Groundwater flooding within an urbanised floodplain

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Abstract

In Europe in recent years there has been a recognition of the need to better understand the risk from groundwater flooding. This recognition has been due both to the occurrence of major flooding events clearly attributable to groundwater, and the inclusion of groundwater flooding in European and national legislation. The case study of the city of Oxford on the River Thames floodplain in the United Kingdom is used to examine the mechanisms for groundwater flooding in urbanized floodplain settings. Reference is made to an extensive dataset gathered during a major flood event in 2007. Groundwater flooding of a significant number of properties is shown to occur in areas isolated from fluvial flooding due to high ground created historically to protect property and the transport network from flood inundation. The options for mitigating this form of flooding are discussed; measures to increase the rate of conveyance of flood waters through Oxford, designed to reduce fluvial flood risk, have also been recognized as a means for reducing groundwater flood risk within the city.

Key words

floodplain, flood mitigation, groundwater, groundwater flooding, urban flooding, Oxford, River Thames

Introduction

Groundwater flooding is the emergence of groundwater at the ground surface away from perennial river channels and can also include the rising of groundwater into man-made ground, including basements and other subsurface infrastructure (Macdonald *et al.* 2008). The impact of groundwater flooding can be severe under conditions where the 'normal' ranges of groundwater level and groundwater flow are exceeded. In Europe, the risk from groundwater flooding has received more attention since its inclusion in the EU Floods Directive (2007/60/EC). The Directive, which came into force in November 2007, includes provisions for: assessing the risk from groundwater flooding (Cobby *et al.* 2009), producing groundwater 'flood hazard maps' and introducing measures to address any significant risk. The inclusion of groundwater within the Directive follows serious groundwater flooding events in the past decade. The impact of groundwater flooding has been most severe in areas of Chalk outcrop and in the floodplains of major rivers. Groundwater flooding in Chalk catchments occurs where antecedent conditions of high groundwater levels and high unsaturated zone moisture content combine with intense rainfall. Groundwater level rises of up to tens of metres can result causing significant flows in dry valleys in localities remote from floodplains. High groundwater levels often persist due to extended periods of drainage from the unsaturated zone causing prolonged flooding (Pinault et al

2005). Examples include the flooding in 2000 and 2003 in southern England (Finch *et al.* 2004) and the Somme Valley (Negrel and Petelet-Giraud 2005).,

The focus of this paper is groundwater flooding in the floodplains of major rivers. Where the deposits associated with floodplains are permeable, these are generally saturated to levels close to the ground surface and hydraulically well-connected to the associated rivers. Here, groundwater can contribute significantly to river flow during summer months and extended dry periods; in wetter periods, rivers can be effluent, recharging the floodplain sediments. During periods of increased flow, and before the banks are overtopped, the naturally high ground of river levees can contain river water while low-lying ground beyond can be flooded due to rising groundwater. In the case of the River Danube floodplain in 2008, damage occurred to buildings due to the water pressure on basements resulting from abnormally high groundwater levels associated with high river levels (Kreibich and Thieken 2008). The onset and recession of groundwater flood events in this type of setting is typically much shorter than that in Chalk catchments.

Floodplains in the past have been attractive locations for urban development for reasons such as their coincidence with sources of water and food, their potential for cultivation and their proximity to transportation routes (Montz 2000). Where settlements were originally located on high ground within or close to river valleys these have inevitably spread onto the floodplain. Historically this development has often continued even with the threat of frequent flooding. In urban areas on the floodplain a cycle can develop in which defences to protect property and infrastructure from flooding increases the general risk from flooding, for example by removing flood storage and hence raising flood levels, which in turn requires more substantial defences. In recent times the folly of continuing this cycle has been recognized and a move made towards working with natural processes to manage the risk of flooding rather than trying to remove it (Fleming 2002).

The topographical changes to floodplains resulting from urbanization can have a significant influence on the location, timing and extent of groundwater flooding. This can make the assessment of risk highly complex. Identifying measures to reduce the risk of groundwater flooding as part of overall flood risk management schemes is challenging. A case study is reported here of the city of Oxford in the United Kingdom, which is located on the floodplain of the upper reaches of the River Thames. Groundwater flooding has been recognized in the city as a component of the overall flooding story (Macdonald *et al.* 2007). The Oxford case study is used as a means to examine the risks from groundwater flooding and the options for mitigating these risks in an urbanised floodplain.

Background

The city of Oxford is situated within a relatively narrow valley of the upper reaches of the River Thames (Figure 1). The floodplain is on average 2 km wide, however it narrows downstream to only 0.5 km. Although most of the city is located on older river terraces and bedrock above the current floodplain, from the late 19th century pressure for housing near to the city centre resulted in significant urban development on the floodplain; it is estimated that currently approximately 3400 primarily residential properties and a large number of commercial properties are located within the 100 year return period flood event envelope as defined by the Environment Agency. The urban areas of Oxford have historically suffered from serious flooding. There were relatively few major flood events in the second half of the twentieth century, however, in recent years there have been four notable floods over the period of a decade, in April 1998, December 2000, January 2003 and most recently in July 2007. The Oxford floodplain is underlain by permeable shallow sands and gravels (Figure 2) and a significant number of properties were affected by flooding from rising groundwater which was either the sole cause or the initial cause prior to inundation from fluvial waters.

In February 2002 the Environment Agency of England and Wales commenced the Oxford Flood Risk Management Study (OFRMS) to identify options to reduce the flood risk in Oxford within the 100 year return period floodplain of the River Thames and its tributary the River Cherwell (Ball *et al.* 2008). During the early stages of the OFRMS it was recognised that groundwater flooding and the links to fluvial flooding were important considerations. Together with the British Geological Survey, a jointly-funded research project was initiated in 2005 on the controls, location and timing of groundwater flooding in the city. The insights from this project have informed the choice of proposed flood mitigation measures.

In July 2007 serious flooding took place within the floodplain of the River Thames in Oxford. This was the result of a moist, subtropical airmass moving slowly north over central England resulting in extreme rainfall on 19 and 20 July. Some of the highest total rainfalls occurred in the headwaters of the River Thames, for example, 140.1 mm in 24 hours in Chastleton, Oxfordshire (Marsh and Hannaford 2008). This rainfall event followed what was the wettest summer in England & Wales since 1912. Resulting flow in the River Thames to the south of Oxford at Sandford peaked at 224.8 m^3/s; this was the maximum flow at this location in 2007 and the fifth highest annual maximum flow since 1894. The peak river flow in Oxford occurred approximately five days after the rainfall event. The total rainfall in Oxford itself for the 19 and 20 July was measured at 60.6 mm. The monitoring in place for the groundwater flooding element of the OFRMS was able to capture the impacts on water levels of the July 2007 event and provides the primary reference for this paper.

Methodology

The approach taken within the Oxford study was to develop a baseline understanding of the river and groundwater system and use any flood events that occurred during the study period to explore the potential role of groundwater in flood events covering a range of return periods. The components of the study are described here.

Topographic data

In 1995 the Environment Agency undertook a topographic survey of the floodplain using LIDAR (Light Detection and Ranging), an optical remote sensing technology that measures ground elevation to centimetric accuracy (Cracknell and Hayes 2007). Amongst other applications within this study, LIDAR data provided a means to assess the urban build-up on the floodplain and its impact on flood pathways and the potential for groundwater flooding.

3-D modelling

A 3-dimensional geological model of the floodplain superficial deposits in the study area was built to aid the conceptualising of the shallow groundwater system and to enable the potential storage capacity of the aquifer to be assessed. The model comprises three layers, including made ground, alluvium and the underlying sands and gravels. The base of the model over the majority of the study area is the Oxford Clay, a Jurassic argillaceous sedimentary rock. ArcGIS, in conjunction with the 3D visualization packages GSI3D (Kessler *et al.* 2009) and GOCAD, were used to construct the model. Borehole logs were used to create a series of cross sections with. surfaces produced by interpolation between the sections. The layers within the geological model were attributed with estimates of storage coefficient made during previous studies within the Oxford floodplain (Institute of Hydrology 1987, Dixon et al 1990, Gardner 1991). The geological model was then combined with groundwater level surfaces contoured using measured groundwater and surface water levels.

Monitoring network

An extensive network of groundwater and surface water level monitoring points exists within the Oxford floodplain resulting from this and previous studies. At some sites monitoring has been undertaken since the early 1980's (Institute of Hydrology 1987). Manual monitoring of water levels was undertaken on a monthly basis between 2005 and 2009; the total number of monitoring points at the end of 2009 was 235. Digital water level recorders were installed in 51 of these monitoring points. At a number of sites there are combinations of two or more of the following: piezometers completed in the gravel aquifer; piezometers completed in the overlying alluvium; surface water stilling wells; and flood water recorders. Data were made available from recorders installed in the upstream and downstream waters at four of the Environment Agency locks in the study area. During the July 2007 flood a further six temporary manual flood water monitoring points were established, which provided additional data in urban areas for the rise and recession of flood waters during the event. As well as water levels, river flows are routinely measured within the study area by the Environment Agency on the River Thames and its tributaries, the Rivers Evenlode and Cherwell. Rainfall is measured on a 15-minute interval at two of the locks. There is also a long rainfall record from the Radcliffe Meteorological Station at Oxford.

Flood observation and impacts

During the period of the study one major flood event (July 2007) and a number of minor floods occurred. Observation during floods is crucial in understanding flood mechanisms. Flood sources and pathways can vary over the period of a flood and a monitoring network cannot feasibly capture all of this for a study area as large as the Oxford floodplain. A questionnaire sent out by the Environment Agency following the December 2000 flood event captured some information on the occurrence of groundwater flooding but generally it is hard to obtain such information; in addition to the reluctance of owners to provide information on the impact of flooding on their property, it is often difficult to identify with confidence that the source of flooding is groundwater. Information was obtained on possible locations of groundwater flooding in 2003 and 2007 based on residents' observations.

Flood mapping

A national assessment of groundwater flood susceptibility undertaken by the British Geological Survey (McKenzie et al 2010) includes the River Thames floodplain in the Oxford area within its 'very high' category, i.e. it has mapped the underlying superficial geology as permeable and the groundwater levels within two metres of ground level. An attempt was made to improve on this broad-scale assessment in Oxford and to quantify risk rather than just susceptibility. Although separate river (1D and 2D) and groundwater models have been developed for Oxford, attempts to link these to enable simulation of the river-aquifer response during flood events is still in the development stage.Preliminary mapping of groundwater flood-prone urban areas was attempted based on the understanding of flood mechanisms gained during the study. LIDAR data were used to identify those low-lying urban areas that are isolated from fluvial flooding, at least for low return period events or in the early stages of higher return period events. For these areas, the minimum level at which groundwater flooding could potentially occur and the level at which fluvial waters would inundate a location were assessed. Based on the understanding of flood water pathways and levels during an event and the likely response of groundwater levels, the potential for groundwater flooding at the locations identified above was assessed. Where Environment Agency property threshold data were available, the groundwater flood levels identified were used to assess the likelihood of groundwater flooding affecting individual properties. Anecdotal information on the location of groundwater flooding in the three recent major floods was used to validate the outcome from this step. Where property threshold data were not available, the reported incidents of groundwater flooding were used to improve confidence. The output from an Environment Agency river flood model (Environment Agency, 2009), which gives the flood elevation for flood return periods of 2, 5, 10, 20, 50, 100, 200 and 500 years, was used to give a preliminary indication of the range of fluvial flood return periods for which groundwater flooding on its own might occur.

Results

Baseline conditions

Analysis of the topographic data for the floodplain, involving the picking of locations which are at the natural floodplain level and interpolating, allowed the thickness of the made ground above the natural floodplain to be mapped (Figure 3). This highlights the built-up residential and commercial areas within the city, the road and rail networks and those sites previously used for dumping waste. The role of this high ground in constraining the movement of flood waters down the floodplain is important.

The geological logs used to create the 3D geological modelling of the superficial deposits underlying the Oxford floodplain all include some alluvium below the ground surface. The model produced has a continuous layer of alluvium of up to 4 metres in thickness, but more typically 1.5 metres, which covers a layer of sands and gravels beneath the floodplain, typically within a range of 2 to 6 metres thickness.

Water level data show that the flow of groundwater within the floodplain sediments is complex, due largely to the influence of locks and weirs on the River Thames and associated bypass streams. These have created numerous zones of recharge from, and discharge to, the river network. Groundwater levels generally fluctuate within the upper few metres of the floodplain sediments with a greater range of fluctuation occurring at the floodplain margins. In the vicinity of rivers and streams, groundwater levels generally correlate well with surface water levels, indicating good hydraulic connection (Figure 4). Dixon (2004) reports hydraulic conductivity of the sands and gravels in the River Thames floodplain in Oxford ranging between 100 and 1000 m/d. This compares with estimates made in the area of the hydraulic conductivity of alluvium of 0.3 m/d by both Gardner (1991) and Hodgson (2008). Building foundations are not thought to have a major influence on groundwater flow within the floodplain as these are generally less than a metre in depth for domestic properties and therefore unlikely to affect lateral groundwater movement within the sands and gravels aquifer. The few large buildings on the floodplain were constructed on raised ground and the foundations will not have penetrated the gravel aquifer sufficiently to significantly change groundwater flow patterns. There is only one location within the urbanised floodplain where a relatively small volume of gravel has been extracted and the void created has not been infilled.

Combining groundwater levels with the LIDAR data allows the depth to groundwater to be contoured; this is shown in Figure 5 for May 2007, a period when the groundwater levels were relatively low. This figure (in combination with Figure 3) highlights that the depth to groundwater is generally greater under the manmade ground and at the valley edges; groundwater is shallower in areas close to the River Thames upstream of locks, where raised heads cause enhanced aquifer recharge from the river, and also at the southern end of the valley where the narrowing of the floodplain causes restricted flow of groundwater down-valley.

The available storage within the unsaturated zone of the floodplain is very small compared with flood water volumes. Estimating this storage is highly problematic due to the variability of the lithology of the floodplain deposits, the challenge in estimating storage parameters and the influence of the capillary zone. However, using an approximation of less than 10% for specific yield of the floodplain deposits (Dixon 2004, Gardner 1991), the volume of available subsurface storage within the floodplain (as defined by the outcrops of alluvium and floodplain gravels, Figure 2) for May 2007 is calculated to have been 2.6 x 10^6 m^3. For comparison, this is equivalent to just over three hours of the peak flow in the River Thames downstream of Oxford during the July 2007 flood event. The available subsurface storage volume would be significantly smaller during typical winter periods.

Flood conditions

Surface flood water pathways

Surface flood waters were observed following generally similar pathways in July 2007 to the floods in 2000 and 2003, which were also primarily River Thames floods (in comparison, the flood in 1998 was associated more with the River Cherwell catchment). Fluvial flood waters flowed south, parallel with the line of the River Thames. Major structures caused barriers to this flow, including the embankment of a dual carriageway (A34), the Botley Road and associated properties, and the Oxford southern bypass road and historic waste dumps in the south (Figure 3). In the south of Oxford, the main Birmingham to London railway line and the urban areas of Grandpont and New Hinksey (Figure 3), both of which run north-to-south, separated the flood waters in the west and the east of the valley. The result of all of these areas of high ground was the creation of a series of flood cells, which gradually filled as flood waters continued to enter the Oxford section of the Thames valley from upstream. The flood waters within these cells eventually overtopped causing flooding of property in the Botley Road area and in the New Hinksey area. Approximately 160 properties were flooded internally in the flood of 2000, a similar number in 2003 and over 200 in 2007. The 2000 and 2003 floods were classified by the Environment Agency as 10 to 15 year return period events and the 2007 flood event as a 15 to 20 year return period event. In New Hinksey, at a few locations, water flowed from the flood cell associated with the Hinksey Stream, east towards the River Thames which had flooded to a lower level. Figure 6 shows a map of approximate peak flood water elevations during the July 2007 flood which identifies the flood cells.

Prior to flood waters overtopping structural barriers to flood, subsurface pipework was also seen to be a key pathway for flow. For example, water from flooded areas was flowing out of storm drains on the downstream side of topographic barriers. The ballast fill that surrounds underground pipes can also provide a high permeability pathway for groundwaters during flood events (*pers. comm.* J. Packman, Centre for Ecology and Hydrology).

Topographic controls on the location of groundwater flooding

River level, flood level and groundwater level data collected during the July 2007 have helped to understand the mechanism by which groundwater flooding occurs within the city of Oxford. Anecdotal information on the location and nature of flooding in 2000 and 2003 suggests the same mechanism controlled groundwater flooding in these events.

In the July 2007 event, responses in groundwater levels were seen both as a result of the rain falling directly on Oxford and the high river levels that occurred in the following days. In the 17 boreholes with automatic water level recorders completed in the shallow gravel aquifer (which are well-distributed across the study area) increases in groundwater level seen in the day following the event ranged from 0.28 m to 1.23 m, with an average of 0.59 m. Groundwater levels did not rise above ground level at any of these sites at this time although in all cases groundwater levels were within the alluvium (n.b. the limited areas of standing water that occurred within the city immediately following the rainfall event were due to the drainage system being overwhelmed by the volume of water). Following the initial peak in groundwater levels there was a period of recession of up to a few days. These groundwaters then responded to the rises in river levels caused by flood waters reaching Oxford from higher in the River Thames catchment. In the majority of the 17 groundwater monitoring sites, groundwater levels rose above ground level at their peak. Artesian conditions were also measured at 12 additional sites that were manually dipped approximately a day before the flood peak.

Groundwater response to rainfall and fluvial flooding at sites in the south Oxford area during July 2007 is shown in Figure 7 along with river flood levels. These include (Figure 1) water levels associated with the Hinksey Stream, the River Thames upstream of Iffley lock and the Weirs Mill Stream and the groundwater level in a borehole, NH1, completed in the sands and gravels in the New Hinksey area (Figure 6). Water levels prior to 19 July 2007 show that the Hinksey Stream and River Thames upstream of the Iffley Lock are at a similar elevation. The Weirs Mill Stream is at a much lower level, similar to the downstream elevation of Iffley Lock. A borehole located next to the Weirs Mill Stream provides evidence that the stream normally acts as a line of discharge from the gravel aquifer. This discharge influences the groundwater level in borehole NH1 (Figure 7). The response in these river and groundwater levels occurred within 4-8 hours of the start of the rainfall event. The groundwater level in NH1 rose by 0.53 m, peaking within approximately 9 hours of the start of the event. After this point, groundwater levels began to recess. The River Thames levels were partially controlled by the raising of the weir boards in anticipation of high flows to follow. The Hinksey Stream has limited management structures on it and continued to rise over the following days, overbanking and flooding into the surrounding area, primarily farm land. Eventually flows in the River Thames were also too great and it too overbanked. After the initial rain-dependent peak the groundwater level at NH1 recessed for approximately two days but then started to rise again. A double peak was seen in the flood waters associated with the Hinksey Stream, caused by the lag in flood waters moving from headwaters of a number of tributaries of the Thames. This double peak is reflected in the shape of the groundwater hydrograph for NH1, demonstrating that the fluvial flood waters have some control on the groundwater levels. The peaks allow a good estimate to be made of the lag between the fluvial floods and the groundwater at NH1; the lag between the first peaks was approximately 20 hours and between the second peaks was approximately 22 hours. Following the second peak, the groundwater levels again recessed, with the gravel aquifer drainage in the locality being controlled by the lower fluvial flood levels associated with downstream of Iffley Lock.

In the area of borehole NH1 there was significant flooding of gardens, a small number of low-lying properties flooded above the ground floor and many more flooded under ground-floor floorboards. This low-lying area has been protected from fluvial flooding in the past three major floods as it is surrounded by high ground created for the main railway line, roads and housing, to raise them above the floodplain. The comparison of groundwater level in NH1 and flood water level in the vicinity, as well as observations of artesian flow, confirmed that the flooding was caused by the emergence of groundwater at surface. At peak flooding the gravel water level was only one centimetre higher than the flood water level indicating that the relatively low permeability alluvium, which is 1.1 m thick at this location, did not significantly inhibit the vertical movement of groundwater.

The depth of groundwater flooding at NH1 was, at its peak, 0.25 m. The peak flood waters had an elevation of 55.54 maOD; the threshold of the nearest flooded property to NH1 is 55.42 maOD. The level beyond which fluvial flooding from the River Thames to the east would breach the high ground and flow into the low-lying area in the vicinity of NH1 is approximately 0.2 m above the highest level to which the River Thames rose in this area.

The situation that occurred in the New Hinksey area was seen elsewhere in the urban floodplain areas of Oxford where built-up ground has isolated low-lying areas, protecting them from low return period fluvial flood events but also creating the conditions for groundwater flooding during these events. Often the groundwater flooding only impacts areas of relatively low importance, such as gardens or outhouses, however there is a significant number of properties on low-lying ground that are vulnerable. Figure 8 illustrates the conditions during the July 2007 flood at a location in the Botley Road area of Oxford, where properties down-gradient of the road were initially protected from fluvial flooding by high ground but during which flooding was reported which may have been due to rising groundwater. In the latter period of the event the properties suffered fluvial flooding as surface flood levels rose above the fluvial flood threshold of the Botley Road. Figure 8 shows an upstream fluvial flood level and an interpolated groundwater level for the area of the properties based on monitoring in boreholes a few hundreds of metres from the location.

The greatest number of potentially vulnerable properties in Oxford, however, are those older properties in which the void, created by raising the ground floor up from the floodplain when they were first built, was converted to living space during the period of relatively infrequent high return period flood events in the second half of the 20th Century. These rooms below the ground floor are relatively low lying, at a level close to that of the natural floodplain. Tens of properties which have basement conversions have been identified in south Oxford and there is evidence of some of these being flooded in the recent events. Some property owners have added waterproof membranes which have been successful in stopping groundwater ingress during flood events.

Recession of water levels after flooding events

A typical characteristic of groundwater floods is its relatively slow onset and recession in comparison with fluvial floods. For example in the Chalk aquifer of northern Europe, flooding in some locations has been seen to last for months after the fluvial flood waters associated with the same events have recessed (Pinault *et al.* 2005). In permeable floodplain deposits the recession of groundwater levels will be significantly faster. The strong hydraulic connection that sees groundwater levels respond quickly to rises in river level also means that rivers are effective at draining aquifers once the fluvial flood event has passed. In July 2007 it took groundwater levels in the gravel aquifer between only two and fifteen days to recede back to below ground level from first becoming artesian. However, it was observed that in some isolated low-lying areas, even though groundwater levels in the gravels recessed, flood waters sitting on top of the relatively low permeable alluvium sediments took a longer period to drain.

Mapping of groundwater flooding

The mapping of groundwater flooding was undertaken to help the Environment Agency gauge the scale of the vulnerability in Oxford from this form of flooding. The approach, described in the methodology section above, was a first-pass mapping exercise which made a number of significant assumptions. Any restriction on the vertical movement of groundwater from the gravel aquifer to above ground level due to the alluvium layer was not taken into account. The mapping exercise made the assumption that groundwater flooding could occur wherever the groundwater head was thought likely to be above ground level. In areas where there were few groundwater level data, an assumption was made, based on the strong hydraulic connection between river and aquifer, that groundwater levels could be estimated by interpolating between adjacent flood cells.

The mapping exercise showed that there are large areas of urban Oxford that could potentially be affected by groundwater flooding that for certain flood return periods would not be prone to fluvial flooding. However, the majority of these areas are gardens and not internal to property. There are estimated to be only tens of properties that may be affected by groundwater flooding at ground floor level where fluvial flooding had not already occurred. However, this assessment was limited by the availability of flood threshold data as there are over 200 properties in areas that could be vulnerable which have not had their ground-floor flood threshold level surveyed. The exercise identified a significant number of properties that are potentially vulnerable to groundwater flooding of rooms below ground level. Walking surveys identified over 80 properties with basements which may be in use as living areas or for storage.

With reference to the output of an Environment Agency river model, the flood events from which properties are most vulnerable to groundwater flooding alone were identified as those with return periods of 10 to 25 years. Lower return period events would appear to result in flood levels that are not sufficiently high to cause serious groundwater flooding; events with higher return periods would likely cause fluvial flooding to mask the initial groundwater flooding. For these events, groundwater would again be an issue if flood defence measures were introduced that held back fluvial flood waters but did not reduce the heads driving water into the gravel aquifer.

Discussion

The experience of flooding in Oxford highlights the complexities created by an urbanized area located on a major river floodplain. Topographical variations, resulting in many cases from construction to protect properties and the transport network from flooding, create complex flood pathways and areas of high vulnerability. Data collected during flood events in Oxford have shown that groundwater flood-prone areas can be created by the isolation of low-lying areas from fluvial flooding as a result of surrounding man made ground. Groundwater levels rise in response to direct rainfall and to elevated river levels and associated fluvial flood zones. Waters from the fluvial flood zones make their way to these isolated low-lying areas by passing through the permeable sediments underlying the floodplain. Although water level data indicate that the low permeability, near-surface alluvium inhibits the flow of water into and out of the underlying sands and gravels aquifer, there is a substantial amount of evidence that the alluvium is sufficiently permeable to allow groundwater flooding to occur. However, data on the alluvium is limited and is not currently sufficient to identify how vertical flow during periods of groundwater flooding is spatially distributed and whether it is dominated by windows of higher permeability material. Where buildings have been constructed the removal of alluvium also provides preferential pathways for upward groundwater movement as do man-made drainage channels.

Where artesian conditions do occur these can result in flooded gardens, cause drainage problems (e.g. inundation of sewerage systems) and create dampness beneath floorboards. Groundwater can also flood properties in these low-lying areas where the ground floor or the inhabited basement is close to the level of the natural floodplain.

Quantifying the risk of groundwater flooding in these urban environments is difficult. The combination of flood mechanisms means that the degree of groundwater flooding will vary according to the nature of the overall flood event. The height to which groundwater levels reach during a flood event will depend on a number of flood event-specific factors: the amount of rainfall directly on the city as opposed to the upstream catchment; the rate at which river levels rise and the period for which flooding persists; as well as the antecedent soil and groundwater conditions. A methodology based on detailed topography, property flood thresholds, groundwater level data and the output from a river flood model has been used here to provide a preliminary assessment of groundwater flood risk which fits well with recent observed and reported flood events.

Options for mitigating groundwater flood risk are limited. Where basements are prone to flooding these can be waterproofed or pumps installed, although the anecdotal evidence available from the 2007 flood event showed the latter not to be effective. Impermeable barriers to the base of the shallow aquifer to stop groundwater flow into an area of housing is an option although the change in groundwater flows patterns could have detrimental environmental impacts outside of flooding periods. The main approach being proposed by the Environment Agency for fluvial flood risk reduction in the Oxford area is to increase the conveyance of flood waters through the Thames floodplain. This would be achieved by the removal or widening of structures that restrict flow, maximising the use of existing channels, and the limited introduction of new channels. Baffles would be installed to maintain flows during low flow periods and to avoid the gravel aquifer being over-drained such that lowered groundwater levels have detrimental impacts on dependent ecosystems.

It is thought that this approach to fluvial flood risk reduction is an appropriate means to reduce groundwater flood risk not just in Oxford but generally in similar settings. It is recognized that there remains the potential for groundwater levels to rise above the ground surface as a result of direct rainfall recharge. This will depend again on antecedent soil and groundwater levels. In the Oxford case, using the attributed 3-D geological model and a water table surface contoured from monitored water level data collected prior to the July 2007 event, a very approximate value for the averaged capacity of the floodplain aquifer to accept recharge was calculated as equivalent to a rainfall event of the order of 150 mm. However, locally, including areas with groundwater flood-prone properties where the water table is relatively shallow, a substantially smaller rainfall event could result in groundwater levels rising above ground level due to direct rainfall recharge alone. In winter periods the risk of this occurring is significantly higher due to the degree of saturation of the shallow floodplain sediments. This insight has implications for the application of sustainable urban drainage systems in similar settings, suggesting that techniques which delay recharge are worth considering, for example green roofs and shallow temporary storage in impermeable open spaces such as car parks.

Conclusions

1. In recent years in Europe there has been recognition that there is a requirement to understand better the risk from flooding as the result of abnormally high groundwater levels. This has been due both to the occurrence of major flooding events clearly attributable to groundwater and the related inclusion of groundwater flooding in European and national legislation.

2. In floodplains underlain by highly permeable deposits, groundwater rise leading to groundwater flooding can be due to direct rainfall recharge as well as flow into the sediments from rivers with high water levels and areas inundated with fluvial flooding. However, the good hydraulic connection between river and aquifer means that the aquifer can drain quickly as fluvial flood waters recess. Groundwater flooding in these settings is relatively short-lived compared with other groundwater flood settings, e.g Chalk catchments.

3. The Oxford case study has shown that manmade ground built up from the natural floodplain to reduce the risk of fluvial flooding of property and the transport network can create adjacent isolated low-lying areas which are prone to groundwater flooding. In Oxford there are a limited number of properties that are flooded above ground level in these areas but potentially tens of properties with inhabited basements that could flood as a result of

abnormally high groundwater levels. It is estimated that these properties are affected by groundwater flooding alone during relatively low return period flood events of 10 to 25 years; during higher return period events groundwater flooding will precede fluvial flood inundation.

4. Appropriate options for mitigating groundwater flooding in these urban floodplain settings are limited particularly where it is the result of direct rainfall recharge. As is proposed through the Oxford Flood Risk Management Study, an effective means to reduce the risk of groundwater flooding at the city scale is to increase the rate of conveyance of flood waters, reducing the heads within the flood cells that can drive water into the underlying permeable sediments. The potential for groundwater flooding due to rainfall alone has implications for the implementation of sustainable urban drainage systems.

5. Generally in urban floodplain settings, fluvial flood assessments will underestimate the extent of flooding if aquifer pathways are not taken into account. Further work is required to link river and groundwater models to simulate flood events, to enable better quantification of the risk of groundwater flooding and to assess the potential for using river level monitoring in early warning systems for groundwater flooding.

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Figure 1 River Thames and its tributaries in the Oxford area. BGS © NERC 2011. Ordnance Survey topographic material reproduced with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office, © Crown Copyright. Licence number 100017897/2011.

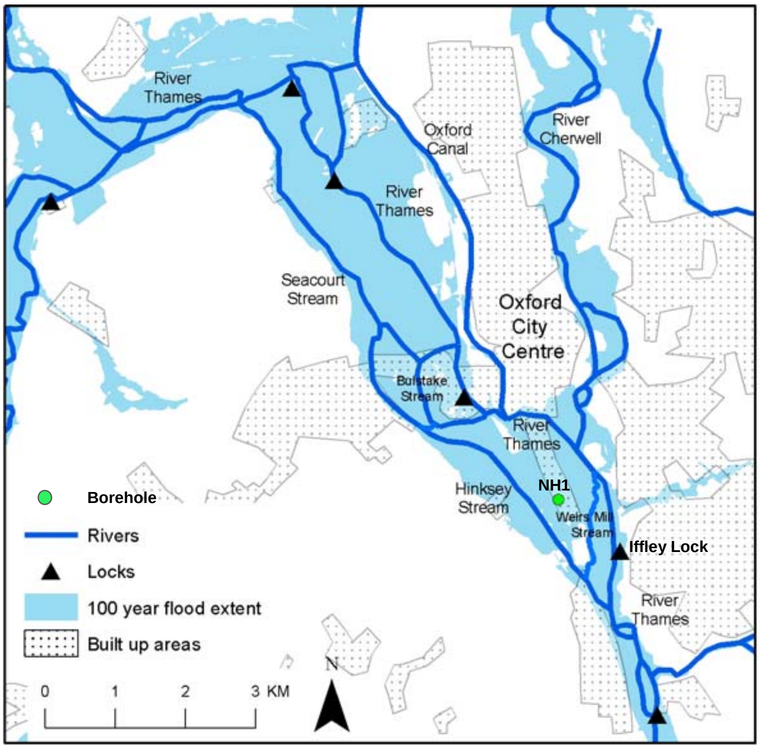

Figure 2 Superficial geology in the Oxford valley. BGS © NERC 2011. Some features of this map are based on digital spatial data licensed from the Centre for Ecology and Hydrology (Moore *et al*. 1994). This map includes NEXTMap Britain elevation data from Intermap Technologies.

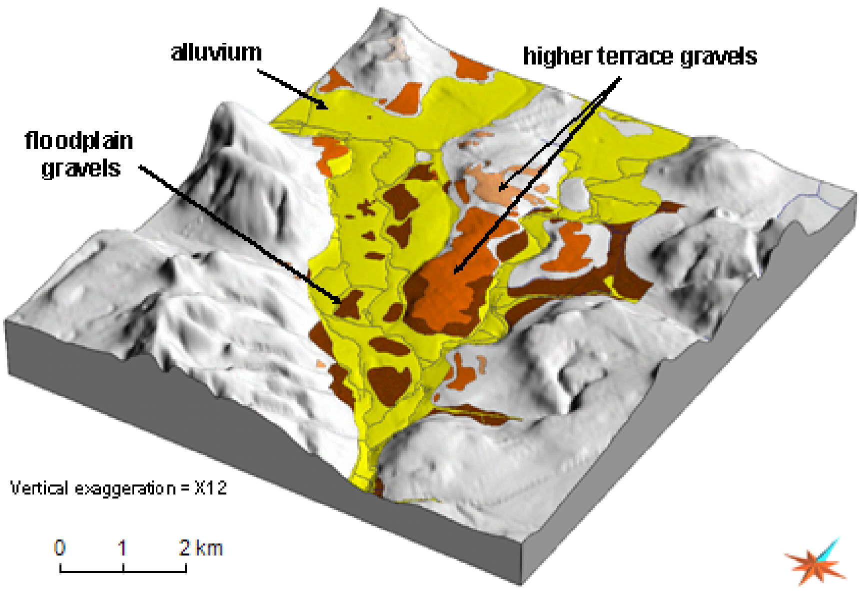

Figure 3 Thickness of made ground above the natural floodplain. BGS © NERC 2011.

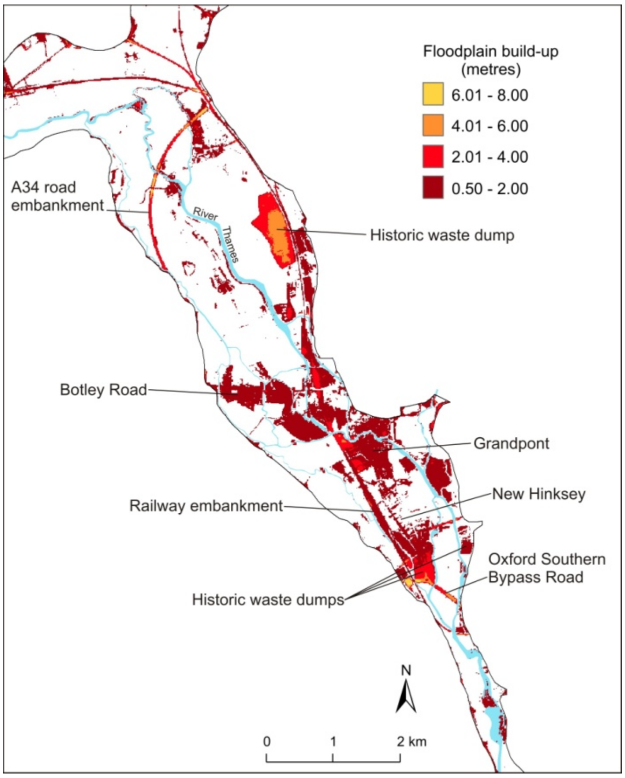

Figure 4 Typical river and groundwater hydrographs from the Oxford floodplain monitoring network. BGS © NERC 2011

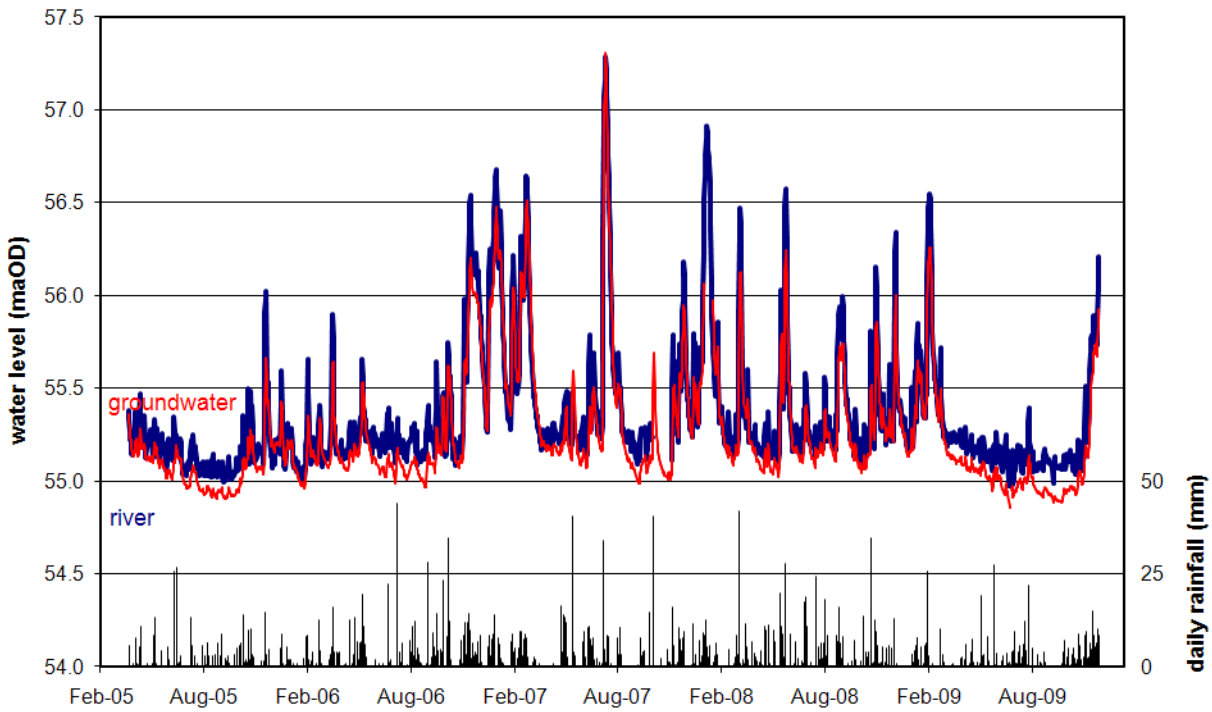

Figure 5 Depth to groundwater within the floodplain superficial deposits in the Oxford valley based on groundwater levels measured in May 2007. BGS © NERC 2011.

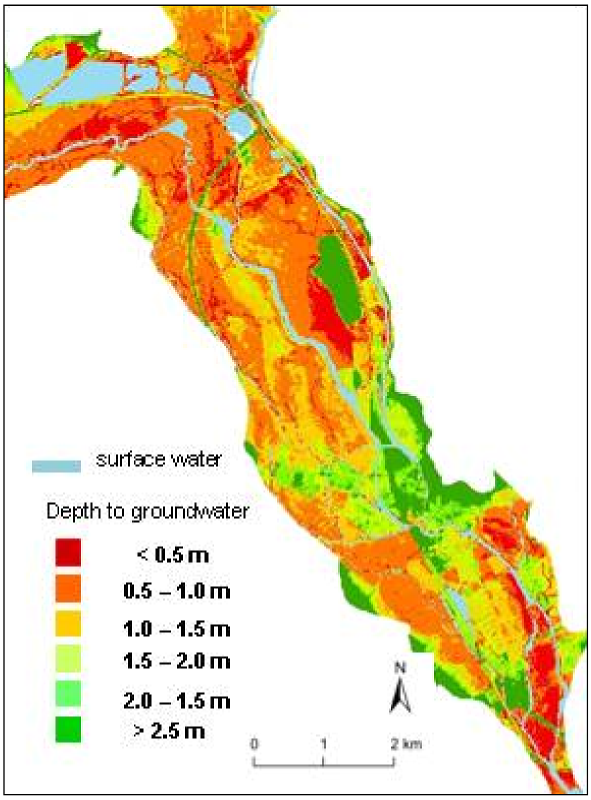

Figure 6 Estimated peak flood water elevation in the Oxford area during the July 2007 flood event. This map includes NEXTMap Britain elevation data from Intermap Technologies. BGS © NERC 2011.

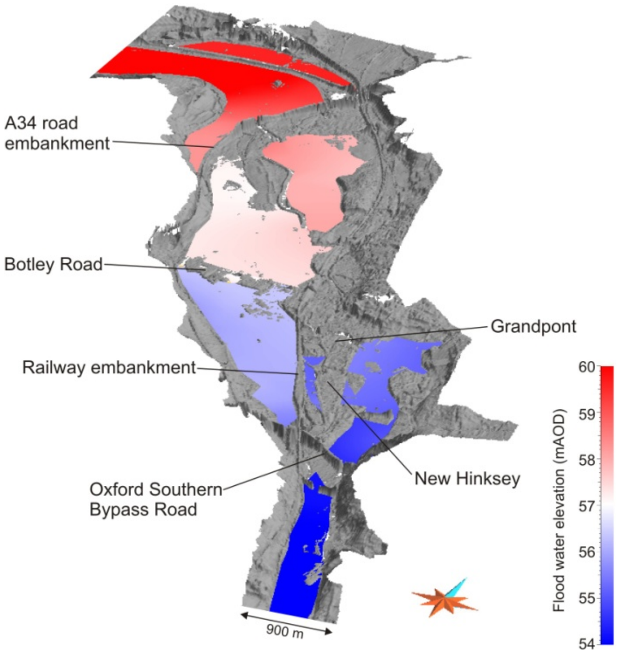

Figure 7 Groundwater levels in borehole NH1 in the New Hinksey area of Oxford during the July 2007 flood event, along with water levels nearby in the River Thames, the Weirs Mill Stream and the Hinksey Stream. Also shown, 15-minute rainfall data, ground level at NH1 and the level of the threshold point above which the River Thames would flood the ground at NH1. BGS © NERC 2011. Rainfall and water level data for the River Thames were provided by the Environment Agency.

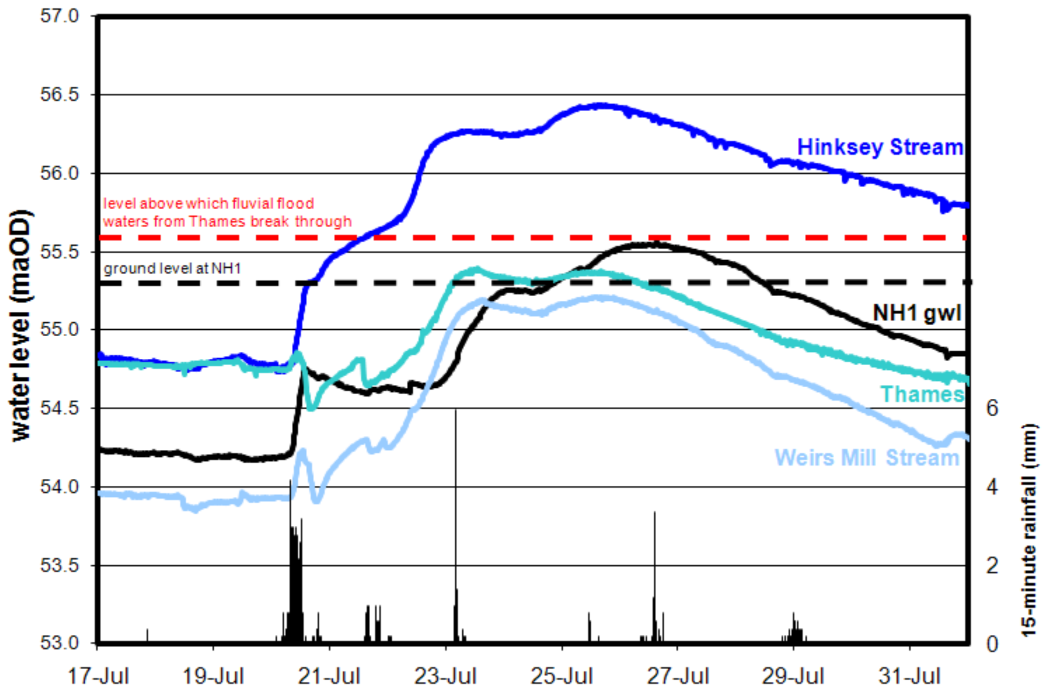

Figure 8 Fluvial flood water levels upstream of the Botley Road and interpolated groundwater levels at an urban location down-gradient of the Botley Road, Oxford during the July 2007 flood event. Also shown, 15-minute rainfall data, the threshold of the lowest property in the urban area down-gradient of the Botley Road and the level above which the flood waters upstream of the Botley Road would overtop. BGS © NERC 2011. 15-minute rainfall data were provided by the Environment Agency.