INVESTIGATING THE INTERDEPENDENCIES BETWEEN SURFACE AND GROUNDWATER IN THE OXFORD AREA TO HELP PREDICT THE TIMING AND LOCATION OF GROUNDWATER FLOODING AND TO OPTIMISE FLOOD MITIGATION MEASURES

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Abstract

In February 2002, the Environment Agency commenced a study to identify sustainable methods to reduce the flood risk in Oxford. Over 3,600 properties are within the floodplain of the Rivers Thames and Cherwell with a 1% (1 in 100) annual flood exceedance probability. During the early stages of the study, it was recognised that out-of-bank flows from the rivers was the most significant factor but that groundwater flooding could not be ignored. This paper addresses the output of a collaborative project that was set up between the Environment Agency and the British Geological Survey to address the groundwater issues and their impact on flooding.

Groundwater level in the shallow gravel aquifer that underlies Oxford responds rapidly to both fluctuations in river level and rainfall. During periods of high rainfall and river level, it is often the emergence of groundwater that is the first sign of flooding for many of the residents. In addition, in recent times, a significant number of properties have suffered flooding from groundwater; fluvial flow was not a factor. Where the latter was significant, the preceding and subsequent high groundwater levels often prolonged the period of flooding.

The aims of the joint project are to:

- better understand the groundwater system and its interaction with surface waters;
- identify the controls on groundwater flooding
- improve the prediction of the timing and duration of groundwater flooding; and
- provide tools to examine the potential flood risk management options.

The tools will also help to predict the impacts of the options on groundwater within the many ecologically sensitive sites in the floodplain.

This paper presents the project methodology and some of the initial findings.

1. Introduction

This paper highlights a collaborative partnership that was set up between the Environment Agency and the British Geological Survey (BGS) in connection with the Oxford Flood Risk Management Strategy.

The Environment Agency commenced the strategy in February 2002 and appointed Black & Veatch as the lead consultant. The aim was to identify options to reduce the flood risk in Oxford, where in excess of 3,600 properties are within the 1% floodplain of the Rivers Thames and Cherwell.

During the early stages of the study, it was recognised that groundwater flooding and the links to fluvial flooding were important considerations. BGS was already undertaking research on groundwater flooding in the south of the city, which was funded from its own research budget. An agreement was reached between the Environment Agency and BGS to collaborate on relevant groundwater issues throughout the whole of the study area. The joint project commenced in April 2005.

2. The Oxford Setting

The study area is the 1% floodplain of the Thames and Cherwell, with the downstream boundary at Sandford Lock on the Thames. The upstream boundaries are Eynsham and Marston on the Thames and Cherwell respectively; refer to Figure 1. The area is approximately 280 km² and includes 33 km of the River Thames and 9 km of the Cherwell. The centre of the city is situated on relatively high ground between the major rivers but there are several urban areas that encroach into the floodplain, which, as a consequence, are prone to flooding.

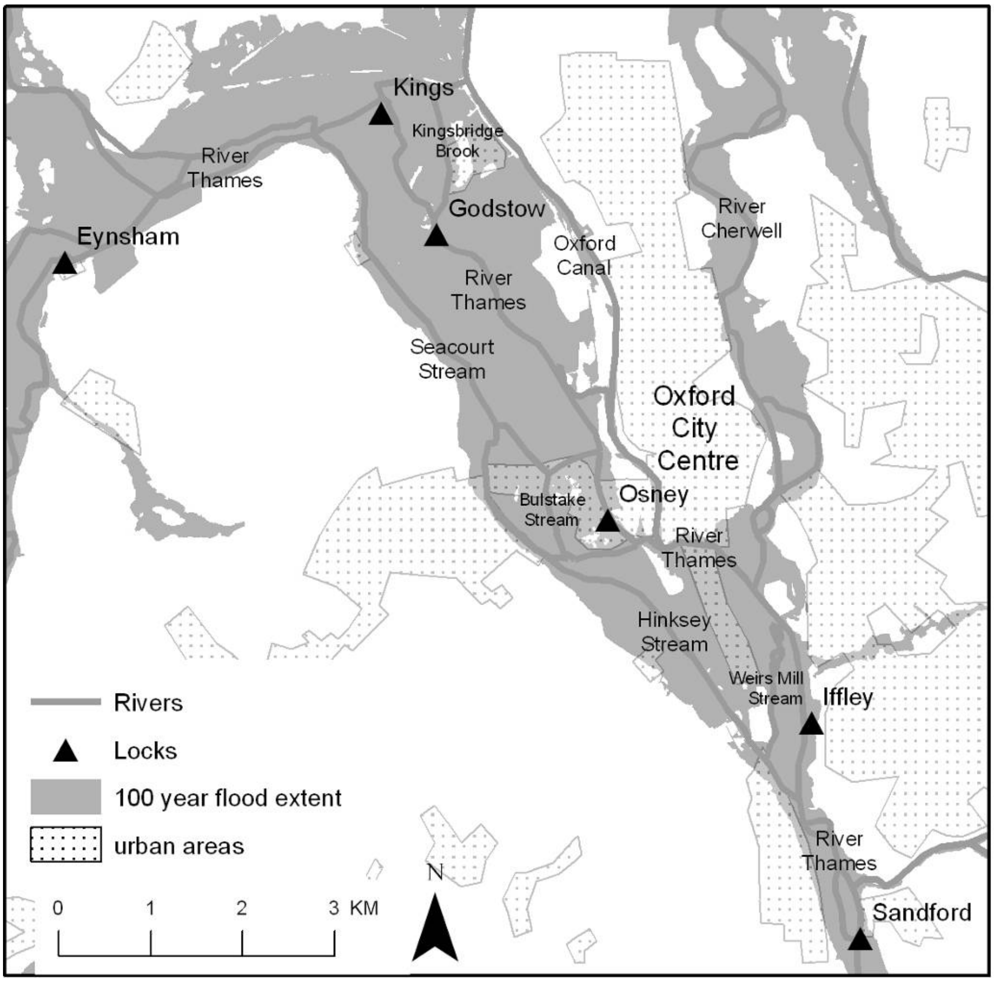

Figure 1 Oxford Flood Risk Management Study Area. BGS © NERC 2007. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007.

The study area is criss-crossed by numerous secondary watercourses, both natural and man-made. These provide an environment rich in marginal and aquatic habitats. The area is environmentally sensitive in terms of its ecological, heritage and landscape value, and contains a number of locally, nationally and internationally designated sites. To allow us to develop sustainable solutions, we need to understand these complex environmental baseline conditions and their interaction with or dependence on the water regime.

3. History of Flooding

There are written records of flooding which date back to the 13th century. More recently, the area suffered major flood events in 1894 and 1947. The latter was classified as a 2.5% event and resulted in internal flooding to more than 3,000 properties. Since then there have been a number of smaller events, such as December 2000 when 160 properties were flooded, and January 2003 when 250 were flooded. These events were classified as 10% and 6% respectively.

The minimum standard of protection currently provided in Oxford is 20%. A repeat of the 1947 event would lead to significant damages, bearing in mind the development that has taken place since that time.

4. Role of Groundwater in Flooding

The alluvial sediments that underlie the floodplain generally comprise 1m of silty clay and 5m of sands and gravels. They are underlain by the Oxford Clay throughout most of the study area. Older gravel terraces form the high ground on which Oxford city centre is built. Figure 2 shows the topography and drift geology of the area. The lateral extent of the drift deposits is limited at the southern end of the Thames catchment. This limits the flow of groundwater through the aquifer and causes high groundwater levels in that part of the study area.

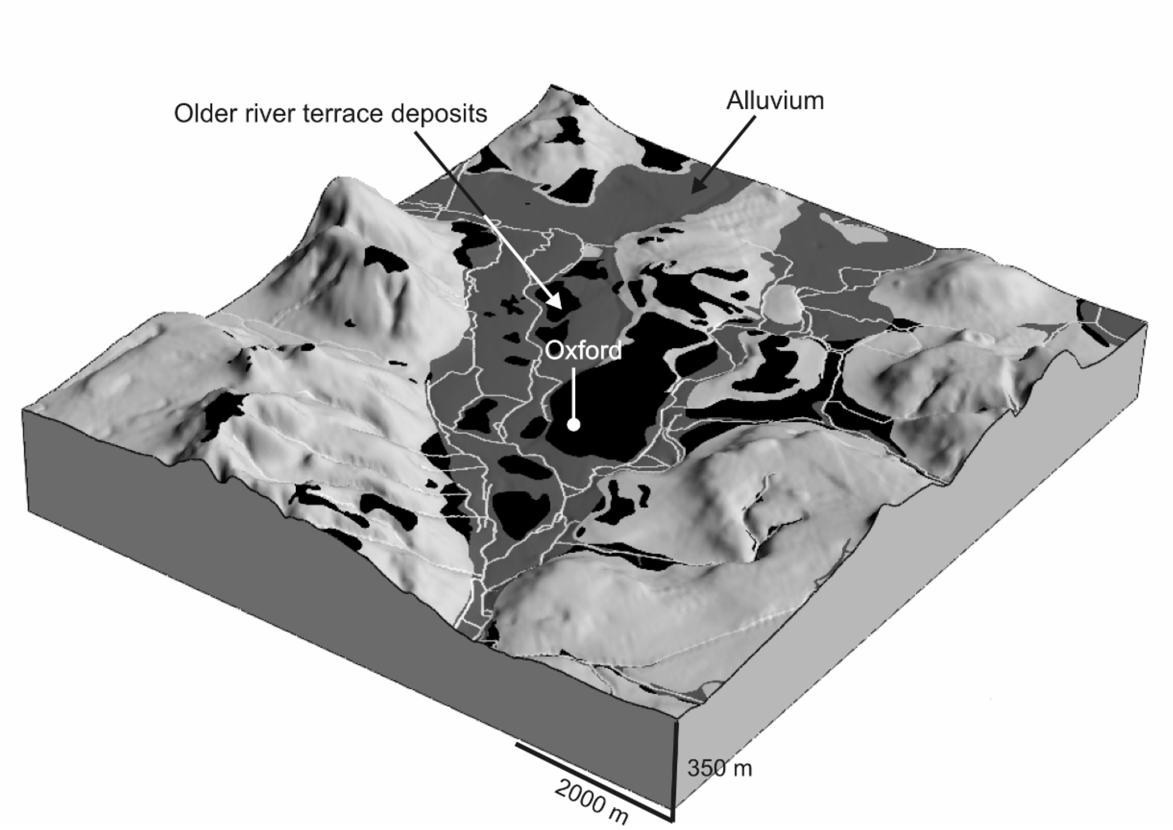

Figure 2 Topography, superficial geology and river network in the Oxford area. BGS © NERC 2007. Some features of this map are based on digital spatial data licensed from the Centre for Ecology and Hydrology (Moore et al, 1994). This map includes NEXTMap Britain elevation data from Intermap Technologies.

The groundwater levels in the aquifer are very shallow, typically less than 1m below ground in winter and 2m in summer. The aquifer is hydraulically well connected to the rivers and streams in the floodplain. Consequently, groundwater levels are sensitive to fluctuations in the river level and rainfall. Groundwater flooding is often an early indication that more extensive flooding is likely to occur.

During the December 2000 and January 2003 events, a lot of properties only suffered from groundwater flooding. Following the December 2000 event, a questionnaire was issued to the 3,664 properties in the floodplain. A large proportion of the 461 responses identified groundwater as a significant contributor to the flooding; refer to Figure 3. The pre-war properties were usually constructed with basements and in time many residents converted these into living areas. A number of such properties were flooded as a result of high groundwater levels and many more came close to being inundated, as evidenced by ponding in their gardens.

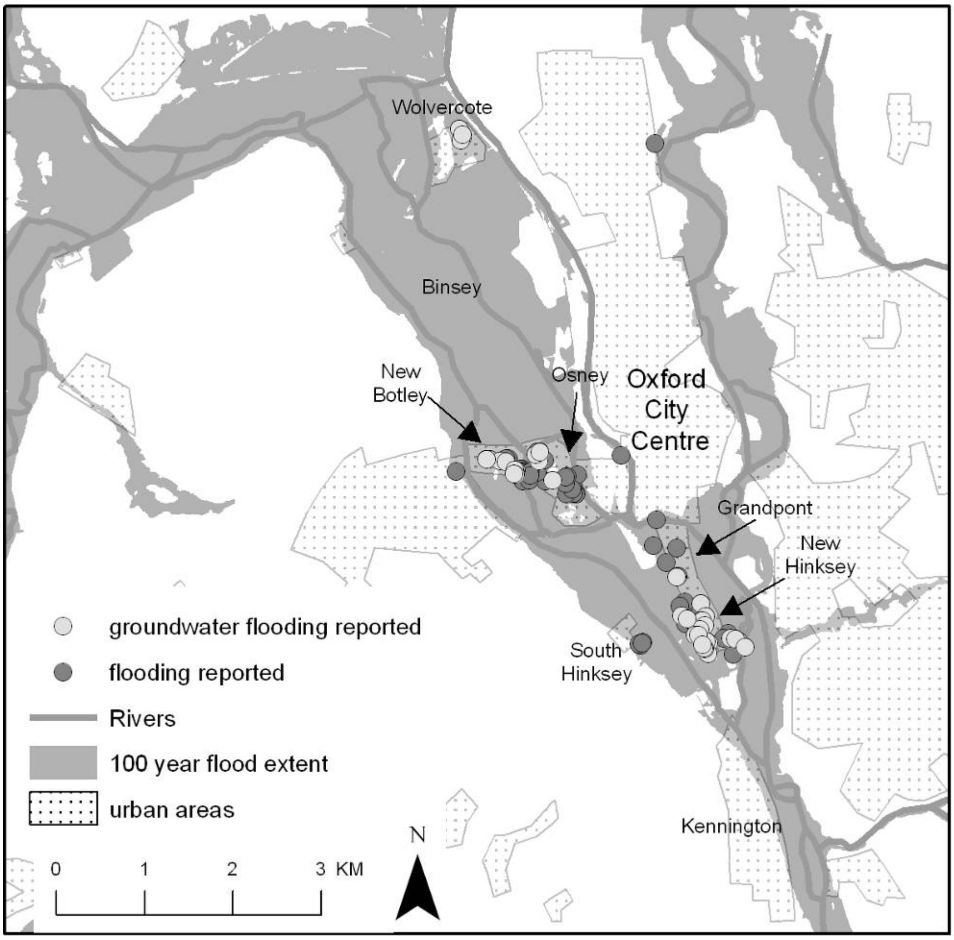

Figure 3 Responses to the Environment Agency questionnaire on the flooding in December 2000, showing where indication of groundwater was given. BGS © NERC 2007. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007.

5. Environmental Sensitivity of the Oxford Area to Groundwater Changes

Environmental survey work has shown the study area is sensitive to groundwater conditions, both in terms of its ecological balance and archaeology.

There are eight Sites of Special Scientific Interest (SSSI) in the study area; refer to Figure 4. Six of these are lowland grassland flood meadows, which are adjacent to watercourses. They could be impacted on by changes to the flow regimes as a result of any works. Four of the SSSIs, namely Pixey and Yarnton Meads, Port Meadow and Wolvercote Common and Green, Cassington Meadows and Wolvercote Meadows, are conglomerated as Oxford Meadows Special Area of Conservation (SAC).

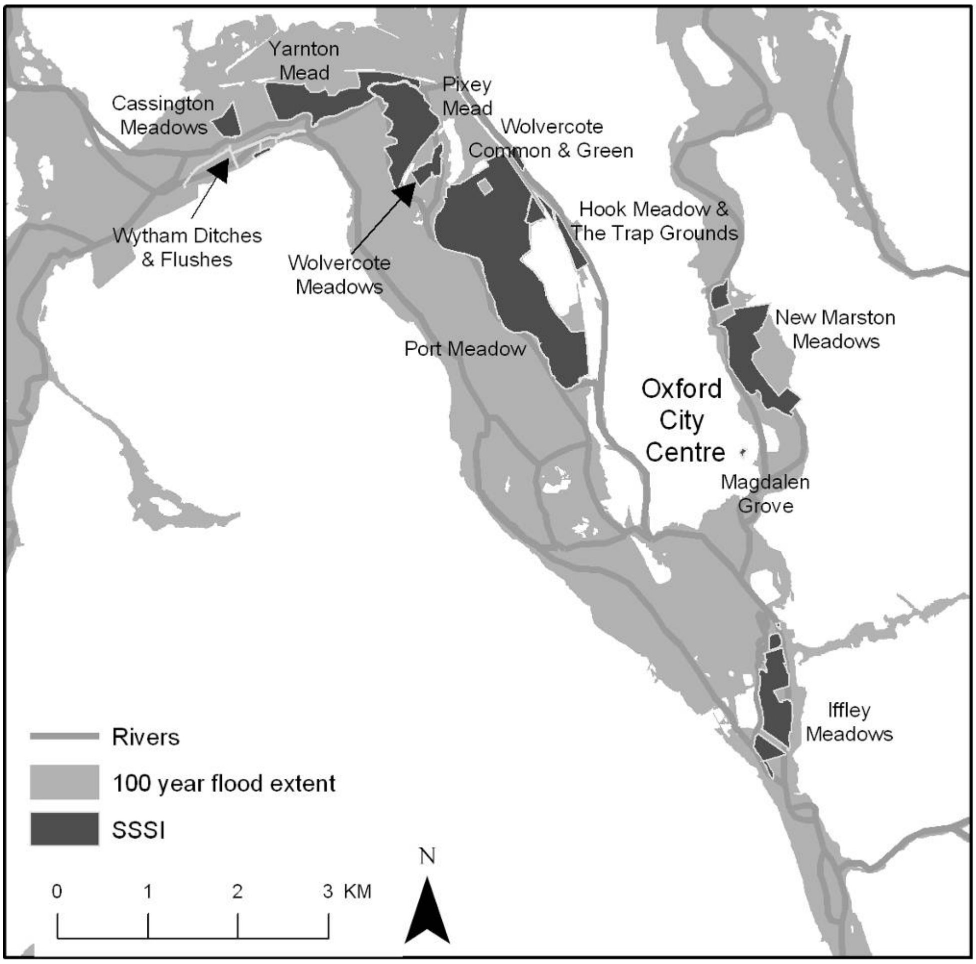

Figure 4 Special Areas of Conservation (SAC) and Sites of Special Scientific Interest (SSSI) within the Oxford floodplain. BGS © NERC 2007. SSSI outlines are © Natural England. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007.

The SAC includes vegetation that is internationally unique and reflects the influence of long term grazing and hay-cutting on lowland hay meadows. Port Meadow is internationally designated as the only known site in the UK which supports a long term, non-introduced population of the protected Annex 2 species, creeping marshwort (*Apium repens*)[1]. The others are examples of MG4 lowland hay meadow habitats[2].

The nature conservation interest in each SSSI within the SAC is dependent on the flooding regime, particularly to frequent seasonal flooding. The sites are linked in some way to the surface water and groundwater systems. The water regime is considered to be an important factor for the conservation of MG4 grassland (Brooks *et al*, 2004) and, therefore, it is important that we have a clear understanding of it. A recent study[3] investigated the requirement for water level management for the survival of creeping marshwort on Port Meadow SSSI. This showed that groundwater plays a dominant role in the hydrology of the site, in conjunction with surface water flooding from the River Thames. Frequent out of bank flooding is also thought to play a role in providing important nutrients that support the interest features of these designated areas. We are also aware that any major alterations to river levels may impact on the surface water flooding and/or groundwater supply, unless carefully managed.

The archaeological assessment of local Site and Monuments Records Data and National Schedule Monuments records in Phase 1 of the study has shown a wealth of historically significant

[1] classified as an Annex 2 Species under the EC Habitats Directive
[2] classified as an Annex 1 Habitat under the EC Habitats Directive
[3] Gowing and Youngs (2005)

archaeological remains, the preservation of which are deemed to be dependent on groundwater levels and flooding regimes. The changes to groundwater levels that result from implementing flood risk management measures need to be thoroughly understood to ensure the preservation of these sites. Borehole data from groundwater investigations within the study area will help define the environmental conditions of the current conservation environment. This will help us understand the groundwater balance within the system to ensure the continued conservation of these significant cultural heritage remains.

6. Addressing groundwater in the Oxford FRM Study

The vulnerability of urban areas to groundwater flooding in Oxford has been highlighted. Discussions with the local residents have demonstrated that those living in these vulnerable areas are well aware of the role that groundwater plays during flood events. It is clear that any scheme must recognise the risk of groundwater flooding and evidence must be provided to back up the Environment Agency's approach. For example, raised defences may not be appropriate if the resulting increased peak river levels or area of managed flooding adversely impacts on groundwater flooding.

In addition, we have highlighted the sensitivity of the ecology in the floodplain to changes in groundwater levels. Options to reduce flood risk must not adversely impact on groundwater levels in the vicinity of the designated sites. There is the potential that options which focus on periods of high river flow could increase groundwater discharge during the remainder of the year and reduce groundwater levels in ecologically sensitive areas. Any option must satisfy Natural England and there must be no detrimental effects. We have already started collecting baseline water levels against which we will assess the impact of the options.

7. Jointly Funded Environment Agency/BGS Project

BGS is a component institute of the Natural Environment Research Council (NERC), from which it receives funding directly to carry out its science programme. Process-research on groundwater flooding forms a component of its current five-year programme, which is due to be completed in March 2010. Prior to discussions with the Environment Agency, BGS had initiated a small research project which focussed on the south of Oxford. The joint project was initiated in April 2005.

8. Methodology

The project is based around the following activities:

Bringing together the existing data: Work to understand the relationship between surface water, groundwater and ecology in the study area, has been underway for more than 25 years. The principal focus of this is the Oxford Meadows SAC. In particular, the impact of dewatering associated with gravel extraction and a drought order that would allow abstraction from the River Thames upstream of Eynsham. The data are being collated and archived by BGS for collaborative use.

Setting up of a monitoring network: The existing coverage of groundwater and surface water level monitoring points was expanded. The centre of the city is situated on relatively high ground between the major rivers but there are several urban areas that encroach into the floodplain. This is particularly the case in the south of the study area where monitoring was almost totally absent; refer to Figure 5. Over 150 groundwater sites and some 50 surface water sites are now routinely monitored across the area. Digital water level recorders are installed in 52 of these.

Development of a conceptual model of groundwater system: The available data, including water levels obtained through the monitoring network, will help to better understand key aspects of the groundwater and surface water system. There are limited data available for low probability events, although a substantial amount of data were collected during the flooding earlier this year. The development of the conceptual understanding has been aided by the creation of a 3D geological model, which is based on the large amount of data for the area in BGS's borehole geology database.

Development of a groundwater model potentially linked with the River Thames model that adequately simulates flooding events: The processes identified through the development of the conceptual model will be incorporated into a groundwater model of the system. The ZOOM object-oriented groundwater computer model (www.bgs.ac.uk/science/3Dmodelling/zoom.html) was jointly developed by BGS, the Environment Agency and the University of Birmingham. It will be developed further during the course of the project to simulate processes relevant to flooding, such as responses to time-variant river stage and recharge from flood waters. It is hoped that a linkage can be established between the ZOOM model and the Agency's ISIS model of the River Thames through Oxford, although the difficulties in doing this are recognised.

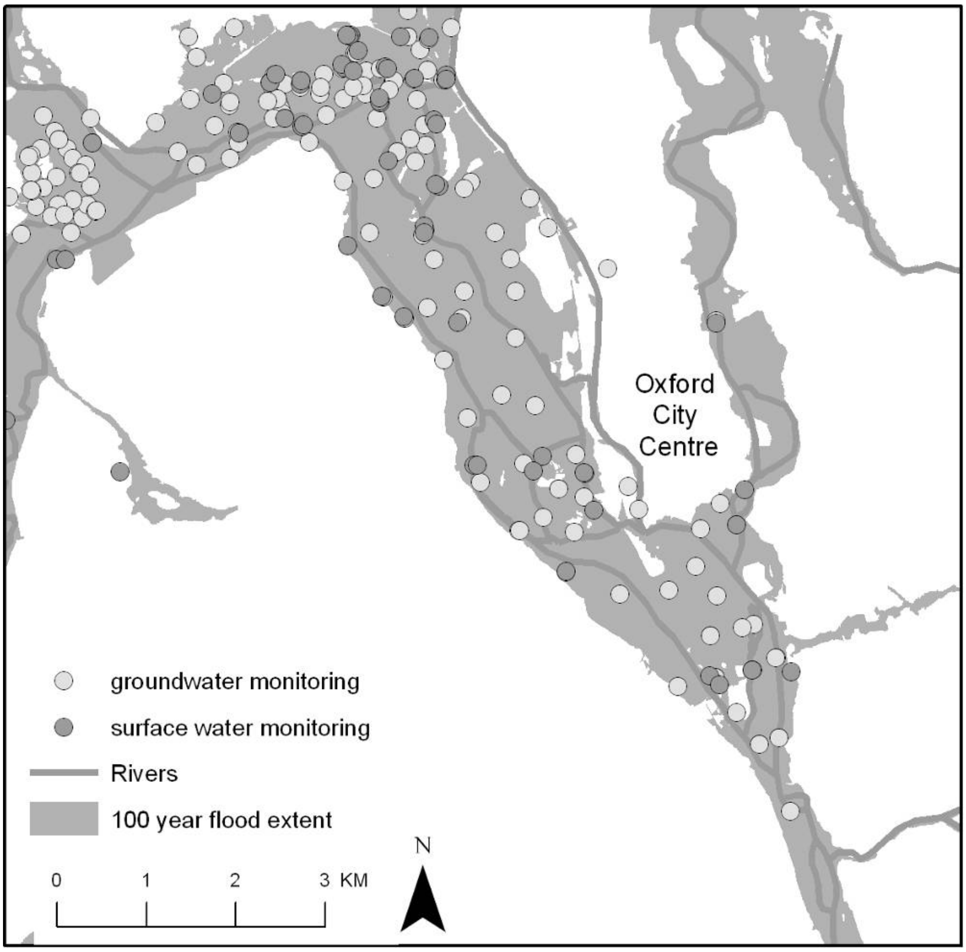

Figure 5 Groundwater and surface water level monitoring network in the Oxford area. BGS © NERC 2007. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007.

9. Results to Date

Data collected from the monitoring network have provided an insight into the dynamics of the groundwater and surface water system. Observations to date include:

- groundwater levels respond rapidly to rainfall, particularly in the parts of the floodplain where the unsaturated zone is thin; refer to Figure 6;

- heavy rainfall often results in a perched water table in the alluvium with a distinct higher head to that in the gravel aquifer. Following the rainfall, the perched water table dissipates over the subsequent days; refer to Figure 7;

- the hydraulic connection between the rivers, streams and the underlying aquifer appears good over most reaches. This is illustrated by the change in groundwater levels resulting from a rise in the level of the Bulstake Stream following an intense period of rainfall. The rise in stream level was 0.8 m with a corresponding rapid rise in the nearby groundwater levels; refer to Figure 8.

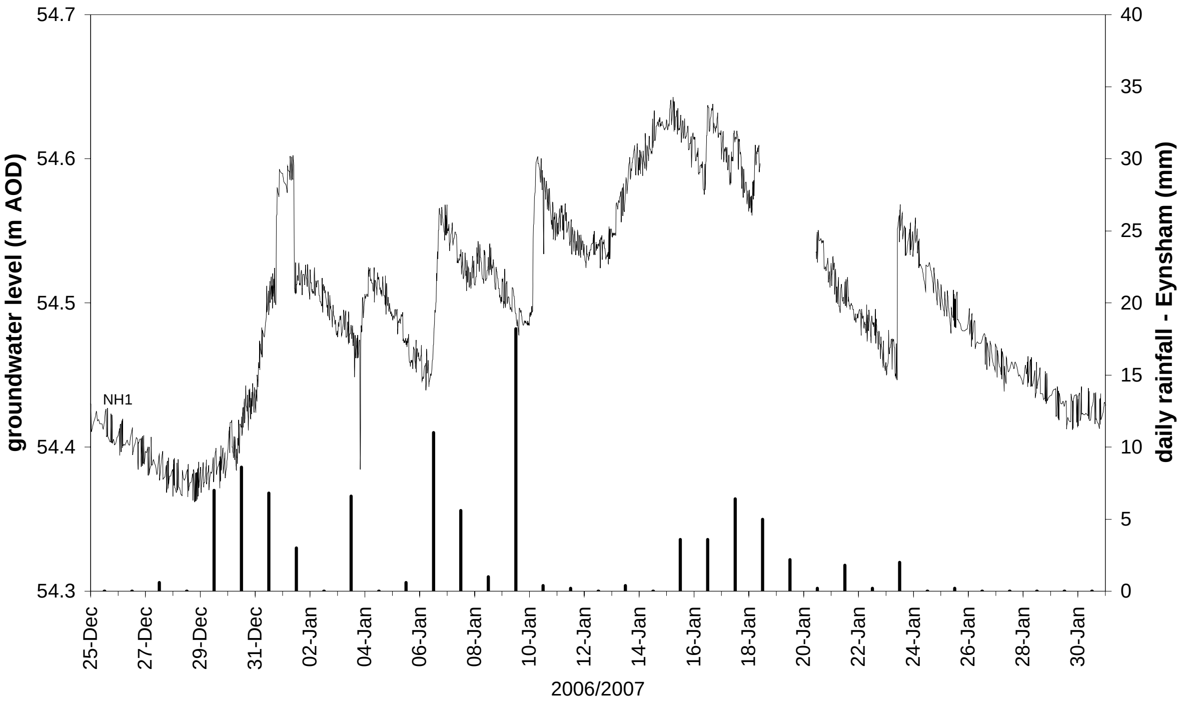

Figure 6 Groundwater level in a borehole in the New Hinksey area of Oxford showing the rapid response to rainfall (n.b. only daily rainfall data from Eynsham Lock were available at the time of publishing this figure).

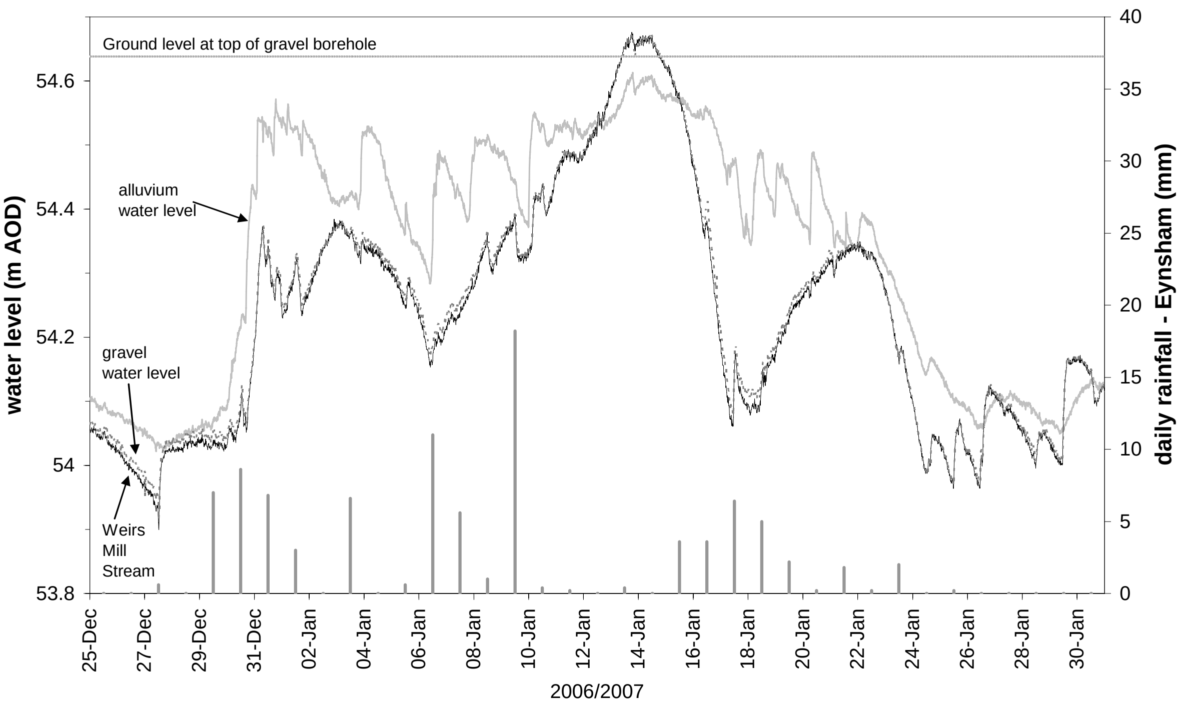

Figure 7 Water level in the Weirs Mill Stream and groundwater levels in nearby holes into the alluvium and gravel aquifer comparing the response to rainfall of the water level in the two layers (n.b. only daily rainfall data from Osney Lock were available at the time of publishing this figure).

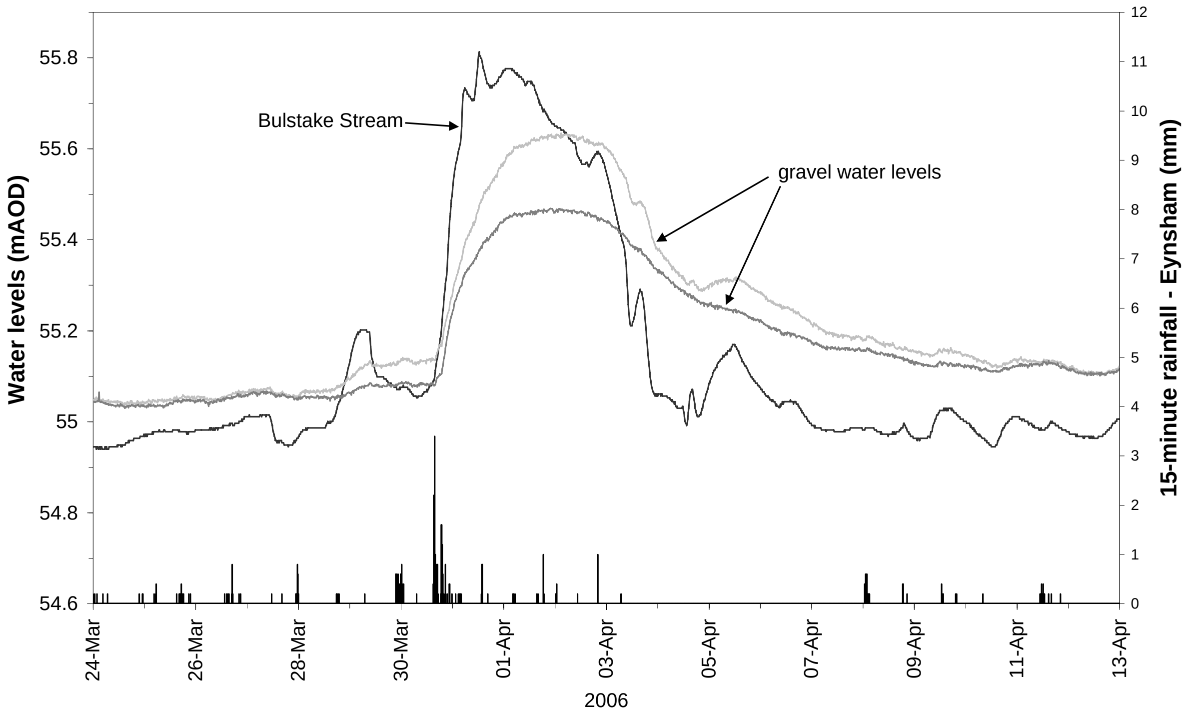

Figure 8 Water level in the Bulstake Stream and groundwater levels in nearby boreholes in the gravel aquifer illustrating the response of groundwater level to fluctuations in river level (n.b. 15-minute rainfall data from Eynsham Lock).

The monitoring data have allowed contour maps of groundwater levels to be drawn which, in conjunction with previous studies, have allowed a better understanding of the broad flow patterns; refer to Figure 9. For example: -

- in the upstream part of the study area, groundwater is recharged from the River Thames and flows towards the Kingsbridge Brook and the Seacourt Stream;

- at Port Meadow, groundwater flows west from the floodplain margins underneath the meadow and the River Thames, and discharges to the Seacourt Stream. It is likely that the higher level terraces which underlie central Oxford to the east provide some recharge to the floodplain gravels;

- the Seacourt Stream drains the gravel aquifer along its full length;

- in the south of the study area, downstream of the Botley Road, groundwater gradients are relatively shallow. Although Hinksey Stream again drains the gravel aquifer outside of high flow periods, its impact on groundwater levels is less significant;

- generally the locks on the River Thames, namely King's, Godstow, Osney, Iffley and Sandford, create local groundwater recharge zones in the upstream areas. Conversely, the by-pass channels are often lines of discharge.

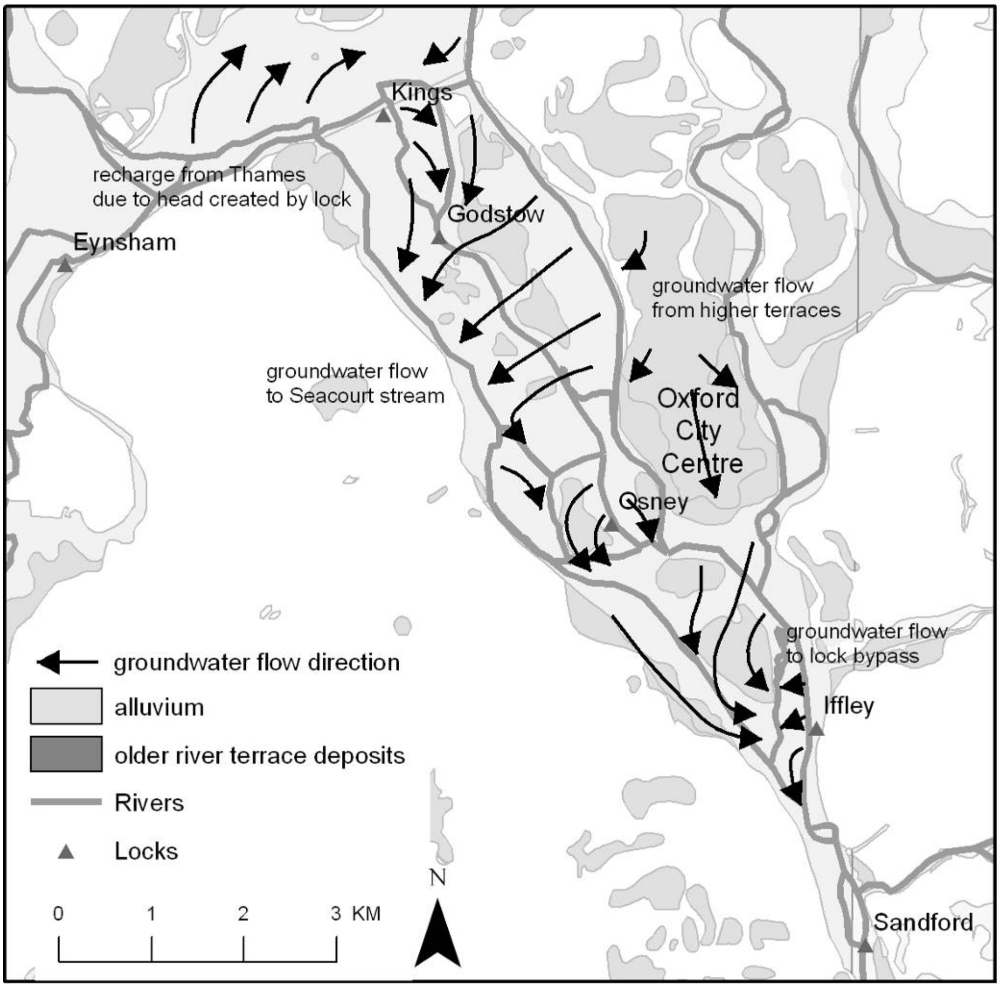

Figure 9 Conceptual groundwater flow model for the Oxford area. BGS © NERC 2007. This map is reproduced from Ordnance Survey topographic material with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2007.

The conceptual model of the steady state flow within the aquifer is the basis for developing a computer model that can be used to assess the impact of the flood risk management options. Currently the modelling has been limited to developing a groundwater recharge layer.

In January 2007, a 33.3% flood event occurred in the Oxford area and data were collected through the monitoring network. At the time of writing this paper, not all data were available and there had been little opportunity to analyse the available data. However, Figure 10 illustrates a general observation on the event. This shows the water level in the Hinksey Stream to the west of the New Hinksey area. The stream was out-of-bank for the period 10 to 17 January. A groundwater level is taken from a borehole in a garden in New Hinksey, 330m to the east of the stream. During the 2003 event, this garden was flooded to a depth of approximately 0.6m.

Although only daily rainfall data is available, the plot shows how responsive the groundwater level is to rainfall. At this stage, it has not been possible to separate the impact of the flood waters on the groundwater level in the New Hinksey borehole, however, any rise would appear to be limited in the context of groundwater flooding. The other point of interest is that the groundwater level in the borehole in the gravels adjacent to the river is higher than the river level. This is surprising given that the working assumption is the river controls groundwater levels. This effect is seen elsewhere on the Seacourt/Hinksey Stream, where the stilling well and borehole are paired. One explanation is that the connection between the stream and gravels is stronger at some point further upstream. Other examples exist elsewhere where groundwater levels are higher than the overlying flood water levels. Analysis of these and other data continues.

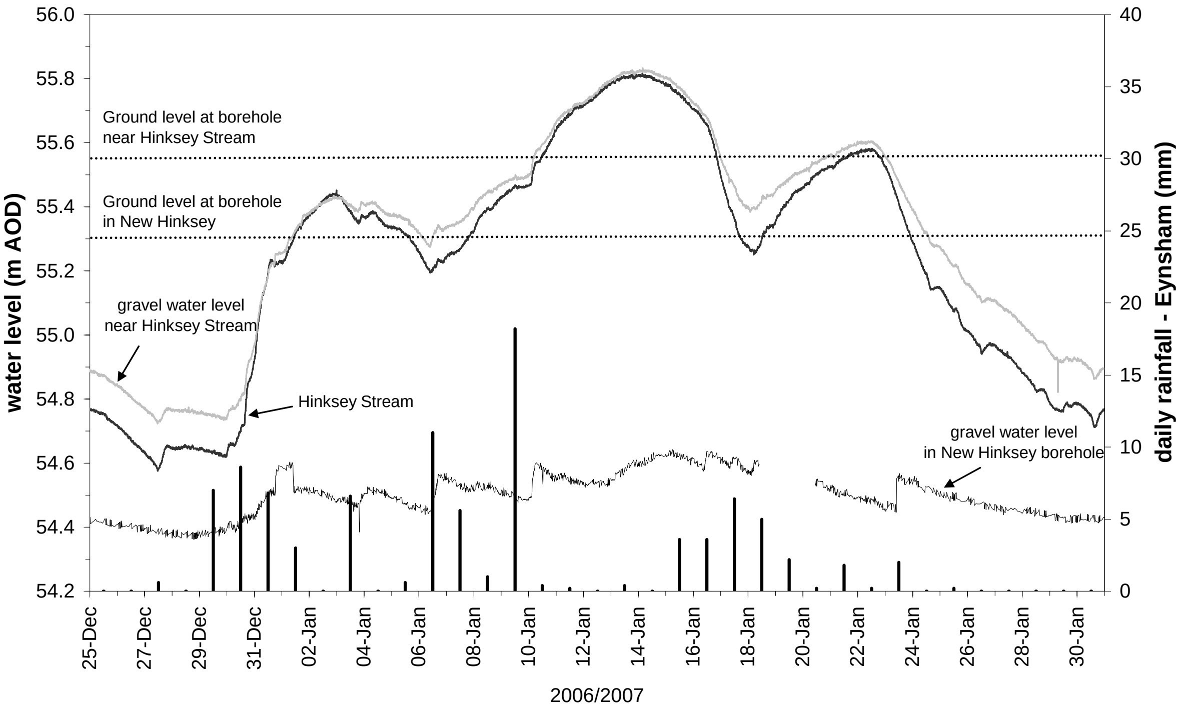

Figure 10 Water level in the Hinksey Stream and groundwater level in a nearby borehole into the gravel aquifer during the January 2007 flood event compared with groundwater level in a borehole into the gravel aquifer in the New Hinksey area approx. 330 m from the Hinksey Stream (n.b. only daily rainfall data from Osney Lock were available at the time of publishing this figure).

11. Summary and future work

This paper explains the importance that groundwater plays in the flooding of Oxford and its relevance to the options to manage flood risk. Our current understanding of the interaction of groundwater and surface water is presented, together with some observations on how the system responds during periods of flooding. The groundwater system is highly responsive to rainfall and to fluctuations in river levels. Analysis of the relative degree and timing of these two sources of groundwater recharge during flooding will continue.

The Environment Agency is collaborating with local experts to jointly solve a local problem and engage with a wider range of affected people and organisations. The team will continue to gather data and review options, with the aim of presenting a robust plan in 2010 to reduce the risk of flooding in Oxford. Partnerships of this nature are important to ensure that all risks are thoroughly reviewed and potential innovative solutions researched. These partnerships, when carefully managed, reduce overall costs and provide benefits to both scientific research and the practical requirement of reducing flood risk.

Acknowledgements
A number of maps in this paper are based on BGS's maps. The Ordnance Survey topographic maps are reproduced with the permission of The Controller of Her Majesty's Stationery Office, © Crown Copyright. All rights reserved. Licence Number 100017897/2007. The study is partly funded by the Natural Environment Research Council and is published with the permission of the Executive Director, British Geological Survey (© NERC 2007). Data are also included within that are © Natural England, © CEH and NEXTMap Britain elevation data from Intermap Technologies. Details of these data are included on the relevant figures.

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