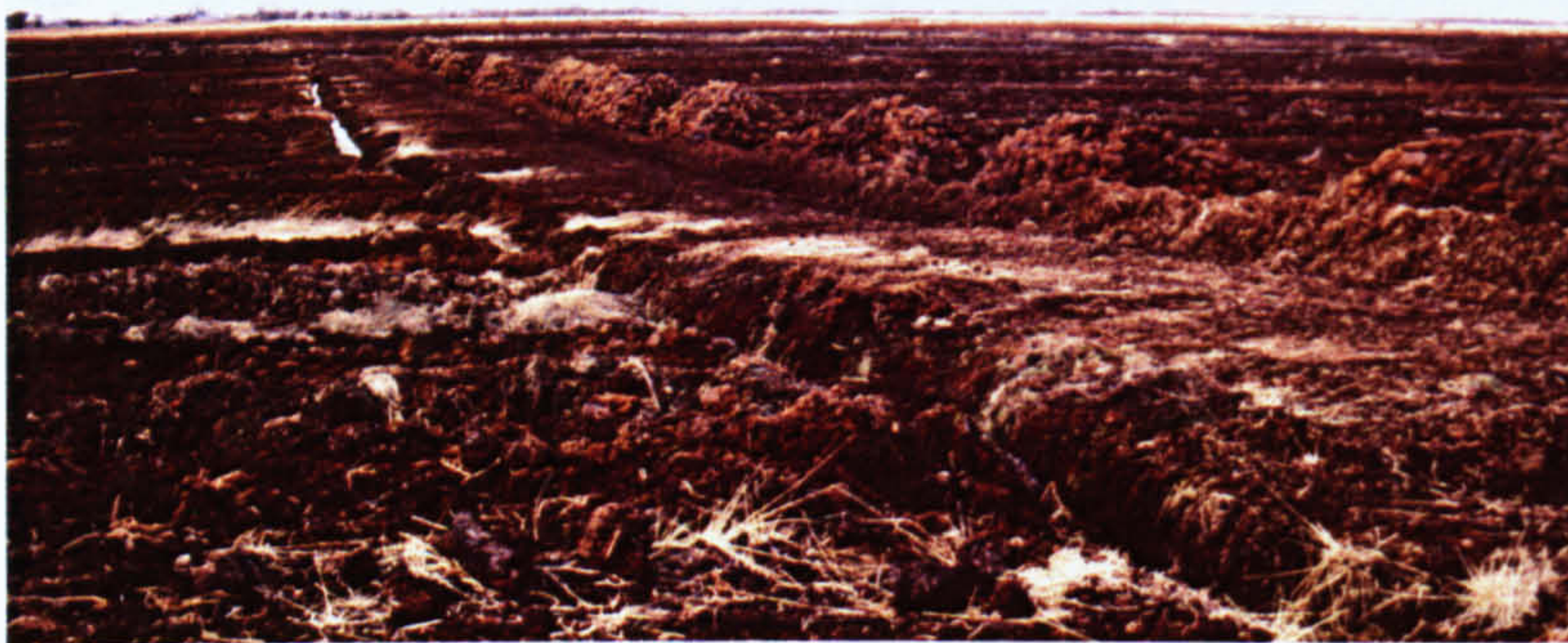
3.2



Site Visit: Wedholme Flow NNR

Frank Mawby,
Site Manager, English Nature

Wedholme Flow was approached through an area of agricultural land thought previously to have been part of the contiguous mire. This land has been drained and is now used for high quality grazing and silage production. Land values in the area are relatively high for the North West of England, where large areas of land are considered low grade and fall under the *Less Favoured Area* (LFA) subsidy scheme. Access to the site was via a farm track through such lower grade land showing signs of wetness with *Juncus* and *Carex* species abundant. The land is grazed by cattle and sheep, with better drained fields on higher ground used for silage production. The farm and farmland are located on a mineral ridge which extends into the sickle shaped mire body. The soil here has a high organic matter content and may have been covered by shallow peat before agricultural development. The current 'mineral' soil and underlying mineral subsoil (drift material) form the hydraulic boundary at this edge of the mire. At the surface, a 1-1.5m deep intercepting ditch isolates surface waters from the farmland and mire.



Stop 1: Mire margin with grazed agricultural land.

Discussion: The surface appears to be showing initial signs of drying but no major features such as slumping are apparent. This is likely to be limited by the steep mineral interface which in effect supports deep peat at the boundary. This subsurface support allows a low surface gradient to extend up to the current mire boundary. Similar conditions have been observed at several Irish sites.

Q. Why is there no grazing on the site?

A. Traditionally there has been no organised grazing on mires in the North of Cumbria, where sites have been utilised under local allotments for domestic fuel. There are small numbers of deer locally but these are restricted by the lack of cover and extent of agricultural land. Such sites have been considered too wet for livestock, whilst better land is readily available. Some low intensity grazing of cattle is seen in the South of the county, for example at Latterigg

Moss. Here higher numbers of deer can also pose a problem.

Grazing is more common in upland sites where better quality land is limited and control over livestock ranges more casual, with very little boundary fencing.

*In the Netherlands and Wales grazing is used to control *Molinia*.*

Stop 2: Central area of the South West Lobe - intact mire surface (no drains except boundary).

Q. Should this area be considered an active raised mire?

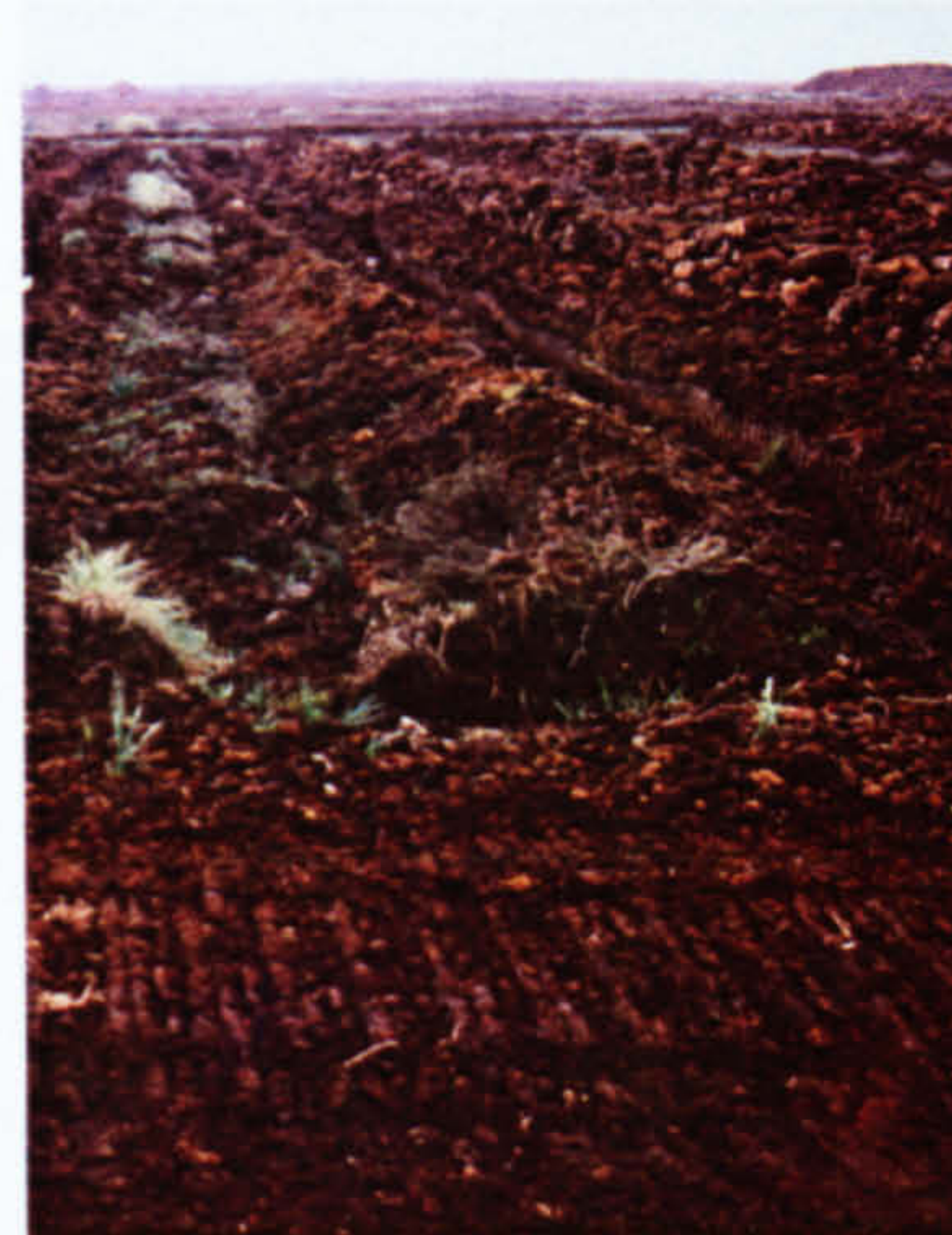
*A. With a *Sphagnum* cover of around 90%, this area was considered desirable by Scottish, Dutch and Belgian representatives. It is similar in condition to sites in Brittany, where the appearance of *Myrica gale*, present here is thought to be a sign of drying. The area was considered active from a peat forming point of view but is showing signs of recent drying.*

The need to collect data or assess potential subsidence from past surveyed levels was highlighted, as it is not clear how close the existing surface level is to a pre-drainage condition.

Q. What are the indicators of active mires?

A. (i) a peat forming vegetation; (ii) indicative macrotopography (mound features evident); (iii) indicative micro-topography (hummock hollow-pools); (vi) within geographical climatic limitations (positive water balance).

Stop 3: Area of regenerating mire, previously drained in preparation for peat cutting which was not carried out. Deep but narrow drains created here, have been blocked for 6 years, and the dam material (laminated corrugated metal sheets) is barely visible. The drain channels themselves are difficult to locate, and *Sphagna* have grown up dams using them as structural support. There is extensive regrowth of *Sphagnum* species including *S.*



papillosum, S. palustre, S. magellanicum, S. capillifolium, S. rubellum, S. cuspidatum and S. subnitens, totalling around 95% cover.

Q. What was the drain blocking intensity and how was it determined?

A. A corrugated metal dam was inserted into the peat extending across the drain boundaries, at an interval determined by channel gradient. The policy was to construct one dam for every 0.3m fall in elevation. In practice additional dams were inserted wherever personal experience determined they may be useful.

Discussion: The Dutch prescription for damming interval is one dam for every 0.1m drop in elevation.

Stop 4: This stop was made next to the furthest extent of the old mechanical cuttings, where deep drains have been dammed with peat. The surface is a ridge hollow pattern created by the cutting practice, with the hollows relatively



wet and filled with water in some cases and the ridges dry with *Calluna* and some *Molinia*. The hollow areas not under water show signs of crusting, surface flow and small scale erosion processes with extensive bare peat.

Q. Why has regeneration been so slow/absent from this area?

A. The hydraulic gradient here is apparently too steep for acrotelm development. The higher areas (ridges) are too dry and well drained by the intervening low areas to develop peat forming vegetation, whilst the low areas themselves are effectively temporary drains subject to high flow rates.

Stop 5: Bottom of old mechanical cutting-face slope, where previously a Hymac machine sunk into the peat. This area adjacent to the active peat milling area is very unstable, subject to both cracking and subsidence. Water flows into a crack feature and re-surfaces within the cutting area some distance away. It's flow route is unknown.

Discussion: Similar problems have been experienced in Ireland. At Clara Bog in the Republic of Ireland, water resurfaces silt-laden, suggesting it had been flowing at the peat-mineral interface.

Stop 6: The stop was made to the North of the mineral ridge in an old cutting area which was subject to a program of drain blocking and back-filling, including the installation of overflow pipes. The pools created were around 1m deep. After 4 - 5 years the pools had been colonised by *S. cuspidatum*, and after 10 years *S. magellanicum* and *S. papillosum* had appeared. In some pools *S. cuspidatum* was transplanted from other parts of the site, and these exhibited an accelerated succession.

Discussion: Several pools have not been colonised by bryophytes and it has been suggested that this may be the result of either increased nutrient levels from waterfowl faeces or suppression of moss sp. by algae which cover extensive areas of open water.

Stop 7: Back-filled drains on the edge of the Newton Arlosh Awards - historically these were allotted to the residents of the Newton Arlosh Parish for domestic fuel and are still owned in some parts by local residents although no cutting is carried out within this part of the SSSI.

Q. The surface between here and the cutting face is quite steep. Would it have been better although controversial, to allow cutting to continue until the level of the now abandoned cutting area was more suitable for re-wetting?

A. The speed of regeneration and ease of re-wetting may have benefited surface re-profiling early in the restoration management of this area, although further peat removal subsequent to the cessation of commercial peat cutting would undoubtedly have been controversial.

Stop 8: Newton Arlosh Awards: the intersecting drain here has caused considerable subsidence, forcing a single dome to re-form with the surface now apparently comprising of two smaller 'peat domes'.

Q. Should this drain be dammed and what are the likely consequences?

A. Blocking the drain may cause instability at the mire margin and a large dam such as that constructed at Clara bog is suggested by Irish representatives.



Experience from Europe

Peat bog rehabilitation work in Wallony, Southern Belgium

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Centre de Recherche de la Nature, des Forêts et du Bois: Ministère de la Région Wallonne.

4.1

An experimental management programme of raised bogs is worked out since 1993 in the Hautes-Fagnes State Nature Reserve. It concerns the protection of undisturbed or little damaged raised bogs. The restoration of degraded and inactive areas and the re-naturalisation of heavy cut raised bogs.

The protection of undisturbed or little-damaged areas of ombrogenous raised bogs is ensured by closing the ditches with peat dams and filling them. Naturally growing trees and shrubs are removed as far as possible. All footpaths running on or along active areas are now forbidden to walkers because of the disastrous effects of trampling on peat soils (destruction of rare species, destruction of highly structured communities, mineralization of upper peat layers).

In degraded raised bogs areas, dominated by *Molinia caerulea*, the superficial peat layer is scraped on experimental plots (100 to 1500m²) in order to remove the vegetation, the accumulated litter and the highly mineralized peat and to restore the ground surface to a level close to the mean perched watertable. This promotes a partial re-wetting of the plots. The scraped surfaces are also profiled with a gentle slope and a microtopography is created to offer an



ecological gradient of moisture and depth, favourable to the re-establishment of different peat moss species. In partly degraded raised bogs, near remaining undamaged sites, the plots are naturally re-colonised by various typical bog plants. *Sphagnum* species especially appear progressively from water- or wind borne diaspores from adjacent undamaged areas. In completely degraded peat bogs, unless local refugia for peat species exist, there is no - or only very slow re-colonisation without human intervention on the plots. In these strongly damaged sites, pioneer (or 'nurse') species are first planted on the scraped surfaces (cuttings of *Eriophorum*

polystachion and of *Eriophorum vaginatum* split from large tussocks), because in summer the microclimate is too extreme for *Sphagnum* survival. The *Sphagnum* fragments, manually collected from ditches, are introduced beneath the cover of these vascular plants, where the substrate is more humid and the microclimate conditions are more suitable to *Sphagnum* establishment (Brooks & Stoneman 1997, Grovnerier & al 1995, Sliva & al 1997, Wheeler & Shaw 1995). In some plots, straw mulch is spread on the *Sphagnum* diaspores because of its positive effect on *Sphagnum* re-colonisation (Quinty & Rochefort 1997, Brooks & Stoneman 1997).

Initial results show that it seems possible to regenerate pioneer bog plants communities but many years of observation will be needed to assess the success of these management methods in terms of restoration of functional peat-land ecosystems.

The re-naturalisation of a heavily cut raised bog is also studied in the Hautes-Fagnes State Nature Reserve. In order to reduce the lateral water drainage and to stop the erosion of the peat bog along the former exploitation scar, the latter has been profiled with a ca 15% slope. Following this, the cut-over area has been wholly remodelled in order to rewet it, by building a system of low dams of peat across the slope. The created lagoons maintain flooded areas at the bottom of the raised-bog. They are progressively colonised by floating *Sphagnum cuspidatum* rafts and fen vascular species. In these flooded areas, it seems that new mire will develop. Later, perhaps a bog building vegetation might arise from the *Sphagnum cuspidatum* carpet.



Un programme expérimental de gestion des tourbières hautes est mis en œuvre depuis 1993 dans la Réserve naturelle d'Etat des Hautes-Fagnes. Il concerne la protection de tourbières hautes non perturbées ou peu endommagées, la restauration d'étendues dégradées et inactives et la renaturalisation de tourbières hautes fortement exploitées.

La protection des étendues non perturbées ou peu endommagées de tourbières hautes ombrogènes est assurée par la fermeture des fossés au moyen de barrages en tourbe et par leur remblaiement. Les arbres et les arbustes qui poussent naturellement sont enlevés dans la mesure du possible. Tous les sentiers traversant ou longeant des étendues actives sont désormais interdits aux randonneurs en raison des effets catastrophiques du piétinement sur les sols tourbeux (destruction d'espèces rares, destruction de communautés hautement structurées, minéralisation des couches de tourbe supérieures).

Dans les étendues de tourbières hautes dégradées, dominées par *Molinia caerulea*, la couche superficielle de tourbe est raclée sur des parcelles expérimentales (de 100 à 1 500 m²) afin d'enlever la végétation, la litière du sol accumulée et la tourbe fortement minéralisée et de rétablir la surface du sol à un niveau proche du niveau moyen de la nappe d'eau suspendue. Cela favorise une réhumidification partielle des parcelles. Les sur-



faces raclées sont également profilées en pente douce et une microtopographie est créée de manière à offrir un gradient écologique d'humidité et de profondeur favorable au rétablissement de différentes espèces de mousses des marais. Dans les tourbières hautes en partie dégradées et situées près des sites non endommagés restants, les parcelles sont recolonisées naturellement par diverses plantes typiques des

tourbières. Des espèces de *Sphagnum* en particulier apparaissent progressivement des diaspores emportées par l'eau ou le vent en provenance des étendues non endommagées adjacentes. Dans les tourbières totalement dégradées, à moins que des refuges locaux pour des espèces des tourbières n'existent, il n'y a aucune ou qu'une recolonisation très lente sans intervention humaine sur les parcelles. Dans ces sites fortement endommagés, des espèces pionnières (ou abri) sont en premier lieu plantées sur les surfaces raclées (boutures d'*Eriophorum polystachion* et d'*Eriophorum vaginatum* prélevées de grandes touffes) parce qu'en été le micro-climat est trop extrême pour permettre la survie de *Sphagnum*. Les fragments de *Sphagnum*, recueillis à la main dans les fossés, sont introduits sous la couverture de ces plantes vasculaires où le substrat est plus humide et les conditions du micro-climat sont plus adaptées à l'établissement de *Sphagnum* (Brooks & Stoneman 1997, Grovner & al 1995, Silva & al 1997, Wheeler & Shaw 1995). Dans certaines parcelles, du paillis est épandu sur les diaspores de *Sphagnum* en raison de son effet positif sur la recolonisation par *Sphagnum* (Quinty & Rochefort 1997, Brooks & Stoneman 1997).

Les résultats initiaux montrent qu'il semble possible de régénérer des communautés de plantes des tourbières pionnières, mais de nombreuses années d'observation seront nécessaires pour évaluer le succès de ces méthodes de gestion en termes de restauration d'écosystèmes de tourbières fonctionnels.

La renaturalisation d'une tourbière haute fortement exploitée est également étudiée dans la Réserve naturelle d'Etat des Hautes-Fagnes. Afin de réduire l'écoulement d'eau latéral et d'enrayer l'érosion de la tourbière le long de la cicatrice laissée par l'exploitation, celle-ci a été profilée avec une pente d'environ 15 %. A la suite de cette opération, l'étendue exploitée a été entièrement remodelée afin de la réhumidifier, par construction d'un système de barrages bas en tourbe à travers la pente. Les lagunes créées maintiennent les étendues inondées au bas de la tourbière haute. Elles sont progressivement colonisées par des masses flottantes de *Sphagnum cuspidatum* et des espèces vasculaires des fagnes. Dans ces étendues inondées, il semble qu'une nouvelle tourbière se développera. Plus tard, une végétation accumulatrice de tourbe pourrait provenir du tapis de *Sphagnum cuspidatum*.

Q. What type of exploitation has resulted in the need for peatland restoration in Belgium?

A. Peatlands have been exploited for peat as a fuel and drained for agriculture.

Q. What is the available recharge at Wallony?

A. Mean annual rainfall is 1400mm at an altitude of 600m, and potential evapotranspiration is 450-500mm.

Q. Would restoration be possible with drain blocking only?

*A. Gradients at the site are too high with high resultant run-off rates, making the creating of open water impossible. In addition, existing dominant *Molinia* communities, with high ET demand had to be removed. *Molinia* has remained absent in the areas scraped, as the*

*water levels which can be maintained have prevented its invasion. Open water is not necessarily an 'original' feature of the site, but it has allowed the reestablishment of more favourable species such as *Sphagnum* at the site.*

Q. Has *Molinia* always been a dominant species in Wallony?

A. No – its appearance at the site corresponds to agricultural improvement.

Q. Is Wallony really a raised bog?

*A. The *Sphagnum* species found at the site, such as *Sphagnum imbricatum*, are typical raised mire species. Peat monoliths reveal that the peat is dominated by *Sphagnum* throughout the development of the mire, with open water communities contain *Nuphar* sp. found in initial layers.*



Raised Bog Restoration in Ireland

Jim Ryan

Duchas - The Heritage Service, Ireland

Jan Streefkerk

Hydrologist: Staatsbosbeheer

4.2

All Irish raised bogs are now damaged and deteriorating due to drainage, peat extraction and burning. Research undertaken during the Irish/Dutch Raised Bog Study Project in the early 1990s demonstrated that peat cutting or drainage, even at the margins of the bog, had widespread effects throughout the whole peat dome initiated by localised subsidence caused by drying out. The consequent increase in surface slope increased the rate of runoff which in turn caused further drying out and subsidence. This effect gradually spread away from the site of the initial damage into the main part of the bog. Ongoing research and analysis of the information collected at that

time has allowed us to identify the connections between changes in vegetation complexes, surface slopes, flow paths and acrotelm thickness. From such information it is possible to identify if the site is in good condition and the possibilities for restoration. Integrated eco-hydrogeological surveys were undertaken of the best remaining bogs in the Republic of Ireland both for selection purposes as potential SAC's and to identify the fundamental conservation actions required at each site. Data will be presented for five bogs which will demonstrate the approach used and the conclusions which can be derived from this information.

Toutes les tourbières hautes irlandaises sont désormais endommagées et se dégradent sous l'effet du drainage, de l'extraction de la tourbe et du brûlis. Les recherches entreprises dans le cadre du Projet d'étude irlandais-néerlandais des tourbières hautes au début des années 90 ont démontré que les prélèvements de tourbe ou le drainage, même à la lisière d'une tourbière, avaient des effets sensibles sur l'ensemble du dôme de tourbe induits par l'affaissement localisé causé par le dessèchement. L'augmentation consécutive de la pente en surface a accru le taux de ruissellement, ce qui a provoqué d'autres phénomènes de dessèchement et d'affaissement. Cet effet s'est répandu progressivement du site d'endommagement initial jusqu'à la partie principale de la tourbière. Les travaux de recherche permanents et l'analyse des informations recueillies à cette époque-là nous ont permis d'identifier les liens entre les modifications des complexes végétaux, des pentes en surface, les voies d'écoulement et l'épaisseur de l'acrotelme. A partir de ces informations, il est possible de déterminer si le site est en bon état et les possibilités de restauration. Les meilleures tourbières qui subsistent en Irlande ont fait l'objet d'études éco-hydrogéologiques intégrées à des fins de sélection comme ZSC et d'identification des actions de conservation fondamentales nécessaires sur chaque site. Des données seront présentées pour cinq tourbières qui illustreront l'approche utilisée et les conclusions qui peuvent être tirées de ces informations.



The acrotelm of a bog system is the upper peat layer in which the peat forming processes are largely regulated. The annual fluctuations of the phreatic water level occur within the reach of the acrotelm and as a result this surface layer is to a greater or lesser extent aerated. The presence of aerobic micro-organisms in the acrotelm induces a relatively quick decomposition of the organic matter.

The depth of the acrotelm is dependent on the degree of humification near the bog surface and varies between 0.1 and 0.7 metres. In an intact acrotelm the organic material is poorly decomposed and as a result the permeability is in general quite high. The vegetation types present on an intact acrotelm are generally dominated by *Sphagnum* species.

In a dried-out and strongly humified acrotelm the permeability decreases considerably. The phreatic water level shows larger fluctuations and is relatively low in the summer period. In such situations the vegetation cover often shows a high abundance of ling heather, whereas *Sphagnum* species play a less important role. From the study of the vegetation and the acrotelm of Clara Bog-East the following

conclusions can be drawn; 72% of the surface of 205 ha is covered with vegetation types which can clearly indicate peat desiccation and contains elements of peat-forming *Sphagnum* communities. However, a well-developed hummock-hollow system such as occurs over large stretches of the western half of the bog, is largely absent which indicates a lowering of the water table in the bog. This is also suggested by the fact that *Sphagnum* species which are normally found on hummocks are restricted to hollow habitat.

There is a close correlation between the vegetation map and the acrotelm map (v.d. Cruysen *et al* 1993). Plant communities which clearly indicate peat desiccation occur on those parts of the bog from which an acrotelm is largely absent, whereas the location of the better developed, central communities is characterised by the presence of an acrotelm (although usually not thicker than 0.1 m).

The Eastern part of Clara Bog was drained by Bord na Mona in 1983 by cutting parallel drains, 18-20 m apart and about 0.40 to 0.60 m deep.

In 1989 an effort was made to block these drains by peat dams. In order to measure the effect of the blocks and the drains, three sites, each with three mini-transects of phreatic tubes between two drains were installed. Based on the analysis of the data S.v.d Schaaf (1994) came to the following conclusions:

- Almost all sites show a regime with a deeper phreatic level and larger fluctuation than normally occur in the central part of Irish Midland bogs. The drain levels on the phreatic level shows that the drainage must have had and still has a strong impact on the bog vegetation.
- Because the distance between the peat dams is relatively large (50-100 m) they are not very effective where the surface slope exceeds a few tenths of a percent.

The distance between peat dams also increases generally with a distance to the road that intersects Clara Bog. It is therefore highly important that the drains on Clara-East be blocked as effectively as possible. Therefore, a management plan for blocking superficial drains on the high-bog is made.

L'acrotelme d'un système de tourbière est la couche supérieure de tourbe dans laquelle les processus de formation de la tourbe sont en grande partie régulés. Les fluctuations annuelles du niveau de la nappe phréatique se produisent à portée de l'acrotelme et en conséquence cette couche superficielle est aérée dans une mesure plus ou moins grande. La présence de micro-organismes aérobies dans l'acrotelme induit une décomposition relativement rapide de la matière organique. L'épaisseur de l'acrotelme dépend du degré d'humification près de la surface de la tourbière et varie entre 0,1 et 0,7 mètres. Dans un acrotelme intact, la matière organique est mal décomposée et il s'ensuit que la perméabilité est en général assez élevée. Les types de végétation présents sur un acrotelme intact sont généralement dominés par les espèces de sphaignes.

Dans un acrotelme desséché et fortement humifié, la perméabilité diminue considérablement. Le niveau de la nappe phréatique fait l'objet de fluctuations plus importantes et est relativement bas en été. Dans de telles conditions, la couverture végétale présente souvent une abondance élevée de bruyère commune, tandis que les espèces de sphaignes jouent un rôle moins important.



Les conclusions suivantes peuvent être tirées de l'étude de la végétation et de l'acrotelme de la partie orientale de la tourbière de Clara (Clara Bog-East) : 72 % de la superficie de 205 ha sont couverts de types de végétation qui témoignent clairement d'un dessèchement de la tourbe et contiennent des éléments de communautés de sphaignes qui forment de la tourbe. Toutefois, un système bien développé de tertres-dépressions, comme celui que l'on trouve sur de vastes étendues de la moitié occidentale de la tourbière, est en grande partie absent, ce qui indique un abaissement du niveau de la nappe phréatique dans la tourbière. Cela est également suggéré par le fait que les espèces de sphaignes que l'on trouve



normalement sur les tertres sont limitées à l'habitat des dépressions.

Il existe une corrélation étroite entre la carte de la végétation et la carte de l'acrotelme (v.d. Cruysen et al 1993). Des communautés de plantes qui témoignent clairement du dessèchement de la tourbe se trouvent sur les parties de la tourbière où l'acrotelme est en grande partie absent, alors que la localisation des communautés centrales mieux développées est caractérisée par la présence d'un acrotelme (dont l'épaisseur ne dépasse toutefois pas en général 0,1 m).

La partie orientale de la tourbière de Clara a été drainée par Bord na Mona en 1983, par aménagement de canaux parallèles, espacés de 18-20 m et d'environ 0,40 à 0,60 m de profondeur.

En 1989, un effort a été fait pour bloquer ces canaux au moyen de barrages en tourbe. Afin de mesurer l'effet des blocs et des canaux, trois sites, dotés chacun de trois mini-sections transversales de tubes phréatiques entre deux canaux, ont été aménagés. Sur la base de l'analyse des données, S.v.d. Schaaf (1994) est arrivé aux conclusions suivantes :

Presque tous les sites présentent un régime avec un niveau phréatique plus bas et des fluctuations plus grandes que ceux qui caractérisent normalement la partie centrale des tourbières du centre de l'Irlande. Les niveaux de drainage sur le niveau phréatique montrent que

le drainage a dû avoir et a toujours un grand impact sur la végétation de la tourbière.

Du fait que la distance entre les barrages en tourbe est relativement importante (50-100 m), ceux-ci ne sont pas très efficaces là où la pente en surface est supérieure à quelques dixièmes d'un pour cent.

La distance entre les barrages en tourbe s'accroît également d'une manière générale avec la distance par rapport à la route qui intersecte Clara Bog. Il est donc de la plus haute importance que les canaux dans Clara-East soient bloqués d'une manière aussi efficace que possible. Par conséquent, un plan de gestion pour le blocage des canaux de surface dans la tourbière haute est en cours d'élaboration.



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Water management in the peatlands of France: an overview of the situation

Nicholas Dupieux

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4.3

Among the different types of habitats managed in France for Nature Conservation, peatlands surely form the ecosystems on which conservationists, until now, have focused their attention in the most accurate way. Indeed, the French peatlands which benefit from various types of biogeographical situations, offer a wide range of biodiversity and landscapes which shelter a huge natural heritage. Unfortunately, during the last 50 years the surface of peatlands has been reduced by half in France, victims of agriculture, afforestation, drainage, filling up, pond digging, infrastructure, peat extraction... Their actual surface is estimated around 60,000 hectares.

In this situation, the different organisations in charge of nature conservation have developed actions to protect the sites with an outstanding natural heritage. It isn't surprising that the first natural reserve ever created in France was proposed to protect a bog.

In 1995, *Espaces Naturels de France* (the federation of the *Conservatoires Régionaux d'Espaces Naturels* which manage 36,000 hectares on almost 1,200 sites) has been in charge of the management of a European Life program for peatland conservation.

Several types of actions have been achieved, such as the protection through land tenure of over 1,000 hectares of peatlands, conservation and restoration actions on 38 sites of emergency actions, the implementation of a national strategy for peatland conservation... In the framework of this program, we have analysed the different actions carried out by nature conservationists in France for peatland conservation, in order to publish a practical handbook for peatland and management and restoration. This handbook was released in late 1998 and published at 5,000 copies.

This study has enabled us to strike the balance of the experiments so far carried out in France in the field of peatland conservation and in various types of actions as peatland grazing, mowing, scrub control, turf stripping, or water management. Analysing these experiments from about 150 different sites has enabled us to propose practical solutions for peatland conservation in France, solutions that we have completed with the analysis of experiments carried out in foreign countries such as the UK, Germany, Belgium or Switzerland.

Concerning water management and hydrological restoration of peatlands, we came to the conclusion that in France, very few experiments had been implemented so far. This situation can be easily explained by the fact that the strategy of peatland conservation in France has, until now, consisted, most of the time, in giving protection to undamaged sites, or at least to sites with a good conservation status. Actually, experiments worthy of the name turned out to be very rare. Only a few sites, here and there, had been concerned by ditch blocking, most of the time carried out on very small scale. What was striking in the analysis of these few experiments was the fact that, in most cases, the techniques implemented consisted in home-made, hand-constructed dams with biodegradable materials (wooden logs, peat...) chosen for their cheapness in both cost and labour but also because of a lack of knowledge concerning the different dam designs and their efficacy. Most of these dams suffered from seepage problems and their efficacy as well as their longevity were very uncertain. In fact, the French managers were discovering and testing ditch blocking methods exactly the way the managers in the UK, Germany or Switzerland had done it ten or twenty years ago. And we can confess that our knowledge in this field was quite poor.

Anyway, this was the situation until the publication of the management handbook which informed the French managers of the different techniques implemented for years abroad to face problems of peat drainage. This synthesis was important at the very time when managers, little by little, got more and more involved in problems of peatland restoration because their actions did not concern only undamaged sites anymore, and also because more and more managers wanted to make demonstrative actions to incite forestry and agriculture services not to drain peatlands.

Despite this information of peatland managers, we can observe that the techniques implemented don't change much : the managers seem reluctant to use new designs or new materials to build dams, they are reluctant to take all the precautionary measures that are advised to make these dams efficient. In fact they are reluctant to use techniques that seem for them expensive in both cost and labour, and also artificial : most of them refuse to use plastic or metal sheet dams, corrugated sheet dams, even plywood dams, even if their efficacy and longevity has been proved. The idea that an expensive long-life dam is more cost-effective less than a cheap one that will need repair after repair has not gained ground among the managers. For instance, we have just been asked to make an expert appraisal for a National Park which planned to restore a large drained bog. This valuation came to the conclusion that 120 plywood dams and 50 corrugated sheet dams should be installed on the site. The Park authorities have decided to build 170 wooden logs dams...

The French managers in charge of peatland conservation need time and information. They still suffer from a huge deficit of knowledge and information in the field both of peatland hydrology, techniques for peatland restoration, and hydrological monitoring. This information, as well as education, turns out to be essential to avoid reproducing the mistakes that have already been done in the past.



Q. Why are restoration practices limited in their extent on so many French sites?

A. Site managers are reluctant to apply 'new' techniques which are now standard procedure in other parts of Europe, as they are not confident of their success and believe them to be obtrusive. In particular man-made materials suitable for damming are considered a visual eyesore. Proof of the rate at which they become overgrown and invisible must be provided to convince managers of their suitability.



Parmi les différents types d'habitats gérés en France pour la conservation de la nature, les tourbières constituent certainement les écosystèmes sur lesquels les spécialistes de la conservation ont jusqu'ici concentré leur attention de la manière la plus précise. En fait, les tourbières françaises, qui bénéficient de divers types de situations biogéo-graphiques, se caractérisent par leur bio-diversité élevée et leurs paysages très variés abritant un patrimoine naturel d'une richesse remarquable. Malheureusement, au cours des cinquante dernières années, la superficie des tourbières a diminué de moitié en France, celles-ci ayant été victimes de l'agriculture, d'opérations de boisement, de drainage et de remblaiement, de l'aménagement de plans d'eau, de la construction d'infrastructures, de l'extraction de la tourbe... Selon les estimations, elles couvrent actuellement une superficie d'environ 60 000 ha.

Dans ces circonstances, les différentes structures en charge de la conservation de la nature ont élaboré des mesures pour protéger les sites abritant un patrimoine naturel remarquable. Il n'est pas surprenant que la première réserve naturelle jamais créée en France ait été proposée dans le but de protéger une tourbière. En 1995, Espaces Naturels de France (la fédération des Conservatoires Régionaux d'Espaces Naturels gérant 36 000 ha répartis sur près de 1 200 sites) a été chargé de la gestion d'un programme Life européen pour la protection des tourbières. Plusieurs types d'actions ont été réalisés, tels que la protection par la maîtrise foncière de plus de 1 000 ha de tourbières, des actions de conservation et de restauration dans 38 sites d'intervention d'urgence et la mise en œuvre d'une stratégie nationale de conservation des tourbières. Dans le cadre de ce programme, nous avons analysé les différentes actions en faveur de la conservation des tourbières menées en France par les spécialistes de



la conservation de la nature afin de publier un guide pratique pour la gestion et la restauration des tourbières. Ce guide a été publié à la fin de 1998 et tiré à 5 000 exemplaires.

Cette étude nous a permis de faire le bilan des expériences menées jusqu'ici en France dans le domaine de la conservation des tourbières et dans des types d'actions aussi divers que le pâturage des tourbières, la fauche, la lutte contre les broussailles, l'étrépage ou la gestion de l'eau. L'analyse de ces expériences émanant d'environ 150 sites différents nous a permis de proposer des solutions pratiques pour la conservation des tourbières en France, solutions que nous avons complétées par l'analyse d'expériences menées dans des pays étrangers tels que la Grande-Bretagne, l'Allemagne, la Belgique ou la Suisse.

S'agissant de la gestion de l'eau et de la restauration hydrologique des tourbières, nous sommes arrivés à la conclusion qu'en France, très peu d'expériences ont été menées jusqu'à présent. Cette situation peut être facilement expliquée par le fait que la stratégie de conservation des tourbières en France a, jusqu'ici,



consisté la plupart du temps à accorder une protection aux sites non endommagés, ou tout au moins aux sites en bon état de conservation. En fait, les expériences dignes de ce nom se sont révélées très rares. Seuls quelques sites, ici et là, avaient été concernés par le blocage des fossés, effectué la plupart du temps sur une très petite échelle. Ce qui était frappant dans l'analyse de ces quelques expériences était le fait que, dans la plupart des cas, les techniques mises en œuvre consistaient en des barrages maison construits à la main avec des matériaux biodégradables (rondins de bois, tourbe...) choisis pour leur caractère peu onéreux en termes de coût et de main-d'œuvre, mais aussi en raison d'un manque de connaissances concernant les différents types de barrage et leur efficacité. La plupart de ces barrages souffraient de problèmes de filtration et leur efficacité ainsi que leur longévité étaient très incertains. En fait, les gestionnaires français découvraient et testaient des méthodes de blocage des fossés exactement de la manière dont les gestionnaires en Grande-Bretagne, en Allemagne ou en Suisse l'avaient fait dix ou vingt ans plus tôt. Et nous pouvons avouer que nos connaissances dans ce domaine étaient médiocres.

Ainsi, telle était la situation jusqu'à la publication du guide de gestion qui a informé les gestionnaires français des différentes techniques mises en œuvre depuis des années à l'étranger pour faire face aux problèmes de drainage des tourbières. Cette synthèse était

très importante au moment même où les gestionnaires, petit à petit, se préoccupaient de plus en plus des problèmes de restauration des tourbières parce que leurs actions ne concernaient plus uniquement les sites non endommagés, et aussi parce que de plus en plus de gestionnaires voulaient mener des actions démonstratives pour inciter les services sylvicoles et agricoles à ne pas drainer les tourbières.

En dépit de cette information des gestionnaires de tourbières, nous pouvons observer que les techniques mises en œuvre ne changent pas beaucoup : les gestionnaires semblent peu disposés à utiliser de nouveaux modèles ou de nouveaux matériaux pour construire des barrages, ils sont peu disposés à prendre toutes les mesures de précaution qui sont recommandées pour rendre efficaces ces barrages. En fait, ils sont peu disposés à utiliser des techniques qui leur semblent onéreuses en termes de coût et de main-d'œuvre, et également artificielles : la plupart d'entre eux refusent d'utiliser des barrages en feuilles de plastique ou de métal, des barrages en tôle ondulée, même des barrages en contreplaqué, même si leur efficacité et leur longévité ont été prouvées. L'idée qu'un barrage coûteux à longue durée de vie est plus rentable qu'un barrage bon marché qui nécessitera réparation après réparation n'a pas gagné du terrain parmi les gestionnaires. Par exemple, on vient de nous demander d'effectuer une expertise pour un Parc national qui envisageait de restaurer une grande tourbière drainée. Cette évaluation est arrivée à la conclusion que 120 barrages en contreplaqué et 50 barrages en tôle ondulée devraient être installés sur le site. Les autorités du Parc ont décidé de construire 170 barrages en rondins de bois....

Les gestionnaires français en charge de la conservation des tourbières ont besoin de temps et d'informations. Ils souffrent toujours d'un énorme déficit de connaissances et d'informations dans le domaine de l'hydrologie des tourbières, des techniques de restauration des tourbières et de la surveillance hydrologique. Ces informations, ainsi qu'une éducation, s'avèrent essentielles pour éviter de reproduire les erreurs qui ont déjà été commises dans le passé.



Ferrière peat bog : an example of drained peat bog restoration in the Massif-Central - Limousin France

Estelle Cournez

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The Ferrière peat bog, which totals 100 ha, is localised on the Plateau de Millevaches, a large shelf with a high peat bog density.

Situated at an altitude of 875 metres, on Massif-Central west foothills, this peat bog has a typical vegetation community with mountainous and atlantic tendency, such as *Andromeda polifolia* or *Narthecium ossifragum*. On this area, 40 hectares have been managed by the "Conservatoire des Espaces Naturels du Limousin" since 1998.

At the beginning of 1995, this peat bog has been damaged by drainage, afforestation and a diversion stream. The damage is concentrated in a central area that covers 8 hectares and includes:

- 14 drainage ditches totalling 4.5 km of drains over 8 hectares
- average spacing between the drains is 25 metres
- drain depth is 80 cm
- drain width is 1 m at the top and 60 cm at the bottom
- slope of this drained area is 1 % on average
- turves left lying at the side of the drain
- 15,200 planted *Pinus sylvestris*

The stream that originally ran across the drained area has also been diverted by the main drain.

Two years after planting, the economic and ecological failures of this afforestation were recognised by the proprietor and the manager of the area, Office National des Forêts. In recognition of the nature conservation interest of this peat bog, a rehabilitation programme was proposed by the Limousin CREN.

The objectives of this programme are:

- To restore the sheet flows and stop the drainage.
- To restore pre-drainage surface flows and allow the diverted stream to follow its natural course.

The rehabilitation work started in January 1999 with the hand pulling of Pines, which weren't higher than 40 cm on average, after 4 years.

We had not found references of similar experiences therefore we have decided to realise the rehabilitation work in two phases. The first in August 1999 concerned the southern half of the drained area. The second in August 2000 concerned the northern half of the drained area.

Each phase has been realised in the same way. First, the sides of drain were mowed with a little tractor and the trees were cut (*Salix* sp. essentially). Then, this vegetation has been exported. The drains have been blocked with peat dams. This peat dams were made of the peat localised in the side of the drains. We were conscious of the risk that this peat could shrink but the difficult of access on the site and the budget that we had, didn't allow us to use another source of peat. We decided not to in-fill the totality of the linear drains because we didn't have enough materials and we chose to take advantage of the drains in order to constitute some aquatic areas. The peat dams have been built by machine, a mechanical digger.

For the rehabilitation of the diverted stream, some wood dams have been installed in the drain in each intersection with the bed of this stream, in order to support the peat dams. The same wood dams have been installed at the

mouth of some drains. The natural bed of the diverted stream has been recovered by the vegetation. The restoration of the stream bed has been realised by hand with adapted tool and with the mechanical digger when it had disappeared. The return of this stream in its natural bed has been realised in august 2000.

The methods used for the first phase seemed to give good results, so the same methods have been employed for the second phase. In total, 70 peat-dams have been built, 23 wood-dams have been installed.

This rehabilitation programme is experimental and to confront the lack of references at the beginning of the programme, we decided to set up some scientific monitoring.

The objectives of the monitoring studies are:

- To assess the impact of the drainage on :
 - the water table,
 - the quality of the peat,
 - the vegetation communities and species
- To assess the efficacy of the rehabilitation methods.

A precise mapping of the vegetation was done in July 1999 and is brought up to date each year. The presence of many indicators, such as dipwells and drains, made this operation easier. The vegetation in the drains is mapped before the dam up. Inventories of flora and fauna using transect lines and quadrats have also been implemented.

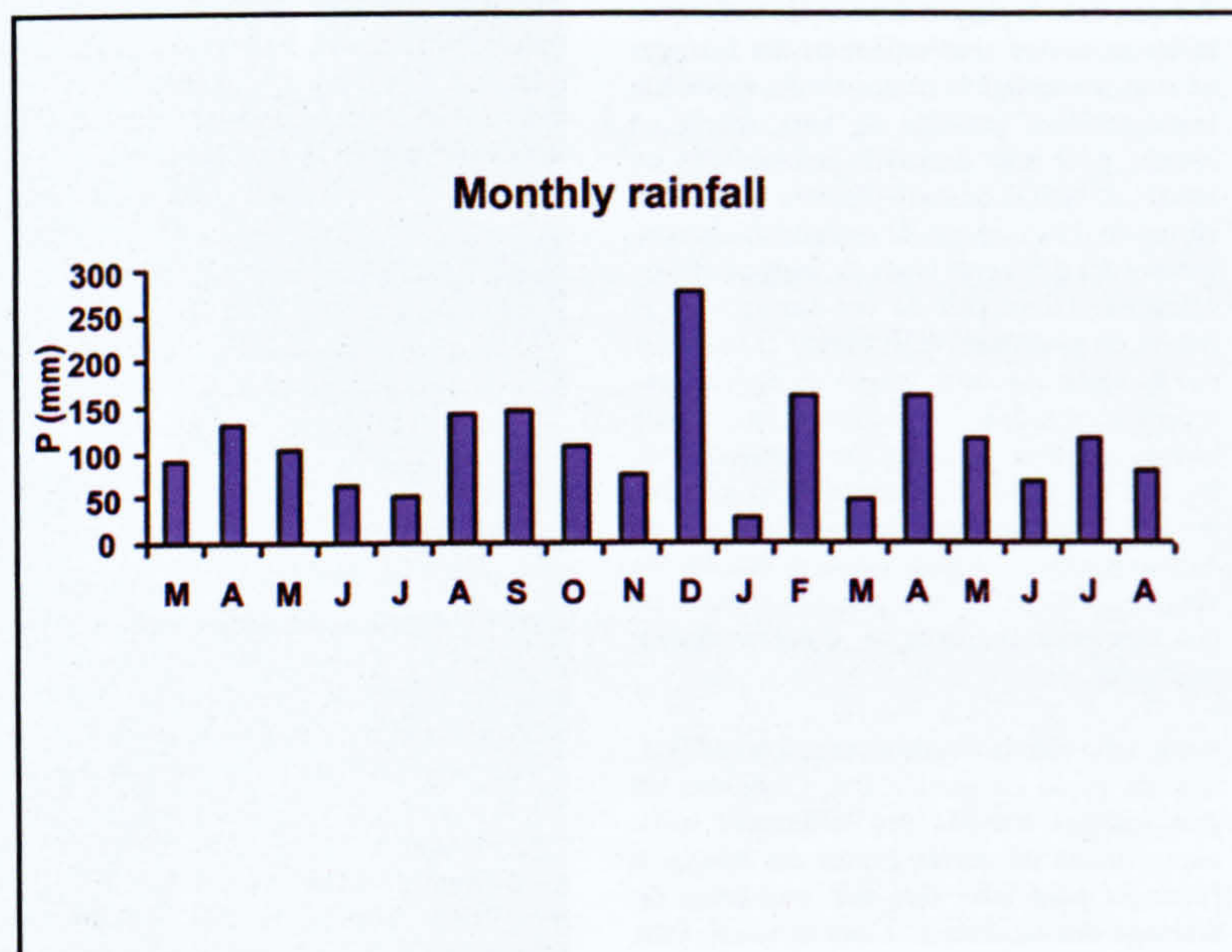
A hydrological study started in February 1999, six months before the beginning of the damming up work. The duration of this study is 30 months, divided in 3 phases. For this study, important equipment has been installed on the drained area including, 31 dipwells, 2 rain gauges, 2 evaporation-pans and 5 stage-boards in the surrounding drains and streams to measure the flow of water. Readings are taken every 2 weeks. This study is achieved by the University of Limoges and the Conservatoire.

Currently data collected are not sufficient to assess the all effects of this rehabilitation, but we can observe the first reactions of the water table.

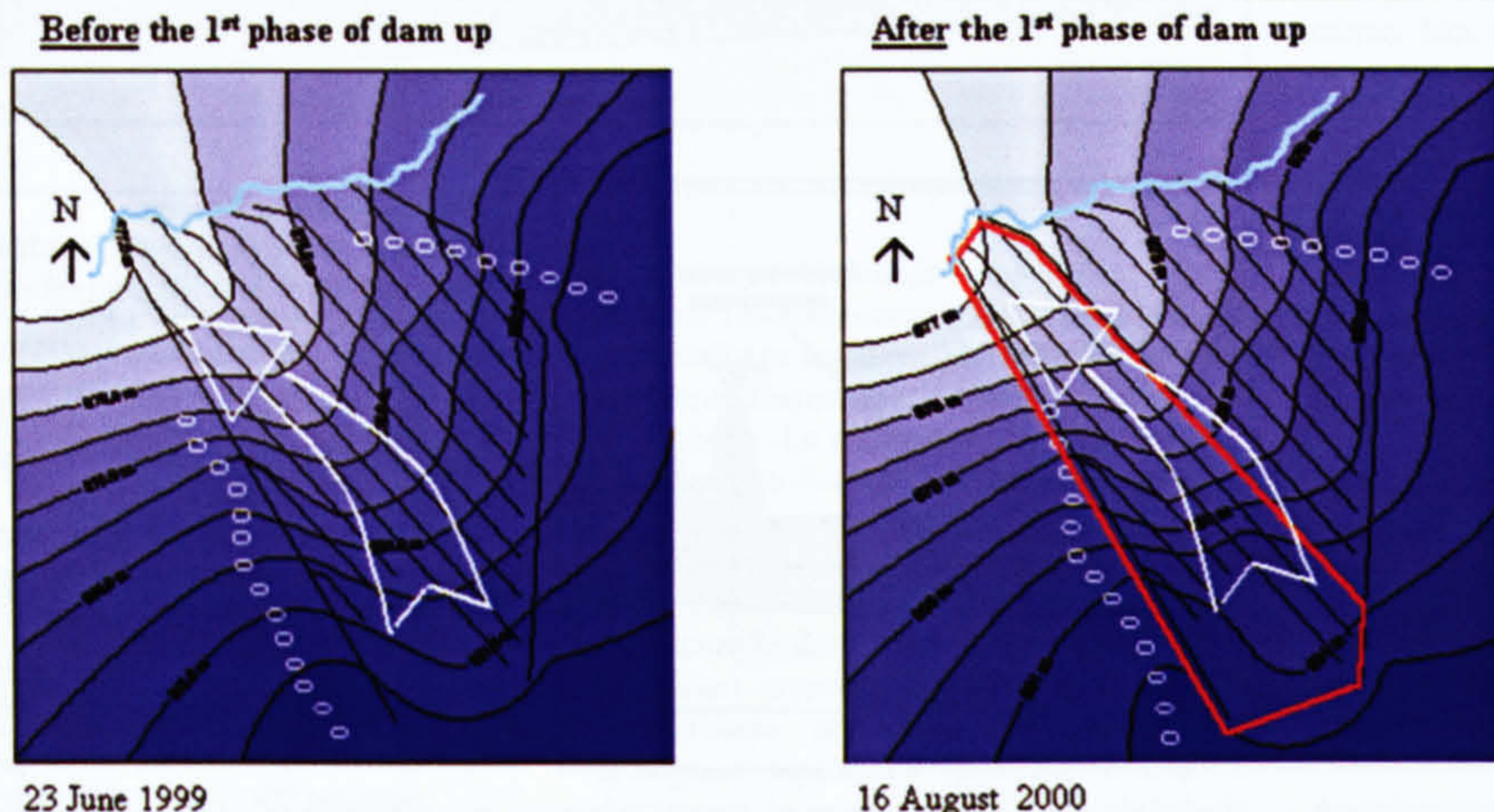
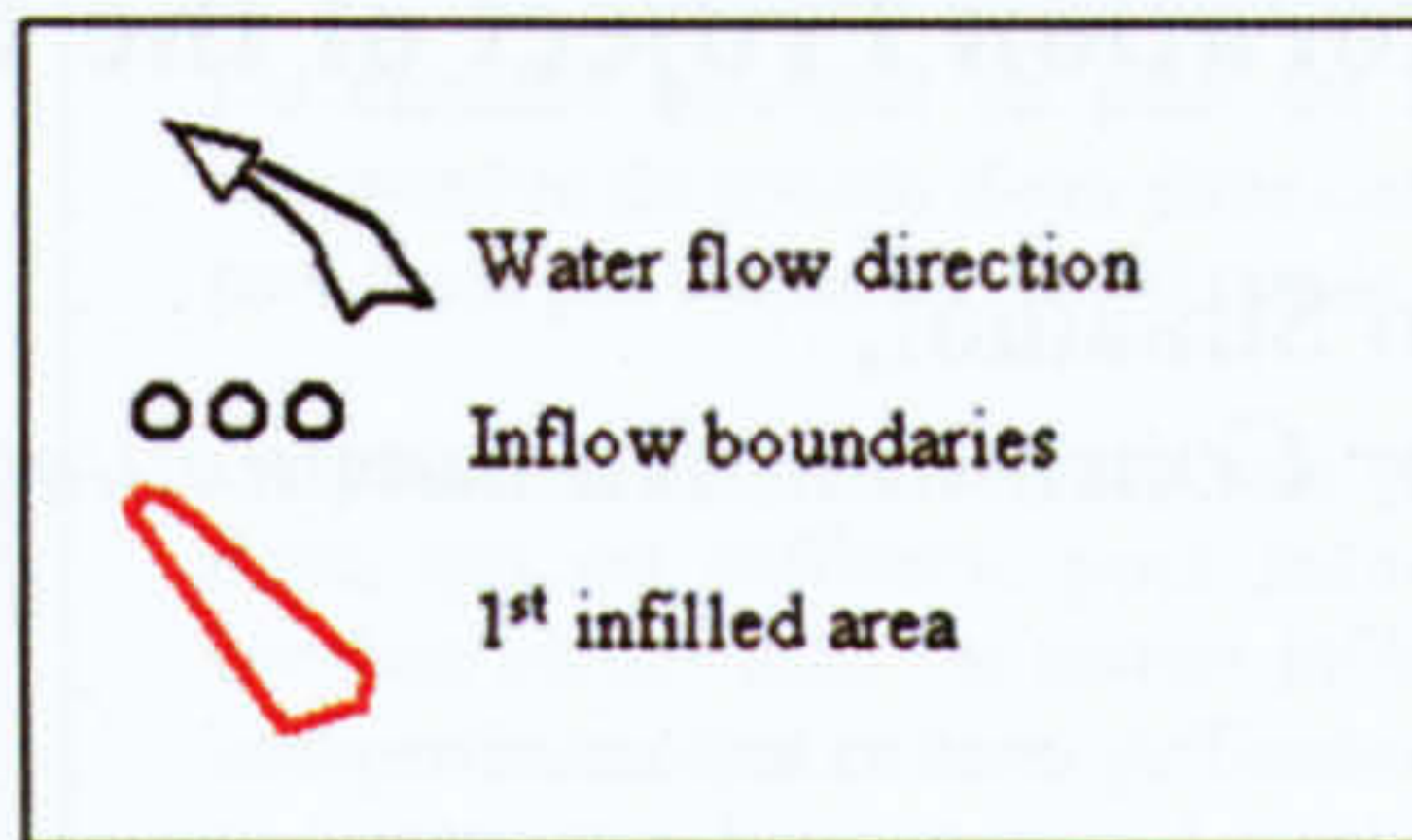
This experience is too new to give conclusions. The study of the evolution of the two half areas of the drained area must to be continued. Already, we can notice in the field that the portions of drains that have not been in-filled are full of water. This area and some areas that had been stripped are colonised by the bog plants including *Sphagnum* species.

Q. Will the mire continue to be grazed when the restoration program planned so far has been completed?

A. The site management will include grazing of Limousin cattle across the site at a low intensity. It is hoped that the peat dams will not be destroyed by cattle crossing drains.



Comparison at the low water period



This figure shows water table level at the low water period. We note a regular water flow before the drains dam up, in June 1999. The south half area has been rehabilitated in august 1999. One year after, on the second figure, we can observe a difference. On the upstream area, we not a raising of the level water table. On the other hand, on the downstream area, we note few modifications. This situation can be explained by the fact that this downstream zone is very close to the main stream of the peat bog, which creates a natural drainage. We observe this phenomenon for all the dipwells localised close to this stream, including the dipwells situated out of the drained area. The raising of the level of the water table of the upstream area is all the more as important since this part of the site is localised next to sources.

La tourbière de la Ferrière est une tourbière acide à Sphaigne couvrant une centaine d'hectares, localisée sur le Plateau de Millevaches, plateau granitique riche en tourbières. Située à une altitude de 875 m, sur les contreforts ouest du Massif Central, elle accueille une faune et une flore à tonalité montagnarde et atlantique.

Début 1995, cette tourbière a subit d'importantes dégradations avec l'ouverture de 4,5 km de fossés de drainage sur 8 ha au centre du site et le détournement d'un ruisseau, en vue d'une mise en valeur sylvicole (plantation de Pins sylvestres - *Pinus sylvestris*).

Le CREN Limousin a découvert ce site en 1997. Il y est aujourd'hui gestionnaire de plus de 40 ha. Le maintien de ce réseau de drainage risquait de compromettre à terme l'intérêt

écologique de l'ensemble de la tourbière. Devant l'échec économique et écologique de cette tentative, il a été décidé, avec le propriétaire (commune) et le co-gestionnaire (O.N.F.), la mise en place d'un programme de restauration conduit par le CERN Limousin, visant à:

- restaurer les écoulements de la nappe : stopper l'effet drainant du réseau de fossés,
- restaurer les écoulements superficiels : permettre au cours d'eau de retrouver son lit naturel.

Après une phase de préparation du site (arrachage des Pins plantés, bûcheronnage et fauche), les fossés ont été obstrués avec des bouchons de tourbe, issus du décapage des bords de fossés. Cette opération a été réalisée à l'aide d'une pelle mécanique. Ainsi, 64

bouchons, d'une longueur de 6 m pour la plupart, ont été implantés.

Le retour du ruisseau détourné dans son lit naturel a nécessité par endroit la réouverture de ce lit, manuellement au taille-pré ou mécaniquement avec la pelle mécanique. Des barrages en bois ont été installés aux intersections entre les fossés et le lit naturel du ruisseau et aux embouchures des fossés, afin de renforcer les bouchons de tourbes.

En raison de son caractère expérimental et de l'ampleur des travaux, ce programmes s'est déroulé en 2 tranches : août 1999, pour la moitié sud de la zone at août 2000, pour la moitié nord.

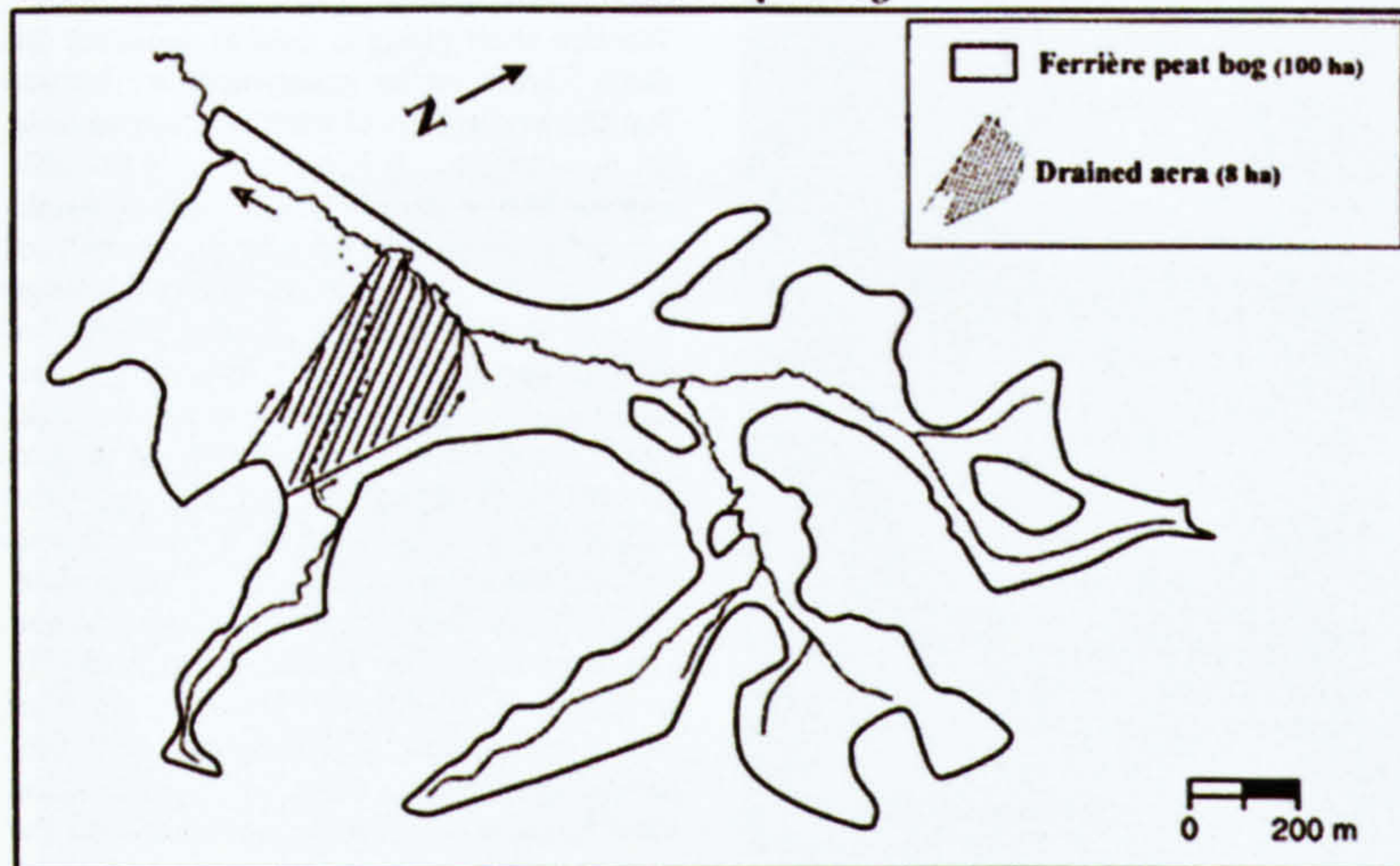
Peu d'expériences de ce type ont été menées en France. C'est pourquoi des suivis scientifiques ont été entrepris, visant à évaluer l'impact du drainage puis l'efficacité de la réhabilitation :

- étude hydrogéologique, confiée à l'Université de Limoges, sur 2,5 ans (fév. 99 - sept. 2001) : 31 piézomètres répartis sur 10 ha, 5 échelles bathy-métriques, pluviomètres, évaporomètres, relevés tous les 15 jours ;
- suivis de la végétation, réalisés par le CREN Limousin (cartographie annuelle précise, transects, placettes);
- suivis de la faune, confiés aux associations naturalistes spécialisées.

Nous n'avons encore que très peu de recul sur cette opération mais il semble que les méthodes employées soient relativement efficaces.

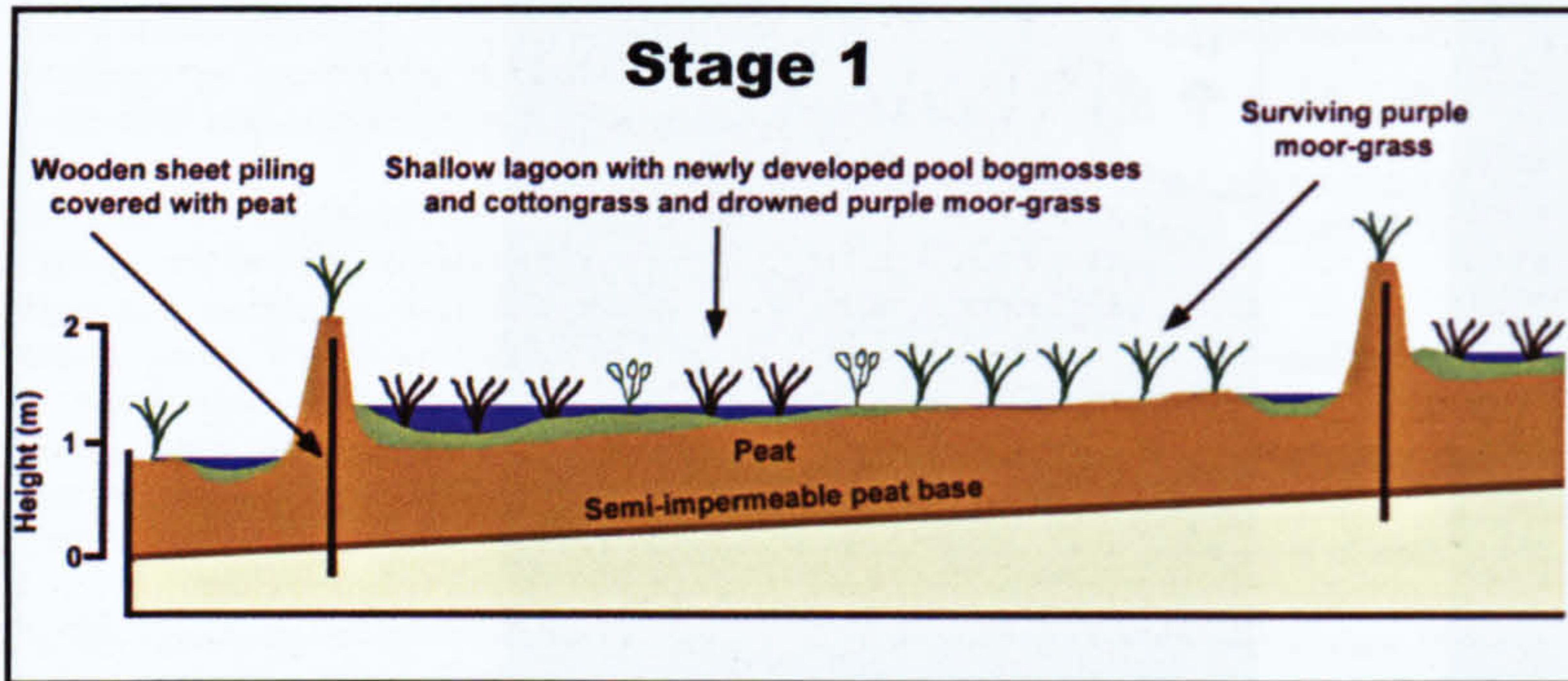
Ce programme a bénéficié du soutien financier de l'Agence de l'Eau Adour-Garonne, l'Europe, l'Etat français, la Région Limousin, l'Office National des Forêts.

Localisation of the drained area on the Ferrière peat-bog



Restoration Project of the Fochteloërveen raised bog

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Funding from the European Union and the Dutch government is enabling Vereniging Natuurmonumenten to implement an ambitious plan to regenerate Fochteloërveen, one of the largest remnants of raised bog in the Netherlands.

Fochteloërveen is a nature reserve in the north of the Netherlands situated on the border between the provinces of Friesland and Drenthe. The reserve, an expanse of peatland surrounded by arable land and forests, covers an area of about 2,500 hectares.

The original bog extended over an area of about 15,000 hectares. More than 80% of this bog has been cut away in 19th century for fuel production followed by reclamation into arable land. Although the remainder of the bog escaped large-scale excavation of turf it has not remained unscathed by human activities.

Turf was cut here on a small-scale up until 1980. Furthermore burning and drainage practices associated with the cultivation of buckwheat have destroyed the acrotelm, the top layer of the peat. The loss of this layer has resulted in greater fluctuations in water level, with low levels in the summer months.

These dry conditions favour the growth of purple moor-grass and restrict the growth of characteristic bog species such as bog mosses, *Sphagnum capillifolium*, *Sphagnum Magellanicum* and *Sphagnum papillosum* and the plants bog rosemary, sundew, cranberry and common and hare's-tail cotton sedge. Purple moor-grass with its deep root-system is able to continue drawing water as levels drop, thus accelerating further water-loss. Besides that drainage of the surrounding, lower lying, arable land and forests resulted in an increase in seepage losses from the remaining bog.

The restoration Process

Essential to the plan is the gradual raising of the water-level in each compartment in steps of 10-20cm.

The first inundation creates a sufficient water depth to drown the purple moor-grass in the lower parts of the compartment and yet is shallow enough for the growth of pool bog mosses. Deep water hinders this growth due to the lack of sunlight. Large surfaces of open water should also be avoided because of the disturbance from the wind preventing terrestrialisation of the water body.

Once the first lagoons have been filled by the growth of pool bog mosses, the water level is again raised by 10 - 20 cm. This process will be repeated several times. Pool bog mosses will continue to grow in the low areas. In the higher areas remaining purple moor-grass will be drowned and conditions made more favourable for the growth of bog mosses. Gradually the mosses will start to form a new acrotelm.

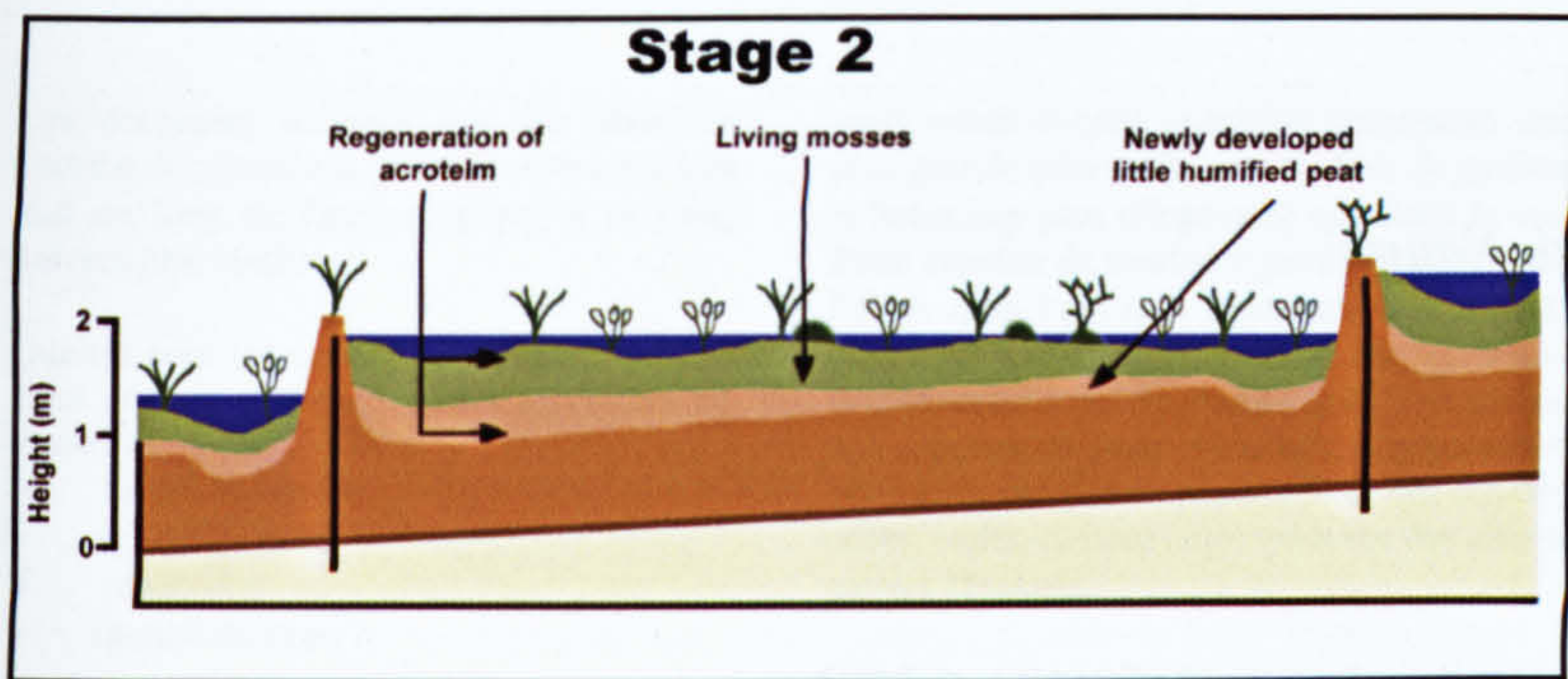
In time the wooded sheet piling will become overgrown and a united raised bog will be formed. The new acrotelm will be able to produce the water-level fluctuations in the bog. A large area of Fochteloërveen will once more be a self-regulating water-system, a living raised bog.



Dam Construction

Wooden sheet piling is used to construct the dams. From earlier experiences we learned that the available peat itself was not suitable for this purpose. It is mechanically unstable and vanishes relatively quickly due to shrinkage and oxidation. Besides the permeability of the peat was too high to prevent leakage through the dams. The wooden planks are driven through the peat into the semi-impermeable layer at the base to prevent leakage. The dams are covered with cut peat to prevent them drying out and warping. The choice for wood is based on its strength and because it is an environmentally friendly alternative to peat dams lined with plastic. Wood is a natural material. It rots extremely slowly in anaerobic conditions. Once the acrotelm has been restored, a process that will take several decades, the dams will have fulfilled their function and will be absorbed into the peat body.



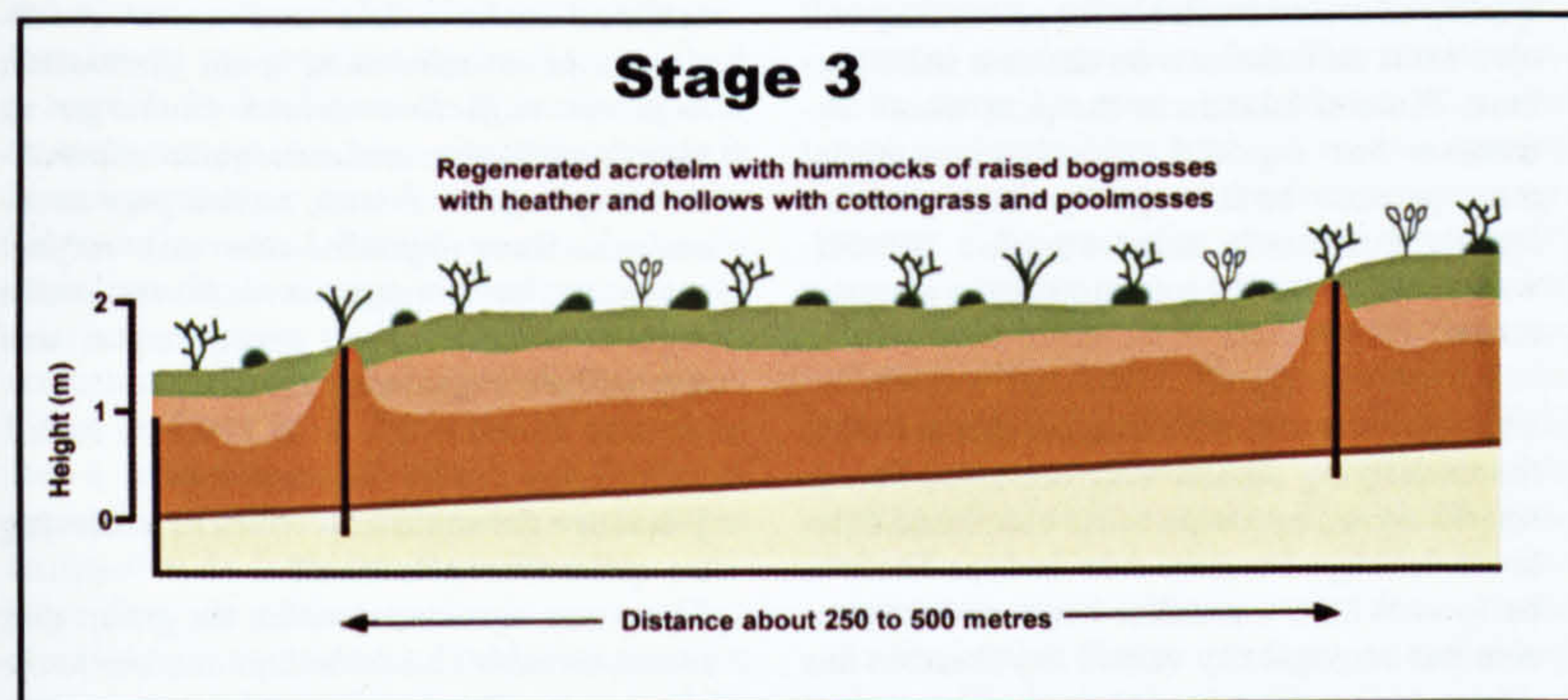


Grâce à un financement de l'Union européenne et du gouvernement néerlandais, Vereniging Natuurmonumenten met en œuvre actuellement un ambitieux plan visant à la régénération de Fochteloërveen, l'un des plus vastes vestiges d'une tourbière haute aux Pays-Bas.

Fochteloërveen est une réserve naturelle située dans le nord des Pays-Bas, à la limite entre les provinces de la Frise et de la Drenthe. La réserve, qui est une vaste étendue de tourbière entourée de terres arables et de forêts, couvre une superficie d'environ 2 500 hectares.

La tourbière originelle occupait une aire de quelque 15 000 hectares. Plus de 80 % de cette tourbière ont été exploités au XIX^e siècle pour la production de combustible puis transformés en terres arables. Bien que le reste de la tourbière ait échappé aux opérations de prélèvement de tourbe à grande échelle, il a néanmoins été affecté par les activités humaines.

La tourbe y a été extraite sur une petite échelle jusqu'en 1980. En outre, les pratiques du brûlis et du drainage associées à la culture du sarrasin ont détruit l'acrotelme, la couche supérieure de la tourbière. La disparition de cette couche a provoqué des fluctuations plus importantes du niveau phréatique, avec des niveaux bas pendant les mois d'été. Ces conditions sèches favorisent la croissance de la canche bleue et limitent celle des espèces caractéristiques des tourbières, comme les sphaignes *Sphagnum capillifolium*, *Sphagnum Magellanicum* et *Sphagnum papillosum* ainsi que le romarin des marais, le rossolis, l'airelle des marais, la linaigrette commune et la queue-de-lièvre. Grâce à ses profondes racines, la canche bleue peut continuer à prélever l'eau à mesure que les niveaux baissent, ce qui accélère les pertes d'eau. D'autre part, le drainage des terres arables et des forêts d'altitude plus basse avoisinantes a provoqué un accroissement des pertes par infiltration de la tourbière restante.



Processus de restauration
Un élément essentiel du plan est l'élévation progressive du niveau d'eau dans chaque compartiment par étapes de 10-20 cm de hauteur.

La première inondation crée une profondeur d'eau qui est suffisante pour submerger les canches bleues dans les parties inférieures du compartiment tout en étant suffisamment faible pour permettre la croissance des sphaignes des mares. Une eau profonde entrave cette croissance en raison de l'absence de lumière du soleil. Il faut également éviter de créer de vastes étendues d'eau libre parce que les perturbations provoquées par le vent empêchent la terrestrialisation de la masse d'eau.

Une fois que les premières lagunes sont remplies par la croissance des sphaignes des mares, le niveau de l'eau est de nouveau élevé de 10-20 cm. Ce processus sera répété plusieurs fois. Les sphaignes continueront à croître dans les parties inférieures. Dans les parties plus élevées, les canches bleues restantes seront submergées et les conditions seront rendues plus favorables à la croissance des sphaignes. Petit à petit, les sphaignes commenceront à former un nouvel acrotelme.

Avec le temps, le rideau de palplanches en bois sera envahi par la végétation et une tourbière haute unifiée se créera. Le nouvel acrotelme sera en mesure d'engendrer des fluctuations du niveau d'eau dans la tourbière. Une vaste étendue de Fochteloërveen redeviendra un système hydrique auto-régulateur, une tourbière haute vivante.



Construction de barrages
Des rideaux de palplanches en bois sont utilisés pour construire les barrages. Sur la base de l'expérience acquise, nous savons que la tourbe elle-même n'est pas adaptée à cet usage. Elle est mécaniquement instable et disparaît assez rapidement en raison de son retrait et de son oxydation. Par ailleurs, la perméabilité de la tourbe était trop élevée pour empêcher les fuites à travers les barrages. Les planches en bois sont enfoncées à travers la tourbe dans la couche semi-imperméable à la base pour empêcher les fuites. Les barrages sont ensuite couverts de blocs de tourbe pour empêcher leur dessèchement et leur gauchissement. Le bois a été choisi en raison de sa résistance et également parce qu'il constitue une alternative écologique aux barrages en tourbe revêtus de plastique. Le bois est un matériau naturel. Il se décompose très lentement dans un milieu anaérobie. Une fois que l'acrotelme aura été rétabli, un processus qui prendra plusieurs décennies, les barrages ont rempli leur fonction et seront absorbés dans la masse tourbeuse.

4.5



Final Discussion

Chaired by Roger Meade
Senior Peatlands Advisor, English Nature

5.0

The following areas were identified as recurring issues throughout the workshop and as such require conclusion:

What are effective starting conditions for mire restoration in terms of

- Land form
- Peat type
- Vegetation
- Water quality ?

Can climatic constraints be identified on a local and regional scale?

What are the main objectives in achieving an optimum water level?

Can baseline monitoring strategies be outlined for vegetation and hydrology?

What are effective starting conditions for mire restoration?

It appears that a post-milling surface is simpler to rewet, being profiled 'flat' and therefore lacking the high-dry/low-wet features of old machine and hand-cut terraces. However, long term maintenance of a high water table in such an area will be dependant on local hydrology and mire edge conditions. For example, if the mire surface has been extensively mined at the boundary so that a realistic lagg must re-establish according to the hydraulic gradient and hydraulic properties of the peat, then this must be taken into account when attempting to increase the water level in the adjacent mire areas. Several water table maintenance strategies were outlined throughout the workshop including the construction of extensive dam structures at Clara and Raheenmore Bogs to overcome draw down at the boundaries and support the 'peat cliffs' created by peat removal. In addition, the pumping of surface water against the hydraulic gradient to maintain wetness in central areas, was demonstrated in the Thorne Moor field trip.

The surface profile then has a strong influence on the ability to rewet a site, but wetness alone does not constitute restoration. The type of peat left at the surface will determine largely the ability of the site to retain moisture, particularly in dry periods and during raised flow rates. The degree of humification of the new surface peat, positioned until recent times within mire catotelm, will determine largely the rate at which an acrotelm can be re-established. If peat removal has been so extensive that the material now at the surface is of fen morphological origin then this situation will be exacerbated. The fen peat will potentially have a lower pH, different organic composition, higher mineral content, lower water holding capacity, and quite different hydraulic behaviour to an ombrotrophic acrotelm peat. Given such immediate obstacles the rate at which a *Sphagnum* domi-

nated surface can be established will be greatly reduced, and will require far more management intervention and ingenuity than a milled deep peat. Several techniques including the creation, flooding and seeding of shallow 'scrapes' in which rush and sedge species could be used as nurse crops were described from sites across Europe.

A wide range of practices for the re-establishment of an acrotelm vegetation community have been described, ranging from re-wetting and allowing invasion of species from remnant communities, to scraping the surface and transplanting *Eriophorum*, and to flooding old drains, broadcasting *Sphagnum cuspidatum* propagules, and combinations of all of the above. Obviously it is only possible to allow invasion by remnant species where remnant acrotelm communities exist in some form such as the upper terraces of old machine and hand cuttings. In a vast milled plain, effectively a peat desert, more active vegetation management is essential.

The underlying mineral topography and the quality of water available for re-wetting will also exert an influence on the new mire surface. Mineral islands in the peat where extraction has exposed underlying material may present both negative and positive issues. Potentially mineratrophic groundwater may enter the mire aquifer in phreatic zones.

The converse may also be true, in that loss to the underlying aquifer may increase. This is less likely as, by virtue of its continued existence, leakage from the mire body is likely to be low. Where a conflict between more recent but ecologically valued dry features has arisen during the mire restoration process, it may be possible to trans-locate the 'drier' communities to the higher ground, which is by definition more difficult to rewet. Such areas may be utilised for viewing platforms and educational features where appropriate, such as those seen at Thorne Moor.

Water quality problems may also occur where drainage regulation is difficult to enforce, such as in Fenns and Whixhall Mosses for example, where domestic sewage infiltrates the old drainage network and can be found within the mire drain channels. In cases where water quality may not be quite what is desired (too high pH or nutrient concentration) any problem will be exacerbated by the relocation of such water by pumping for example.

It was suggested that observed differences between sites within similar climatic zones, could point to potentially achievable future conditions.

Which of the countries represented can prescribe the condition and or depth of peat left by peat mining corporations when peat removal ceases?

England and Wales - the mineral planning consent which gives peat merchants license to extract, can be used to specify the depth of peat left across a site.

Northern Ireland and France - no regulation within the current planning law structure.

Republic of Ireland - no guidelines to regulate site conditions.

Belgium - no industrial exploitation so this is not a consideration.

Can climatic constraints be identified on a local and regional scale?

There are climatic restraints on mire formation, and these will continue to apply to the restoration of mire forming conditions. Many sites now degraded may have been initiated under colder and wetter conditions. As a minimum, peat formation requires sufficient excess recharge to slow humification and subsequent mineralization of organic matter, so that peat accumulates. Some degraded sites, now subject to restoration management schemes, are in regions with small net precipitation, and this will slow any recovery rate.

What are the main objectives in achieving an optimum water level?

There was agreement within the group that the water table should be kept as close to the mean ground surface throughout the year as is possible. This is most commonly achieved by slowing flow rates within, and losses from the site, in most cases by blocking drains created by peat cutters, and at many sites by creating shallow, bunded open water to hold water at the surface in previously dry areas with the aim of increasing the storage potential of the peat.

Can baseline monitoring strategies be outlined for vegetation and hydrology?

The branches of site monitoring are identified as water level and flow, basic water quality indicators, temporal and spatial variations in vegetation communities and the presence of indicator species. A combination of most of these are applied by the delegates present. The main issues which arose in discussion of methodology were the need for clarification of management aims in monitoring, the scale of application, appropriateness of indicator species within a regional and national context, and the final processing/use of the data collected, such as predictive modelling.



Les domaines suivants ont été identifiés comme des questions qui se sont représentées tout au long de l'atelier et qui, à ce titre, doivent être résolues :

Quelles sont les conditions de départ effectives pour la restauration des tourbières en termes de

- forme du terrain
- type de tourbe
- végétation
- qualité de l'eau ?

Des contraintes climatiques peuvent-elles être identifiées aux échelles locale et régionale ?

Quels sont les principaux objectifs de l'obtention d'un niveau phréatique optimal ?

Peut-on esquisser des stratégies de surveillance de base pour la végétation et l'hydrologie ?

Quelles sont les conditions de départ effectives pour la restauration des tourbières ?

Il semble qu'une surface après broyage est plus facile à réhumidifier, ayant un profil «plat» et étant par conséquent dépourvue des caractéristiques de dessèchement élevé/faible humidité des anciennes terrasses où la tourbe a été extraite par des machines et à la main. Toutefois, le maintien à long terme d'un niveau phréatique élevé dans une telle zone dépendra de l'hydrologie locale et des conditions à la lisière de la tourbière. Par exemple, si la surface de la tourbière a fait l'objet d'une exploitation intensive à la limite de sorte qu'une couverture réaliste doit se rétablir conformément au gradient hydraulique et aux propriétés hydrauliques de la tourbe, il faut en tenir compte lorsqu'on essaie d'accroître le niveau phréatique dans les étendues de tourbière adjacentes. Plusieurs stratégies de maintien de la nappe phréatique ont été décrites au cours de l'atelier, dont la construction de vastes barrages sur les tourbières de Clara et de Raheenmore pour faire face à l'abaissement du niveau aux limites et soutenir les «falaises de tourbe» créées par l'extraction de la tourbe. Par ailleurs, le pompage d'eau de surface contre le gradient hydraulique pour maintenir l'humidité dans les zones centrales a été démontré lors de la visite de terrain à Thorne Moor.

Le profil de la surface exerce ensuite une forte influence sur la capacité de réhumidification d'un site, mais la restauration ne saurait se limiter à la seule humidification. Le type de tourbe subsistant à la surface déterminera dans une grande mesure la capacité de rétention d'humidité du site, en particulier en période sèche et lors de l'élévation des débits. Le degré d'humification de la nouvelle tourbe de surface, située jusqu'à une période récente dans l'acrotelme de la tourbière, conditionnera dans une grande mesure le rythme auquel un acrotelme peut être rétabli. Si l'extraction de tourbe a été si intensive que la matière qui se trouve maintenant à la surface tire son origine morphologique dans les fagnes, cette situation sera alors exacerbée. La tourbe de fagnes aura potentiellement un pH plus bas, une composition organique différente, une teneur plus haute en substances minérales, une capacité de rétention d'eau plus faible et un comportement hydraulique très différent par comparaison avec la tourbe d'un acrotelme ombrotrophe. Compte tenu de ces obstacles immédiats, le rythme auquel une surface dominée par la sphaigne peut être rétablie sera considérable-

ment réduit et cette opération nécessitera une plus grande intervention en matière de gestion et beaucoup plus d'ingénierie que dans le cas d'une étendue de tourbière profonde ayant fait l'objet d'un broyage. Plusieurs techniques, dont la création, l'inondation et l'ensemencement de «poches» dans lesquelles des espèces de jonc et de laïche pourraient être utilisées comme plantes-abri, ont été décrites, celles-ci étant employées sur des sites à travers l'Europe.

Un large éventail de pratiques pour le rétablissement d'une communauté végétale d'acrotelme a été décrit, allant de la réhumidification et de l'envahissement non entravé par les espèces des communautés restantes jusqu'au raclage de la surface et à la transplantation d'*Eriophorum*, en passant par l'inondation des vieux canaux, la dissémination des propagules de *Sphagnum cuspidatum* et des combinaisons de toutes ces méthodes. Manifestement, on ne peut permettre l'envahissement par les espèces restantes que là où des communautés d'acrotelme subsistent sous une forme ou une autre, comme les terrasses supérieures des anciens prélèvements effectués à la machine et à la main. Dans une vaste plaine ayant fait l'objet d'un broyage et qui est en fait un désert tourbeux, une gestion plus active de la végétation est essentielle.

La topographie des minéraux sous-jacents et la qualité de l'eau disponible pour la réhumidification exerceront également une influence sur la nouvelle surface de la tourbière. Les îlots minéraux dans la tourbe où l'extraction a exposé le matériau sous-jacent peuvent présenter des défis négatifs et positifs. Les eaux souterraines potentiellement minéralisées peuvent pénétrer dans l'aquifère de la tourbière dans les zones phréatiques. L'inverse peut également être vrai, en ce sens que les pertes dans l'aquifère sous-jacent peuvent augmenter. Cela est moins probable étant donné que du fait de son existence continue, les fuites de la masse de la tourbière ont de fortes chances d'être lentes. En cas de conflit entre des caractéristiques sèches plus récentes mais écologiquement prisées durant le processus de restauration de la tourbière, il peut être possible de procéder à la translocation des communautés «plus sèches» vers les terrains d'altitude plus élevée qui sont par définition plus difficile à réhumidifier. Ces espaces peuvent être utilisés pour l'installation de plates-formes d'observation et d'équipements éducatifs, le cas échéant, comme cela est le cas à Thorne Moor.

Des problèmes de qualité de l'eau peuvent également surgir là où il s'avère difficile de faire respecter la réglementation en matière de drainage, comme dans les tourbières de Fenns et de Whixall, par exemple, où les eaux usées domestiques s'infiltrent dans l'ancien réseau de drainage et se retrouvent à l'intérieur des fossés de la tourbière. Dans les cas où la qualité de l'eau n'est pas ce que l'on souhaite (pH ou concentration d'éléments nutritifs trop élevé), tout problème sera exacerbé par le transfert de cette eau, par pompage par exemple.

Il a été suggéré que les différences observées entre des sites à l'intérieur de zones climatiques similaires pourraient mettre en lumière les conditions futures potentiellement réalisables.

Quels sont les pays représentés qui sont en mesure de prescrire l'état et/ou la profondeur de la tourbe laissée par les producteurs de tourbe lorsque leurs opérations d'extraction cessent ?

Angleterre et pays de Galles - l'autorisation d'exploitation de minéraux qui permet aux producteurs de tourbe d'effectuer des opérations d'extraction peut être utilisée pour spécifier la profondeur de la tourbe à laisser sur l'ensemble d'un site.

Irlande du Nord et France - aucune réglementation dans le cadre de la législation actuelle en matière d'aménagement.

Irlande - aucune ligne directrice pour réglementer l'état des sites.

Belgique - pas d'exploitation industrielle de sorte que ceci n'est pas une considération.

Des contraintes climatiques peuvent-elles être identifiées aux échelles locale et régionale ?

Il existe des contraintes climatiques s'exerçant sur la formation des tourbières et celles-ci continueront à s'appliquer au rétablissement des conditions de formation des tourbières. De nombreux sites désormais dégradés ont peut-être vu le jour dans des conditions plus froides et plus humides. Au minimum, le processus de formation de tourbe exige une réalimentation suffisamment excédentaire pour ralentir l'humification et la minéralisation subséquente de la matière organique afin que la tourbe puisse s'accumuler. Certains sites dégradés, qui font maintenant l'objet de programmes de gestion de leur restauration, sont situés dans des régions où les précipitations nettes sont peu élevées, ce qui ralentira leur rétablissement.

Quels sont les principaux objectifs de l'obtention d'un niveau phréatique optimal ?

Le groupe a été d'accord que le niveau de la nappe phréatique devrait être maintenu aussi près que possible de la surface moyenne du terrain, pendant une partie aussi grande que possible de l'année. Ceci est couramment réalisé en ralentissant la vitesse d'écoulement à l'intérieur du site et les pertes du site, dans la plupart des cas en bloquant les canaux créés par les tourbières, et sur de nombreux sites en créant des étendues d'eau libre peu profondes retenues par des digues à la surface de zones précédemment sèches dans le but d'accroître le stockage potentiel de la tourbe.

Peut-on esquisser des stratégies de surveillance de base pour la végétation et l'hydrologie ?

Les domaines de la surveillance des sites sont identifiés comme étant le niveau phréatique et l'écoulement d'eau, les indicateurs de base de la qualité de l'eau, les variations temporelles et spatiales des communautés de végétaux et la présence d'espèces servant d'indicateurs. Une combinaison de la plupart d'entre eux est appliquée par les délégués présents. Les questions principales soulevées lors du débat sur la méthodologie ont été le besoin de clarification des objectifs de la gestion en matière de surveillance, l'échelle d'application, l'adéquation des espèces servant d'indicateurs dans un contexte régional et national ainsi que le traitement/l'utilisation final(e) des données collectées, comme la modélisation prédictive.



Tuesday 10 October Arrival & Welcome
Mardi 10 octobre Arrivée & Ouverture

Arrival and registration at the Belmont Hotel, Thorne
Arrivée à Belmont Hotel, Thorne. Installation, enregistrement

Wednesday 11 October
Mecredi 11 octobre

Thorne Moors

Roger Meade	Welcome <i>Accueil</i>	
	Introduction to the Reserves to be visited by the Site Managers <i>Présentation des réserves par les gestionnaires des réserves d'English Nature</i>	
Peter Roworth	Humberhead Peatlands	6
Joan Daniels	Fenn's Whixall and Bettisfield NNR	11
Frank Mawby	Glasson Moss & Wedholme Flow	17
Katharine Birdsall	Water loss at Thorne Moors through different vegetation communities <i>Pertes en eau et nappes phréatiques à Thorne Moors</i>	8
Tom Dargie	Monitoring vegetation change at Thorne Moors following re-wetting <i>Le suivi de la végétation à Thorne Moors après remise en eau</i>	8
Kevin Bull	Site Visit: The Humberland Peatlands NNR <i>Visite de terrain: la réserve de Humberland Peatlands</i>	9
	Travel to Fenn's Moss and the <i>Hanmer Arms</i> / Voyage vers Fenn's Moss. Arrivée à <i>Hanmer Arms</i>	

Thursday 12 October
Jeudi 11 octobre

Fenn's & Whixall Moss

Kevin Gilman	Hydrological changes due to restoration work <i>Changements hydrauliques dus aux travaux de restauration</i>	13
Karen Horton	Vegetation change in relation to restored water levels <i>Changement de végétation et restauration des niveaux d'eau</i>	14
Joan Daniels	Site Visit: Fenn's, Whixall and Bettisfields Mosses NNR <i>Visite de terrain: Fenn's, Whixall and Bettisfields Mosses RNN</i>	15
	Travel to <i>Posthouse Hotel</i> , Carlisle / Voyage vers Carlisle. Installation au <i>Posthouse Hotel</i>	
Nicko Straathof	Restoration Project of the Fochteloërveen raised bog <i>Projet de restauration de la tourbière haute de Fochteloërveen</i>	32
Phillippe Frankard	Peat bog rehabilitation work in Wallony, Southern Belgium <i>Travaux de réhabilitation des tourbières en Wallonie, sud de la Belgique</i>	24

Friday 13 October
Vendredi 13 octobre

Wedholme Flow

Ryan & Streefkerk	Raised Bog Restoration in Ireland <i>Restauration des tourbières hautes en Irlande</i>	26
Nicholas Dupieux	Water management in the peatlands of France: an overview of the situation <i>Gestion de l'eau dans les tourbières de France : Un aperçu de la situation</i>	28
Estelle Cournez	Ferrière peat bog : an example of drained peat bog restoration in the Massif-Central - Limousin France <i>Restauration d'une tourbière dégradée par des travaux de drainage et d'un ruisseau détourné</i>	31
Charlotte MacAlister	Hydrological regimes following rehabilitation work at Wedholme Flow <i>Régimes hydrauliques après travaux de restauration</i>	19
Andy McMullen	Monitoring hydrological conditions from microfossils in the peat <i>Suivi des conditions hydrauliques dans les macro fossiles</i>	20
Frank Mawby	Site Visit: Wedholme Flow <i>Visite de terrain: Wedholme Flow</i>	22
Barbara Young	The View From The Bogs <i>L'optique des tourbières</i>	2

Saturday 14 October Issues
Samedi 14 octobre Les Enjeux

Roger Meade	Final Discussion <i>Discussion finale</i>	34
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6.2

Delegates

Peatlands in Focus:*A gallery of images capturing the nature of the English Bogs*

Running in parallel to the main text is a collection of pictures from the various bogs. Here the various themes are brought together.

Delegates on the workshop**Page 4 (bottom)**

All the delegates pose for a group photograph on Wedholme Flow [Geoffrey Lindop]

Page 32 (Bottom left)

Joan Daniels discusses a point with Frank Mawby while the other delegates look at a drainage ditch. [Geoffrey Lindop]

Page 32 (Centre right)

Frank Mawby points out items of interest on the site visit to Wedholme Flow [Geoffrey Lindop]

Page 33 (Bottom Left)

Delegates looking at bubbles of marsh gas on Wedholme Flow [Geoffrey Lindop]

Page 33 (Centre right)

Roger Meade discusses a point with Frank Mawby at one of the stops on the Wedholme Flow site visit [Geoffrey Lindop]

Thorne, Crowle & Goole Moors**Page 5 (centre)**

Thorne Moors Location Map [Geoffrey Lindop]

Page 6 (bottom left)

Thorne and Crowle Moor Drainage Map [English Nature / Geoffrey Lindop]

Page 7 (top right)

Thorne Moors: Middle Moor [Peter Roworth]

Fenn's Whixall & Bettisfield Mosses**Page 10 (centre)**

Location Map [Geoffrey Lindop]

Page 13 (lower left)

Berrington Pool [J Mason]

Page 24 (top right)

General view [J L Daniels]

page 11 (top centre)

Drainage Map [English Nature / Geoffrey Lindop]

Page 15 (top right)

Lifting Bridge over the Shropshire Union Canal [J Clarke]

Page 28 (bottom left)

General view [P Boardman]

Wedholme Flow**Page 17 (centre)**

Locator Map [Geoffrey Lindop]

Page 19 (bottom left)

Effects of damming on Wedholme Flow [Frank Mawby]

Page 23 (right)

This sequence of pictures is roughly the same scene in different years
(Top) prior to 1991
(Middle) 1991
(Bottom) 1994 [Frank Mawby]

Page 18 (top right)

Old ditches full of water on Wedholme flow [Frank Mawby]

Page 20 (top centre)

Fire recovery [Frank Mawby]

Page 18 (bottom centre)

General view of Wedholme Flow looking south. Cumbrian Fells in the distance. [Frank Mawby]

Page 20 (Centre left)

General view of Wedholme Flow [Frank Mawby]

Page 19 (top right)

Aerial view of Wedholme Flow Feb. 1998 [English Nature]

Page 22 (bottom right)

Dam construction on Wedholme Flow [Frank Mawby]

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Peatland Maintenance

- Page 7 (centre left)**
Scrub clearing on Thorne Moors with a Morooka and brush flail [Peter Roworth]
- Page 9 (lower left)**
Sheet pile dam on Angle Drain [Peter Roworth]
- Page 16 (bottom left)**
Preparing the weed-wiper at Fenn's [J L Daniels]
- Page 9 (top right)**
Two 4-inch pumps on Thorne Moors [Peter Roworth]
- Page 11 (bottom centre)**
Felling and stump treating on Fenn's, Whixall & Bettisfield Mosses [J L Daniels]

Peatland Vegetation, Trees & Plants

- Page 7 (right)**
Sphagnum on Thorne Moors [Peter Roworth]
- Page 7 (bottom)**
Cotton Grass on Thorne Moors [Peter Roworth]
- Page 8 (upper left)**
Juncus effusus growing in drains on Thorne Moors [Peter Roworth]
- Page 8 (bottom right)**
Mature birch killed off by rising water levels on Thorne moors [Peter Roworth]
- Page 11 (middle)**
Cloudberry (Fenn's & Whixall) [J L Daniels]
- Page 13 (top right)**
Utricularia minor (Fenn's Whixall) [J L Daniels]
- Page 14 (right)**
Bog Asphodel [J Robinson]
- Page 14 (lower left)**
Cotton Sedge at Fenn's Moss [J L Daniels]
- Page 15 (bottom right)**
Eriophorum on Fenn's Moss [J L Daniels]
- Page 16 (top left)**
Tussocks of eriophorum on Fenn's Moss [J L Daniels]
- Page 16 (middle right)**
Utricular at Fenn's [J L Daniels]
- Page 20 (bottom left)**
Sundew (South Solway) [Frank Mawby]
- Page 27 (Bottom right)**
Deadwood on Fenn's Moss [P Boardman]
- Page 27 (Bottom left)**
Sundew (Fenn's Moss) [J Robinson]

Peatland Birds & Reptiles

- Page 12 (top)**
Snipe at Fenn's Whixall & Bettisfield Mosses [J Robinson]
- Page 25 (top right)**
Curlew photographed on Fenn's Moss [J Robinson]
- Page 25 (lower left)**
Adder on Fenn's Moss [W Hankers]

Peatland Insects, Butterflies, Moths & Caterpillars

- Page 12 (lower left)**
Common Darter (Fenn's & Whixall) [J Clarke]
- Page 18 (centre left)**
Dragonfly on Wedholme Flow [Frank Mawby]
- Page 24 (bottom left)**
Large Heath on Fenn's Moss [R Key]
- Page 27 (upper Left)**
Common blue caterpillar (Fenn's Moss) [J Clarke]
- Page 29 (Top Left)**
Hymenoptera on tetralix (Fenn's) [A Berry]
- Page 29 (centre)**
Broad bodied chaser (Fenn's) [J Clarke]
- Page 29 (bottom left)**
Bog bush cricket (Fenn's) [RW]
- Page 29 (bottom right)**
Common blue damsel fly (Fenn's) [J Clarke]

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- Page 14 (top centre)**
Hand cutting Tools [W Hankers]
- Page 22 (top right)**
Conventional peat cutting [Frank Mawby]
- Page 22 (centre left)**
Active peat cutting on Wedholme Flow (1988) [Frank Mawby]
- Page 26**
Peat stack & Profile (Fenn's Moss) [W Hankers]
- Page 27 (top right)**
Peat Cutting on Fenn's Moss [J L Daniels]

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- Page 21**
Wedholme Flow Macrofossil Diagram [Andy McMullen]
- Page 30 (bottom right)**
Monthly Rainfall on Ferrière Peat bog [Estelle Cournez]
- Page 31 (top)**
Comparison of low water period on Ferrière Peat bog [Estelle Cournez]
- Page 31 (Bottom)**
Map of the drained area on Ferrière Peat bog [Estelle Cournez]
- Pages 32 & 33**
Three stages of the restoration process on Fochteloërveen bog [Nicko Straathof]

6.3

Photographs

Acknowledgements

The inspiration and original idea for this European workshop came from the *Eurosite* 1999 AGM in the Netherlands. Discussions with Jan Streefkerk and Jim Ryan revealed the need for a wider European forum to pool ideas about work on peat bogs. Discussions with English Nature colleagues focussed the workshop on our success/failures in regenerating sphagnum moss, which explains the title of the workshop. Thus, from being a visit to Cumbrian Bogs it developed into an event to examine the three most important lowland peat bog sites in England and to set the wide range of issues faced at these sites in a European context. English Nature colleagues who gave much help and advice were, Dr Roger Meade, Dr Joan Daniels, Peter Roworth and Kevin Bull. The backing and support of Nicole Nowicki and Philip Eckersley from *Eurosite* set the meeting on course.

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Workshop Organiser



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