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FLOOD 1 Final Report

Groundwater Resources Programme

Open Report OR/08/055

BRITISH GEOLOGICAL SURVEY

GROUNDWATER RESOURCES PROGRAMME

OPEN REPORT OR/08/055

FLOOD 1 Final Report

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Keywords

Groundwater flooding, Chalk, unsaturated zone.

Front cover

Groundwater dripping across a dissolution feature in the unsaturated zone of NHB2 borehole, Brighton..

Bibliographical reference

ADAMS B, BLOOMFIELD J, GALLAGHER A, JACKSON C, RUTTER H AND WILLIAMS A . 2008. FLOOD 1 Final Report. *British Geological Survey Open Report*, OR/08/055. 75pp.

Keyworth, Nottingham British Geological Survey 2008

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Acknowledgements

FLOOD 1 was a joint project with BRGM, University of Brighton and BGS. The overall project leader was Dr Marie-Luce Noyer of BRGM and Professor Rory Mortimore of Brighton University was the project leader for the UK element of the study. BGS are grateful for the project leadership provided by these two individuals and for the opportunity to work with staff of both organisations. While overall project administration fell to BRGM as project leaders, BGS would like to acknowledge the UK project administration provided by the University of Brighton, particularly through the efforts of Dr David Pope who enabled us to meet the INTERREG reporting and budgetary requirements throughout the life of the project. Professor Denis Peach was BGS' project Director and member of the FLOOD 1 Steering Group until his appointment as BGS' Chief Scientist in April 2007.

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Summary

The FLOOD 1 project was carried out by the French Geological Survey (BRGM), the University of Brighton and the British Geological Survey from April 2004 to June 2008 inclusive. It was carried out under the INTERREG IIIA initiative of the European Union which provided 50% of the funding, the remainder coming from the three project partners and a number of industrial partners who also formed the Project Advisory Group.

The project was set up to develop appropriate early warning systems for groundwater flooding in Chalk catchments following the particularly severe groundwater floods during the winter of 2000-01. It focussed on flooding in the Patcham area of Brighton and in the Somme Valley of northern France. Research sites were set up to the north of Brighton and in the Hallue sub-catchment of the Somme. An additional site was established at East Ilsley in the Pang Valley of the Berkshire Downs; a Chalk catchment that suffers from groundwater flooding, has been extensively studied and within which there are a number of research sites which were established for the LOCAR thematic research programme.

Three main objectives were addressed by the project, namely:

(i) To understand the hydraulic behaviour of water flow in the unsaturated zone which leads to triggering of groundwater flood events.

(ii) To develop unsaturated zone monitoring techniques, including non-intrusive ones such as Magnetic Resonance Sounding (MRS), to reduce cost and environmental impact, and to improve areal representation of the data.

(iii) To produce more appropriate methodologies and tools for forecasting groundwater flood events capable of operating within a much longer timescale than is currently possible (i.e. days and weeks rather than hours).

Whilst FLOOD 1 was a joint project, this report only covers the work carried out by the BGS. Separate reporting procedures will be followed by the other two partners and a joint report prepared for the INTERREG authorities by the overall project leader (BRGM) will contain each partner’s technical report as annexes. During the life of the project a number of joint meetings were held to discuss progress and various issues in the development of our understanding of the processes involved in groundwater flooding in the Chalk. The only project staff working full time on the project were two Research Assistants based at the University of Brighton. The detail of their work will appear as their PhD theses in due course.

The project succeeded in addressing all three of the objectives outlined above and has without doubt increased our knowledge of the unsaturated zone of the Chalk, not least because it provided unique observations of water movement in this zone.

1 Introduction

The FLOOD 1 project was funded under the INTERREG IIIA initiative of the European Union. This is an Anglo-French programme which aims to encourage the idea of working together on areas of joint interest, for example tourism, social inclusion, sustainable development and economic development. Funding was available for organisations in East Sussex, Brighton & Hove, Kent and Medway working with organisations in the Seine-Maritime, Somme, Nord and Pas-de-Calais regions. FLOOD 1 focussed on groundwater flooding in Brighton and the Somme Valley. It was led by the French Geological Survey (BRGM) and included the University of Brighton (UK project manager) and the British Geological Survey. Single representatives from each organisation formed the project's Scientific Steering Committee and a separate Project Advisory Panel was established from a number of consultancies and government agencies (see Appendix 1). The INTERREG authority supported 50% of the cost of the project with the remainder of the funding being provided by the project's commercial partners (who were represented on the Project Advisory Panel), BRGM, the University of Brighton and BGS.

Floods in Chalk catchments had frequently been considered to result primarily from surface runoff. Thus, many flood prediction tools existing prior to this project were based on this premise; these tools normally being used over a time scale of up to 48 hours. However, in some recent flood events, including those in the Somme and at Brighton in the winter of 2000-01, groundwater was recognised to have played the principal role.

During 2000-01, large floods occurred in the northern part of France, Belgium and the southern part of United Kingdom, especially in valleys on Chalk outcrops. In many of these regions, a sudden rise of the groundwater level was recorded just before the floods. Another common characteristic was the long duration of the flood events which lasted weeks or months.

During the development of the research proposal for the FLOOD 1 project, the key to understanding this flooding process was believed to lie in the unsaturated zone, which was not at that time part of any flood monitoring system. The indications were that the unsaturated zone plays a fundamental role in the generation of Chalk groundwater floods, notably by storing water during periods of high rainfall and discharging this stored water after reaching a threshold of water content. Preliminary modelling (Pinault et al., 2005) and chemical investigations of different types of water (springs, rivers, groundwater) carried out by BRGM in the Somme river catchment suggested that groundwater was a major contributor to the triggering and the persistence of these floods.

Chalk has two principal kinds of porosity, that within the matrix (material) and that due to fractures. Experimental measurements in the field (down to 3 m depth) or in the laboratory on chalk samples, suggest that the water may first flow through the matrix at a low velocity. Then, when the matric potential of the unsaturated zone reaches a certain threshold, it is thought to flow through the fractures, with an increased velocity. A premise for the FLOOD 1 project was that this kind of dual behaviour, suggested by both theoretical and experimental work, could explain the triggering of groundwater flooding. If this threshold could be identified for different kinds of chalk, improved monitoring networks and better flood forecasting would result.

Generally, there has been little information or reliable data available on the deep (below 3 m) unsaturated zone for three main reasons:

(i) The available technology for monitoring water content in the deep unsaturated zone is relatively complex and expensive.

(ii) An infrastructure that disturbs the studied environment is required and it is, therefore, difficult to rely on the accuracy of the observed data.

(iii) It has had little economic interest until very recently (it was thought to have no resource potential for agricultural and water management purposes).

Another premise of the FLOOD 1 project was that better predictions of flood magnitude and duration would enable stakeholders to identify vulnerable elements within a community and more accurately assess risk. The project, therefore, planned to develop a new and different approach which would also minimise false alarms since it would take account of the state of the groundwater system and the severity of rainfall events. This would enable the authorities responsible for flood warning and relief to take more appropriate and timely decisions.

The main objectives of the project were:

(i) To understand the hydraulic behaviour of water flow in the unsaturated zone which leads to triggering of groundwater flood events.

(ii) To develop unsaturated zone monitoring techniques, including non-intrusive ones such as Magnetic Resonance Sounding (MRS), to reduce cost and environmental impact, and to improve areal representation of the data.

(iii) To produce more appropriate methodologies and tools for forecasting groundwater flood events capable of operating within a much longer timescale than is currently possible (i.e. days and weeks rather than hours).

It must be emphasised that the nature of groundwater flooding is such that it is generally not possible to provide an engineering solution to prevent it. However, by providing a reliable early warning system it is possible to provide the opportunity to take appropriate action to minimise the impacts. It is of course possible to provide engineering solutions for the management of the groundwater once it has arrived at the surface but the cost effectiveness of such measures needs to be considered carefully and such issues were beyond the scope of the FLOOD 1 project.

The purpose of this report is to describe the work carried out by the British Geological Survey within the FLOOD 1 Project and to present an early warning system for groundwater flooding for the Chalk in general and for the Patcham area of Brighton in particular.

To support the project, three research sites were established within the life of FLOOD 1. One site was established on the Chalk of the South Downs at North Heath Barn (TQ 287 105) which is north of Patcham. Another was sited at East Ilsley (SU 499 811) in the Pang Valley to capitalise on the knowledge of the catchment from many previous studies including the LOCAR thematic research programme (Wheater and Peach, 2004). BRGM established a research site in the Hallue sub catchment of the Somme Basin at Warloy Bellon.

2 Groundwater Flooding

2.1 THE METEOROLOGICAL CONTEXT OF THE 2000-01 GROUNDWATER FLOODING IN THE UK

The widespread and prolonged flooding in the autumn and early winter of 2000-01 established a major new hydrological benchmark and served to underline the UK's continuing vulnerability to rare climatic conditions (Marsh and Dale, 2002). Exceptional rainfall which commenced in mid-September resulted in the most extensive fluvial floods since the snowmelt-generated floods of March 1947. Active frontal systems continued well into 2001 which resulted in unprecedented rises in groundwater levels and prolonged groundwater flooding, especially in southern England.

In fact there had been several years of high recharge prior to 2000 which, in some catchments, had resulted in year-on-year increases in groundwater level, see Figure 1. In the lead up to this period of intense meteorological activity, January and March 2000 were unusually dry, but rainfall in April and May was exceptionally high with Kent, Sussex and eastern Hampshire receiving 260% of its long-term average rainfall in April and 187% in May (Binnie Black and Veatch, 2001). Despite a dry spell from June to mid September, groundwater levels in the Chalk remained at or above average for the time of year due to the late recharge experienced from the April/May rainfall. Thus the summer recession commenced later than usual in 2000 and was suddenly halted by the rainfall in the autumn. The unsettled weather in the latter part of September resulted in Soil Moisture Deficits that were well below average by early October, effectively priming the system to receive recharge from any subsequent rainfall events.

In the second week of October, active frontal systems produced notable storm rainfall totals in the UK; the highest rainfall intensities were associated with convectional storms developing along a front which straddled the headwaters of the River Ouse in Sussex and the River Medway in Kent. At Barcombe, some 17 km north east of Brighton in the Ouse catchment, daily totals of 27 mm or more were registered on eight occasions over the September-December 2000 period including a 45-year return event on the 11 October (Marsh and Dale, 2002).

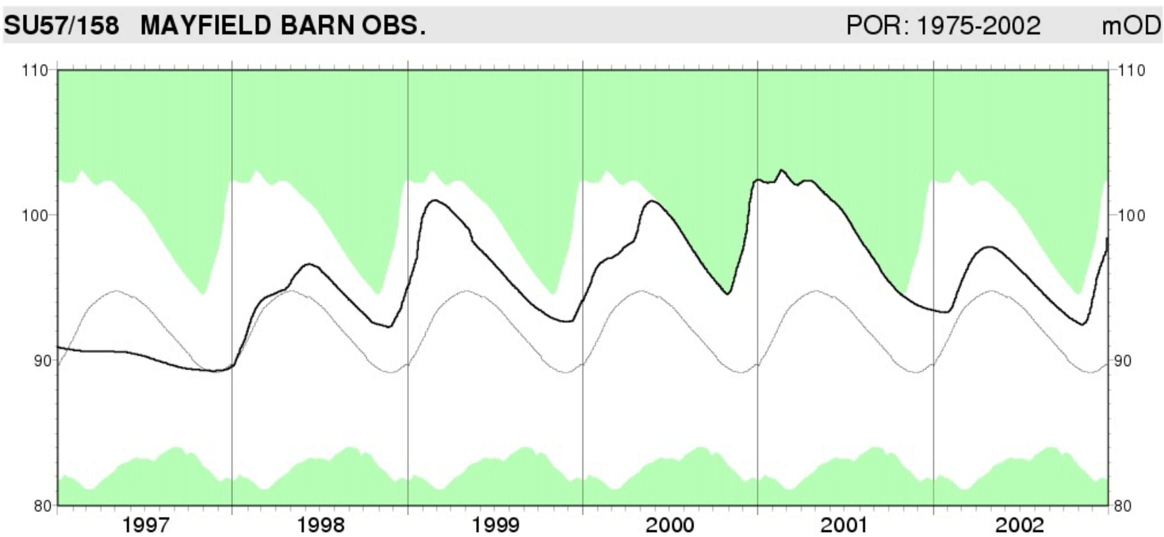

Figure 1 Hydrograph from the Mayfield Barn borehole in the Pang catchment

2.2 ANTECEDENT CONDITIONS TO THE 2000/2001 FLOODING

The severity and extent of the 2000-01 flood can be attributed to the meteorological conditions through late 2000 and early 2001 coupled with, in some catchments, high antecedent groundwater levels. As noted above, in many catchments groundwater levels were high, for example see Figure 1 from the Pang catchment. This was due to two main factors: firstly there had been several years' high recharge, which in some catchments resulted in year-on-year increases in groundwater level (see Figure 1); secondly the summer recession didn't start until late in 2000, and was suddenly halted by the rainfall in the autumn of 2000. As a result groundwater levels had not recessed as much as they might otherwise have done and the recovery was initiated from a higher groundwater level than might otherwise have occurred.

However, in the Brighton catchment groundwater hydrographs show very little autocorrelation (autocorrelation is a measure of the correlation of a time series with itself), typically only a few months, and tend to show flashy behaviour at higher groundwater levels with limited variation in annual groundwater minima. These characteristics are entirely consistent with Chalk with relatively well developed and connected secondary fracture porosity, in small catchments close to major discharge areas such as the coast. For example, Figure 2, the hydrograph for North Bottom Barn (TQ 322 118) is typically flashy and there is only a three month autocorrelation in groundwater levels at this site. One consequence of these hydrograph characteristics is that in the Chalk aquifer between the Rivers Adur and Ouse (known as the Brighton block), unlike other parts of the Chalk, groundwater levels generally return to similar conditions following recession regardless of the antecedent recharge season.

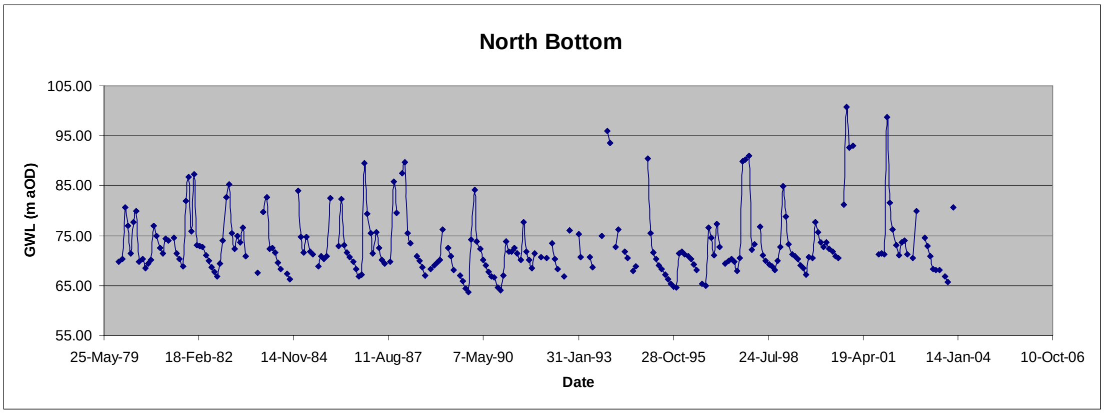

Figure 2 Hydrograph from the North Bottom Barn borehole north of Brighton (TQ 322 118).

Perhaps the most significant factor in the 2000-01 floods was the rainfall. In the period from September 2000 to April 2001 there were eight successive months of exceptional rainfall. As a result, the Southern Region of the UK received 201% of its long term average (1961-90) rainfall during September to December 2000. Long term effective rainfall series (together with the outstanding rainfall totals over the 2000-01 recharge season across most major aquifer outcrop areas) suggest that, for the Chalk at least, there is no recorded precedent for the magnitude of groundwater replenishment experienced over the extended 2000-01 recharge season.

The consequence of this exceptionally high rainfall with, in some catchments, the initiation of recharge at a higher than normal groundwater level, was groundwater flooding over a very widespread area. Significant flows occurred in "dry" valleys in localities remote from floodplains. River flow reflected the high rainfall as well as the contribution from groundwater. Flows at most river gauging stations greatly exceeded the long-term averages for extended periods.

After the end of the 2000-01 recharge season, Chalk river flows remained substantially above average throughout 2001. It is significant that many rivers recorded their highest annual runoff on record during 2001. It is also significant that rivers in less permeable catchments had below average flows in 2001. It can therefore be surmised that there was considerable baseflow support to the Chalk rivers throughout 2001. Observations from other work suggest that there is a gradual, long term release of water from storage in the Chalk "unsaturated" zone (e.g. Lewis et al., 1993), and hence high baseflows would be expected.

2.3 THE REGIONAL HYDROGEOLOGICAL RESPONSE

While extensive areas of Britain and northern France were affected by flooding in 2000-01, some areas experienced sustained problems for months, whilst others were subject to flooding for a shorter period of time. Looking at borehole and river hydrographs in general, it becomes apparent that different hydrographs exhibit different behaviour. Some show a strong yearly autocorrelation in levels/flow i.e. the effects of recharge are cumulative. Other catchments appear to be more "self-contained" in that high recharge one year may affect levels/flow for that year, but there is no year-on-year cumulative effect. It is not clear whether this is a catchment effect, or whether it is due to regional conditions. Catchment characteristics that could contribute include:

- Catchment size: the larger the catchment, the greater the cumulative effect of recharge.
- Position in the catchment: the levels measured in a borehole are a reflection of both recharge at that point and contribution from upstream in the catchment. Measurements made high up in a catchment have a reduced contribution, there being a smaller upstream catchment.
- Chalk properties: both saturated and unsaturated. If the unsaturated zone has low matric conductivity and a high proportion of bypass flow, it might be expected that there is less long-term ("delayed") drainage through the unsaturated zone. Additionally, the lower the transmissivity, the longer it will take for recharge to be transported out of the catchment, and the greater the cumulative effect.
- Effects of superficial deposits: extensive impermeable cover could change the pattern of recharge across the catchment.

However, there is some evidence that this may be more of a regional effect. Recent work has indicated that some areas show more yearly autocorrelation than others. For example, and as noted earlier, boreholes from the South Downs (e.g. Figure 2) generally show little year-on-year correlation, whereas those on the stretch of Chalk between Berkshire to East Anglia (e.g. Figure 1) do.

Within the areas under investigation for FLOOD 1, there were different responses to the 2000-01 rainfall. Patcham in Brighton experienced flooding for a few weeks, whereas other catchments were flooded for months, some even into the next recharge season. However, the catchments are quite different:

- Hallue – mean flow less than 1 $m^3 s^{-1}$ – "plateau[1]" site

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[1] The Hallue valley was referred to as being on a "plateau". This is taken to be a relatively flat area above the level of the major drainage channel in the area. In the case of the Hallue, this is the Somme. The Pang is also referred to as a plateau site as it is topographically similar, and elevated above the Thames.

- Brighton – not on a river but at the downstream end of a dry valley.
- Pang - mean flow of approximately $1\ m^3\ s^{-1}$ – "plateau" site. Flooding of cellars continued until May.
- Somme – much larger catchment; flow approximately $23\ m^3\ s^{-1}$.

Thus, the Pang and Hallue catchments are (from a catchment size and initial characteristics viewpoint) relatively similar. The catchment contributing to the Patcham flood in Brighton is different in that it has no usual surface discharge. The Somme is a much larger river and catchment, more like the Thames than any of the other catchments.

It is, therefore, concluded that:

- The 2000-01 flooding was only to be expected given: 1) antecedent groundwater conditions, and 2) rainfall/recharge events that occurred in late 2000/early 2001.
- The Chalk releases water from storage over an extended period of time; the length of time depending on catchment characteristics. Whilst this would not cause groundwater flooding, it could account for the fact that some catchments still experienced the effects of the 2000/2001 rainfall late into 2001.

2.4 THE GROUNDWATER LEVEL RESPONSE IN BRIGHTON

The only location in the Brighton area where groundwater levels were being continuously monitored during 2000-01 was Houndean Bottom (TQ 3930 1020) near Lewes (Binnie Black and Veatch, 2001). The Binnie Black and Veatch report (2001) includes a plot of groundwater levels at Houndean through the winter of 2000-01 alongside a plot of the dipped levels recorded intermittently during the period of interest at the Ladies Mile borehole (TQ 3171 0940) in Patcham. The first and largest rise in groundwater level occurred between October 10 and 14, 2000 when levels rose by 18.5 m in 4 days. The Chilgrove borehole (SU 8356 1440), a few miles to the west of Brighton, is the site of the longest unbroken sequence of groundwater level reading in the UK and possibly the World. The UK Hydrogeological Summary for December 2000 (CEH and BGS, 2000) ranked the level recorded at Chilgrove that month (flowing at the surface) as the highest level of the 165 year period.

The Environment Agency developed a simple spreadsheet model to link groundwater levels at the Ladies Mile borehole to the onset of groundwater flooding at Patcham. This model indicates that a water level of 49.5 m AOD at Ladies Mile corresponds to the trigger level for flooding at Patcham (Binnie Black and Veatch, 2001). However, it has also been reported (I. Molyneux personal communication) that as the groundwater level at the Ladies Mile borehole fell below 49.5 m AOD groundwater continued to flow at the surface until a different specific level was reached. Thus groundwater flow commenced at a higher groundwater level than at which it ceased. This non-linearity of response was thought to indicate that a particular (but unknown) process was occurring either in the unsaturated zone, or in the zone of the aquifer that is unsaturated under normal recharge conditions. The Environment Agency's spreadsheet model, which was based on observations at the Ladies Mile borehole, was not available for evaluation to the FLOOD 1 project. This observed non-linearity of response of groundwater emergence at the surface to groundwater level in a particular observation borehole is discussed further in Section 6.2.

2.5 GROUNDWATER FLOODING AT PATCHAM, BRIGHTON

2.5.1 The 2000-01 flood event

As noted in the introduction, it was the flooding events in Brighton and in the Somme Valley in the winter of 2000-01 that provided the main stimulus for the FLOOD 1 project. Patcham (Brighton) was affected by serious flooding between 2-19 November 2000 causing the closure of the London-Brighton railway line and the A23 road south of the A27. The ground floors of some 15 houses were inundated as well as the basements of several others. On 15 December further rainfall caused sewers to become surcharged. Rainfall in mid-February 2001 resulted in further basement flooding but no surface flooding. Excluding the cost of disruption to rail services, the total cost of the November flooding has been estimated at £800 000 (Binnie Black and Veatch, 2001).

2.5.2 Previous Flood events in Patcham

The Binnie Black and Veatch report (2001) includes a table of previous flood events in the Patcham area going back to 1958. Maps obtained from East Sussex County Council show the locations of groundwater emergence in 1877, 1913, 1915, 1916 and 1925. Appendix 2 lists those flood events for which the FLOOD 1 project team have been able to locate an associated record. This project has not obtained reports of other flooding events in the Patcham area but the possibility that there have been more events than those listed should not be discounted.

It is evident that, due to the scale of construction, engineering works related to the building of the A27 and A23 dual carriageways will have significantly altered the surface and subsurface drainage of the area immediately north of Patcham. In the winter of 2000-01 surcharging of sewers and flushing of storm drains resulted in local focussing of significant surface flooding, i.e. the built environment was having a significant effect which would have been quite different to the impact of the built environment in 1876. There is insufficient data to be able to evaluate whether flooding events prior to these major changes to the built environment were more or less severe (in either duration or flood volumes) than those that have occurred since their construction. Binnie Black and Veatch (2001) in discussing the 2000-01 flooding event state “Although this is thought to represent the worst case of flooding of this type in the last 100 years, similar less severe flooding is likely to occur once every 20 or 25 years or so”

2.6 GROUNDWATER FLOODING AT EAST ILSLEY, THE PANG VALLEY

During preparation of the FLOOD 1 project proposal it was decided to include provision for the development of a research site near the village of East Ilsley in the Pang Valley on the Chalk of the Berkshire Downs. There were two main reasons for his. Firstly, the Pang is a Chalk river which has been subject to a significant amount of hydrological and hydrogeological research over a long period. Indeed, the recent thematic research programme LOCAR (**Lo**wland **Ca**tchment **R**esearch) funded by the Natural Environment Research Council had established a research infrastructure comprised of a series of monitoring and experimental facilities (Adams et al., 2003; Wheater and Peach, 2004). Of particular interest to BRGM within the FLOOD 1 project were four so-called “Recharge Sites” which provided information on variations in water tensions within the unsaturated zone, rainfall and groundwater levels with time. The data available from these sites would be extremely useful in calibrating the Neutron Magnetic Resonance tool that BRGM hoped to refine as a means of monitoring changes in variation in water content within the unsaturated zone of Chalk aquifers (see the second project objective, Section 1). The second main reason for selecting a site near East Ilsley was that the village is prone to groundwater flooding.

The River Pang, where it joins the Thames, has a baseflow index of 0.86 (Gustard et al., 1992) indicating the importance of groundwater in this Chalk catchment. The perennial head is at a site known as the Blue Pool (SU 5840 7160) which is a karstic spring near the village of Stanford Dingley. However, in "normal" years the river rises at Hampstead Norreys (SU 5310 7635) some 9 km upstream of the Blue Pool. Upstream from Hampstead Norreys, the usually dry valley of the Pang River is clearly visible in the field and can easily be traced on a topographic map. Near the village of Compton two branches of the stream converge. One branch, the Churn valley has a southerly alignment, while the branch running from above East Ilsley is oriented east-southeast. Intermittent pools of water occur upstream of East Ilsley during some winters in the field between the A34 and the slip road from the A34 to the village (SU 4920 8150). These pools are formed from groundwater when the water table reaches the surface. The formation of these ponds gives an indication that flooding in the village may soon follow, although some basements might well be flooded prior to their formation. Several residents have installed pumps in wells below their basement floors which cut in when the water table reaches a pre-determined level.

2.6.1 The 2000-01 flood event

During the winter of 2000 2001, the Pang valley groundwater system was responding to the unusual meteorological events of the previous 18 months. The rainfall prior to that winter had been close to the 30-year average (1969 – 2000), but in April 2000 rainfall was the highest in the 30-year record for that month and was followed by above average rainfall in May. Whilst the following 4 months had close to average rainfall, there then followed the wettest winter in 40 years (see section 2.1) with a total of 640 mm of rainfall; 125 mm more than the previous wettest winter of 1976-77. The winter began with the highest recorded October rainfall on record with the following five months receiving above-average rainfall (Finch et al., 2004).

These exceptionally high rainfall figures resulted in extensive groundwater flooding in the upper reaches of the Pang catchment. Flow started just below West Ilsley at SU 477 822 and the Environment Agency's West Berkshire Groundwater Scheme abstraction borehole at Hodcott (SU 485 819) was completely inundated. Pools of groundwater formed in the field between the A34 and the East Ilsley Slip Road (see above) and properties were flooded in East Ilsley and Hampsted Norreys. At Hampsead Norreys a new culvert was dug behind Water Street to re-route the river so as to avoid most of the village and alleviate the flooding of properties (Robinson et al., 2001). In an attempt to alleviate the worst of the flooding, the Environment Agency operated parts of the West Berkshire Groundwater Scheme boreholes in the upper Pang valley. Ex-public water supply boreholes were also pumped to route some of the groundwater down the valley away from the flooding streams.

2.6.2 Previous Flood events in the Pang Valley

In early 1994 East Ilsley suffered what was then the worst floods to affect the village for 33 years; the event being judged by residents as "almost as bad as the 1961 floods" (Newbury Weekly News, 3 March 1994). An East Ilsley resident, Mr Marcus Goddard, regularly monitored the groundwater level in his garden well from 1923 until 1997 when ill-health forced him to stop. In 1994 he is reported as saying that in the mid 1920s there was flooding in four years out of five but it seems to have tailed off. "I have lived here all my life, and in recent years it has not happened so often" (Newbury Weekly News, March 3, 1994). The data collected by Mr Goddard have been made available to the BGS by East Ilsley resident, Mr Bob Moulton. Abstraction from the public water supply borehole at Compton between 1965 and its decommissioning in about 1990 would have reduced the likelihood of groundwater flooding. However, since the Compton borehole has been disused, the Pang is considered essentially to be acting as a natural river (Finch et al., 2004).

3 UK Research Sites & Initial Observations

3.1 INTRODUCTION

As a key element of the project, three research sites were established. One is located on the Chalk of the South Downs at North Heath Barn (TQ 287 105) which is north of Patcham, an area that suffered from significant groundwater flooding in the winter of 2000-01. The other UK site is located at East Ilsley (SU 499 811) in the Pang Valley to capitalise on the knowledge of the catchment from many previous studies including the LOCAR thematic research programme (Wheater and Peach, 2004). BRGM established a research site in the Hallue sub catchment of the Somme Basin at Warloy- Baillon. This chapter focuses on the two UK FLOOD 1 research sites the design of which are, to varying extents, based on the so called recharge sites employed in the LOCAR thematic research programme (Peach et al., 2004).

3.2 INSTRUMENTATION

3.2.1 Jacking Tensiometers

The Jacking Tensiometers that were installed at all three of the FLOOD 1 research sites were a key factor in the development and success of the project. These instruments have been developed by the Centre of Ecology and Hydrology over a number of years.

The construction of each individual tensiometer is shown in Figure 3. It consists of a chamber, open on one side. A porous ceramic plate is bonded to the chamber, so as to close the open side. The ceramic plate has a small pore size, so that it retains water in the pores by capillary action until the differential pressure between the water and air is much greater than atmospheric pressure. Since the pores of the ceramic plate remain full, air cannot pass through it and the chamber remains full of water down to an absolute pressure equal to the saturated vapour pressure of water at the prevailing temperature (about 12 hPa at 10° C). In principle, therefore, the borehole tensiometer can measure unsaturated zone water potential down to about –988 hPa (-988 mbar).

A pressure transducer is fitted to the top of the chamber to measure the pressure of the water inside. Since water can pass freely through the ceramic plate, even though air is excluded, the water pressure inside the tensiometer will come to equilibrium with that in the formation, allowing the water potential in the formation to be measured.

At low potentials, air enters the tensiometer by a variety of means and to maintain its ability to measure water potential in the medium, it is necessary to refill the tensiometer with water. This is accomplished by two valves. One allows water to enter the tensiometer through a tube to the surface and is opened by an electrical solenoid, controlled from a small 12 volt battery. The other allows the water out, as it is displaced by the incoming water and opens automatically when the pressure in the chamber is greater than that outside. In case of failure of one of these latter valves, two are connected in series.

Small tubes connect the valves with the inside of the chamber. The inlet valve introduces water near the mid-point of the chamber, whilst the outlet valve takes it from the top of the chamber, very close to the pressure transducer diaphragm. This ensures that as much of the air as possible is removed.

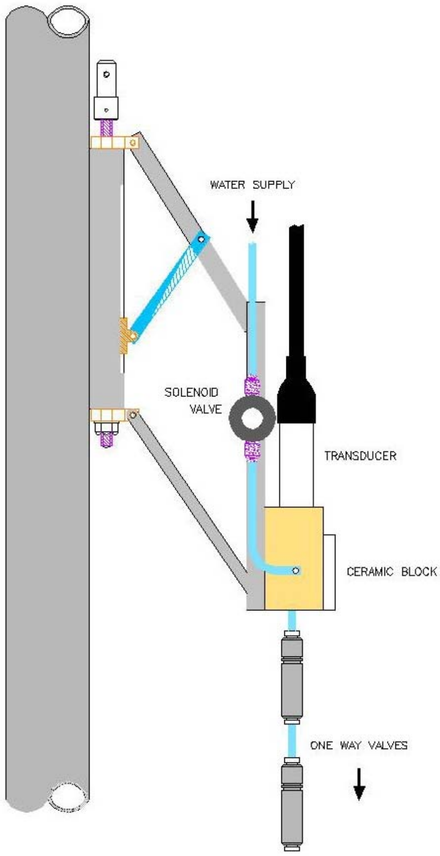


Figure 3. Schematic diagram of a borehole tensiometer, showing the component parts

The tensiometers are mounted on an aluminium alloy tube, made in 5 m long sections. The lower sections have the tensiometer units mounted onto them at predetermined positions. The upper sections are plain and serve only to carry the lower sections. Small screw jacks are welded to the aluminium tube sections. The tensiometer units are fixed to these, so that when the jack is operated, the ceramic plate is pressed against the side of the borehole. This makes a hydraulic connection between the water in the formation and that inside the tensiometer.

Smaller diameter aluminium alloy tubes, connected to the screw thread of each jack, extend to the surface for operating the jacks. A 2 mm inside diameter flexible plastic filling tube, a twin-core electrical cable for operation of the solenoid valve and a heavy duty pressure transducer signal cable also extend to the surface. The upper part of the plastic filling pipe is more flexible than the lower part, to prevent expansion caused by freezing from damaging the system.

3.2.2 Shallow instrumentation

Shallow instrumentation was also deployed at the Brighton research site to monitor both water content and pore pressures in the upper few metres below ground level. The instrumentation installed is detailed in Section 3.3.

3.3 THE BRIGHTON SITE, NORTH HEATH BARN

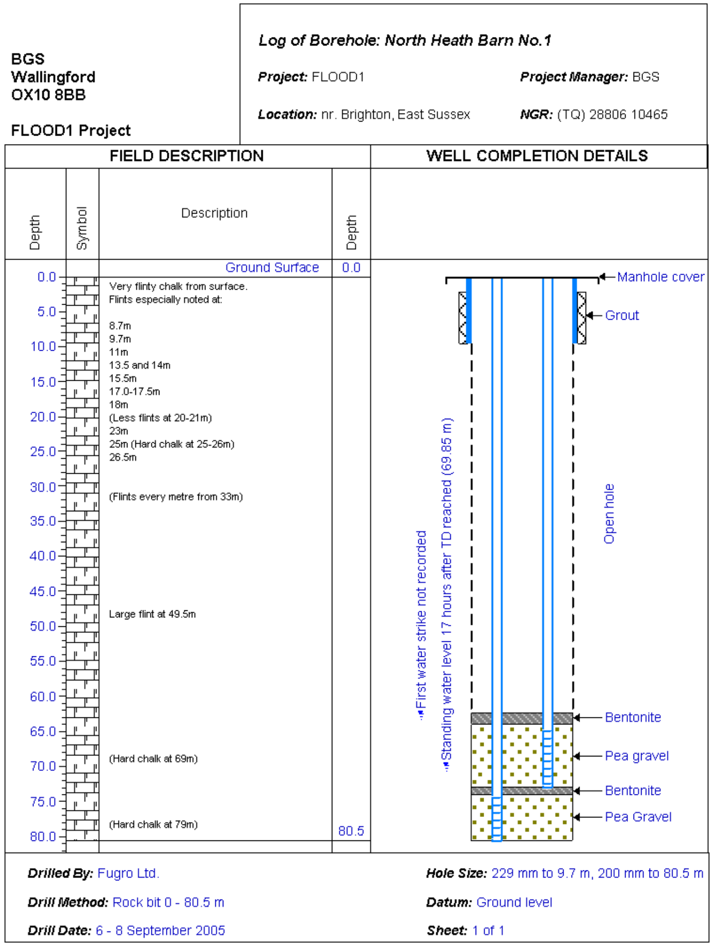
The North Heath Barn site (TQ 287 105) is situated on a steep slope on the edge of the A23 valley to the north of Patcham. Groundwater flooding occurred in the base of the valley during 2000-01, with a major problem being approximately 1 km further down the valley where groundwater flooding caused extensive damage to homes. Although severe, the flooding only lasted for a matter of weeks.

The Lewes Chalk is at outcrop and dominates the catchment; the boreholes penetrate the Lewes Chalk and go into the Newpit Chalk at a depth of 40.5 m below surface. The catchment is characterised by transitional province lithologies, as it was formed on the margin of a Mesozoic basin. In this setting, the succession is relatively condensed, and some marls are lost from the succession. Hardgrounds occur, signifying breaks in the sedimentary sequence. The Patcham catchment is characterised by many tight folds and faults. Axes and fault lengths are in the order of kilometres. It has extreme relief and the landscape is mature.

Following considerable delays in negotiations to obtain an access agreement for the chosen field site, drilling at North Heath Barn eventually commenced on 6 September 2005. Two boreholes were drilled, the first (NHB1) using a rock roller bit to a depth of 80.5 m at 200 mm diameter and the second (NHB2) drilled to a total depth of 81.2 m and cored from a depth of 1.6 m at 143 mm diameter. The holes were logged using downhole borehole geophysical equipment including closed circuit TV (CCTV). Details of completions of these two boreholes following drilling and installation of piezometers in the first borehole are shown in Figure 4. Pressure transducers were installed in the two piezometrs and in the annulus of the first borehole to monitor groundwater heads at the different depths. Jacking Tensiometers were eventually installed in the second borehole in October 2006 to allow water tensions to be monitored at different depths above the water table. Table 1 shows the depths at which individual tensiometers were installed at this site.

Table 1. Depths at which Jacking Tensiometers were installed in NHB2.

Tensiometer No	**Depth m**
1	15.5
2	20.5
3	25.5
4	30.5
5	35.5
6	40.5
7	45.5
8	50.5
9	55.5
10	60.5



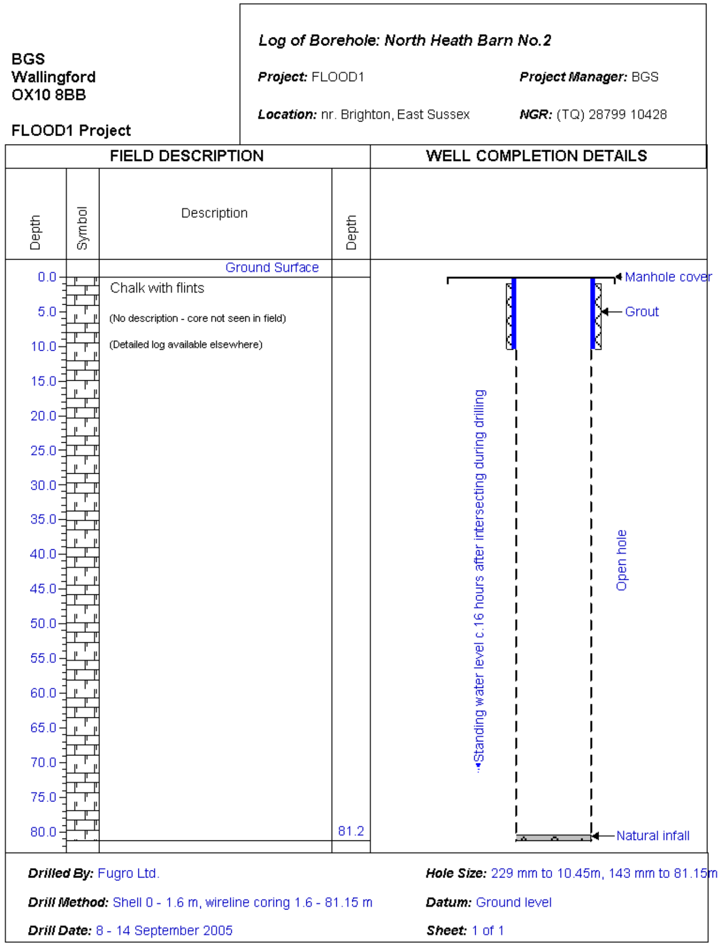


Figure 4. Completion details of North Heath Barn boreholes 1 and 2

Additional instrumentation was also installed at this site to enable monitoring of water tensions and content at shallow depths. Figure 5 shows the layout of the shallow instrumentation at this site.

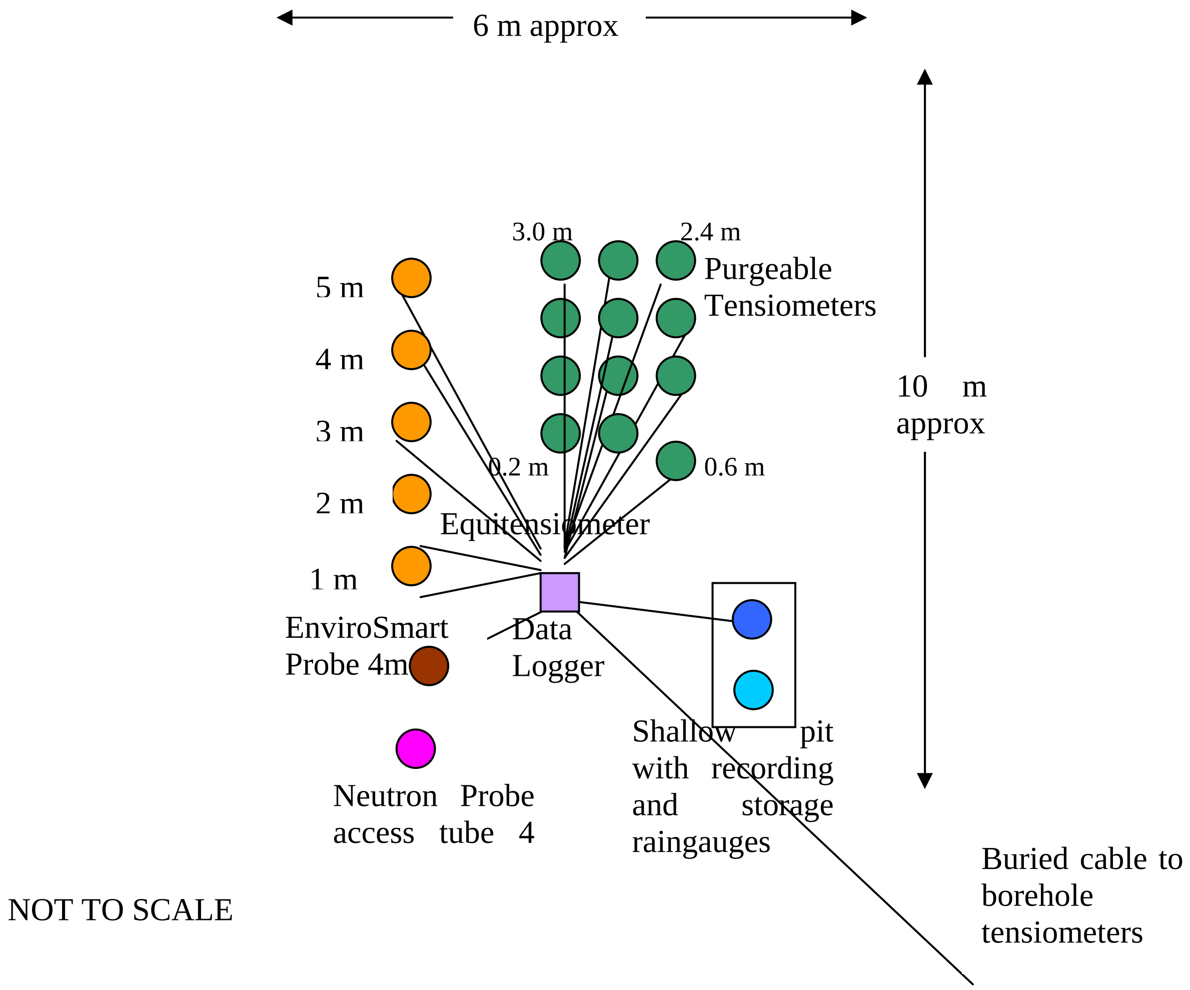


Figure 5. Schematic of shallow instrumentation installed at the FLOOD 1 research site at North Heath Barn, Brighton.

3.4 THE PANG VALLEY SITE AT EAST ILSLEY

The site is located less than a kilometre to the east of the village of East Ilsley on the northern side of the valley at an elevation of approximately 20 to 25 m above the valley floor (SU 499 811). Shallow instrumentation was not deployed at this site as it was hoped to capitalise on the LOCAR research sites that were available in the Pang catchment (Peach et al., 2004, Adams et al., 2004). The detailed geology of the Pang Valley based on remapping at the 1:50 000 scale for the LOCAR programme is described by Aldiss et al. (2002).

Drilling at the site in the Pang valley was completed in February 2005 with two boreholes EI1 and EI2 drilled to depths of 40 and 40.5 m respectively. The completion details are shown in Figure 6, and geophysical logs from borehole EI1 are shown in Figure 7. The geophysical logs are compared to logs from an existing borehole at Banterwick Barn (approximately 3.5 km east of the investigations site, SU 5121 7775) to facilitate stratigraphic interpretation. The second borehole to be drilled was cored from 5.86 m to its full depth and detailed lithological description of the core was carried out by the University of Brighton. "Divers" for monitoring groundwater heads were installed in the two piezometers and the annulus of Borehole 1. Jacking Tensiometers were installed in borehole 2 in mid-November 2005 to monitor water tensions at different depth above the water table. Table 2 shows the depths of installation of the individual tensiometers.

Table 2. Depths at which Jacking Tensiometers were installed in EI2.

Tensiometer No	**Depth m**
1	10
2	13
3	15
4	17
5	18
6	19
7	21
8	22
9	23
10	24

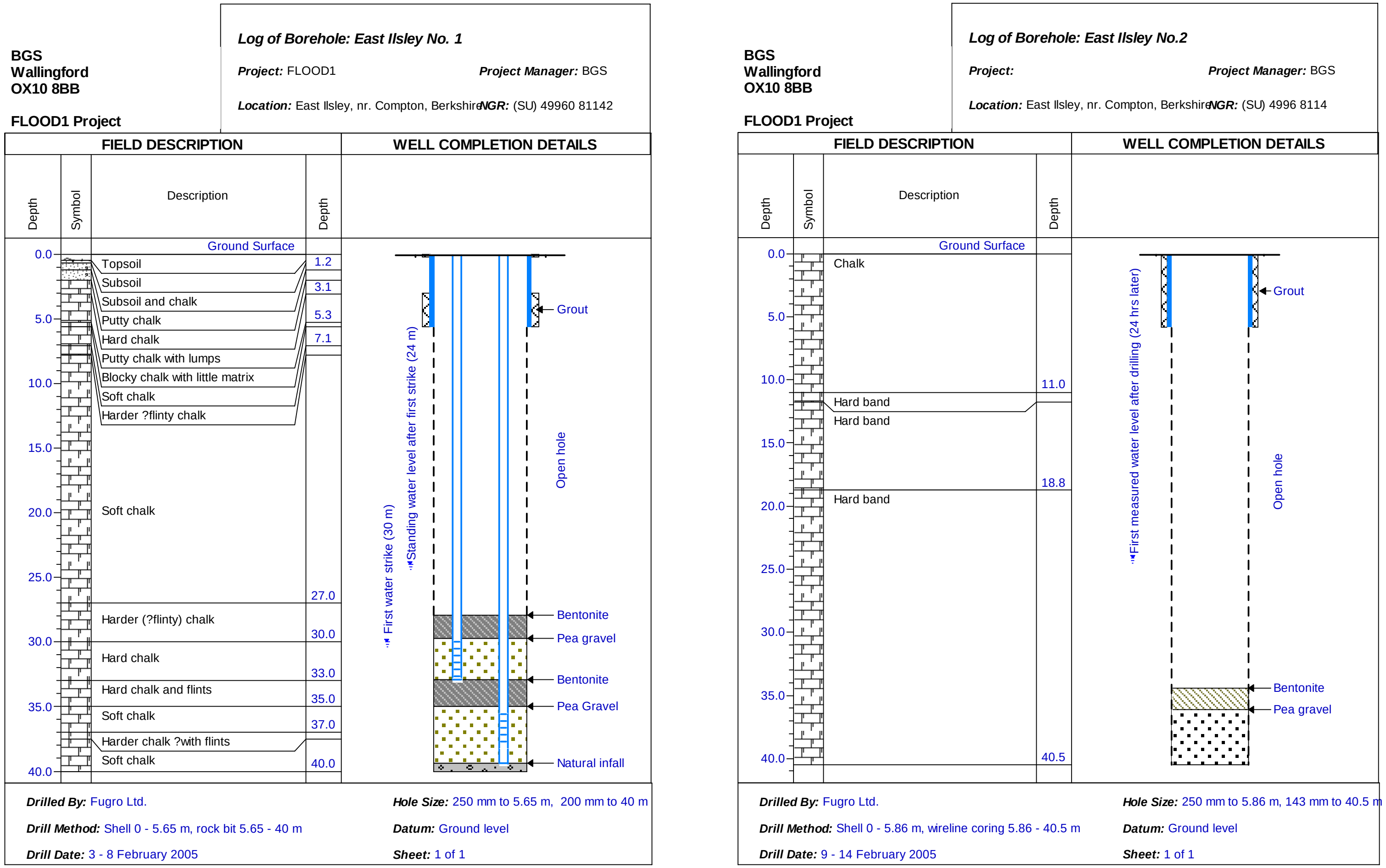


Figure 6. Completion details of East Ilsley boreholes 1 and 2.

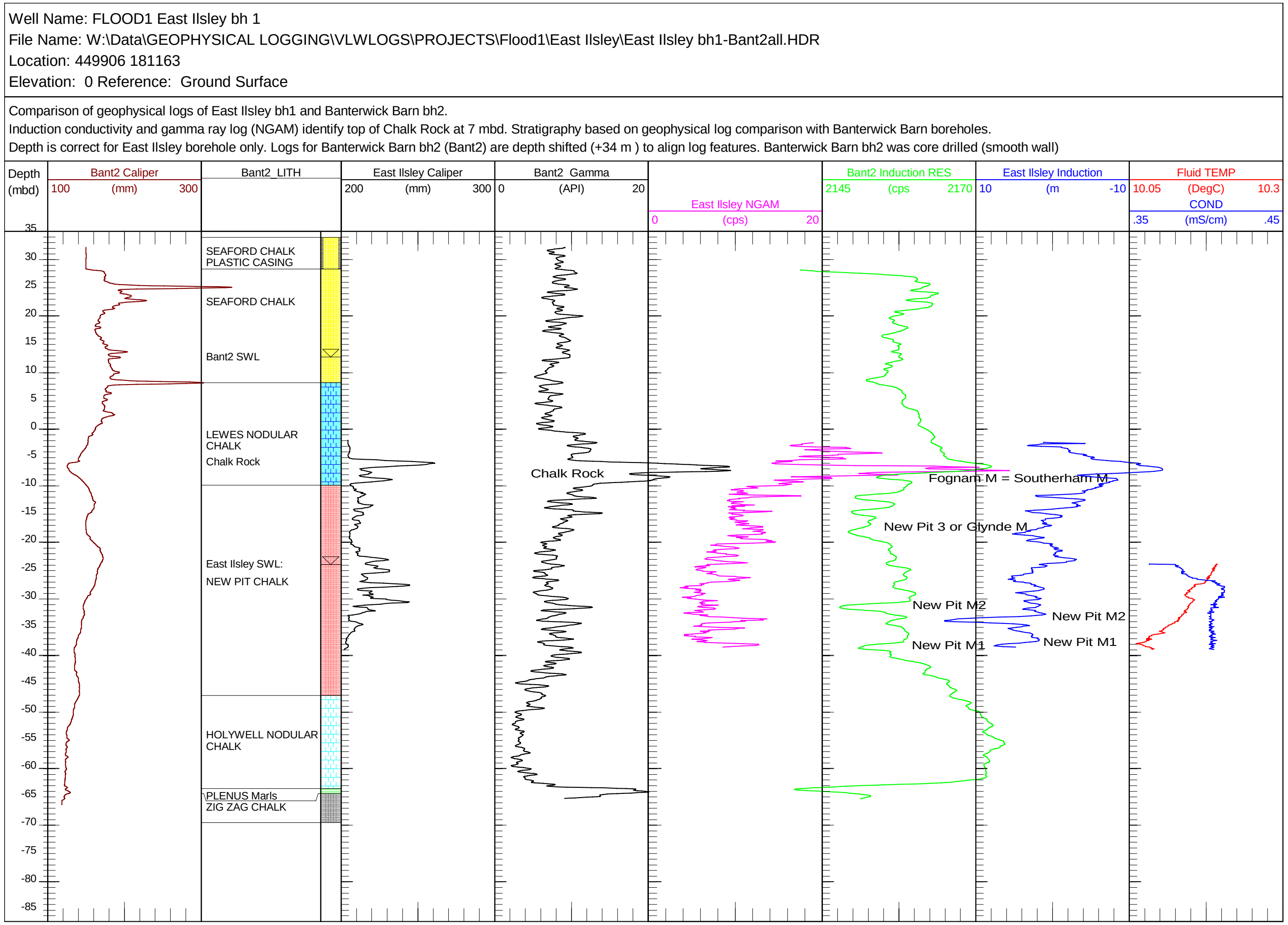


Figure 7. Comparison of geophysical logs from East Ilsley borehole 1 (EI1) and Banterwick Barn borehole 2 (Bant2)

4 Unsaturated Zone of the Chalk

It is useful to discuss briefly the development of understanding of flow in the unsaturated zone of the Chalk in order to put the findings of the FLOOD 1 project into context.

The difficulty of understanding the processes involved in the movement of water through the unsaturated zone of the Chalk stems from the wide range of observed behaviour that has been reported in the literature, including:

- Large piezometric surface variations.
- Rapid response to recharge, often followed by initial relatively rapid recession.
- Slow movement of nitrate and pesticides through the unsaturated zone.
- The need to delay part of calculated recharge in order to get models to fit.
- Maintenance of water levels during periods of drought.
- Discrepancies noted between recession drainage from chalk catchments and the calculated amount due to gravity drainage from porosity – too much water coming out of catchment.
- More rapid response to recharge as the recharge season progresses.
- Observations of horizontal (air filled) fractures in the unsaturated zone which must form a barrier to vertical movement of water.

Any theories of unsaturated zone flow and transport have to be able to incorporate these observations. However, some experimental observations appear to contradict others. It is suggested that the results are not contradictory, but reflect the variability of the Chalk.

Mathias et al. (2005) provide a useful summary of the development of understanding on flow in the chalk unsaturated zone. Until the late 1960s flow in the unsaturated zone of the Chalk was believed to be predominantly via fractures. The rapid response of the water table to high intensity rainfall events and the appearance of bacteria in production boreholes were cited as evidence for this assumption. However, a study by Smith et al. (1970) on the tritium content in chalk pore-water concluded that 85% of the total flow through the unsaturated zone was by intergranular flow through the matrix at less than 0.9 m/yr. This led to the development of the concept of “piston flow” whereby the rapid response of the water table was thought to be due to piston-displacement of water within the unsaturated zone rather than flow through it (Price et al., 1993). As Mathias et al. (2005) report, since the analysis by Smith et al. (1970) there have been parallel schools of thought as to whether flow in the matrix of the Chalk unsaturated zone is significant (e.g. Wellings, 1984; Hodnett and Bell, 1990; Haria et al., 2003) or not (e.g. Oakes et al., 1981; Barker and Foster, 1981). Mathias et al. (2005) carried out some simple modelling analyses which led them to the conclusion that flow in the matrix of the unsaturated zone of the Chalk is significant and that ignoring it may result in serious misunderstanding of the system. However, due to the fact that they used a steady state approach for their modelling analyses, they were not able to estimate the proportion of total infiltration that enters the matrix.

Although previous work is not described in detail here, it is interesting to note some of the variability in results that have previously been reported. Early work at various Chalk sites in the southeast of England (Wellings, 1984) suggested that fracture flow was likely to occur when matric potentials rose above approximately -50 hPa: above these potentials, there was observed to be a rapid increase in hydraulic conductivity which was interpreted as the fracture system conducting water. These observations were reinforced by analysis of lysimeter data from Fleam Dyke in Cambridgeshire (Jones and Cooper, 1998) which showed that rapid drainage (greater than 1mm/d – the derived hydraulic conductivity of the matrix) occurred through the lysimeter when the 5m profile was at potentials of greater than -50hPa. Work at this site suggested that fracture flow accounted for around 30% of the annual drainage. In contrast, at Bridget's Farm in Hampshire (Wellings, 1984), where matric hydraulic conductivity was high (around 6 mm/d), matric potentials only rose above -50 hPa under exceptional rainfall events and it was assumed that fracture flow was a very rare event. It is suggested that these two sites are possibly at two different ends of a spectrum, and that fracture flow can account for anything from 30% or more to almost zero percent of annual recharge (at the near surface). Until now, with the installation of Jacking Tensiometers in relatively deep boreholes, what was happening at greater depths was not recordable.

A study by Lewis et al. (1993) found that water draining from two chalk river catchments in recessions was significantly greater than could be explained by gravity drainage from porosity. It was concluded that this discrepancy was probably due to slow release of water by drainage of chalk in the unsaturated zone. They calculated that drainage of water equivalent to some 0.25 – 0.30 % of the volume of the rock in the unsaturated zone would be sufficient to account for the anomaly. Assuming that the fissure porosity would have drained completely and relatively quickly, the water must then have come from the matric porosity.

However, this conclusion was at odds with the observation that the matric pore space does not drain to any significant degree due to the narrow throats of individual pores (Price et al., 1993). A recent observation from the Bridgets Farm site (Roberts and Rossier, 2006) is that after the extreme recharge event of the winter of 2000/2001, there was a large increase in water stored in the unsaturated zone in the unweathered Chalk, between 3 m and 8 m depth. This increase was persistent in the unsaturated zone over a prolonged period of time. This again suggests that the variability of the Chalk is greater than has previously been allowed for.

Following detailed experimental work, Price et al. (2000) concluded that the water responsible for the discrepancy in storage noted by Lewis et al. (1993) is located on the irregularities on fissure surfaces within the unsaturated zone. This additional storage explains why the water table is slow to respond to recharge events for much of the recharge season, and why the Chalk is so resilient to drought. The concept of filling and draining of the irregularities on fissure surfaces led to a new model for the generation of fissure flow in the unsaturated zone of the Chalk (Price et al., 2000). According to this new model, fissure flow is not generated by water moving down a fissure from the soil, but by suction in the surrounding blocks falling to a level where first the irregularities on the surfaces of the blocks are filled with water and then the narrower fissures also become filled. Thus fissure flow can be generated at any depth in the profile, and in a sequence of uniform vertical permeability is likely to originate near to the water table rather than high in the unsaturated zone. An additional conclusion from this work was that there will be significantly more water in storage in the unsaturated zone at the end of a recharge season than at the beginning of the following one for the same level of the water-table. Thus it follows that the water table's response to recharge events will be relatively quicker at the end of a recharge season than at the beginning.

Haria et al. (2003) show that water can also be held in storage along horizontal fractures due to film generation at contact points between blocks vertically above each other. Figure 8 of Haria et al. (2003) shows how, at low drainage fluxes, the hydraulic conductivity at contact points between chalk blocks is sufficient to transmit water downward. As the recharge season progresses and downward flux increases, the small contact area becomes restrictive to vertical water movement. Consequently a thin water film develops at the contact point to accommodate the increased vertical flux (Hodnett and Bell, 1990). These water films increase in thickness so increasing the hydraulic conductivity by enlarging the cross-sectional water filled porosity thereby reducing the tortuosity of flow pathways. Thus the horizontal fractures are providing greater storage within the unsaturated zone in addition to that described by Price et al. (2000).

It is, therefore, suggested that the three proposed mechanisms for water flow through the unsaturated chalk may not be mutually exclusive, but that they interact, dependent on Chalk rock properties, fracturing, and antecedent conditions. Thus:

- Water movement through the matrix occurs when matric potential is low, and recharge rates are low to high. This is the predominant mechanism during wetting up, but becomes proportionally less important once matric potentials are high and there is the opportunity for pressure pulses through the matrix and fracture flow.
- Pressure pulse through the matrix occurs when matric potential is high, and recharge rates low to high. This can only occur if the pores are fully saturated.
- Water movement through fractures can only occur when matric potential is high and recharge rates are high. The role of flow along fracture surfaces (film flow) is probably included under this, as if matric potentials are low, water is unlikely to be able to flow along the fracture surface, instead being absorbed into the matrix.

The combination of mechanisms, it is suggested, can account for the observations of the hydraulic behavior of the Chalk. The data from the FLOOD 1 Brighton and Pang research sites have been analysed and compared, and the results discussed in the light of the above hypothesis in the following chapter.

5 Data from the two Research Sites

5.1 EAST ILSLEY RESEARCH SITE

5.1.1 Introduction

The location and instrumentation installed at this site is described in Section 3. Tensiometer suctions and water level readings were recorded at 15 minute intervals. Barometric pressure was also recorded, to allow conversion of the pressure reading to water levels. Water levels were measured at three depths in borehole 1 and in one at borehole 2. The data show that there is very little difference between the head measurements at the three depths in EI1 and so thess data are considered as one water level. The nearest rainguage to the site is at West Ilsley (NGR SU 485 836) about 2.8 km from the East Ilsley site.

Figure 8 shows the daily rainfall (to 22/01/2008) and the daily average water level for the site. As can be seen, two different regimes can be distinguished during the monitoring period. From the start of monitoring to the end of 2006 the water level was below 23 m below casing top (mbct). Following the wet autumn and winter of 2006/7 the water level rose rapidly and remained high for the rest of the monitored time. During this high water level period the unusual storm event of 20 July 2007 produced a sharp recharge event which helped to keep the water levels elevated. This unusual summer recharge event was caused by 18 hours continuous rainfall starting at 2300 on 19 July and peaking with 80 mm of rain falling between 0800 and 1400 on 20 July. The groundwater recession stopped at around 0700 on July 20, and the rapid groundwater level rise started at mid-day on the same day. The wet autumn of 2007 was also followed by a rapid increase in the water level in early 2008, though not to the level reached in 2007. The East Ilsley site shows a markedly different response to rainfall as compared to the Brighton site. Here there is a damped response to rainfall with no clear response to distinct periods of rain, with the exception of the July 2007 event.

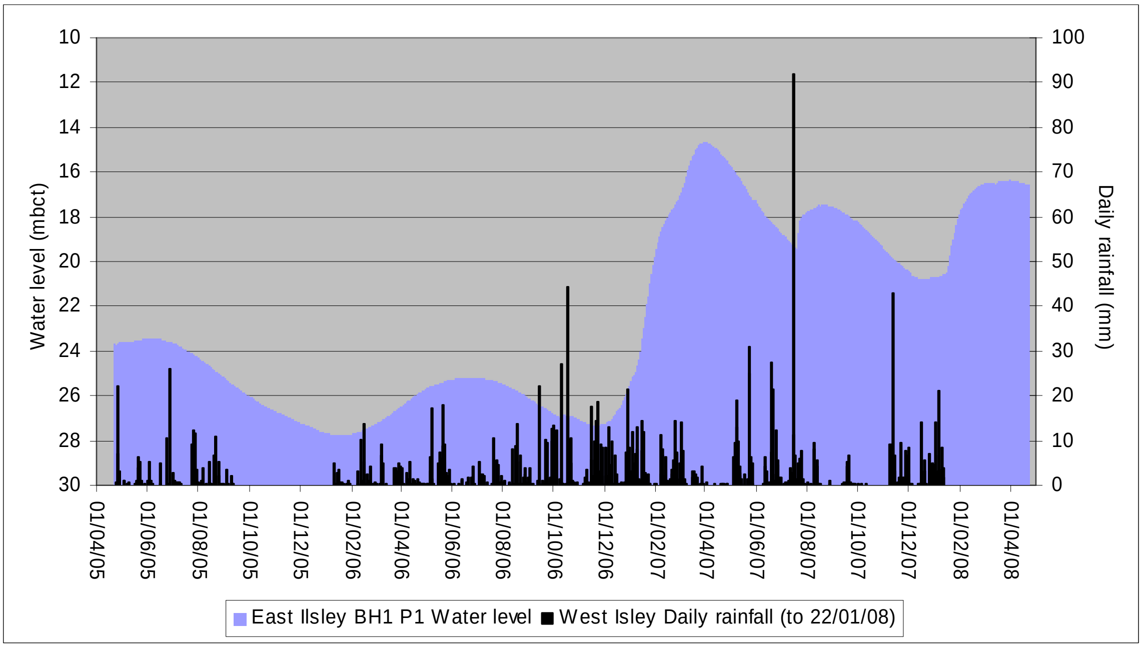


Figure 8. Daily rainfall and daily average water level at the East Ilsley research site.

Figure 9 shows the tensiometer data from the site, along with the water level. This shows that the tensiometer depths (10 to 24 mbgl) are such that they are nearly all below the water table for the period after January 2007. Also, the tensiometers at 10 and 15 mbgl (not shown in Figure 9) did not appear to be functioning correctly for any of the monitoring period. The discussion of the tensiometer data at this site will, therefore, be confined to the dry period before the end of 2006, and thus will not be of direct relevance to flood prediction.

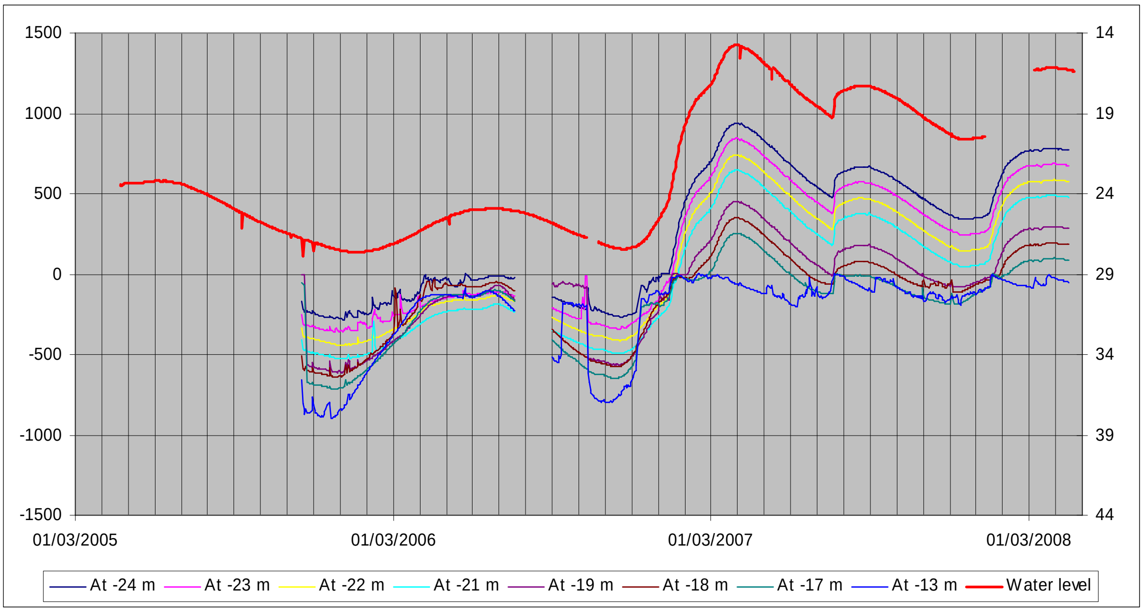


Figure 9. Tensiometer data from the East Ilsley site.

5.1.2 Tensiometer Data

At East Ilsley, matric potentials decline to a minimum of below -800 hPa for the tensiometer at -13m, decreasing with depth to around -250 hPa at -24 m, i.e. the deepest tensiometers have the highest (least negative) matric potential (i.e. are most saturated). At this site matric potential decreases systematically with depth during the drier periods (September through to December 2006), with the shallowest tensiometers showing the most negative (driest) readings. During the wetter months, this order is disrupted, with No 5 (-18 m) being the wettest, and No 7 (-21 m) being the driest. During the “recession” and “recovery” periods, the time series frequently cross over with the shallow tensiometers drying out relatively rapidly compared to the deeper ones.

The overall pattern of response at all depths is similar, with all tensiometers showing the end of the recharge season within 2 weeks of each other (the shallowest responding first, followed by successively deeper ones). Again, the start of the recharge period is shown in all tensiometers within a few days of each other, with the shallowest responding first, indicating wetting from the surface downwards, rather than from the water table upwards.

The tensiometers indicated that during 2006 matric potentials continued to rise (increasing saturation) until the end of June. This is confirmed by the water table also rising over this period. The end of the recession period (turning point in the matric potential curve) occurred between 3 and 25 November (depending on depth). Groundwater levels started to recover during the first week of December.

As noted earlier, the data for the tensiometers at -10 and -15 m have not been presented, although initially it was thought that they were showing evidence of perched water tables.

Both tensiometers gave readings of around zero. No 3 (15m depth) was just above the Glynde Marl and No 1 (10m depth) is some 2 m above the Southerham Marl. No 1 appeared to be responding to barometric effects, and was assumed not to be working correctly. No 3 showed very little variation over a long period of time, being around 0.5 hPa, but shows occasional periods when it becomes negative. These periods do not appear to be associated with any significant rainfall events, and are now assumed to be instrumental in origin.

5.1.3 Rainfall and water level data

One of the aims of the monitoring sites was to find a ‘trigger point’ which would indicate that a rapid rise in water level leading to groundwater flooding was likely to occur. Whilst the depth of the unsaturated zone monitoring at East Ilsley has precluded this, it is important also to see whether any of the saturated zone data might be useful. There were rapid water level rises in January 2007, July 2007 and January 2008 (Figure 8). These can be picked out in Figure 10, which shows the rate of change of water level (i.e. the gradient of the water level hydrograph). The water level generally does not change by more than 0.03 m from day to day, either when rising or when falling, and in fact during the drought period of 2005/6 the rate of increase and that of recession are very similar and are probably related to the hydraulic properties of the aquifer. The response to the prolonged wet period in the autumn of 2006 is clearly seen as the gradient increases to over 0.1 m/day in early January and the rate of increase continues to rise to a peak of 0.35 m on 22 January 2007. After this date the water level continues to rise (+ve gradient) but at a slower rate until a second gradient increase on March 1. These changes in gradient are obviously a result of the antecedent rainfall although, as Figure 11 shows, it is not clear exactly how much rain is required or how long the delay between rainfall and increased gradient is.

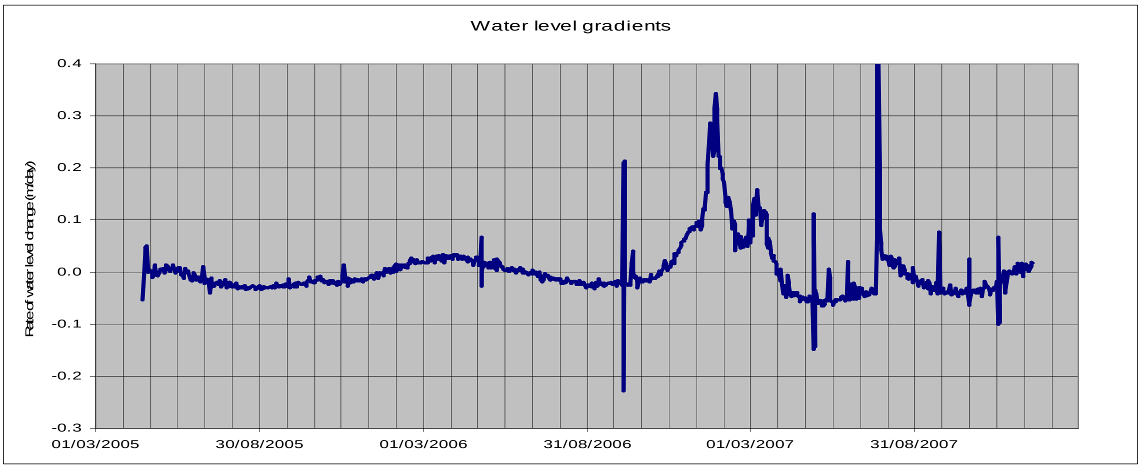


Figure 10. Gradient of groundwater hydrograph.

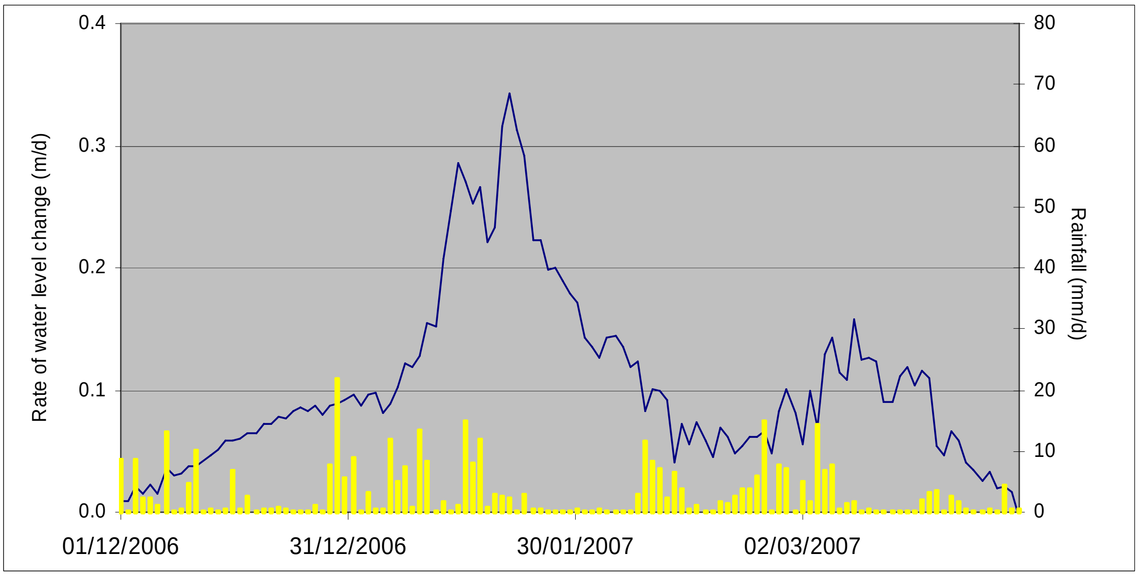


Figure 11. Gradient of groundwater hydrograph and daily rainfall.

5.2 NORTH HEATH BARN

5.2.1 Introduction

As noted in section 3.1, there was a significant delay in achieving access to the North Heath Barn site which resulted in the two boreholes not being drilled until September 2005. Following completion of the two boreholes, it transpired that the Jacking Tensiometers that were to be installed in the second borehole were not yet ready for installation. It should be noted here that the Jacking Tensiometers were still undergoing development. In their original form (Wellings, 1984) the tensiometers had to be removed from the borehole for repriming. In the design being used for FLOOD 1, which had been developed for the LOCAR thematic research programme, the need for removal had been obviated by the introduction of priming tubes feeding from the individual tensiometers to the surface. However, during the LOCAR programme there had been continual problems with this approach and these were only overcome for the first time in the FLOOD 1 installations. The development of a satisfactory solution to these problems led to the Jacking Tensiometers not being ready upon completion of the two Brighton FLOOD 1 boreholes.

Whilst waiting for completion of the Jacking Tensiometers, the opportunity was taken to run a CCTV log of the NHB2 borehole. Because of the clarity of the results, it was decided to delay the installation of the Jacking Tensiometers so that regular CCTV logs could be run in order to monitor changes in wetness of the borehole walls (see Section 5.2.2). The Jacking Tensiometers were eventually installed in the NHB2 borehole in October 2006 at the depths shown in Table 1. In addition the following shallow instrumentation was installed at the North Heath Barn site:

12 purgeable tensiometers at 0.2 – 2.4 m depth

5 equitensiometers at depths of 1 – 5 m below ground levels

16 Envirosmart probes at depths of 0.1 – 3.6 m depth

All these instruments record data (soil water potential (suction) and water content) at 15 minute intervals. Data recording started on 02/02/2006 and continued throughout the duration of the project. Rainfall data are also recorded at this site.

The equitensiometers measure greater suctions than the purgeable tensiometers and the Envirosmart probes measure water content. To calibrate the Envirosmart probes three neutron probe access holes were drilled and manual measurements were taken during the early part of the project. Health and Safety legislation changes during the project meant that it was not feasible to continue these measurements on the regular basis envisaged during project inception. It is hoped that the instrument calibrations carried out by BRGM as part of the project may be useful for calibration of the Brighton probes. At this stage it has been assumed that the changes measured by the probes are correct though the absolute values may be incorrect.

Figure 12 shows the rainfall and water levels measured at North Heath Barn. Comparison with Figure 8 shows that the water level varies over a greater range (35m cf. 13m) than at East Ilsley and also that the 'bottom' of the hydrograph is flatter with a 'base level' of about 72 m bct. The data cover a shorter time period than that at East Ilsley, but the marked contrast between the water level prior to the winter of 2006-07 and that afterwards shown at East Ilsley is not seen here. This is further evidence of the significant differences between the two sites.

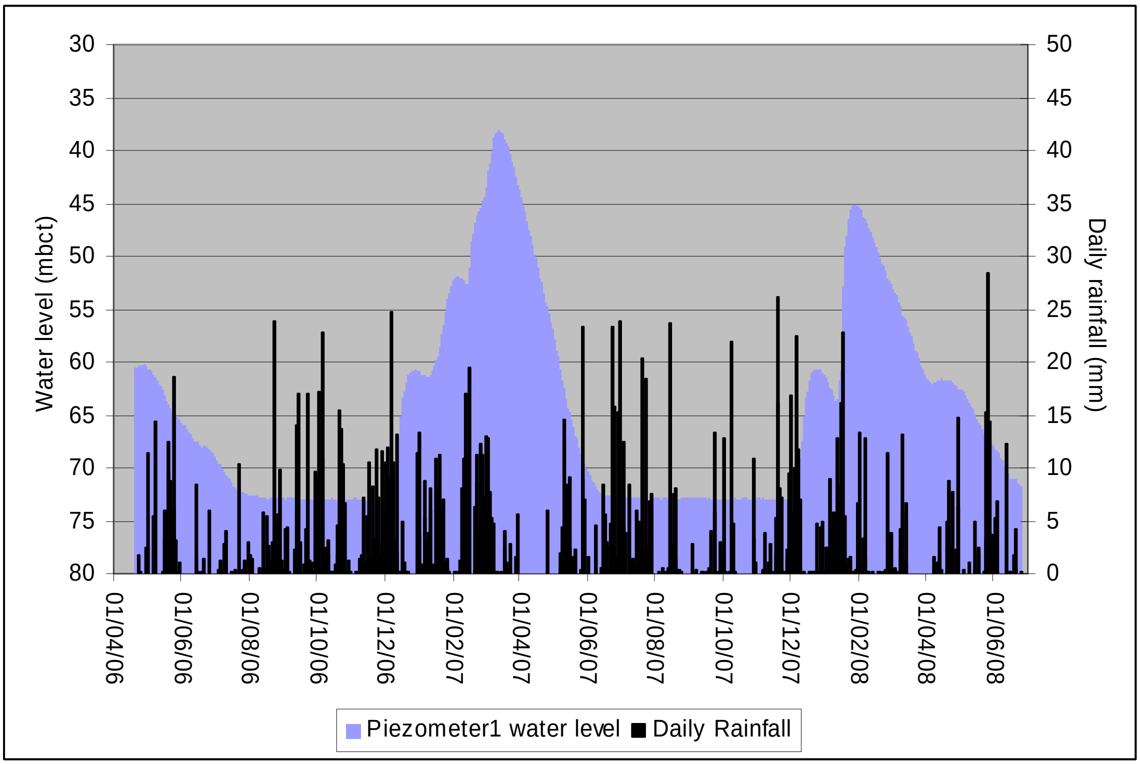


Figure 12. Daily rainfall and daily average water level at the North Heath Barn research site.

5.2.2 CCTV observations at the Brighton research site

Following completion of the 2 deep boreholes, a suite of geophysical logs (including CCTV) were run by the Southern Water Plc's logging unit in NHB2. This was followed some time later by a similar suite of geophysical logs (again including CCTV) using new geophysical logging equipment that had recently been acquired by the BGS. The new CCTV equipment (manufactured by Geovista Ltd) has a ring of super-LEDs incorporated around the side viewing lens (See Figure 13). Using this new CCTV equipment significant amounts of moisture were observed on parts of the borehole wall, well above the water table. The greater intensity of light provided by the LEDs in the new equipment reflected moisture on the borehole wall to such an extent that, when the borehole was very wet, the ring of LEDs can clearly be observed (Figure 13). The side-viewing lens is operator controlled and may be rotated through 360°. This view of the borehole wall and the excellent lighting provided a very detailed picture, allowing the operators to discriminate continuous thick marl layers, discontinuous thin wispy marl plexus, plastic marl, fractured marls etc, and the degree and nature of the fracturing, fracture fill material, as well as solution of the chalk material.

Figure 13. (A) left, the Geovista Ltd borehole CCTV sonde with side viewing lens and surrounding ring of LEDs, and (B) right, the ring of LEDs reflected on a wet borehole wall.

Footage recorded using the Geovista CCTV sonde was subsequently compared with that recorded by a telespec TS800 CCTV camera sonde at NHB2 on the same day (Figure 14). The difference is marked, and probably accounts for there having been no previous reports of such observations from Chalk boreholes.

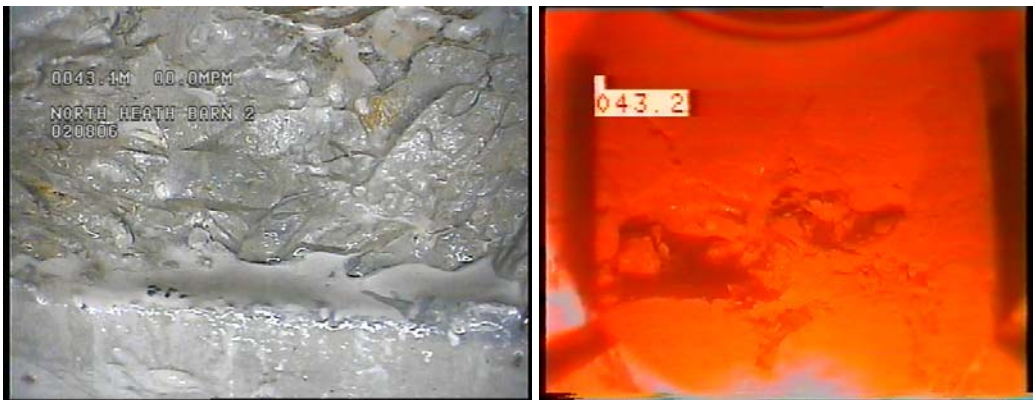


Figure 14. Video stills showing Glynde marl at 43.15 m bd on 2nd February, Geovista CCTV camera (left) and Telespec camera (right).

It was decided that regular CCTV logs should be made of the NHB2 borehole to see if the degree of wetness on the borehole wall changes with time. Additionally the new equipment was used to investigate whether such wetting up was occurring in chalk boreholes elsewhere. It was found that there were areas of damp walls at all of 7 different boreholes logged across southern England.

The NHB2 borehole was logged periodically from February 2006 through to October 2006. The surveys revealed that borehole wall-wetness changed throughout the year with wet zones expanding in winter and spring and shrinking in late summer and autumn (Figure 15). The zones of wetness, therefore, change with time in response to recharge. This is illustrated by the increase in wall-wetness observed between the February and May CCTV surveys, and by the progressive decrease in wall-wetness from May to October, during which period wall-wetness concentrates around regionally significant marls.

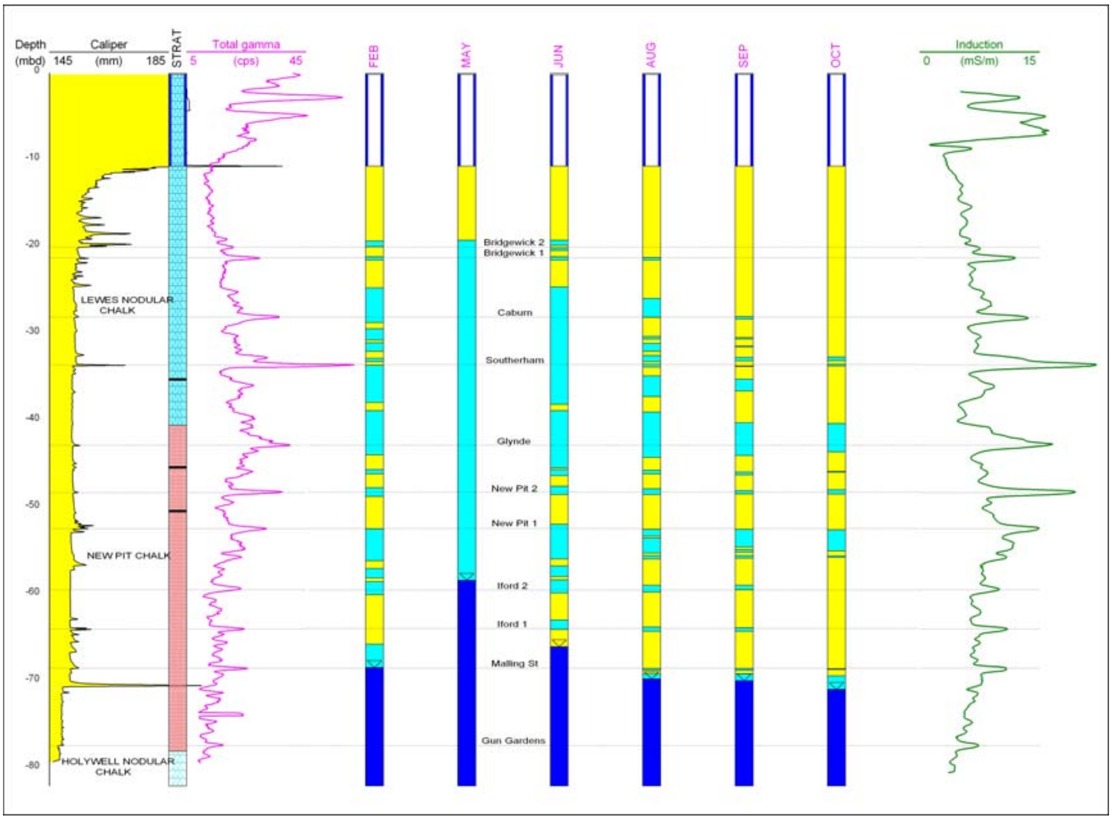


Figure 15. Variation in wall-wetness with time at NHB2.

It is important to clarify what is meant in this discussion by wall-wetness. Wall-wetness varies in two ways; the thickness of the water film, and its circumferential distribution (the percentage of the wall that was wet in a horizontal plane at any given depth). A thick film of water clearly reflects the ring of LEDs that surround the side viewing lens, whereas a completely dry wall is non-reflective. There is an intermediate category of partially wet or damp. For the purpose of this discussion any section of borehole wall that was slightly reflective, i.e., partially wet or wet is classified as wet.

There are draw backs to this approach, in that an intermediate category allows the wetting and drying characteristics of individual marls at NHB2 to be assessed over time in a qualitative manner. The problem with this potentially more detailed approach lies in the subjectivity involved in defining the point at which a fully wet zone becomes partially wet and visa versa. In fact a partially wet borehole wall was generally observed at the margins of a fully wet wall, only in a few instances was a partially-wet only horizon observed. It is, therefore, possible to present the data with two categories only, wet or dry, and in the process maintain clarity without losing too much detail.

A crucial observation when defining wall-wetness is to recognise that the borehole wall at the base of the casing, and directly below, is not wet, otherwise the wetness may represent infiltration entering the borehole via the annulus behind the casing. It is also fairly common to observe moisture inside both plastic and steel blank casing near the surface. This is due to condensation of water vapour. Indeed it is not unusual to find that the shallow-most fluid in boreholes has a low fluid Electrical Conductivity (EC), reflecting this origin.

The circumferential distribution of wall-wetness observed at any one time is limited by the field of view of the side-looking lens. The side-viewing camera has a field of view that approximates to the distance from the lens to the borehole wall in both the vertical and horizontal planes. The diameter of NHB2 is approximately 150 mm, the CCTV sonde is 70 mm in diameter, the field of view when the sonde is centralized is, therefore, approximately 40 mm. Such a small field of view provides for a detailed picture but makes inspection of the entire borehole wall impossible. Experience, however, revealed that a thoroughly wet and reflective zone was generally present over 360° of the borehole wall. Only at the upper and lower margins of a wet zone, where there was a transition from a fully wet and reflective film to a dry wall, was the circumferential wetness likely to be affected by heterogeneity in the Chalk and fall significantly below 360°.

Marls are identified by characteristic peaks on the gamma and induction logs, in pink and green respectively. Wall-wetness observed in each CCTV survey is indicated by the light blue sections on the central six columns. The location of three of the Jacking Tensiometers installed after CCTV surveys were completed is indicated by the black bars in the “STRAT” column.

Fourteen individual wet zones were observed on 2 February 2006 between the upper most marl, the Bridgewick Marl 2 at 19.3 m below datum (bd) and the water table at 68.5 m bd, this represented 52 % of the uncased borehole wall above the water table. Piezometer data from NHB1 shows that the watertable at this site rose by 8 m in the first three weeks of April 2006. By the 3 May recharge events in the intervening period had raised the watertable to 59 m and increased wall-wetness such that a continuous film of water was present from the Bridgewick Marl 2 to the water table, representing 82% of the uncased borehole wall above the watertable. Subsequent surveys documented how wall-wetness gradually reduced until on the 2 October three wet zones remained. These were centred on the Southerham Marl (at 33.6 m bd), on the Glynde Marl at 42.9 m bd, and on the broad Griotte Marl Zone, below the New Pit Marker Marl 1, at 54.6 m bd. The rest water level on the 2 October was at 70.1 m bd.

The Bridgewick Marl 2 remained the shallowest wet horizon from February until end of June, and in August the Bridgewick Marl 1 became the shallowest wet horizon. By September the shallowest saturated marl was the Caburn Marl at 28.1 m bd, and by October it was the Southerham Marl at 34 m bd.

After 6 months of surveying using CCTV equipment, the site was instrumented with the deep borehole tensiometers. It was hoped that the data produced from this installation would provide a more quantitative assessment of the variation in moisture on the borehole walls that had been observed by the CCTV.

In summary, water films were observed at some depths throughout February to October 2006, the persistently wet sections being closely correlated with marl seams. It was interpreted that the marls seams were impeding the vertical flow of water, in some cases creating perched water tables. Matric potentials above the marls, therefore, become close to zero or positive, and water forms a film on the borehole wall (analogous to a fracture surface). This water is then free to flow along the fracture surface under gravity until matric potentials further down the borehole are low enough for the water to be absorbed back into the matrix. (This is described and explained in detail in Gallagher et al., in preparation). Figure 16 shows such water movement in the unsaturated zone of borehole NHB2 at a height of 32 m above the water table.

Figure 16. Groundwater dripping across a dissolution feature developed above the Southerham

5.2.3 Shallow tensiometer data from the Brighton research site

The tensiometer data collected at Brighton is not as easy to decipher as that at East Ilsley. This is partly because there are far more instruments and also because there are instruments at very shallow depths, which react to individual rainfall events. Figures 17 and 18 show the data from the shallow purgeable tensiometers and those from the deeper equitensiometers. The data from the puregeable tensiometers is confused by the effect of purging the probes, which was initially carried out on a monthly basis.

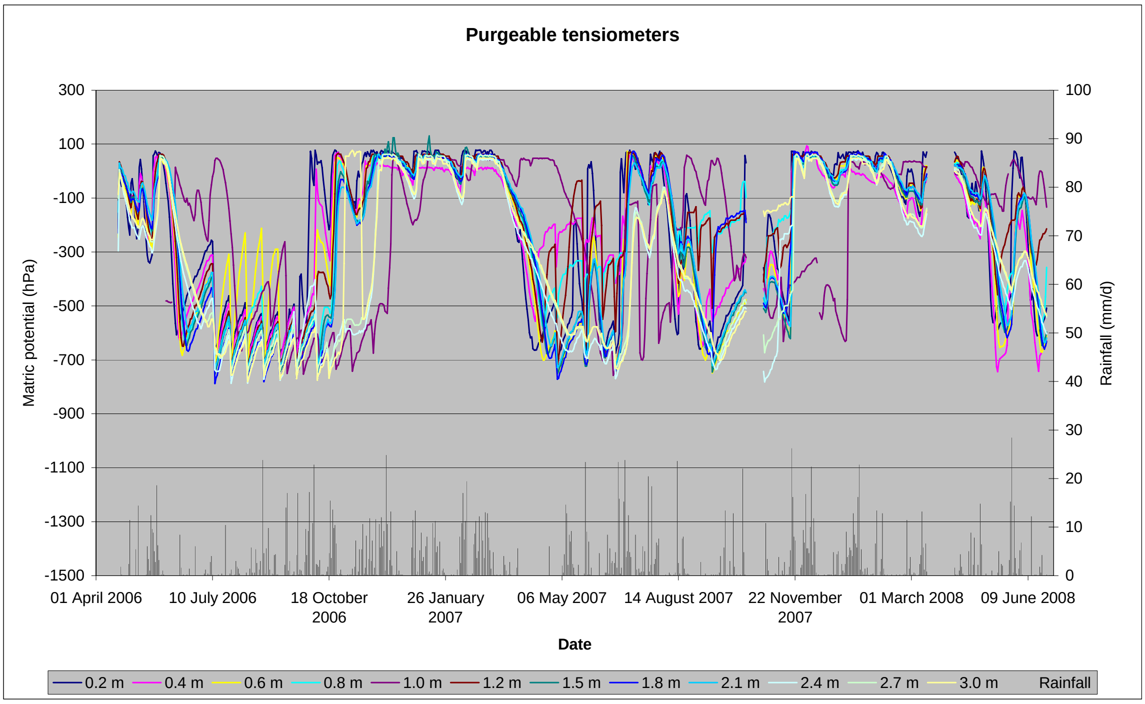


Figure 17. Data from the shallow tensiometers at the North Heath Barn site.

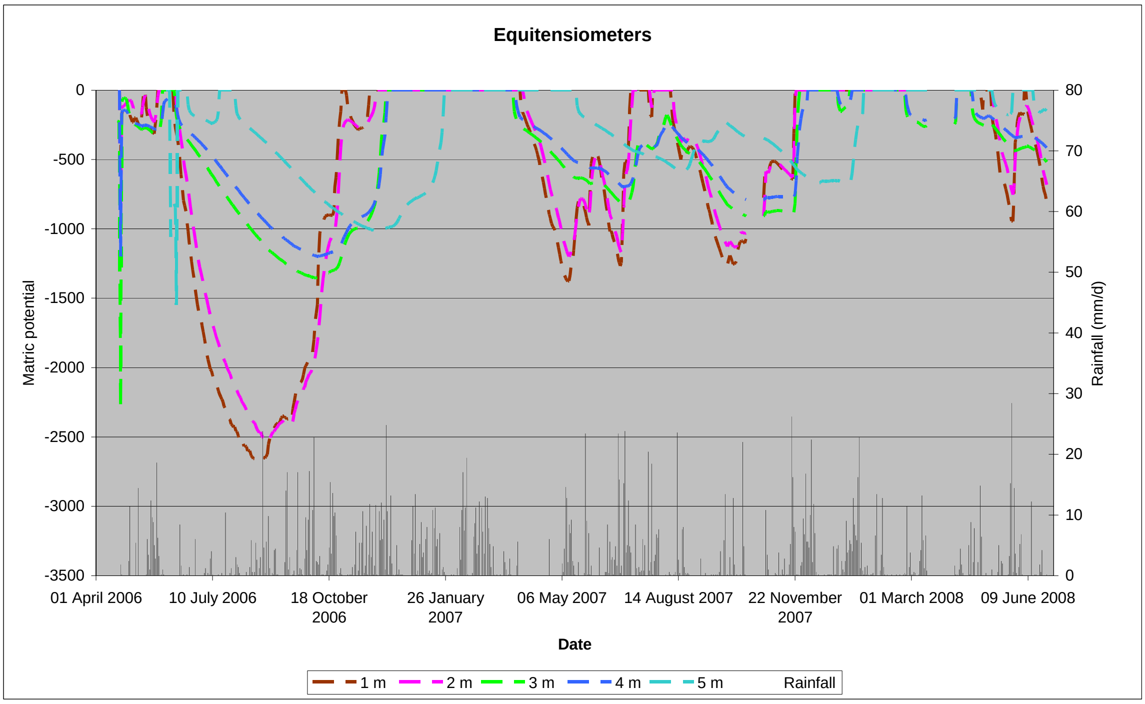


Figure 18. Equitensiometer data from the North Heath Barn site.

The equitensiometers react conventionally, in that the shallower probes register higher suctions than the deeper ones. Also the shallow probes wet up more rapidly at the start of the recharge season and also seem to respond more to rainfall events.

5.2.4 Deep tensiometer data

The data from the Jacking Tensiometers is shown in Figure 19. From mid-October 2006 the data are interpretable. As at East Ilsley, the deeper tensiometers were inundated during the winter periods, but they dried out in the summer and the shallower tensiometers remained above the water table throughout the recording period. Figure 20 shows the detail of the responses from before the onset of water table rise in December 2006 and December 2007. During both of these periods the 60 m tensiometer shows a rapid decrease in suction 10 days before the water table inundates it and 2 days before the water table starts to rise. This is consistent with the CCTV observations, which imply a rapid wetting of the borehole walls at the start of the rise in groundwater level.

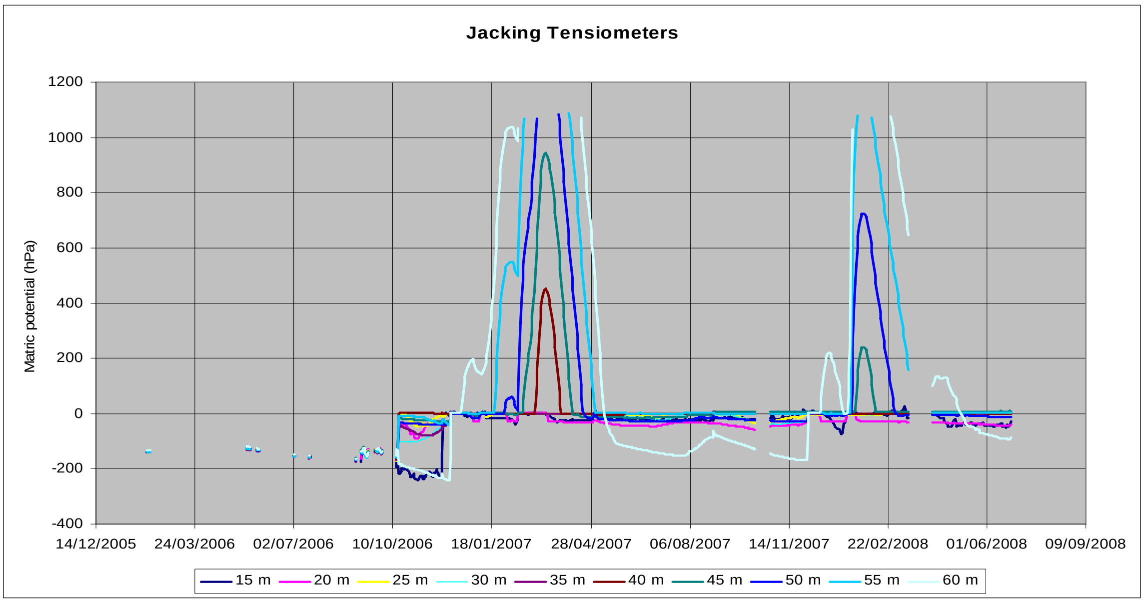


Figure 19. Data from the Jacking Tensiometers in the NHB2 borehole.

Figure 20. Jacking tensiometer data from the NHB2 borehole showing rapid change in suction prior to water level rise.

The Brighton tensiometer data show periods when the borehole wall is wet throughout the length of the borehole, followed by periods of drying out at some levels: 1 (-15 m), 2 (-20 m), 7 (-45 m) and 8 (-50 m). The eighth (-50 m) horizon appears to drain much more rapidly than the others, showing the first negative readings when the borehole walls started to dry out after being saturated. This is corroborated by the camera surveys which show that this horizon was only observed to be wet when the whole of the borehole was saturated. No 2 (-20m) which is immediately below the 19.5 m marl horizon has a distinctive switch on/off: during periods of drying out, the matric potentials instantly decrease from being positive to around -25 hPa, then immediately return to positive values (of around 3 hPa) when the borehole walls wet up again. During the wet periods, those tensiometers that at other times show drying (1, 2 and 7), all have a similar positive head of between 1 and 3 hPa. The other tensiometers (including 8), during these periods, return values of around zero. The positive head seen in 1, 2 and 7 is difficult to explain lithologically – none of these horizons are immediately above marl seams. The fact that these horizons appear to drain rapidly when recharge decreases, also suggests there should not be a layer that impedes water movement.

The evidence for a perched water table at -40.5m bd (approximately 1 m above the Glynde Marl) at Brighton is more compelling. Matric potentials measured were in the range of 1 to 3 hPa for a long period, but became negative for two periods in early 2007, following dry periods. Further evidence for the existence of a perched water table is provided by the results of the CCTV survey which showed this to be at the top of the most persistently wet zone of the borehole.

5.2.5 Envirosmart© water content measurements

Sixteen water content probes were installed at the site, at depths from 0.1 to 3.6 m. The top nine probes (0.1 to 1.5 m) started logging on 16 August 2006 but the lower probes failed to work. The entire probe assembly was removed and replaced in January 2007, which resulted in no change in the status of the lower probes, but a change in reading for some of the upper probes (see Figure 21). A faulty connection having been identified, the lower probes finally started working on 1 May 2007.

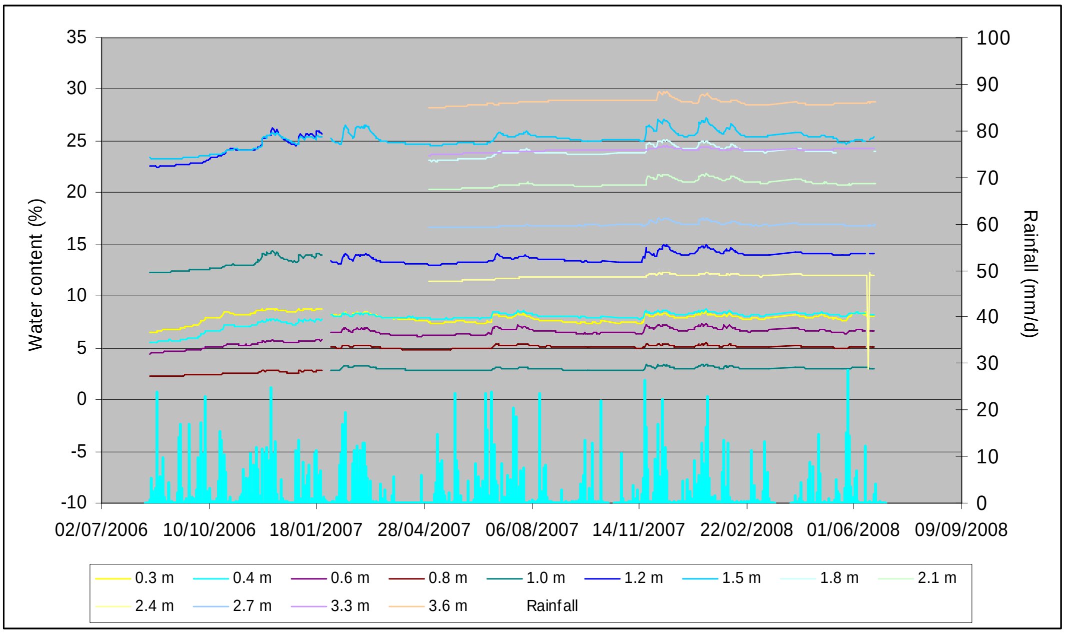


Figure 21. Water content data from the Envirosmart probes at the North Heath Barn site.

The values presented here for water content measured by these probes are those which were output from the instrument. It is obvious from the data that there is an issue with the instrument calibration (water content in the Chalk is expected to be around 20-35%). However, the relative changes in water content seem to be consistent between the probes and also of an appropriate magnitude and so it is assumed that the probes are functioning correctly. However it is a concern that the readings in some of the probes changed on reinstallation. The probes at 0.1, 0.2 and 3.0 m showed a response that was correlated with barometric pressure and so have not been presented here.

Generally there is a correlation between water content and rainfall, with water content in all the functioning probes showing an increase following periods of intense rainfall. As can be seen in Figure 22 it is possible to identify some variation of the timing of these changes with depth, with the deeper probes responding later than the shallower ones, though this is not true for all.

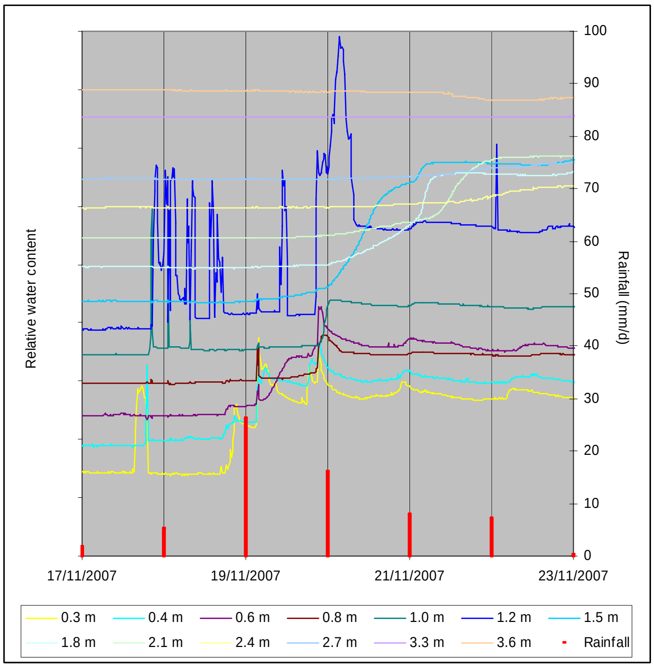


Figure 22. The effect of one rainfall event on measured water content. The water content values are scaled so that the shallowest probe is shown at the bottom of the graph.

5.2.6 Rainfall and water table data

During the spring of 2006 and the winter of 2006-07 there was a clear relationship between water level and rainfall, with water levels being closely related to cumulative rain (with a time lag of around 8-10 days), and water level rise ceasing, and even recessing slightly after dry periods (Figure 23). However the same clear relationship is not seen for the winter of 2007/8. This could be due to problems with the rain gauge, as the filter had become clogged by January 2008, possibly leading to the under-recording of rainfall from the previous download on 4 December 2007. The interpolation in the rainfall record in March 2008 is based on a difference between the gauge readings and the volume collected during that period (when some hourly records were lost due to logging problems).

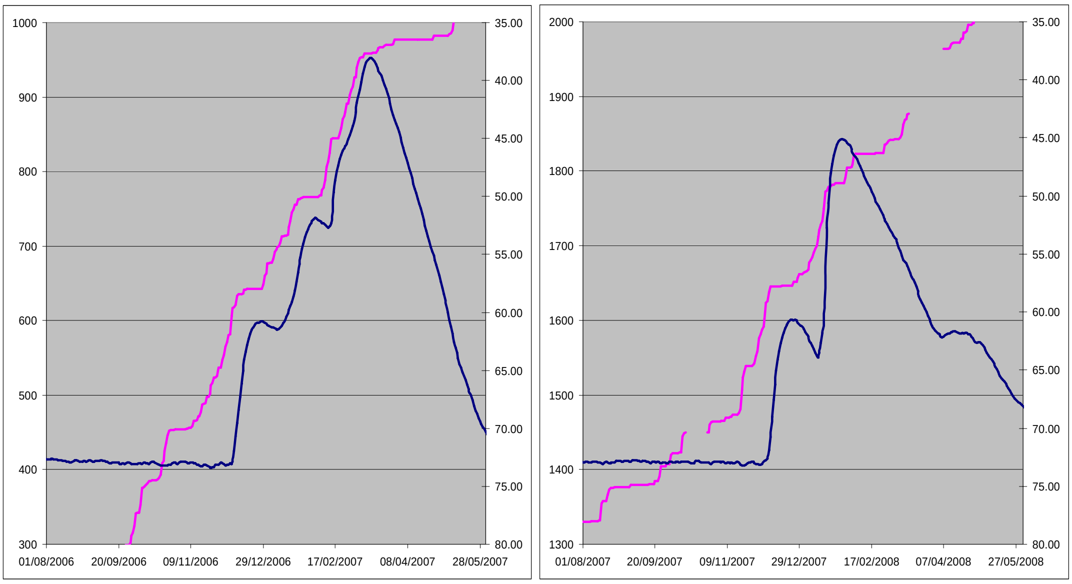


Figure 23. Comparison between water level and cumulative rainfall for November-December 2006 and 2007 at the North Heath Barn site.

Because of the uncertainty over the rainfall record for the winter of 2007/8, the groundwater hydrograph gradient comparison with daily rainfall is only shown for winter 2006/7 (Figure 24). This shows very rapid response to rainfall once groundwater recharge has started, with responses to new wet periods being seen within 5 days.

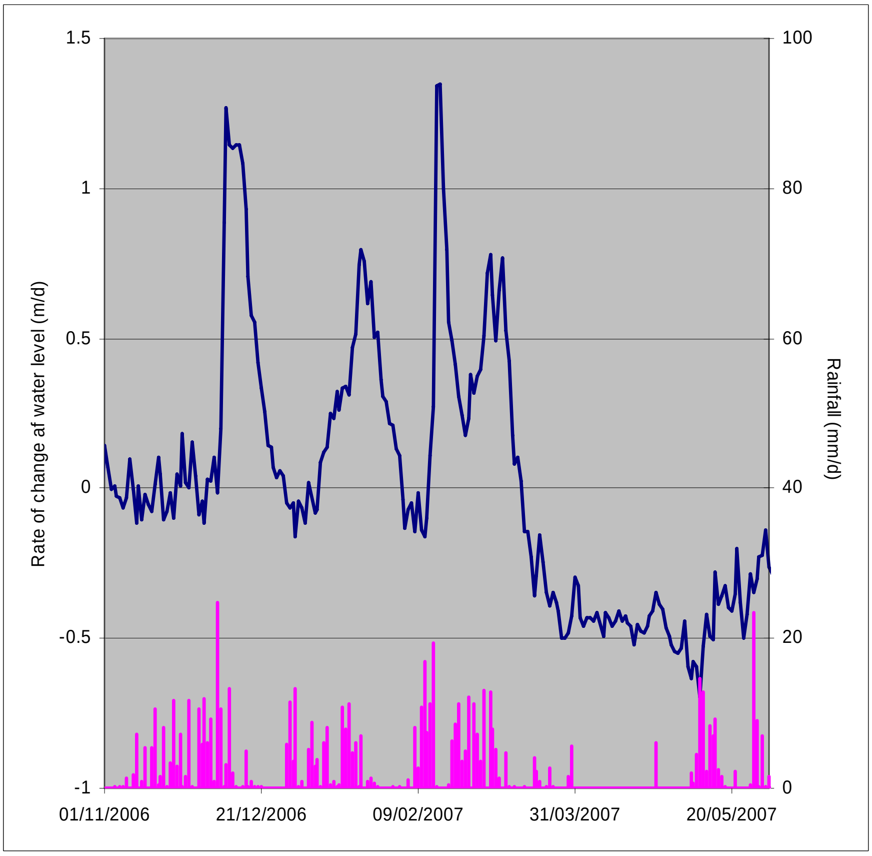


Figure 24. Rate of change of water level (hydrograph gradient) during winter 2006/7 at the North Heath Barn site.

5.2.7 Comparison of sites and discussion of results

Water moves from high potential to low potential. In the unsaturated zone, potentials are negative – therefore, water will move from near-zero (almost saturated) to more negative values. Total potential is matric potential plus elevation potential. If field capacity was achieved, then a graph of total potential with depth would be a straight line – water is neither moving up nor down. In reality this state is never achieved in the Chalk (as observed by Wellings, 1984, at Bridget's Farm): drainage continues beneath the Zero Flux Plane (ZFP), and only at the point of the ZFP is there no water movement up or down. The ZFP has been observed to reach depths of up to 5 or 6 m during drought conditions (Wellings, 1984). From deep borehole tensiometers, it can be observed that drainage continues throughout the year: the fact that water levels recess is due to recharge being less than discharge, not because recharge ever ceases. This was suggested by Lewis et al., (1993) and various other lines of evidence have added to it since. The implications are significant: firstly water availability to plants may not be as restricted as is assumed – the ZFP can penetrate to several metres depth, and the concept of root constant and wilting point may not be valid on the Chalk. Secondly, if recharge is continuing throughout the year, this is generally not accounted for in modelling, where recharge is either directly transmitted to the water table, or where it may be delayed by a few months. With delayed recharge, the true maxima and minima water levels are never achieved, as during the recession period, recharge is continuing, and preventing the true minimum being reached, and during the recharge period, the deficit in the unsaturated zone is replenished, therefore, preventing a true maximum being achieved.

At East Ilsley, the system behaves as would be expected if there is hydraulic continuity between the different horizons. The system is more damped than at Brighton, responding slowly through the season, and is reflected in the fact that the water table does not show any relationship with rainfall events over a shorter (days) time period. There are no recessions after periods of no rain, and it is difficult to correlate changes in rate of recovery with rainfall events. Matric potentials are generally low, and only increase above -50 hPa after prolonged rain and when the water table is close to the horizon being observed. This would appear to be a site where fracture flow rarely occurs.

Brighton appears to act as a multi-layered system – there is some degree of hydraulic separation between the layers and the changing matric potential of each layer appears to be independent. The system also is at high potential: little additional input would be required to saturate the fractures and initiate fracture flow, and, during the recharge period, this results in the rapid response (within days) that can be seen at the water table after a period of rain. The rapid response to recharge is followed by a rapid recession if input ceases, as was seen on two occasions during the early recharge period in 2006.

From the data available, it appears that some horizons probably do not drop below -50 hPa, the matric potential at which the fractures are assumed to contribute significantly to unsaturated zone flow; this is reflected in the observation of patches of wet borehole walls throughout, and after the end of, the recession period. It is likely that certain horizons with lower permeability may support a perched water table. It is suggested that where a perched water table develops, lateral flow can occur, and this may provide rapid lateral transport of recharge. In the borehole, the high matric potential areas are observed as wet walls immediately above and below marl horizons. Here matric potentials rise high enough for the fractures to become saturated and conduct water. The borehole is acting as a major fracture surface, and transports water downwards until the walls are of low enough potential that the water is re-absorbed into the matrix.

The water level recesses to a plateau at around -70 m bgl. Geophysical logging observed a major fracture from 70.2 to 70.6 m bgl, with a maximum diameter of 196 mm. The evidence suggests that this exerts a major control on the water levels observed in this borehole. It is suggested that during the recharge season, rainfall above a certain threshold initiates fracture flow and rapid transport of water to the water table. If the input is above a threshold level, the system is unable to discharge water at the rate of recharge, and the water level rises; however, as soon as the input ceases or reduces, drainage becomes dominant and water levels fall. The shape of the hydrograph is, therefore, a fine balance between the input through a responsive unsaturated zone, and the discharge through the saturated zone which appears to be controlled by a major feature at -70 m.

6 Modelling Activities

6.1 INTRODUCTION

The application of mathematical models by BGS within the FLOOD 1 project has focussed on two objectives:

1. the development of conceptual understanding of groundwater flow within the Brighton catchment, particularly under extremely high groundwater levels and,
2. the development of tools to predict groundwater level maxima to form part of an early warning system for groundwater flooding within the region.

With these aims in mind and given budgetary considerations, the approach has been to develop models that are parsimonious, that is, only as complex as the observational data permits. With regard to the development of conceptual understanding, modelling has been used to understand the relationship between groundwater levels and the onset and cessation of groundwater flooding. The work described in Section 6.2 shows that some of the behaviour observed in the Brighton catchment, which was previously postulated to be related to flow through the unsaturated zone, can actually be attributed to saturated groundwater flow mechanisms. Section 6.3 describes the quantification of recharge over time using a distributed recharge model. This provides estimates of the amount of recharge to the aquifer that occurred during the winter of 2000-01.

Two methods have proved successful for the prediction of extreme groundwater levels. The application of multiple linear regression and neural networks for the simulation of annual groundwater level maxima is discussed in Sections 6.4 and 6.5. Given a distribution of cumulative rainfall between the annual groundwater level minim and maxima, these can be used to provide probabilistic estimates of the occurrence of a given maximum groundwater level.

6.2 SIMPLE SATURATED ZONE MODELLING

6.2.1 Introduction

The observed non-linear relationship between the issuing of water at the Patcham roundabout and water levels measured at the nearest EA observation point during the 2000-01 flooding events at Brighton have been described in Section 2.4. Specifically, the water continued to emerge from the ground when the water level at the observation point was lower than it had been when the flow started. This was thought to indicate that some unusual processes were occurring either in the unsaturated zone, or in the zone of the aquifer that is unsaturated under normal recharge conditions. Before this hypothesis was investigated in detail, a simple saturated zone flow model was constructed to investigate whether the observed non-linearity was in fact unusual.

6.2.2 Model design

The USGS saturated groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) was used to investigate this phenomenon. Within MODFLOW the ground surface is not represented explicitly, and there is no representation of the unsaturated zone. Recharge is added directly to the model at the water table, in the uppermost active node.

A simple 4-layer model was constructed, having an areal extent of 10 km x 5 km and a total thickness of 100 m. The grid spacing is 200 m. The boundary conditions used were no-flow boundaries (representing groundwater divides) on all boundaries except at one edge of layer 4 (the bottom layer) which was a fixed head boundary at 0 m representing a discharge to the sea (see Figure 25). The MODFLOW drain node model was used to represent a spring. This model removes water from the model when the water table rises above a certain (specified) elevation. Discharge stops when the water table drops below the same level.

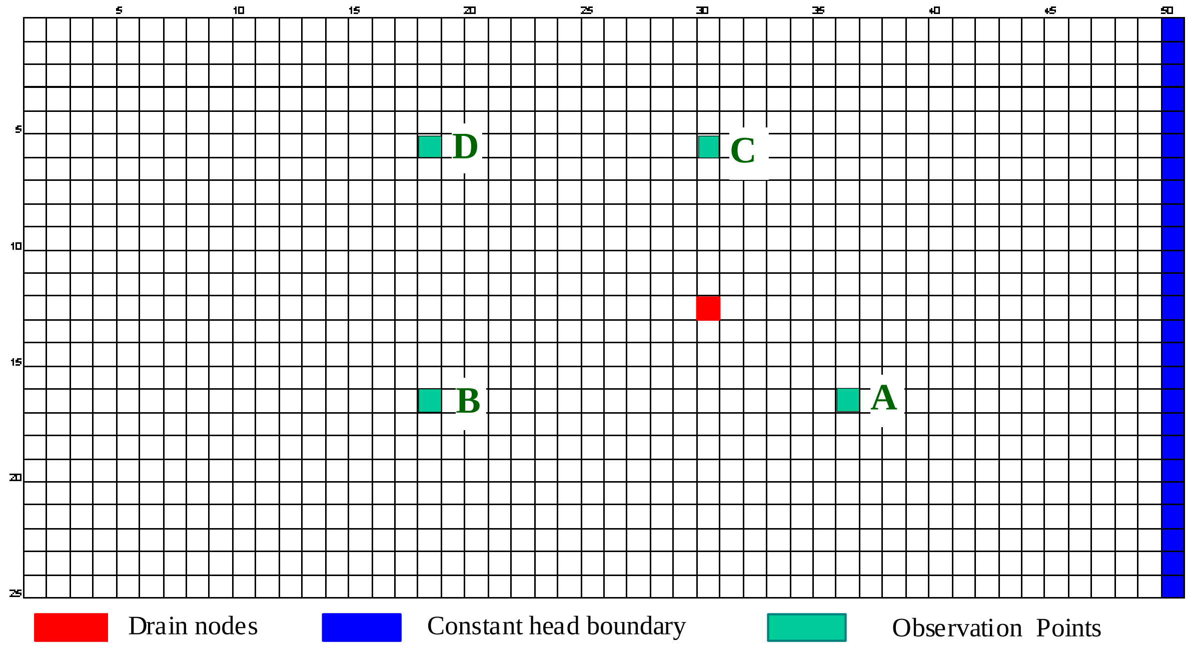


Figure 25. Plan of model showing grids and boundary condition in layer 4, and position of spring in layer 1. Also shows location of water level monitoring points

The layering of the model was set up as shown in Figure 28 so that it would be possible to assess the effect of a low or high permeability layer on the discharge from the spring. The model was initially run in steady state (i.e. with a constant recharge rate) so that an appropriate level could be set for the elevation of the spring. The steady state water table is shown in Figure 26.

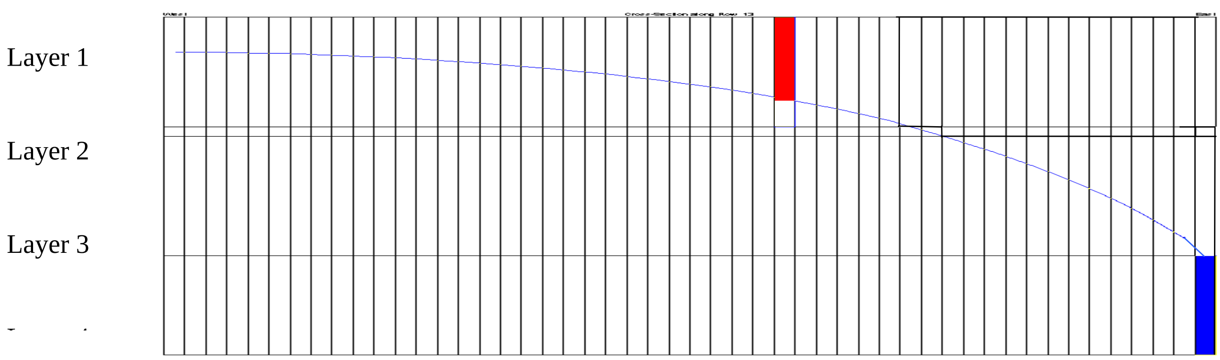


Figure 26. Sectional view of model showing layering and steady-state water table position

Table 3 shows the parameters used. These were chosen to be typical of Chalk properties, with a higher permeability at the water table and a lower one at depth. The steady-state water table shown in Figure 26 was generated by a constant recharge rate of 0.001 m/d.

Table 3. Parameters used.

	Top m	Bottom m	Hydraulic Conductivity
Layer 1	150	65	10 m/d
Layer 2	65	60	10 m/d
Layer 3	60	0	4 m/d
Layer 4	0	-50	4 m/d
All layers have S_s = 0.0001 and S_y = 0.01, for both model runs. Vertical hydraulic conductivity is set as 1/10th of horizontal.			

6.2.3 Results

Figure 27 shows the model results, as a comparison of the spring flow and water levels for the period of time around which the spring starts flowing and that at which it stops flowing. The dashed lines are added to indicate the water level at each of the observation points (Figure 26) at which the spring flow started. There is noticeable (though small) difference in the water level at the start and end of spring flow at Observation Points A, B and D. This is without the presence of a low permeability layer in the vicinity of the spring. If one is included the effect is more marked.

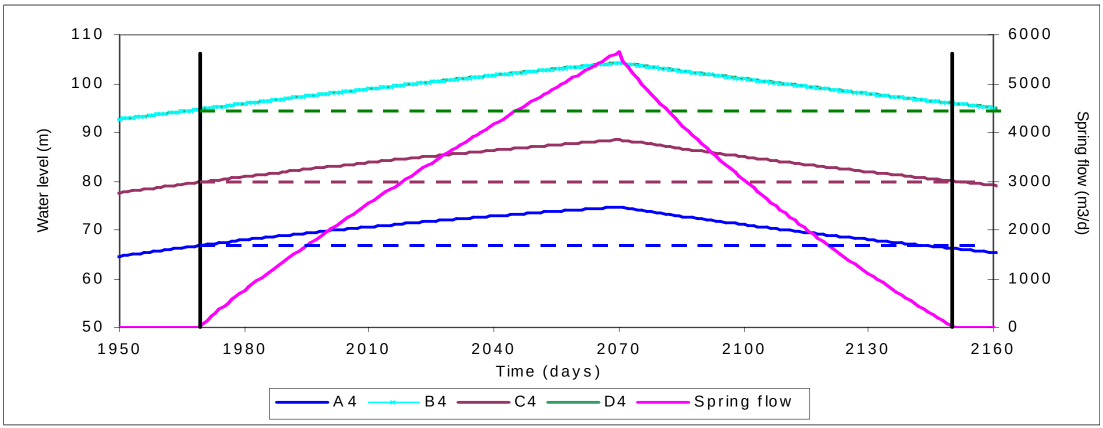


Figure 27. Model results.

The groundwater head at observation boreholes B and D (which are both "upstream" of the spring) are greater at the time of cessation of flow of the spring than at the time of commencement of flow (Figure 27). At borehole C, the groundwater heads at these two times are identical. At borehole A, which is "downstream" of the spring and, therefore, analogous to the Ladies Mile borehole at Patcham, the groundwater head at the time of cessation of flow is lower than that at the commencement of flow. Thus a time lag effect can be seen with a model which does not include the effect of the unsaturated zone. It was concluded that the groundwater level behaviour in the Ladies Mile observation borehole near Patcham during the 2000/2001 flood event could be due to saturated zone (rather than unsaturated zone) processes.

6.3 RECHARGE MODELLING

6.3.1 Purpose of recharge modelling

Recharge modelling of the Brighton catchment was undertaken in order to develop recharge time-series for incorporation into the statistical (regression) models that have been developed to predict annual groundwater maxima. See Section 6.4

6.3.2 Modelling approach

Initially the modelling focussed on the region around Patcham, which covers an area of approximately 100 square kilometres (Figure 28). The boundary of the model was defined based on (i) groundwater level contours (ii) the position of abstraction boreholes and their source protection zones and, (iii) the outcrop of the Chalk aquifer. The model has not been extended to cover the full outcrop of the Chalk between the Rivers Adur and Ouse. However, the model could be extended to cover this larger area at a later stage if this is required.

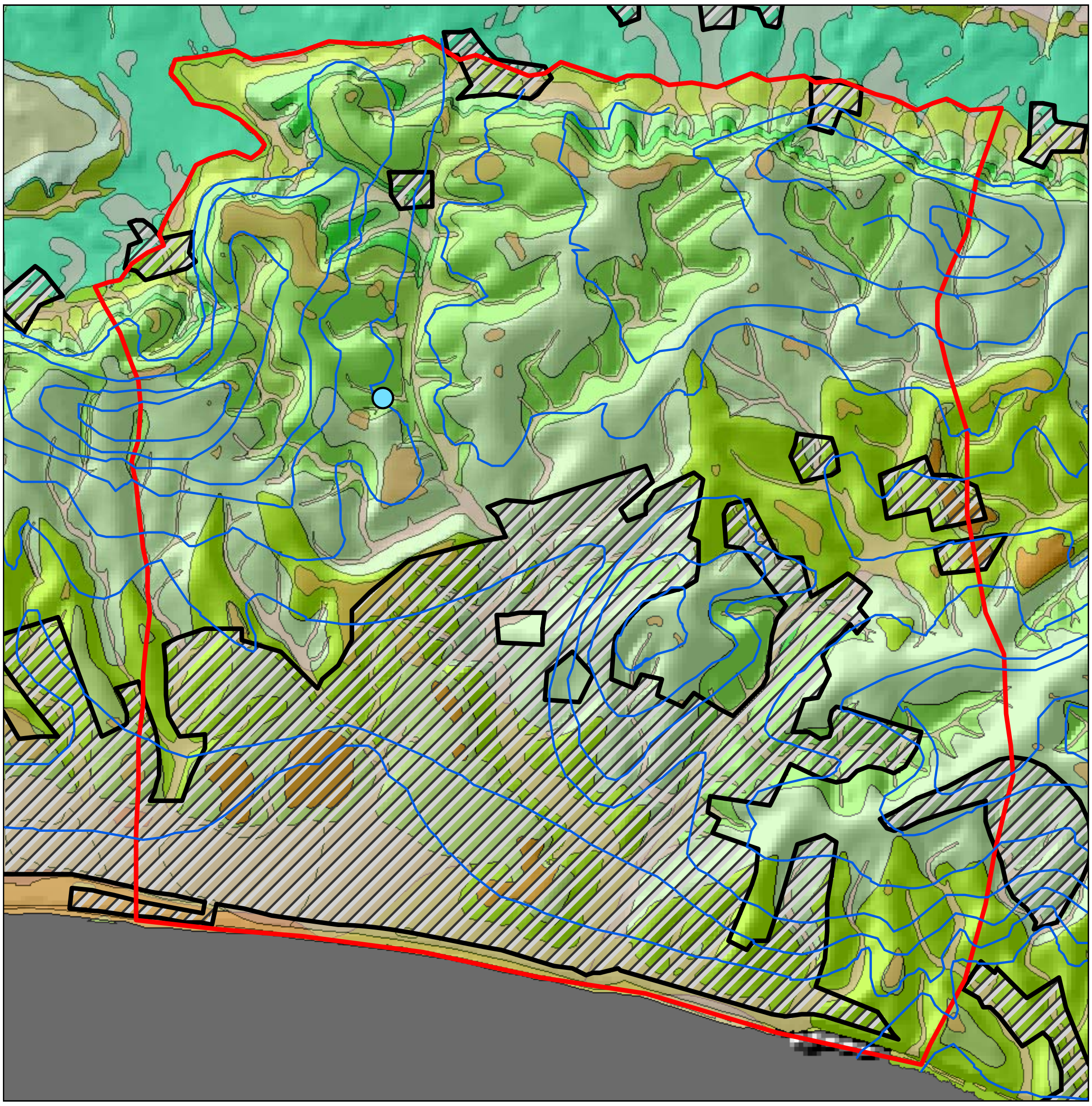


Figure 28. Distributed recharge model boundary (red) superimposed on geological map of Patcham catchment and groundwater level contours for March 1993. North Heath Barn investigation site - blue circle, urban areas - hatched regions.

The system has been simulated using BGS's distributed recharge model ZOODRM (Mansour and Hughes, 2004). The code uses a Penman-Grindley type soil moisture balance method and the Brighton model incorporates the following features:

- Daily rainfall record at the Mile Oak, Shirley Rd, Lewes Rd, Falmer, Housdean, Patcham, Balsdean, Clayton and Plumpton gauges.
- Monthly MORECS potential evaporation.
- The spatial variation of rainfall based on the Met Office 1km LTA data set.
- Surface runoff routing based on an aspect map developed from the DTM and geology at surface.
- Distributed crop coefficients (root constant, C and wilting point, D) based on CEH land cover map 2000 (i.e. 10 land use types). C and D values have been based on previous recharge modelling studies of UK Chalk presented in the literature and compared to those applied in the recharge model of the Brighton and Worthing Chalk blocks developed by Entec (Entec, 1999).
- Modification to rainfall recharge due to urban areas.

Leakage from pressurised water mains in the urban areas has not yet been included in the model.

6.3.3 Results

Some results of the modelling are shown in Figures 29 and 30. Figure 29 shows the average recharge over the catchment for the period January 1990 to November 2003. This varies from approximately 0.5 mm/day at the coast to 1.5 mm/day over the north-eastern interfluve. The simulated long-term average recharge is 0.83 mm/day or 81 Ml/day over the 97.6 square kilometre area. The simulated mean monthly recharge rates for the period September 2000 to March 2001 are shown in Table 4 below. These are significantly greater than the long-term averages of the winter months. For example, the mean monthly recharge rate for the month of October between 1990 and 1999 is 87.7 Ml/day. For October 2000 it is simulated to be 635 Ml/day.

Table 4. Simulated mean monthly recharge rates for September 2000 to March 2001.

Mean daily recharge	**Sep 00**	**Oct 00**	**Nov 00**	**Dec 00**	**Jan 01**	**Feb 01**	**Mar 01**
mm/day	1.43	6.51	5.09	3.08	3.14	2.61	2.65
Ml/day	140	635	496	300	306	254	259

Figure 30 shows the comparison between the observed groundwater hydrograph at North Bottom with the simulated recharge at this location. Again, this shows the significant amount of recharge that is simulated during winter 2000/2001

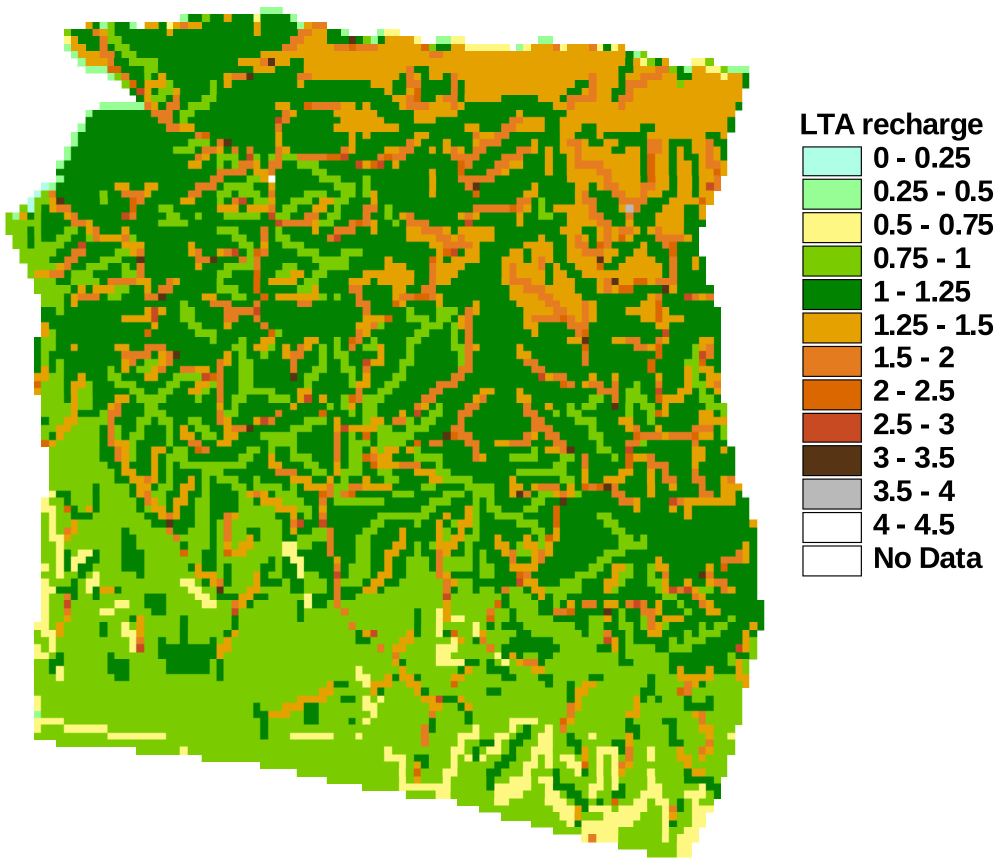


Figure 29. Simulated average daily recharge for the period January 1990 to November 2003

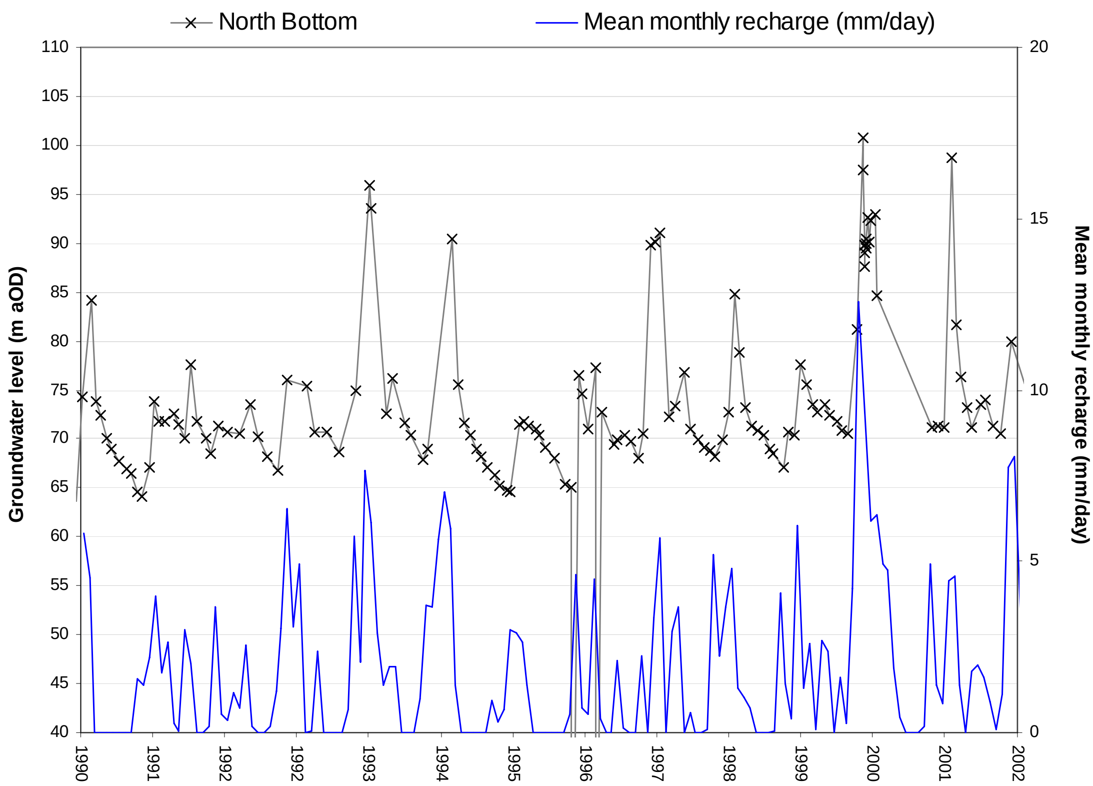


Figure 30. Comparison of simulated mean monthly recharge rates with groundwater level at North Bottom

6.4 GROUNDWATER LEVEL MAXIMA PREDICTION MODELLING

6.4.1 Background & aims

Following flooding in the Brighton area in the winter of 2000, there is a need for predictive models of groundwater flooding events. Deterministic models have high predictive capability, but they require relatively detailed conceptual models and they often need to be conditioned with extensive field observations. In contrast, stochastic models generally only require relatively simple conceptual models and are less data intensive. Given uncertainties regarding the detailed processes and ground conditions leading to the flooding event in the three FLOOD 1 research catchments, a statistical approach to predictive modelling of high groundwater levels has been developed based on the observation that the groundwater flooding event was associated with exceptionally high rainfall and, in two of the research catchments, high antecedent groundwater levels.

The aim of the statistical model described in this section is to predict maximum annual groundwater levels a hydrometric season in advance at an observation borehole, based on antecedent groundwater levels and assumptions about rainfall. Groundwater level data from a borehole at St Peters Church, central Brighton [TQ 3150 0492] have been used in the development of the model. This data set was used as there was a relatively long historical record and the borehole is situated centrally within the Brighton block.

6.4.2 Methodology

A multiple linear regression method has been developed to predict maximum annual groundwater levels. Annual groundwater level minima and the cumulative rainfall total between the annual minima and subsequent annual groundwater level maxima are taken as the two independent variables in the regression and the annual maximum groundwater level is taken to be the dependent variable. As with all regression models it was important first to establish that the independent variables are independent (that they are not co-correlated), that they show homeostasis and do not exhibit significant autocorrelation. The period between antecedent minima and groundwater level maxima could have been used in the regression, however at St Peters Church the cumulative rainfall total between the annual minima and maxima and the period between the annual minima and maxima are co-correlated so that latter has not been used in the regression model.

The regression model has been calibrated using monthly groundwater level data from the borehole at St Peters Church, Brighton. The rainfall data was an average of rainfall data from four Environment Agency rain gauges (Falmer, Clayton Pumping Station, Patchham water works, and Plumpton) in or near Brighton. The model was calibrated for the period 1981 to 1998 and validated for the period 1998 to 2003.

6.4.3 Results – model calibration and validation

Based on the calibration the following linear regression model was obtained

An. Max. GWL (m OD) = (An. Min GWL (mOD)*1.118) + (Cum. Rain (mm) * 0.008)

The model had an adjusted R^2 of 0.99 and a standard error of estimate of 0.94. Model validation was performed by substituting observed annual groundwater level minima and cumulative rainfall totals into the regression expression to calculate annual maxima.

The results of the model calibration and validation are shown in Figure 31. The monthly groundwater levels are shown in dark blue, the maximum annual groundwater levels from the calibration are shown in pink and the modelled maxima for the validation period, 1998 to

2003 are shown in yellow. The model was calibrated on 17 years of data. To assess how sensitive the model is to a given years observations, a leave-one-out jack-knife assessment was performed. The coefficients of these 17 additional jack-knife regressions were used to predict groundwater levels from the validation period. They are shown in the Figure 31 in pale blue and give an indication of the sensitivity of the model.

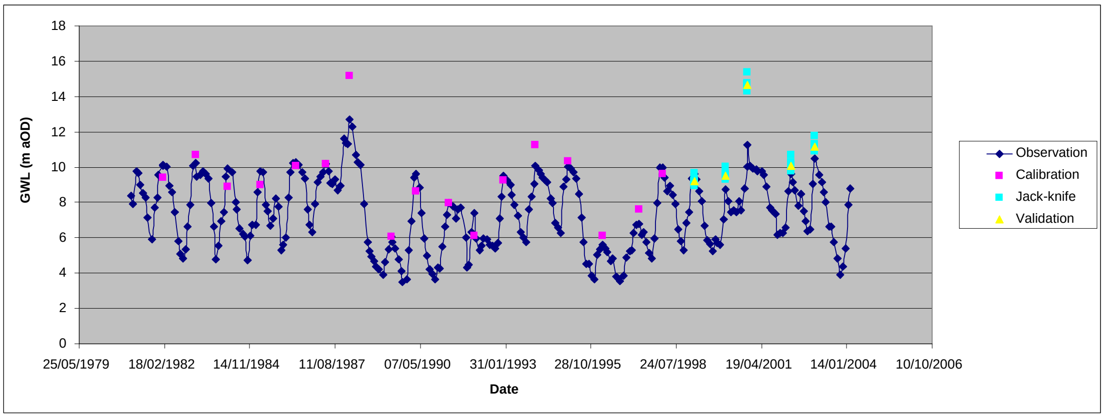


Figure 31. Results of the linear regression model for St Peters Chruch, Brighton. The monthly groundwater levels are shown in dark blue, the maximum annual groundwater levels from the calibration are shown in pink and the modelled maxima for the validation period, 1998 to 2003 are shown in yellow. The pale blue indicate the sensitivity of the regression model based on jackknife re-sampling.

The model describes the maximum annual groundwater levels well with the exception of winter 2000 where the model over-predicts the groundwater levels by about 3m. It is thought that this can be explained at least in part by the observation that the true maxima during the winter of 2000 was likely to have been higher than the observed maxima, groundwater level observations having been made on a non-continuous basis. In addition, groundwater flooding may cause groundwater discharge points not normally active to became active. If this is the case then the relationships between groundwater level minima, maxima and cumulative rainfall may be non-linear and a linear model may not be so successful in representing the annual groundwater level maxima. However, as the figure shows that high annual maxima are consistently over- rather than under-predicted, the model should still be useful for predictive purposes.

6.4.4 Results – model prediction

How can the methodology be used to predict annual groundwater level maxima? Based on the calibrated regression model, once groundwater recession has stopped and groundwater recharge has started the observed annual groundwater level minima can be used in conjunction with an estimate of rainfall for the coming season to predict the following annual maximum.

Three methods could be used to provide the rainfall prediction. The cumulative rainfall for a range of typical and atypical years could be used with the observed minima. For example, a 'worst case scenario' could be to use the cumulative rainfall for the 2000 recharge event. This way predicted maximum groundwater levels could be seen in the context of historic representative events. A second approach is to find the mean or some other descriptor of distribution of values of cumulative annual rainfall for the calibration period. Then, using the mean, a series of standard rainfall scenarios could be applied to the regression model, e.g. 50%, 75%, 125% and 150% of mean rainfall. By making a prediction based on these values a spread of representative maximum groundwater levels would be obtained. A third, probabilistic, approach would be to characterise the distribution of values of cumulative annual rainfall for the calibration period in terms of a mean and standard deviation and then use a Monte Carlo simulation to produce a probability distribution of predicted annual groundwater level maxima. This third approach has the benefit of providing a probabilistic prediction. The first approach is easiest to apply and communicate to non-technical staff and the public, while the second approach allows reinterpretation of the prediction as the recharge season progresses.

For practical purposes, once a model has been calibrated and validated, it is recommended that the model is re-calibrated using all available data and the new regression then used for prediction. This is because regression models tend to improve with more cases (years).

In summary, this model enables maximum groundwater levels to be predicted up to a hydrometric season in advance. This methodology requires limited modelling expertise, can be run on a spread sheet and needs only limited commonly available data. It would be ideal as a first tier screening for possible high groundwater level events and could be incorporated in regulating authorities staged response and warning systems.

6.5 PREDICTION OF ANNUAL GROUNDWATER LEVEL MAXIMA USING ARTIFICIAL NEURAL NETWORKS

In addition to the application of the multiple linear regression method to predict annual groundwater level maxima, artificial neural networks have been applied for this purpose. An artificial neural network (ANN), often just called a neural network (NN), is a mathematical model or computational model based on biological neural networks. Practically they can be regarded as non-linear statistical data modelling tools.

Artificial neural networks have been used for some time to model rainfall runoff relationships (e.g. Dawson and Wilby, 1998; Imrie et al., 2000; Shamseldin, 1997) and more recently groundwater level hydrographs (e.g. Coulibaly et al., 2001; Daliakopoulous et al., 2005; Nayak et al., 2006; Lallahem et al., 2005). ANNs are entirely data driven and, therefore, assume no underlying statistical or physical model in mapping input data to output data. They are quick to set up and run, with data requirements that can be tailored to the available data, and capable of producing well calibrated models based on training data.

An ANN consists of an interconnected group of neurons, which are linked by a series of connections or synapses (Figure 32). In most cases information is passed through the network from a series of input nodes, via a number of hidden neurons that transform the signal, to one or more output neurons. Fundamentally a neural network consists of the following three basic components (Figures 32 and 33):

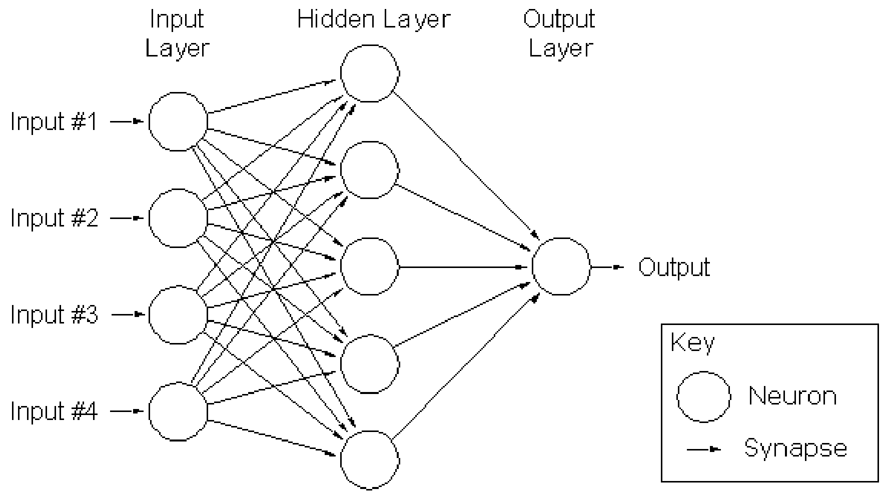


Figure 32. Structure of a simple neural network model

- Synapses, which are the links that connect neurons. Each synapse is associated with a weight or strength that scales the signal or input to the neuron.
- Summing junctions that sum the input signal after each has been weighted by its respective synaptic weight.
- Activation functions that transforms the input signal. These functions limit the permissible amplitude of the output signal to some finite value (often between zero and one).

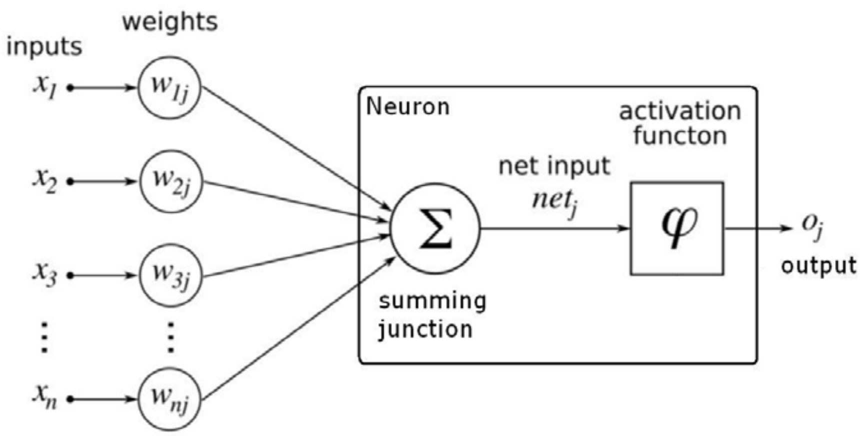


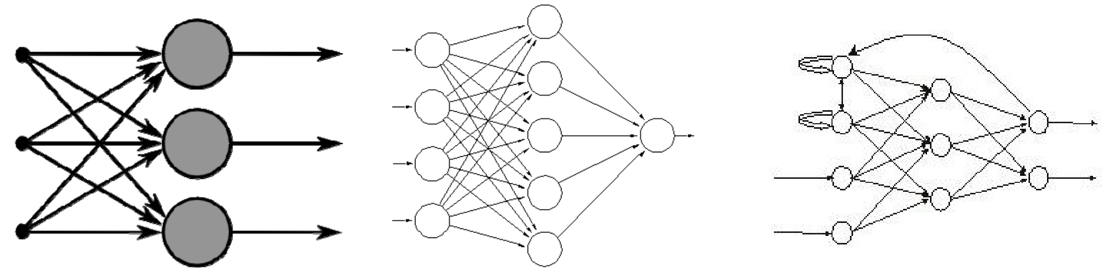
Figure 33. Basic components of a neural network

By adjusting the synaptic weights, the neural network can be made to transform a series of inputs into an output signal in order to simulate a series of observations. The process of fitting the neural network model output to observed data by modifying the synaptic weights is referred to as training or learning. This learning procedure is performed by solving an optimisation problem in which the objective function is based on the difference between the simulated network output and observed data. For example, in the principal application of neural networks used in this work to predict annual groundwater level maxima, models take annual minima and cumulative rainfall as input and are trained by comparing the output to the historic maxima. Once this learning procedure has been completed the network can be used to make predictions.

Whilst a basic neural network is a relatively simple computational structure, it is possible to construct many different types of network with different numbers of neurons and patterns of connection. The design of neural network architectures is an active area of research, however, modelling with ANNs in hydrology has tended to be use one of a limited number of topologies (Figure 34). Use of neural networks in hydrology differs from the classic application of neural networks in that instead of structural recognition (e.g. character recognition software) time-series modelling depends on the current values of the input as well as values at previous time steps. This makes the inclusion of some form of memory structure highly advantageous.

FEEDFORWARD NEURAL NETWORKS

The feedforward neural network (FFNN) is one of the simplest types of network. It consists of an input layer, one or more hidden layers of neurons and an output layer (Figure 34a and 34b). The flow of information is in one direction through the network. FFNNs are capable of approximating any input/output map, although they train slowly, typically requiring three times more training samples than network weights (Daliakopoulous et al., 2005). Critically for modelling an aquifer's response to rainfall this network topology does not include any memory structure, so unless input data contain some information on antecedent conditions (i.e. previous groundwater levels or groundwater levels from another site) such networks might be expected to perform poorly.



(a) (b) (c)

Figure 34. Example (a) single-layer feedforward, (b) multi-layer feedforward and (c) recurrent neural networks

FFNNs can contain only one layer or multiple layers of neurons. In a single-layer FFNN (Figure 34a) input nodes receiving the input data map onto a single layer of output neurons, which transform the signal into the output. The single layer refers to the output layer. Multi-layer FFNNs contain additional layers of neurons which are inserted between the input nodes and the output neurons (Figure 34b). Because of the additional connections and larger number of interactions between the neurons the model acquires a "global perspective" (Churchland and Sejnowski, 1992).

INPUT DELAY NEURAL NETWORK

The Input Delay Neural Network (IDNN) is similar to the FFNN, except that the inputs are fed through a delay layer. This delay layer contains a "temporal window" which holds the most recent inputs, and feeds the sum of these as input to the next layer. The delay layer can be considered a static memory structure as it is not modified during training.

RECURRENT NEURAL NETWORKS

A Recurrent Neural Network (RNN) is one in which a form of feedback loop is incorporated (Figure 34c). These feed back loops direct output from a neuron or hidden layer back into the input of a previous neuron or previous layer. By incorporating these feedbacks the network gains a form of "memory".

The neural network models used to predict annual groundwater level maxima within the FLOOD 1 project have been developed using the JOONE software (Figure 35). This software has been used because both the user interface and the underlying neural network code can be downloaded at no cost from the internet (www.jooneworld.com) and because it is relatively easy to use and is well supported.

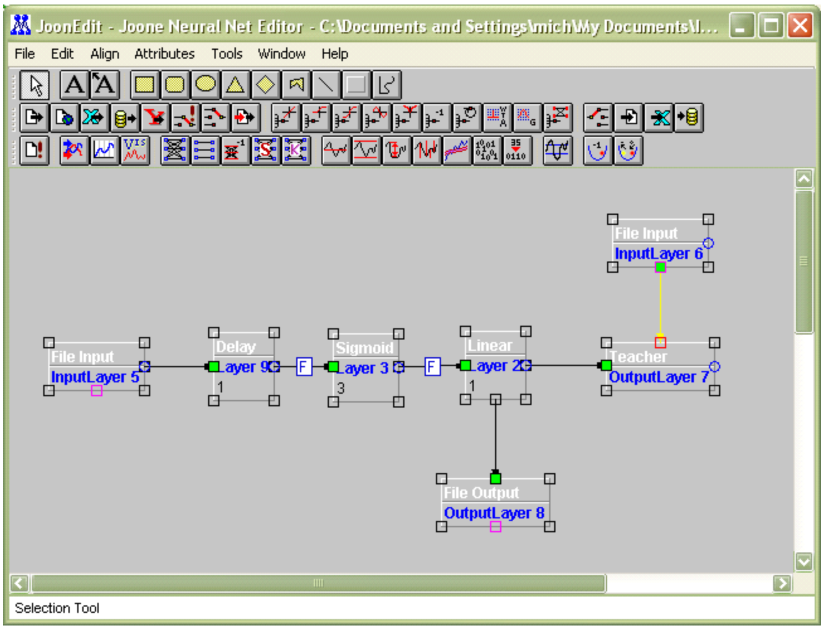


Figure 35. The JOONE neural network modelling graphical user interface

The three different network architectures discussed above have been evaluated using JOONE for the purpose of simulating continuous groundwater level time-series. However, due to the inadequate length (generally less than 25 years) and presence of gaps in the groundwater level records it has not been possible to use this approach within the Brighton study area. Whilst it has only been possible to use a neural network to predict the annual maxima within the Brighton catchment, the work has shown that it is possible to simulate a series of monthly groundwater levels given a longer historic time series and a "well-behaved" borehole hydrograph. Figure 36 shows the fit of the best neural network model to monthly groundwater levels in the Chilgrove House Chalk borehole, the location of which is shown in Figure 37. The model used to generate the results plotted in Figure 36 is based on an input delay feedforward network trained using monthly time-series of total rainfall, mean temperature and groundwater level between 1836 and 1960. The trained network is then used to predict groundwater levels between 1961 and 2006.

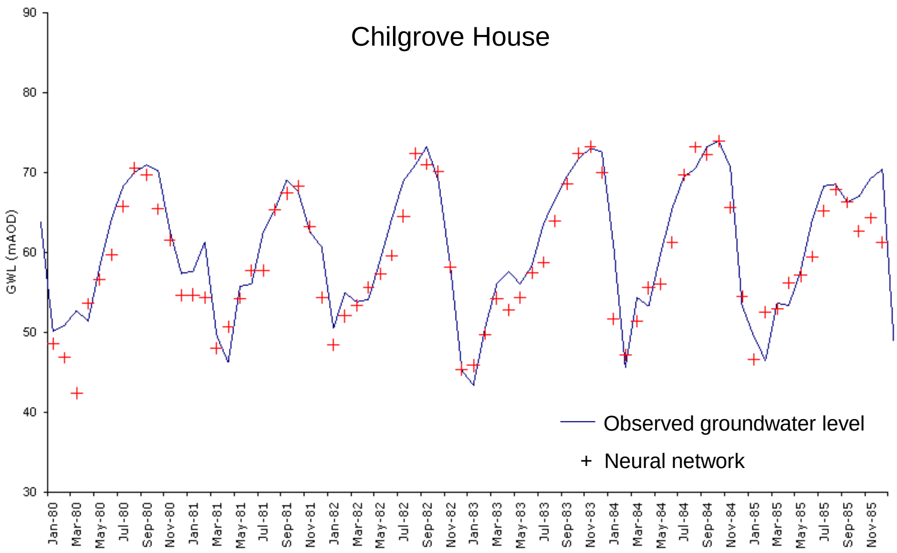


Figure 36. Comparison of simulated (crosses) and observed (solid line) of groundwater level time-series at Chilgrove House borehole (1980-85) using an input-delay neural network.

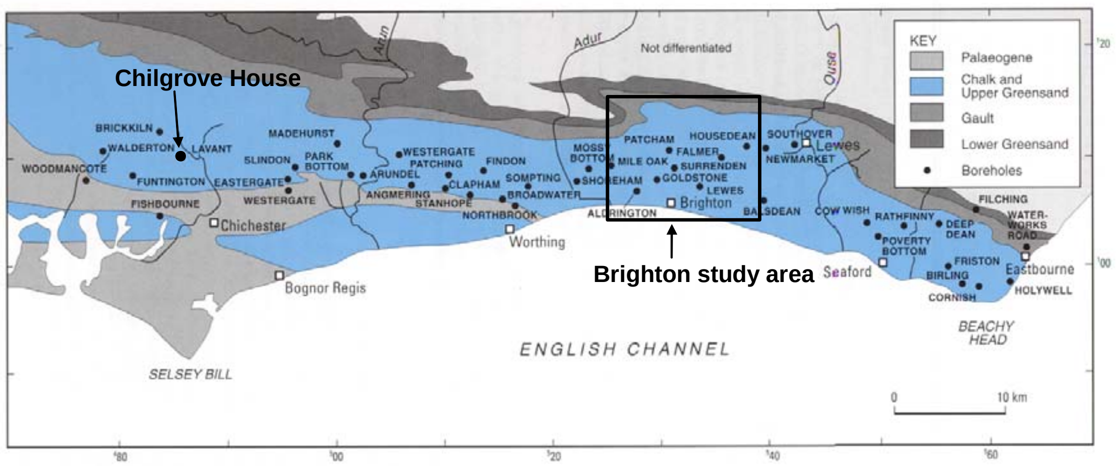


Figure 37. Location of Chilgrove House borehole

Figure 38 shows the results of the application of a feedforward neural network to predict the annual groundwater level maxima at the St Peters Church borehole within the Brighton catchment (Figure 39). The figure also shows the predictions obtained using the multiple-linear regression (MLR) model, described previously. The two models were constructed using the following input data associated with the sixteen annual maxima between 1981 and 1997:

- the level of the annual minima prior to the seasonal high groundwater level, and
- the total rainfall between the annual minima and subsequent maxima.

Both the NN and MLR models produce good predictions of the six annual maxima between 1998 and 2003. In general the MLR method predicts slightly higher groundwater levels than those measured and the neural network model slightly lower levels. The values of the fit, between the six observed maxima and the model results, as described by the R-squared measure are 0.95 and 0.96 for the MLR and NN models, respectively.

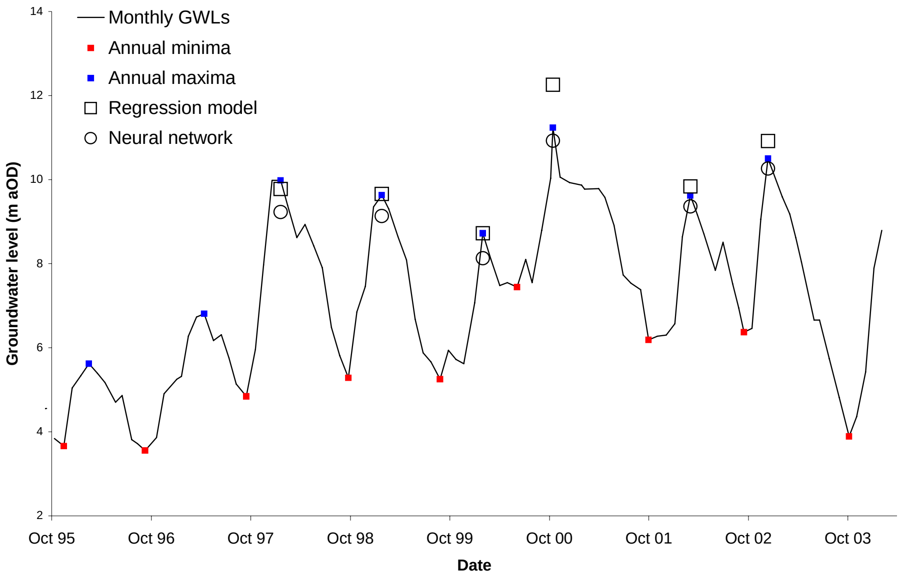


Figure 38. Comparison between predicted annual groundwater level maxima between 1998 and 2003 using a neural network and the multi-linear regression method.

This example shows that the use of a neural network is a suitable means by which to predict extreme groundwater levels. Neural networks provide both an alternative and complementary method to predicting extremes using multiple-linear regression when limited information is available and without the need to produce a detailed conceptual understanding of the behaviour of the system. That is not to say, however, that an understanding of the hydrogeology of a region prone to groundwater flooding is not beneficial when developing such simple models. The applicability of both NN and MLR models should be determined in conjunction with a consideration of the possible controls on groundwater hydrograph response. For example, groundwater maxima may be bounded due to the activation of spring discharge points under high groundwater levels. Such information is helpful when deciding what input data are required to develop an adequate model and how to formulate the problem.

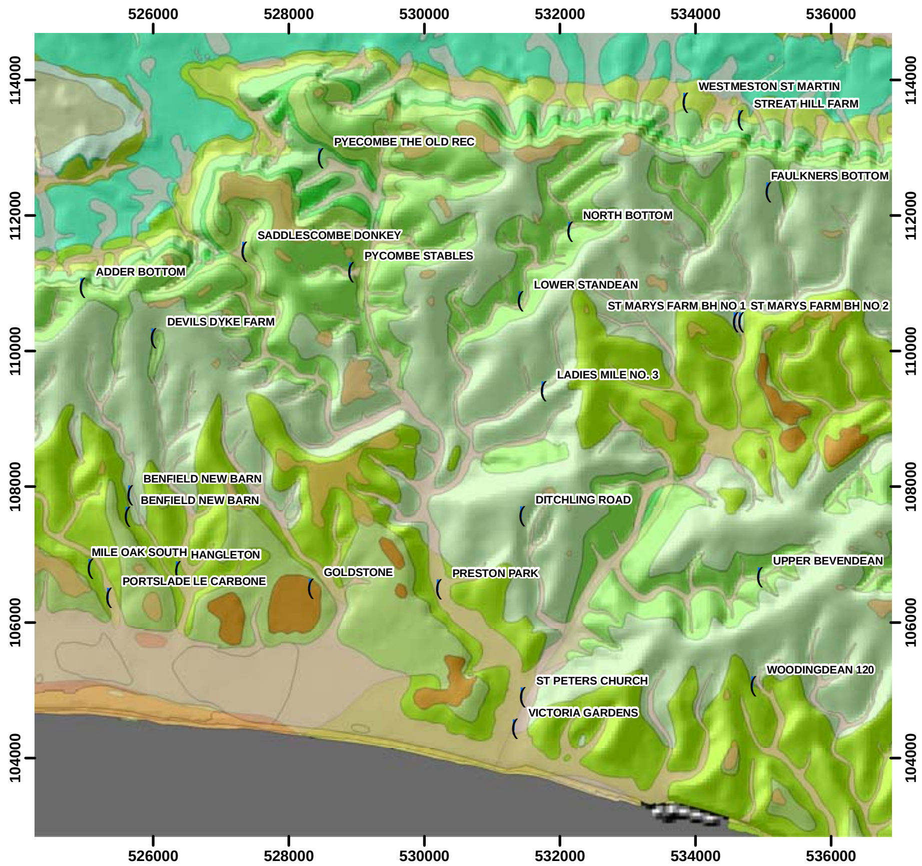


Figure 39. Location of observation boreholes within the Brighton region

BENEFITS AND DISADVANTAGES OF NEURAL NETWORKS IN HYDROLOGY

The application of neural networks in this study has been successful in predicted annual groundwater maxima based on information about rainfall and annual groundwater level maxima. However, it has not been possible to develop adequate neural network models of continuous groundwater level time-series, that could be used to predict extremes. The following points summarise some of the advantages and disadvantages of neural network, which have been gained from the experience during this study. These points provide a guide to the possible future application of neural networks for the prediction of time-series.

There are a number of significant benefits of using neural networks to approach hydrological modelling problems:

- A neuron can be linear or nonlinear. An artificial neural network constructed of nonlinear neurons is itself nonlinear. This allows the modelling of inherently nonlinear systems, such as the response of an aquifer to a rainfall event.
- No underlying statistical model is assumed, and the output is entirely data driven.
- Neural networks are applicable to a wide variety of problems, including time series modelling and prediction. The same network topology can be used to model many different problems with very little modification.
- With the right software it can be quick to set up a given network structure, train and validate a model. Experimentation with different network topologies takes a small amount of time, and training and model runs are relatively quick compared to the run time of a conventional groundwater model.

Inevitably there are disadvantages to using neural networks, a few of which are listed below:

- As no underlying statistical model is assumed, neither is any underlying physical model assumed. This means that input data outside of the range of the training data will produce dubious outputs.
- Coupled with the issue of out of range prediction is the lack of ability of a neural network to process non-stationary data. It is possible to de-trend data, but this increases the unquantifiable uncertainty in the outputs. This limits the suitability of neural networks when applied to catchments in which storage is being depleted (e.g. the Permo-Triassic sandstones of the Eden Valley).
- The lack of a physical model means that no understanding of the hydrological processes is likely to be developed through neural network modelling alone.
- The selection of a suitable network topology is somewhat hit and miss. A relatively small number of network topologies are used in the hydrological literature, and some guidance is given on network size.
- A number of situations can lead to poor predictive ability. These include overtraining or using an unsuitable network.
- It is very easy to get mediocre results, but difficult to get good or acceptable results.

6.6 NUMERICAL REGIONAL GROUNDWATER MODELLING

The modelling approach adopted on this project by BGS has been to use relatively simple numerical models to test conceptual understanding and to develop predictive tools. The resulting models are parsimonious with respect to the number of model parameters required and the limited amount of available data within the Brighton catchment. Along with other relevant factors, such considerations have meant that a regional numerical groundwater model of the Chalk aquifer around Brighton has not been developed.

Experience of developing regional numerical models of the Chalk in the UK has shown that this requires a significant effort and relatively large budget. This is a result of the need to develop a detailed conceptual model of the aquifer system based on good quality, *spatially extensive* field data. Furthermore, if the purpose of a model is to predict the extremes of state variables, such as groundwater level, then the development effort becomes even greater. In fact, because of the representation of aquifers within numerical models as equivalent porous media and the inability to quantify the spatial heterogeneity of aquifer properties, it may not even be possible to simulate the fluctuations of groundwater level in an observation borehole using a numerical groundwater model.

In particular the development of a “good” regional groundwater model of the Brighton Chalk is considered a difficult task because of the nature of the aquifer system, which is characterised by relatively steep topography and complex geological structure. It is this complexity that results in the difference in the shape of the borehole hydrographs across the catchment, some of which are relatively smooth sinusoidal time-series and some of which are “spiky”.

Given budgetary constraints it is for the reasons outlined above that the development of a regional groundwater model of the Brighton Chalk block was not feasible within the project.

7 An Early Warning System for Groundwater Flooding in Brighton

7.1 INTRODUCTION

This chapter describes an early warning system that, within the context of the available data, provides a fit-for-purpose methodology for forecasting groundwater flood events in the Chalk. The model is capable of operating within a longer timescale than had previously been possible – thus meeting the third objective of the FLOOD 1 project.

The system currently used by the Environment Agency for the prediction of groundwater flooding events at Patcham in Brighton is based on monitoring groundwater levels at the Ladies Mile borehole. From observations made during the flooding events of 2000-01 a critical level was designated as the point at which groundwater flow at the surface will occur.

The methodology proposed in this chapter involves a set of nested models based on the research described in the previous chapters and our previous understanding of the hydrogeology of the Chalk. It must be pointed out that the methodology has not been tested on a real flooding event as no groundwater flooding has yet occurred in either of the two UK FLOOD 1 research catchments following the complete development of the methodology. It should also be recognised that the early warning system does not include specific trigger levels to initiate either the next step of the methodology or promulgation of warnings of varying severity. Such trigger levels will be developed through experience of use of the system.

It is not within the remit of this project to describe the means of providing warnings to those who are liable to be impacted by groundwater flooding events as this type of communication with the public is beyond the area of expertise of the project team. However, it would seem logical that groundwater flood warning should be integrated into the existing surface water flood warning approach adopted by the Environment Agency.

7.2 THE EARLY WARNING SYSTEM

The proposed early warning system consists of a series of consecutive steps, some of which may overlap with each other in the timing of their operation. The methodology involves the use of different models at different times and these models depend on data from the continued monitoring of groundwater levels, meteorological data (and monitoring of weather forecasts), and the degree of saturation of the unsaturated zone (using tensiometer data). The nature of the proposed early warning system is such that different models to those proposed here can be used within the same framework thus allowing future development of the system as different techniques and/or data become available. Indeed, for the Patcham area of Brighton, the Environment Agency's existing model based on groundwater levels recorded at the Ladies' Mile borehole could be used within the proposed framework.

With continued use of the system, the operating agency will gain experience of catchment-response and will be able to determine appropriate trigger levels for the instigation of both the different steps in the system and also for the different levels of alert. Thus the timings of the initiation of the different steps given here are only recommendations and the users must determine more appropriate ones for their applications. Equally the timings of alerts and indeed the nature of published alerts must also be determined by the appropriate responsible authority.

PRELIMINARY STEP

Initially the nature of the catchment's response to recharge must be determined by consideration of the long-term hydrographs of various monitoring boreholes. If the hydrographs show that there is strong autocorrelation year on year (as in the Pang and Hallue catchments) then, as the next step of the system, in the summer months groundwater levels that are significantly above the average will be taken as an indication of an increased probability of groundwater flooding in the subsequent recharge season. In those catchments where there is little year-on-year autocorrelation (e.g. Brighton) then the lack of any above average groundwater level does not have a bearing on the probability of subsequent groundwater flooding. This first step is effectively a once only determination although it would be worth reassessing the determination every 5 to 10 years or so to see if hydrograph behaviour is changing for any reason.

STEP 1

The determination of the catchment's response to recharge (Preliminary Step) is a once only determination and thus the early warning system will normally be initiated in the summer months by consideration of the hydrographs of the key monitoring boreholes to see if groundwater levels are significantly above average. Having noted that in some catchments, including the Brighton catchment, hydrograph response year on year is such that summer groundwater levels return to a similar level (and even in the summer of 2000 gave no indication of the year on year increase in base level recorded in some other catchments such as the Pang), summer levels should still be monitored for any signs of unusual behaviour including an early onset of the recharge season. Any indication of above average groundwater levels indicates that subsequent winter groundwater levels will possibly be higher than average for average subsequent rainfall/recharge. Should subsequent rainfall/recharge be higher than average then the probability of groundwater flooding is increased. Step 2 is initiated once recharge has commenced thus allowing the minimum seasonal groundwater level at one or more key observation boreholes to be identified.

STEP 2

Following the onset of recharge and the identification of the minimum groundwater level for the current year, a statistical model to predict maximum groundwater levels at one or more key observation boreholes based on antecedent groundwater levels and assumptions about future rainfall is applied. The multiple linear regression method has been described in Section 6.4; annual groundwater level minima and the cumulative rainfall total between the annual minima and subsequent annual groundwater level maxima are taken as the two independent variables in the regression and the annual maximum groundwater level is taken to be the dependent variable. Section 6.4.4 describes three methods which could be used to provide the rainfall prediction.

Thus once this model has been run for a range of future rainfall scenarios, monitoring of the actual cumulative rainfall and reference to the model results will indicate what the resultant groundwater level might be. It must of course be realised that this approach does not directly indicate the likelihood of groundwater flooding but rather indicates what subsequent groundwater levels might be. The predicted groundwater levels need to be compared to those of previous flood events (e.g. as recorded in 2000-01) in order to assess the likelihood of groundwater flooding.

For practical purposes, because regression models tend to improve with more cases (years), it is recommended that the model is re-calibrated using all available data and that regression then used for prediction. As noted in chapter 6.4, this model enables maximum groundwater levels to be predicted up to a hydrometric season in advance, it requires limited modelling expertise, can be run on a spreadsheet and needs only limited commonly available data.

STEP 3

To some extent, the results from the application of the statistical model of the second step will determine the time of initiation of the third step. However, the third step is effectively running in the background at all times as it involves the monitoring of the degree of saturation of the unsaturated zone. As reported in Section 5.2.4, once the unsaturated zone reaches a critical saturation level, the groundwater table rises rapidly and this can give rise to groundwater flooding. Thus, once this third step is reached, the monitoring agency should be ready to raise the level of alert to those parties who would be affected by any groundwater flooding. Once this third step has been initiated the fourth step, must be run in parallel with it.

STEP 4

This step involves the monitoring of local weather forecasts. Any storm events which may occur in the catchment(s) concerned will have a significant effect on recharge and, depending on the state of the aquifer and the predicted magnitude of any forecast storm, it may be necessary to raise the level of alert even further.

It should be noted that in many catchments intense rainfall events of long duration may result in surface runoff flooding and will increase the possibility of groundwater flooding at almost any time. Therefore, weather forecasts should of course be monitored throughout the year for indications of extreme rainfall events that will impact on the groundwater regime.

SUMMARY

P Determine whether hydrographs from boreholes in the catchment show strong autocorrelation year on year (e.g. as in the Pang) or whether there is a consistent return to a general summer baseline level (e.g. as in Brighton).

1. Monitor summer groundwater levels - are they significantly above average? Initiate step 2 once recharge has started – i.e. when the hydrograph of the key observation borehole(s) has started to rise.

2. Use statistical modelling to determine probability of groundwater flooding.

3. Monitor the data on saturation degree of the unsaturated zone.

4. Monitor local weather forecasts.

7.3 TIMINGS OF LEVELS OF ALERT

The following are only suggestions as to when the level of alert should be raised. Also no indication is given of the nature of the alert that should be given to the public at any particular level; this is for the monitoring agency to determine.

Level 1. This is the normal situation when there is no indication that there will be any flooding in the coming winter

Level 2. This is the level of alert when summer groundwater levels are significantly higher than average (trigger level to be determined by operating agency) and/or the recharge season has started significantly earlier than average (again trigger date to be determined by operating agency).

Level 3. This level is initiated when the statistical modelling indicates that there is a significantly higher than average probability that groundwater levels will rise to levels equal to those recorded during previous groundwater flood events e.g. that of 2000-01 (trigger level to be determined by operating agency).

Level 4. To be initiated when saturation levels in the unsaturated zone are seen to reach a critical value (trigger level to be determined by operating agency) and/or the weather forecasting agencies are predicting imminent storm events in the catchment(s).

Level 5. The ultimate level of alert issued if level 4 has been achieved and the weather forecasting agencies are predicting imminent storm events in the catchment(s) and/or saturation of the unsaturated zone has been achieved but groundwater levels have not yet risen to flood event levels.

Whilst the early warning system has been described as a series of steps, it must be realised that in many catchments, extreme storm events at any time of the year may in some circumstances give rise to groundwater flooding. Thus warnings may be need to be raised to Level 4 or 5 should major storm events be predicted at any time – again this will depend to some extent on the experience of the monitoring/operating agency.

7.4 FURTHER DEVELOPMENT OF EARLY WARNING SYSTEMS FOR GROUNDWATER FLOODING

The system as described is qualitative in its current state and this is due to the fact that it has not been possible to test the system in practice. Also to test adequately the methodology would have required a groundwater flooding event occurring during the final stages of the project – something which did not happen. As the system is used the experience so gained will enable the operating agency to develop appropriate quantitative measures to replace the qualitative aspects. However, it will be necessary to review constantly such quantitative elements as they will need to be refined with time (as the experience of use increases). Thus it is recommended that the operating agency regularly reviews the use and operation of the early warning system in order to refine the different elements involved.

There is no reason why this system should not be translated to other chalk groundwater systems that are prone to groundwater flooding. It is recommended that this should be done on no greater than a catchment scale and, where there is much hydrogeological variation, on a sub-catchment scale. It will also be necessary to identify appropriate groundwater level monitoring points for each (sub) catchment.

8 In Conclusion

The FLOOD 1 project has succeeded in addressing the three main objectives of the project as described in section 1.

(i) As a result of the studies carried out in FLOOD 1, our understanding of the hydraulic behaviour of water flow in the unsaturated zone of the Chalk has developed significantly. It has long been known that the use of the term “unsaturated zone” for that part of the Chalk between land surface and the water table is, to some extent inappropriate, due to the high pore water content which cannot be drained due to the small pore throat diameters which are characteristic of chalk. The monitoring of pore tensions in the unsaturated zone of the Chalk has shown that, following recharge, a critical saturation can be reached which is immediately followed by a rapid rise in groundwater levels. In times of extreme recharge (as in the winter of 2000-01) this can lead to initiation of flow in high permeability horizons at shallow depths which are normally dry. Additionally the water table may even intercept the land surface. Both of these instances can give rise to groundwater flooding. Thus the groundwater flood triggering point postulated in the first project objective can be seen to be the critical saturation of the unsaturated zone. It should be noted that once flow in the unsaturated zone has been “triggered” there is still no reason to believe that drainage beyond the minimum saturation due to the narrowness of the pore throats can be achieved.

A major advance has been made in our understanding of the unsaturated zone of the Chalk from the observations made by CCTV and the subsequent monitoring of pore water tensions in the borehole at the North Heath Barn experimental site. The observed wetting up and drying out of borehole walls at key horizons in the unsaturated zone is believed never to have been observed before. Such flow has been postulated (e.g. Zaidman et al., 1999), but apparently never before observed.

(ii) Development of the MRS technique was undertaken solely by BRGM. Thus no detail of this aspect of the project is provided in this report. However, while the technique is not yet capable of monitoring variation content in water content of the unsaturated zone, significant progress was made in refining the sensitivity of the technique during the FLOOD 1 project.

The use of new CCTV equipment with high intensity LED lighting proved to be significant in providing a new insight into the movement of groundwater within the unsaturated zone of the Chalk. This was a fortuitous finding as the new CCTV equipment was only used following a delay in the planned installation date of the Jacking Tensiometers at the Brighton investigation site. The initial CCTV survey of the borehole had been carried out with older equipment which, because of its lower intensity of illumination, did not “see” the moisture on the borehole walls.

The Jacking Tensiometers provided quantification of the wetting-up and drying-out of the unsaturated zone as exposed in the Brighton and Pang investigation boreholes. The data acquired by these installations were critical to the development of our understanding of the hydraulic behaviour of water flow in the unsaturated zone. This equipment has provided a significant advance in our knowledge of the hydrogeology of the Chalk.

(iii) The project has been successful in producing an appropriate methodology for an early warning system for groundwater flooding in chalk catchments. Initially it is recommended that it should be applied to the Brighton catchment as there is an identified need for it and, as a result of the FLOOD 1 project, there is an appropriate infrastructure to support it. There is scope for further development of this application and this will depend upon a number of factors, not least the degree to which the Environment Agency (as the agency responsible for the provision of flood warnings) put the early warning system in place for Brighton.

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APPENDIX 1

The Project Advisory Group was comprised of the following people and organisations:

From the UK:

Raymond Coe, Black & Veatch

Martin Eade, Brighton & Hove City Council

Diana Williams, East Sussex Fire & Rescue Service

John Ellis, Environment Agency

Paul Shaw, Environment Agency

Paul Richems, Channel Tunnel Rail Link (Union Railways North Ltd.)

Colin Warren, Halcrow

David Patterson, Highways Agency

Lindsay Frost, Lewes District Council

Mike Millar, Southern Testing

Mike Packman, Southern Water

From France:

N.B. The French organisations represented on the Project Advisory Group tended to have different representatives at different meetings. Those listed below are the most recent representatives.

Philippe Rycek, Conseil Général de la Somme

Anne Siron, Conseil Régional de Picardie

Laurent Roy, DIREN Picardie.

APPENDIX 2

Chronology of reported groundwater flood and extreme weather events in Brighton

1850 - 2001 (presumed not comprehensive)

Year	Months	Source	Text	Location of Spring|(s)	Comments
1850	July	http://www.dundee.ac.uk/geography/cbhe/#searching	1850 July 17 "Storm at Brighton: A storm of lightning, thunder and rain, of almost unexampled violence, broke over Brighton. During the preceding days the temperature was very high. Indications of a coming tempest were discernible during the whole of the afternoon, and at about a quarter to 7 o'clock it burst over the centre of the town ... The rain came down in torrents, and the widest streets were turned into streams over their whole width. The torrents flowed down the steep streets towards the sea, and, being stopped by the embankments, laid the lower part of the town under water. The inhabitants were driven into the upper stories, the goods were floated out from the cellars and ground-floors, and the boats were brought from the salt to float for the first time in fresh water. By the aid of these the terrified refugees were rescued ..."		No mention of groundwater flooding
1877	Jan-25	Map from East Sussex County Council	The water all sank into the ground at this point on Jan 25 but before this it had run in very large quantities	TQ 297 092	1877 assumed as script style and colour same as for other 1877 entries
1877	Jan-31	Map from East Sussex County Council	About 360 gallons per minue ran past this point on Jan 26, 1877; but on Jan 31, no water ran here but there was water standing on the ground above.	TQ 298 092	

Chronology of reported groundwater flood and extreme weather events in Brighton

1850 - 2001 (presumed not comprehensive)

Year	Months	Source	Text	Location of Spring|(s)	Comments
1877	Jan-25	Map from East Sussex County Council	Water ranout of the top of this well	TQ 301 089	
1877	Jan-31	Map from East Sussex County Council	About 550 gallons per minute flowing past this point on Jan 26 1877. No water ran past this point on Jan 31 but sank into the ground at this point and higher up.	TQ 292 103	
1877	January	Map from East Sussex County Council	Extent of surface flows - furthest south surface flooding reached	TQ 300 075	
1888	August	http://www.dundee.ac.uk/geography/cbhe/#searching	1878 August Rainfall observer at Brighton (Buckingham Place) noted, p[47], "Rainfall 4.52 in., greatest in Brighton in any August during 30 years"		
1882	October	http://www.dundee.ac.uk/geography/cbhe/#searching	1882 October Rainfall observer at Brighton (Hove Town) noted (p[71]) "the largest amount of rainfall recorded as having fallen in Brighton in one month during 60 years; on 15th and 16th, 3.00 in fell., and from 20th to 22nd, 2.35 in."	No mention of groundwater flooding	No mention of groundwater flooding
1913	February 1 - 20	Map from public records office	Water commenced to run out of the ground from channel on both sides of the road, at this point, and ceased on Feb 20.	TQ 301 081	
1915	December 30 - January 21	Map from public records office	Water broke up on west side of roadway in footpath under flagstone opposite entrance gates to Ashburnham Dec 30 1915, & ran down west side of road. Estimated quantity about 1/2 million gallons per 24 hours. Ceased running Jan 21, 1916.	TQ 301 083	
1915	Dec-30	Map from public records office	Water broke up here and formed pond but did not run over the roadway southwards	TQ 298 092	

Chronology of reported groundwater flood and extreme weather events in Brighton

1850 - 2001 (presumed not comprehensive)

Year	Months	Source	Text	Location of Spring|(s)	Comments
1916		Map from public records office	Water ceased running at Sunnyside on Jan 24 1916. The last spot on the road where water ceased running	TQ 302 087	
1925	January 10 - 24	Map from public records office	Springs broke out Jan 10 ceased flowing about Jan 24	TQ 302 087	
1958		Binnie Black & Veatch Report 2001	Flooding where the bypass in Patcham now crosses the A23 road. Fire brigade installed a permanent pump, which removed flood water and remained pumping for over a year.		
1960		Binnie Black & Veatch Report 2001	The ground floor of the Park Court buildings flooded soon after being built before occupancy. 1960 floods not generally thought to be as bad as 2000.		
1962		Binnie Black & Veatch Report 2001	References to flooding in a letter to Mr. Harris from his father.		
1974		Binnie Black & Veatch Report 2001	Flooding in Patcham believed to include surface runoff.		
1988		Binnie Black & Veatch Report 2001	Reports of flooding in the basement of the BT building next to Southern Water Authority in Preston Park		
1995		Binnie Black & Veatch Report 2001	Flooding of basements which nearly but not quite reached the surface.		
2000	November	Binnie Black & Veatch Report 2001	Extensive flooding throughout Patcham caused by the emergence of springs and prolonged surface runoff. At least 15 properties inundated. A23 road and the main London-Brighton railway closed. Estimated cost of flooding impact (excluding closure of railway) £800,000.	TQ294 098	

Chronology of reported groundwater flood and extreme weather events in Brighton

1850 - 2001 (presumed not comprehensive)

Year	Months	Source	Text	Location of Spring|(s)	Comments
2001	February	Binnie Black & Veatch Report 2001	Cellars of houses in Old London Road begin to fill again. Groundwater also discharging to the surface from drain covers lower down the road.		