



**Strategy for Flood and Coastal  
Erosion Risk Management:  
Groundwater Flooding Scoping  
Study (LDS 23)**

**Final Report**

**Volume 1 of 2**

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## Summary

This report documents the findings of a scoping study commissioned by Defra's Flood Management Strategy Unit to provide information on the scale, distribution and nature of groundwater flooding in England. The findings will feed into the ongoing exercise to develop a new Government Strategy for Flood and Coastal Erosion Risk Management in England.

The overall objective of the project is:

*“To provide information on the scale, distribution and nature of groundwater flooding in England in order to feed into the development of a new Strategy for Flood Management & Coastal Protection.”*

The study covers eight key tasks as set out in the project Specification:

1. *A literature review of major conurbation groundwater management to identify the scale of the problem.*
2. *Review reports and investigations on flooding in permeable catchments.*
3. *Identify generic causes of groundwater flooding.*
4. *Provide maps of susceptible areas to groundwater flooding at a suitable scale for national assessment.*
5. *Quantify the scale and general likelihood of groundwater flooding in terms of the number of properties, density, area of land or other suitable measures.*
6. *Consider the range and applicability of potential preventative measures and flood forecasting techniques that may be suitable for promoting in a strategy.*
7. *Consider the synergy with water resources and source protection issues and areas where knowledge in these areas may contribute to the understanding of groundwater flooding.*
8. *Public perception of groundwater flooding.*

The scoping study has focused on three main causes of groundwater flooding:

- Groundwater flooding caused by the natural phenomena within permeable hard rock aquifers of groundwater emergence after periods of higher than average recharge.
- Groundwater returning to its natural level after the cessation of over abstraction.
- Groundwater flooding caused by the cessation of pumping in closed mines.

Each of these is considered under separate chapters within the report and under the tasks identified in the Project Specification.

### **Groundwater flooding from permeable catchments**

This report analyses the characteristics of groundwater flooding in permeable catchments. It covers flooding arising from the emergence of groundwater in areas where water is not regularly seen and in areas remote from the recognised river network. This study excludes fluvial flooding from permeable catchments and the seasonal inundation of river valley gravels prior to the river flowing out of bank.

### ***Review reports and investigations on flooding***

Information on the frequency, location and extent of groundwater flooding was sought from the Environment Agency and Local Authorities. Emphasis was placed on the most extreme and widespread groundwater flooding event (2000/01) but also on the more localised occurrences in 1994/95 and 2002/03. However, the quality of available information is highly variable across the country and it is suspected that there has been a high degree of under reporting in all areas where flooding was experienced. The costs per property of flooding from groundwater are found to be in excess of those from fluvial floods as a result of the extended duration of the flood. Further, the value of assets affected by groundwater flooding has increased considerably over the last thirty years. It is our understanding that under reporting has arisen as a result of there being no organisation responsible for the situation and a reluctance of homeowners to declare flooding because of its impact on property prices and insurance premiums.

Reports and academic papers investigating groundwater flooding have been reviewed.

### ***Identify generic causes of groundwater flooding***

Until very recently, the causes of groundwater flooding have received very little attention within the academic literature. This report assesses the current level of understanding and puts forward a hypothesis for the causes of flooding that explains the geographical extent seen in 2000/01. Groundwater flooding appears to be largely restricted to the surface outcrop of Chalk where there are no overlying impermeable drift deposits. Chalk is particularly vulnerable to prolonged periods of high recharge leading to the development of very large groundwater heads as a result of its 'dual porosity' characteristics. Aquifers that have either very high storage or very high transmissivity appear to be significantly less vulnerable to prolonged periods of high recharge. However, localised instances of groundwater flooding cannot be ruled out as there is insufficient documentary evidence to disprove it and under certain (rare) hydrological scenarios, flooding could be anticipated. Local topographic and geological factors dictate the exact location and degree of flooding.

### ***Quantification of the scale and general likelihood of groundwater flooding***

Assigning return periods to the non-independent peaks of groundwater level data is particularly difficult and explains the absence of information in the published literature. Groundwater level records for boreholes considered representative of the major aquifers do however, show that the peak levels reached in 2000/01 are unprecedented – in records extending back 40 years or more. The Compton borehole record in the Sussex Chalk shows that the 2000/01 peak exceeded any previous peak by a large margin in a record dating back to 1894. Several reports cite the occurrence interval for the 2000/01 long duration rainfall event in the south of England as a surrogate for flooding, and arrive at return periods in excess of 100 or 200 years. Notwithstanding a period of around thirty years in which no flooding was reported from the southern Chalk, localised groundwater flooding appears to be a relatively common phenomena in some locations with records suggesting a frequency of 1 in 7 years over the long term.

Records supplied by the Environment Agency suggest that in total almost 500 properties were flooded in 2000/01 from hardrock aquifers and a further 221 from superficial deposits in the same year. However, this is considered to be a significant underestimation of the true extent of the problem. It has not always been possible in

the data supplied by the Environment Agency to ascertain whether a report refers to a single property or a village. The Fire Service record of call outs to flooded properties suggest it was a considerably larger problem than data supplied by the Environment Agency suggests. Detailed reports of local areas suggest the actual number of properties is much larger – amounting to 700 properties in Hampshire for example. Widespread disruption was also caused by the closure of roads and disruption to the sewerage network. In addition, farmland was flooded for prolonged periods of time.

### ***Provision of maps of areas susceptible to groundwater flooding***

A predictive model has been developed for this study to ascertain how many properties are vulnerable to groundwater emergence and to identify the geographical extent of the problem. The model represents and is calibrated on, the 2000/01 event. Whilst the maps depicting the exposed Chalk aquifers are based on observed flooding, those for all other aquifers are more predictive and reflect the greater uncertainty in knowledge. Those areas where groundwater is predicted to be close to the surface were assessed to indicate the number of properties, (totalled by Environment Agency Area). Properties within the zone could be expected to experience anything from groundwater emergence into cellars to surface flooding and incursion into properties. However, within the zones identified some properties will be more vulnerable to rises in groundwater than others depending on the presence of cellars and the impact of local topography. It has not been possible to distinguish between water just below the surface and that at ground level. The property count will include properties where groundwater is below the surface but there is no cellar, so no groundwater would be observed. It is estimated that 1.7 million properties are vulnerable in England, of which 112,855 already fall within the 1 in 100 year indicative floodplain. Thus approximately 1.6 million additional properties are located in areas where groundwater could be expected to rise close to the surface in an exceptionally wet winter. Those most vulnerable are the 382,407 properties located on the exposed Chalk aquifers of southern England where groundwater levels fluctuate widely.

### ***Consider the range and applicability of potential preventative measures and flood forecasting techniques***

Whilst groundwater flooding can be anticipated well in advance of its actual occurrence enabling mitigation measures to be undertaken, its long duration compounds the social and economic costs. Unlike fluvial flooding, groundwater flooding typically lasts for many weeks causing severe property damage and high social costs. Groundwater flooding during the winter of 2000/01 lasted for up to three months and in some cases would have persisted for longer had alleviation measures not been adopted.

Groundwater forecasting models, whilst in their early stage of refinement, do provide early warning of impending groundwater flooding. Forecasting and flood preparedness form important components of flood response measures. The principal means of protection from groundwater flooding are: removal of possessions, goods and materials from flood-prone areas; construction of diversion works; improvement of capacity of local drains and ditches; large-scale flood schemes; groundwater pumping; and property improvements.

***Comment on the public perception of groundwater flooding***

The public are generally less well educated on groundwater flooding than fluvial flooding and in 2000/01 found it difficult to comprehend the causes. This may have arisen because, in the past, public flood awareness campaigns have concentrated on fluvial flooding but this is compounded by the apparent loss of community knowledge of where flooding from groundwater occurs and how often. This loss of knowledge may be partly due to the period of around thirty years when there were few groundwater flooding events.

Matters are made worse by there being no governmental agency with a clear responsibility for groundwater management. However, several of the Environment Agency's Area offices have proactively developed a management approach and it is recommended that this best practice is adopted nationally by the Environment Agency.

***Recommendations (in order of priority)***

1. Groundwater flood risk maps for areas overlying exposed Chalk in particular should be produced and used to influence planning decisions. To produce these, local details of floods areas, flood cause and flood extent needs recording in a systematic manner. The frequency of flooding from groundwater needs further investigation in order to assess the cost benefit ratio for any remediation works.
2. A flood management process should be put in place at the national, regional and local levels comparable to that already in place for fluvial and coastal flooding. A public awareness campaign comparable to that for fluvial flooding and including an understanding of the causes of flooding would be beneficial. Catchment Flood Management Plans (CFMPs) should also incorporate groundwater flooding issues.
3. A study should be undertaken to confirm that widespread groundwater flooding has not occurred in the other major aquifers.
4. Criteria used in the assessment of damage resulting from groundwater flooding need to be reviewed.

**Rising groundwater in major conurbations: Undertake a literature review of major conurbation groundwater management**

Rising groundwater in major conurbations first became an issue with the cessation of groundwater abstraction that followed the decline in heavy industry in the 1960s. Detailed studies were initiated by groups of stakeholders that identified the causes and possible remedies. Solutions are being brought about through water resource management partnerships between the Environment Agency and the water companies, although neither has legal responsibility to control levels. This report identifies those major conurbations subject to rising groundwater and the measures being taken to remedy the problem. Rising groundwater in conurbations is well documented and water levels are generally monitored by stakeholders.

***Recommendations***

Many of the current ongoing solutions are based on the goodwill of the parties involved, which is clearly a potential risk for the future. Ideally, formal agreements

between stakeholders should be implemented and until then, the situation monitored.

### **Rising groundwater in mining areas**

The cessation of pumping of water from abandoned metal and coal mines has been identified as a cause of both groundwater rebound and subsequent environmental pollution from poor water quality. The Coal Authority is responsible for monitoring rising groundwater levels in coal mines, with the Environment Agency reviewing the situation through formal dialogue. Under the new Water Act the Coal Authority may, if appropriate, take action to prevent or mitigate the effects of the discharge of water from coal mines. This study presents an updated situation report on the characteristics of rising groundwater in coal mines. Rising groundwater in metal mines is identified as only being a problem in South Crofty tin mine where the quality of the water is of concern rather than any flooding implications.

### ***Recommendations***

No recommendations are made in this study.

### **Consider the synergy with water resources and source protection zones**

Current large-scale groundwater models of Chalk regions across Southern England are being developed by the Environment Agency to provide water resources management tools as part of the Catchment Abstraction Management Strategy (CAMS) process. Low flow investigations are also being undertaken as part of the Restoring Sustainable Abstraction Programme (RSAP). These initiatives provide an opportunity to assess whether practical solutions are possible to alleviate the risk of groundwater flooding which are consistent with water resource management objectives. Given the timing of groundwater flooding from permeable catchments and the volumes of water involved it is unlikely that problems can be resolved by management of groundwater levels.

### ***Recommendations***

1. Groundwater flooding should be incorporated in the CAMS process and Restoring Sustainable Abstraction Programme (RSAP).
2. Source Protection Zones for groundwater abstractions in areas of rising groundwater need to be reviewed to ensure that the underlying assumptions have not changed since 1996 when they were defined.

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*NB Appendices B, C, D, E and F are printed at A3 size and bound in Volume 2*

**Acronyms used in this report**

ABI	Association of British Insurers
AMD	Acid Mine Drainage
BFIHOST	Base Flow Index derived from the Hydrology Of Soil Types
BGS	British Geological Survey
BRE	Building Research Establishment
CAMS	Catchment Abstraction Management Strategy
CCIRG	Climate Change Impacts Review Group
CEH	Centre of Ecology and Hydrology – Wallingford
CFMPs	Catchment Flood Management Plans
CIRIA	Construction Industry Research and Information Association
COW	Critical Ordinary Watercourse
Defra	Department for Environment Food and Rural Affairs
FLAIR	Food and Local Agriculture Information Resource
GARDIT	General Aquifer Research, Development and Investigation Team
GEMs	Groundwater Emergence Maps
ICE	Institution of Civil Engineers
IDBs	Internal Drainage Boards
IFM	Indicative Floodplain Map
IHDTM	Integrated Hydrological Digital Terrain Model
IOW	Isle of Wight
LOCAR	LOWland CAthment Research
NRA	National Rivers Authority
NGR	National Grid Reference
PPG	Planning Policy Guidance
PWS	Public Water Supply
RSAP	Restoring Sustainable Abstraction Programme
SPZ	Source Protection Zones

# 1 Introduction

## 1.1 Project Background

The Department for Environment Food and Rural Affairs (Defra), on 16 September 2003, invited Jacobs to submit a tender for a Groundwater Flooding Scoping Study as defined by Defra's Project Specification.

Jacobs submitted a technical and financial proposal to Defra on 7 October and were awarded the contract on 29 October.

As stated in the Project Specification, the overall objective of the project is:

*“To provide information on the scale, distribution and nature of groundwater flooding in England in order to feed into the development of a new Strategy for Flood Management & Coastal Protection.”*

The study covers eight key tasks as set out in the Project Specification:

1. *A literature review of major conurbation groundwater management to identify the scale of the problem.*
2. *Review reports and investigations on flooding in permeable catchments.*
3. *Identify generic causes of groundwater flooding.*
4. *Provide maps of susceptible areas to groundwater flooding at a suitable scale for national assessment.*
5. *Quantify the scale and general likelihood of groundwater flooding in terms of the number of properties, density, area of land or other suitable measures.*
6. *Consider the range and applicability of potential preventative measures and flood forecasting techniques that may be suitable for promoting in a strategy.*
7. *Consider the synergy with water resources and source protection issues and areas where knowledge in these areas may contribute to the understanding of groundwater flooding.*
8. *Public perception of groundwater flooding.*

When considering the issues and scope of its review of its strategy of flood and coastal erosion risk management, Defra decided to include the topic of groundwater flooding as an integral part of the review process in view of the recent and frequent events of groundwater flooding that have occurred across central, eastern and southern England during the last ten years. Although the occurrence and cause of flooding from rivers and watercourses is well understood and Defra, through the Environment Agency, has a responsibility to provide alleviation and protection measures, it has no similar responsibility for groundwater flooding. Indeed there is no government agency that has a statutory obligation for measuring and reporting such events or in providing advice and affording protection to those affected.

It is outside the brief of this national scoping study to provide a detailed examination of the individual causes and occurrences of groundwater flooding as they vary according to a wide range of physical parameters that include climate, soils, land use, topography, drainage, superficial deposits, bedrock, hydrogeology, water features and the built environment. Consequently a number of generalisations have had to be made in order to provide a general outline of the present understanding of groundwater flooding and rising groundwater and their possible impact upon the environment and the public.

This study has focussed on addressing the eight tasks listed above and in doing so has had to include an extensive literature search and data collection phase because of the paucity of information on the subject of groundwater flooding. Whilst there is some evidence in historic literature of groundwater flooding occurring over the last two centuries, there is a significant shortage of site-specific data and there is very little reported professional knowledge and understanding of its causes, occurrence, extent, frequency and impact.

Nevertheless, the Environment Agency staff in each of its 23 area offices within England (the 3 Welsh Areas are covered by The National Assembly for Wales) have been able to provide very useful information and opinion to enable area based maps to be produced for much of the country as well as those that have been prepared at a national scale. However, the study is broad-based and whilst it has been possible to derive a national picture of groundwater flooding, the representation of data at an area-based level must be viewed with caution.

## **1.2 Data Collection**

Prior to the commencement of the study, the Environment Agency Southern Region, Hampshire & IOW Area Office sent a questionnaire to all of the Environment Agency's area offices (in England) to obtain information regarding the occurrence of groundwater flooding. Based upon this information and subsequent specific enquires undertaken by Jacobs, data was obtained from a wide range of sources which included the following:

- *Environment Agency*
- *Government Agencies*
- *Research Institutions*
- *District and Parish Councils*
- *Emergency Services*
- *Mining Organisations*
- *National Interest Groups*
- *Insurance Companies*
- *Professional Institutions*
- *Libraries and Websites*

A list of those consulted is enclosed in Appendix A.

## **1.3 Definition of Terms**

### **1.3.1 Introduction**

This study has been commissioned to examine the occurrence and the consequences of two hydrogeological processes that give rise to flooding events. They are "groundwater flooding" and "rising groundwater" both terms that have been variously defined in existing hydrogeological literature. Definitions are therefore provided below to ensure clarity in the current report. Both processes result from the rise of groundwater in permeable strata. Groundwater flooding being the emergence of water at the ground surface through a natural process and rising groundwater being the rise of groundwater levels from a previously lower level following the reduction or cessation of groundwater abstraction. Thus the two terms can broadly be distinguished by groundwater flooding being a natural process and rising groundwater being of anthropogenic origin.

A more detailed explanation of these terms is given in the following sections.

### **1.3.2 Groundwater Flooding**

For the purposes of this study the term “groundwater flooding” (also commonly referred to as “clearwater flooding”) has been defined as the type of flooding that can be identified as being caused by water originating from beneath the ground surface from permeable strata through a natural process (rather than through anthropogenic activities such as leakage from pipes and seepage into ground excavations).

Groundwater flooding can also be differentiated from surface water flooding by its persistence, with a typical duration that is measured in weeks rather than hours and days and has a tendency to occur throughout the winter, often extending into spring and sometimes into the early summer.

Therefore, for the purposes of this study, the collection, analysis and reporting of groundwater flooding has been confined to:

- *The process by which groundwater in permeable catchments emerges at the ground surface at elevations that are higher than normal following prolonged periods of excessive rainfall;*
- *Having a long duration in excess of a month; and*
- *Attaining a level and extent to cause potential damage to land, property, infrastructure or inconvenience to people’s way of life.*

This definition precludes events arising from shallow permeable deposits, surcharged sewers or leaking mains. It also excludes the inundation of floodplains by groundwater prior to the river overtopping its banks.

A distinction is also made between groundwater flooding and fluvial flooding from permeable catchments. Bradford and Faulkner (1997) classified floods in permeable catchments on the basis of the contribution the groundwater component made to the total flood volume. Table 1-A modified from Bradford *et al* distinguished type 1 floods in which baseflow played an insignificant part compared to type 2 in which baseflows were dominant. Type 1 events arise when the permeable catchment responds in a manner more typical of an impermeable catchment. These events most commonly arise from either short duration high intensity rainfall events in which the infiltration rate is exceeded or from rapid snowmelt or rainfall on a frozen catchment. These will all produce short duration peaked events with little groundwater involvement. Type 2 floods on the other hand, are characteristically long duration large volume events in which baseflow (groundwater) is the dominant source.

Type of flood event	Characteristics
1 Flash floods	High intensity summer storms or rainfall on a frozen catchment; little or no baseflow
2 (a) Groundwater inundation	Limited surface flow, winter/spring. Mainly headwater valleys
2 (b) Groundwater 'surge'.	Moderate to large flows, winter/spring after higher than average recharge during winter/spring
2 (c) Groundwater 'surge' with additional quick runoff	Large flows during winter/spring produced by higher than average recharge combined with winter storms and/or snowmelt.

**Table 1-A Simple flood classification in permeable catchments (modified from Bradford & Faulkner 1997).**

Flood frequency estimation in permeable catchments has been the subject of several research projects including components in the Flood Estimation Handbook (IH, 1999), continuous simulation research (Calver *et al* (1999) and detailed catchment studies (Calver *et al.* 2000)). These studies largely refer to the fluvial component of permeable catchment floods. There is no clear distinction between groundwater flooding and fluvial flooding from permeable catchments as at some point groundwater will enter the river network. Emphasis in the current report is placed on the flooding arising from groundwater prior to it entering the established river system and is confined to the type 2 events as described above.

Based upon the definition above, there are a number of processes that are consequently excluded from this study including:

- *Short-term localised saturation of the ground that originates from a range of possible causes such as a burst in an underground pipe, a leaking drain, a rainstorm occurring on poorly drained ground or from a sudden and intense storm;*
- *Excess sub-surface water in shallow or perched groundwater bearing deposits;*
- *Excess sub-surface water in permeable deposits that have a rapid response to storm rainfall;*
- *Excess sub-surface water in permeable river deposits such as alluvial or terrace material that may have a hydraulic connection with a watercourse or river within the same floodplain;*
- *Excess sub-surface water originating from sewer exfiltration during normal or surcharged conditions; and*
- *Flooding as a result of overtopping of perennial river channels even where the dominant contribution to the flow in the channel is from the underlying aquifer.*

The conditions under which groundwater flooding is likely to occur are given in Section 2.

### 1.3.3 Definition of Emergence

Within this study an “emergence” has been defined as the appearance of groundwater at the land surface or below the surface in sub-surface structures such as excavations, cellars, communication conduits and tunnels.

### **1.3.4 Definition of Rising Groundwater in Conurbations**

For the purposes of this study, the term “rising groundwater” in reference to conurbations has been defined as the rise of groundwater levels in permeable strata from previously long-term lower levels, which were due to the abstraction of groundwater for public or industrial purposes, to the extent that there are perceived risks to the built environment. The term “groundwater rebound” is also used to describe this process and implies that groundwater levels are returning to previously higher levels following a period of artificial lowering as a result of significant groundwater abstraction.

Based upon this definition there are a number of processes that are consequently excluded from this study including:

- *Temporary rising groundwater resulting from failure of sub-surface pumping equipment;*
- *Construction sites where dewatering has ceased; and*
- *Small-scale areas such as business parks or minor wellfields where pumping has been curtailed.*

### **1.3.5 Definition of Rising Groundwater in Mining Areas**

In the case of mining areas, “rising groundwater” has been defined as the rise of groundwater levels in subsurface operations from previously long-term lower levels to the extent that there are perceived risks to the natural environment or to the built environment. The term “mine water rebound” is also used to describe this process and implies that groundwater levels are returning to previous levels following a long period of time during which they were artificially lowered by the pumping of water from underground workings to enable the extraction of ores or deposits together with the country rock to take place and to facilitate their removal to the ground surface.

For the purposes of this study, only large mining areas where dewatering of mines has been necessary to enable the extraction of coal or metals have been examined and the effects and consequences on the environment from current or abandoned mining operations other than flooding have been ignored, such as the pollution of surface water, the pollution of overlying aquifers, the emissions of gas and the impingement on landfills.

Based upon this definition there are a number of processes that are consequently excluded from this study including:

- *Small-scale mining where the rates of water abstraction are not likely to cause flooding when discharged to the surface;*
- *Surface flooding originating from the failure of mine ponds;*
- *Open cast mining operations; and*
- *Mineral workings.*

## **1.4 Report Structure**

The structure of this report and the context of each of the eight key tasks, numbered and specified as within the Project Specification, is detailed below:

### **Section 1 – Introduction**

This section sets the context of the study and provides a definition of key terms.

### **Section 2 – Permeable Catchments**

This section details work undertaken regarding groundwater flooding in permeable catchments and covers the following key tasks:

2. *Review reports and investigations on flooding in permeable catchments.*
3. *Identify generic causes of groundwater flooding.*
4. *Provide maps of susceptible areas to groundwater flooding at a suitable scale for national assessment.*
5. *Quantify the scale and general likelihood of groundwater flooding in terms of the number of properties, density, area of land or other suitable measures.*
6. *Consider the range and applicability of potential preventative measures and flood forecasting techniques that may be suitable for promoting in a strategy.*
8. *Public perception of groundwater flooding.*

### **Section 3 – Rising Groundwater in Major Conurbations**

This section details groundwater rebound, within the vicinity of major conurbations, following a reduction in long term water abstraction. The following task is specifically covered:

1. *A literature review of major conurbation groundwater management to identify the scale of the problem.*

### **Section 4 – Rising Groundwater in Mining Areas**

This section details the causes and impacts of rising groundwater within coal and metal mines.

### **Section 5 – Synergy with Water Resources and Source Protection**

This section provides information concerning the relationship between water resources, groundwater flooding and rising groundwater. The following task is specifically covered:

7. *Consider the synergy with water resources and source protection issues and areas where knowledge in these areas may contribute to the understanding of groundwater flooding.*

### **Section 6 – Conclusions and Recommendations**

This section details the study's findings and makes recommendations for future studies and research.

### **Section 7 – References and Bibliography**

This section details all books, periodicals and reports referred to during the course of the study.

### **Section 8 – Websites**

This section details all websites referred to during the course of the study.

## 2 Permeable Catchments

### 2.1 Introduction

Throughout most of England the geological formations comprise permeable rocks with the exception of:

- The crystalline rocks of Cornwall, western Devon and the Lake District;
- The gritstones of the Pennines; and
- The thick clay deposits of the Weald and London basins in the south-east and the low lying areas of Bedfordshire, the East Midlands, Lincolnshire, North Yorkshire, the Fens, and the Somerset Levels.

Their ability to absorb, store and release groundwater varies greatly but the primary groundwater-bearing formations (aquifers) in order of the amount of water that is stored within them are the Cretaceous Chalk, the Permo-Triassic Sandstones, the Jurassic Limestones, the Permian Limestones and the Carboniferous Limestones. Their extent across the country is shown in Appendix D Map 'Aquifer' which indicates where they appear at the ground surface without indicating their extent either horizontally or vertically in the sub-surface. The map also does not include the extent of the complex distribution of superficial deposits that may cover these formations, which is an important aspect when considering how water can emerge from them at the surface.

### 2.2 Occurrence of Groundwater Flooding

#### 2.2.1 Collection of Recorded Incidences

The principal recorded incidences that were available to the study were associated with the recent flooding events of the winters of 1994-95, 2000-01 and 2002-03 that were compiled from records held by the Environment Agency, Local Authorities, Highway Authorities and the Emergency Services.

The initial point of contact was the Environment Agency whose 23 area offices in England had been sent a questionnaire by staff in the Hampshire and IOW Area Office prior to the commencement of the study. The responders were from a wide range of disciplines in the Environment Agency including flood defence, development control, strategic planning, groundwater protection and contaminated land, environmental protection and water resources. This reflects the fact that groundwater flooding is ill-defined and there is no centre of responsibility for groundwater flooding within the Environment Agency. Consequently, the quality and comprehensiveness of the collated data is highly variable. Attempts have been made throughout this study to clarify the data via telephone interviews with Environment Agency Area experts.

As might be expected the Environment Agency offices that had the most incidences provided the greatest detail regarding the number of events, their location and extent and the number of properties affected. Consequently the most detailed information that was obtained from the questionnaire and follow-up were the Area offices of Hampshire & IOW (Southern Region), South Wessex (South West Region) and the West, South East and North East Thames offices (Thames Region). Each of these Area offices has produced internal reports of the 2000-01 event and the Hampshire & IOW office has also produced a report on the 2002-03 event

(Environment Agency, 2001 and 2003). The latter office also commissioned consultants to prepare a report on the individual villages affected by the 2000-01 event (Halcrow, 2001)

The type of data obtained from each of the offices differed to a degree in that South Wessex reported the number of properties affected at each site, Thames Region reported the length of valley affected and Hampshire & IOW reported the villages affected. Insufficient time has been available in this study to harmonise this data, which is presented in Appendix B 'Occurrence/National/1', but the distribution of incidences and frequency provides a general indication of groundwater flooding occurrences.

It is essential to note that the reports logged by the Environment Agency Area offices are frequently uncorroborated reports of groundwater flooding. As it is clearly difficult to always identify the source of water, it has to be assumed that the occurrences database will include some incidents arising from sewerage leaks, mains leakage or surface runoff. Whilst the database has been filtered for these it must be assumed that there is some noise remaining in the data.

The occurrences database should be considered as a sample of the actual occurrences and not a comprehensive list. The logged calls will predominantly be reports of flooded properties rather than gardens and roads that cause less distress. However, where the public was aware that the Environment Agency's remit did not include groundwater flooding, help may have been sought from other authorities – most notably the Parish Councils or fire service. It should also be noted that the public is very aware that making a report of flooding may result in their property being blighted in relation to both its resale value and insurance cover. It appears that groundwater flooding has been significantly under-reported because there is no government agency responsible for responding to this type of hazard and thus there is a lack of a co-ordinated data gathering procedure across the country.

In order to produce the most comprehensive database of flooded locations, the Fire Services covering the counties of Oxfordshire and Berkshire were contacted. It is our understanding that the 46 Fire Brigades that cover England each maintain an Access database of all incidents. This includes all call outs to pump flooded properties. The Berkshire Fire Service provided detailed records of the occasions that pumps were used to pump groundwater from properties within the county during the flood of 2000-01. This showed that the fire service database is a superb supplementary record of flooded properties if treated appropriately. The fire service record grid references, date and reason for call and action. In some cases additional notes are available. Whilst the database does not distinguish between, groundwater and surface water, the latter were eliminated by restricting the query to dates in which groundwater flooding was known to have occurred in the area. Those arising from fluvial floods or from domestic appliances were eliminated as far as possible by plotting the reports against known aquifer areas. Unfortunately, insufficient time was available during this study to obtain information from all the other brigades. There is no centrally held fire service database and to comply with data protection requirements, each request has to be made in writing. This is regrettable as this database holds a significant amount of relevant information and is clearly one in which there is the potential for future utilisation.

Less comprehensive information was available from several Local Authorities particularly from their web sites, although this was not property specific. Attempts to access more comprehensive information from some local authorities met with opposition. Contact was also made with the Highways Agency to identify where and

to what extent the road network was disrupted. Initial conversations suggested that the information they could supply would add little to our findings and would be time consuming to interpret.

Finally, some data was gleaned from environmental groups. Most notably, the Chilterns Society website produced detailed information on spring source migration along with reports of flooded areas.

### **2.2.2 Historic Data and Anecdotal Information**

During the study, a brief literature review of historic flooding information was undertaken using long term hydrogeological monitoring records and water supply memoirs. These provided a basic background to previous flooding events that appeared to originate from groundwater sources and principally refer to the Chalk hills surrounding the London Basin. Because of the sparse information that could be gleaned from these sources it was decided that the study should concentrate on the events of 1994-95, 2000-01 and 2002-03.

## **2.3 Frequency of Occurrence**

Applying standard statistical techniques used in fluvial flood estimation, to estimate the return period of groundwater level peaks is difficult. The techniques require independent peaks. Groundwater peaks are closely related to the summer minima which, in turn, are related to the previous peak. This dependence or memory can extend back many years in some aquifers. Selecting independent peaks reduces the total number of peaks considerably and therefore the level of confidence that can be placed on the results. It is therefore only possible to state the number of occurrences of high groundwater levels or groundwater flooding in this study rather than formal frequency analyses.

It is apparent that, within living memory, the most geographically extensive groundwater flooding events occurred for periods of up to 4 months between November 2000 and July 2001. In some places, e.g. the Marlborough Downs, a slightly more severe event of shorter duration occurred in January 2003 although this is believed to have been caused by surface runoff from the less permeable lower Chalk.

Prior to these events, Southern England experienced significant groundwater flooding in the winters of 1988-89, 1993-94 and 1994-95 according to reports in the literature and personal interviews. Prior to these dates there appears to have been no flooding for 30 years in Hampshire, Dorset and Wiltshire and not for 20 years in Sussex.

In spite of the gap of 20 to 30 years in groundwater flooding, a long-term groundwater hydrograph of 80 years at Whitedale, East Hampshire appears to indicate that groundwater emerged in the nearby village of Hambledon, fairly frequently (equating to approximately every three years over the full record length). Flooding of the village itself is slightly more infrequent and approximates to every five years over the full record (Hambledon PC, pers comm.) Comparing groundwater levels and flooding occurrences in West Sussex using the 167 year record at Chilgrove shows a similar frequency of occurrence. In conclusion recent groundwater conditions experienced in the southern Chalk appear to be more extreme than any experienced in the last 100 years.

The 2000/01 flooding was largely driven by exceptional rainfall over much of the period September 2000 to March 2001. Over England and Wales as a whole, rainfall for the eight month period starting in September 2000 was 166% of the long term average (Marsh and Dale, 2002). The typical rainfall pattern of higher totals in the west and north was reversed with the south east recording 1036mm (183% long term average) and the North East only 779mm (133% LTA). In large parts of southern England rainfall totals exceeded 180% of the long term average for the 3 month period starting in September 2000. Within the EA Thames Region, the period October 2000 to April 2001 was the wettest 7 month period recorded in a series going back to 1885. Robinson *et al* (2001) calculated return periods for the rainfall based on aquifer unit areal rainfall. Areal rainfall is estimated from a network of raingauges that, when combined, are considered to represent the area in question. They found that for the 4, 6, 8 and 9 month periods starting in September 2000, areal rainfall for each of the major aquifer units of Thames region was generally unprecedented in a record series dating back to 1920. For the 9 month period starting in September 2000, the return period is estimated to be in excess of 75 years for the Great Oolite Limestone aquifer of the Cotswolds and in excess of 100 years for all other aquifer units within Thames Region. Marsh and Dale (2002) using different techniques estimate return periods for some durations within the south east of England to be in excess of 200 years.

However, whilst recharge rates were very high and the recharge season exceptionally long it is not without precedent. Morris (2001) analysed the borehole water level record from Stonor observation borehole (SU78/45A), located in the Chalk aquifer of the south-west Chilterns (NGR SU74198924). It was shown that the 2000/01 recharge season was only the third longest on record being exceeded by those of 1974 and 1992 without, it appears, any reported flooding. In 1992, groundwater levels rose 18.95m from a summer minimum of 62.7m to a peak at 81.66m. In contrast, during the 2000/01 recharge season, levels rose by only 16.52m, some 2m lower than in 1992. However, in 2000, recharge started from a summer minimum only 5m below the 1992 winter peak. This is unique within the Stonor record, all previous periods of very high recharge had occurred after below average summer minima.

It is the combination of the higher than average summer minimum and the extreme rainfall that produced the record peak in the Stonor borehole in 2000/2001. This tendency for a long memory within the Stonor record is particularly clear in the latter few years. Whilst the memory within the Stonor record is long compared to that of much of the southern Chalk it does highlight the importance of year on year fluctuations in recharge and recession rates. It also hints at the difficulties of estimating return periods using borehole water levels as many statistical techniques require independent peaks. Water levels in the Chalk are clearly dependent on the previous summer minima- and in turn the previous winter maxima- so dual probability analysis is required.

Blackburn and Hoskins (2003) searched the England-Wales long term precipitation series dating back to 1766 for trends in the September-October-November rainfall totals over the last half century and over the entire period of record and detected none. They do report however, that Jones and Conway (1997) found an increase in winter precipitation (December to February) that may be of importance in terms of aquifer recharge. Whilst it is tempting to identify a trend and assign to climate change, there is insufficient documented evidence to make a comment. Arnell (1998) using the 1996 Climate Change Impacts Review Group (CCIRG) scenario noted that the impact of the predicted increase in winter recharge may be reduced by the higher evaporation reducing the length of the recharge season. It has not

been possible within this scoping study to review the effects of climate change scenarios on groundwater levels generally. However, any change in climate that would lengthen the recharge season or increase the volume of recharge could result in an increase in groundwater levels. The likelihood of this causing flooding will be dependent on aquifer properties.

## 2.4 Causes of Groundwater Flooding

This section reports on the current understanding of the causes of groundwater flooding and the controls on its spatial and temporal distribution. There is very little information available on historical groundwater flooding so specific reference is made to the 2000/01 event. This period saw the most extreme and spatially extensive flooding and, in comparison to previous events, is well documented. Conclusions are drawn from this period in the anticipation that similar processes would occur again under the same hydrological circumstances.

The overriding characteristics of the spatial and temporal distribution of groundwater flooding presented in the previous section are that the flooding occurred:

- *almost wholly on the surface outcrop of the Chalk aquifer;*
- *during a prolonged period of high rainfall; and*
- *when groundwater levels in most aquifers were at higher than average levels.*

It should be noted that there is very little technical information available on high groundwater levels, with studies of groundwater fluctuations generally concentrating on low levels. Studies have largely been concerned with water resource planning, low flow alleviation and impact of climate change on groundwater levels (Arnell 1998). Flooding from permeable catchments is discussed in detail in the Flood Estimation Handbook (IH, 1999) and supporting papers although this is regarding fluvial flood estimation. Only in recent years, with the implementation of the LOWland CATCHment Research (LOCAR) program, has research emphasis been placed more concertedly on processes and therefore on high groundwater levels.

Considerable knowledge on the behaviour of groundwater levels has been built up with the development of groundwater simulation models. However, these are usually calibrated and validated on low flows and they generally do not perform well at above-average flows. This is largely because at high groundwater levels, the permeability and storage characteristics of the Chalk in the normally unsaturated zone are very different and the properties of the Chalk in this zone are poorly understood or documented.

Although a general understanding of the causes of groundwater flooding is becoming apparent, the location, timing and extent is difficult to predict principally because of the heterogeneous nature of the Chalk. This has recently come to light in Picardy where the Somme basin has been affected by flooding during the last three years and European research funds are being sought by an Anglo-French consortium of BGS, the Environment Agency, Southern Water, the Highways Agency and Union Railways, together with the French organisations BRGM and ANTEA, to obtain a better understanding of the engineering and hydraulic properties of the Chalk to assist in the planning and design of engineering projects within this widespread and strategically important aquifer.

The Environment Agency in its presentations to villages in Wiltshire (Environment Agency, South West Region, 2003), (*Environment Agency, South West Region,*

*Groundwater Presentation, Salisbury Plain, November 2003*) states that groundwater flooding is caused by the association of a number of factors which are:

- *Geological conditions;*
- *Presence of dry valley, winterbournes, springlines, fault lines;*
- *Presence of properties located adjacent to dry valleys;*
- *“16 weeks of heavy rainfall” – defined as a total of 400 mm in Wiltshire.*

Whilst there is a scarcity of academic papers on the actual causes of groundwater flooding some assumptions can be made from aquifer properties. The major aquifers of England can be characterised into three groups according to the relative importance of primary and secondary flow characteristics within the aquifer. It is these characteristics that ultimately define the response of the aquifer to recharge and hence to recession or flooding propensity.

The first group includes karstic and Jurassic limestones and are characterised by having a well connected network of fissures. These aquifers generally respond rapidly to recharge and this is reflected in the rapid dissipation of the water into the fluvial network. Consequently, groundwater levels in the interfluvial areas tend not to build up to any great extent. Periods of high recharge are more readily visible as transient responses in observation borehole levels and in the flow records of rivers draining the aquifer rather than prolonged changes in groundwater levels .

Those aquifers characterised by intergranular (Darcian) rather than fissure flow similarly have a low propensity to cause groundwater flooding. The Lower Greensand is typical of this group in having high storage but low permeability and therefore these aquifers are very slow to respond to recharge. The Permo-Triassic aquifers, whilst having a greater degree of fissuring than the Greensand, are also slow to respond. Aquifers with very high storage characteristics require exceptionally large recharge to create a significant groundwater level response. Aquifers in this group are able to accommodate extremes in recharge so that changes in the water balance will be observed over periods of several years rather than in individual seasons. Annual fluctuations in the Permo-Triassic aquifers are therefore typically in the region of only 2 to 5m.

Falling between the two extremes of the highly fissured and karstic aquifers and those displaying intergranular flow, are the Chalk aquifers. These aquifers have hydraulic characteristics referred to as “dual porosity”, carrying and storing water through the pores in the rock matrix and through fissures. The matrix Chalk has a very high porosity and extremely low permeability. During periods of very high recharge, the fissure faces of the matrix Chalk in the unsaturated zone above the water table take up a significant volume of water and eventually become saturated. This transient storage volume is about 0.3% (Price et al, 2000). The fissure volume, which has a secondary porosity of well below 1% in the interfluvial Chalk (Robinson 1976) then becomes the main storage volume and groundwater levels rise rapidly and ultimately cause flooding. Typically in the Chalk interfluvial, groundwater levels can rise 20 to 40 m in a recharge season. The fissure system, particularly in the interfluvial, has a low to medium permeability and is therefore relatively slow in transporting the water down gradient to dissipate these heads. Once the recession starts, water discharges slowly via fissures and is maintained by the release of intergranular pore water. It can take several months for groundwater to decline from these very high levels thus perpetuating groundwater flooding events. It appears that it is the exchange mechanism between the two porosities ie fissure and intergranular, in the unsaturated zone which gives the Chalk its unique characteristics.

Given the effects of the dual porosity it would be reasonable to assume that wherever there are Chalk aquifers there is the potential for groundwater flooding. However, it appears that ground water flooding is largely confined to the exposed Chalk outcrops of southern England typified by the South Downs, Wiltshire and Berkshire Downs and Southern Chilterns. It is clear that where the Chalk is covered by glacial drift, especially including Boulder Clay, this has the effect of buffering the aquifer from extremes of recharge by smoothing the release of percolation into the Chalk aquifer over a longer period and reducing the rapid build up of groundwater level. This would explain the absence of groundwater flooding in the north east of Thames Region, parts of East Anglia and parts of the Chalk outcrop further north.

Although groundwater flooding is virtually unrecorded in major aquifers other than the Chalk it is possible that this may relate in some degree to a lack of reporting. It is therefore possible that these aquifers could cause groundwater flooding if a certain combination of climatic and hydrogeological conditions were to occur. Further work beyond the scope of this study is needed to clarify the likelihood of such flooding.

Although the reported groundwater flooding is strongly associated with the Chalk it is important to note that flooding did not occur at every location on the Chalk that a simple rise in groundwater level across the whole aquifer would predict. This indicates that the precise nature of groundwater flooding across the Chalk was affected by local variations in a number of factors, which may include:

- *Details of rainfall distribution;*
- *Recharge characteristics of the interfluvial Chalk blocks;*
- *Degree of karstification in the Chalk;*
- *Chalk permeability and porosity profiles in the valley bottoms; and*
- *Buffering effects of any overlying low permeability drift deposits.*

It is clear from the above discussion that the particular nature of the dual porosity present in the Chalk is a potential explanation why groundwater flooding is almost wholly associated with this aquifer. The precise mechanisms for flooding at different locations on the Chalk, however, can only be identified by a site by site consideration of a number of factors.

## **2.5 Vulnerability to Groundwater Flooding**

### **2.5.1 Identification of Vulnerable Areas**

Whilst the close association of Chalk and groundwater flooding was recognised, it was not clear at the commencement of this study whether all areas of Chalk produced flooding events given the required amount of recharge, nor whether other aquifers across the country had also been the source of groundwater flooding.

Due to brief nature of this study it is not possible to answer either of these questions with absolute certainty. However, in interviewing a number of Environment Agency hydrogeologists across the country from each Region and from most Area offices it appears that groundwater flooding is predominantly a Chalk phenomenon. The potential causes of groundwater flooding and potential explanations why it predominantly occurs on the Chalk outcrop have been discussed in Section 2.4. However, a few other, more localised aquifers may have produced local flooding events which are described in the sections below.

The map of occurrence of groundwater flooding (Appendix B/Occurrence/National/1) that accompanies this report indicates the localities where groundwater flooding events have been observed and recorded by the Environment Agency. The spatial distribution of these events closely follows the outcrop pattern of the Chalk aquifer. This study has investigated the possibility of groundwater flooding occurring in areas underlain by other aquifer types but the recorded level of detail for these occurrences is insufficient to obtain a firm conclusion. An alternative approach was therefore adopted to examine the characteristics of the Chalk that may be associated with groundwater flooding and then compare them with other aquifers. A simple predictive model was constructed for this purpose, incorporating all the major aquifers to compare the location and extent of the predicted flooding events with the distribution of recorded occurrences and the distribution of aquifer types.

### ***Aquifer Hydraulic Characteristics***

The key differences between the Chalk aquifer and other major aquifers have been discussed in Section 2.4.

The Chalk aquifer stretches north-eastwards from Wiltshire through Hertfordshire to North Yorkshire and south-eastwards through Hampshire to East Kent. An examination of the occurrence of groundwater flooding in other aquifers has not provided any conclusive evidence of groundwater flooding. There may be a possibility of flooding emerging from the Carboniferous Limestone, which is a rapid response fissured aquifer, as high baseflows occur in rivers in its outcrop area following prolonged rainfall. However, these are typically upland areas where it is likely groundwater emergence would go un-reported. Other formations such as the Jurassic Limestones and the Magnesian Limestones may produce localised flooding but the largest aquifer in the country, the Permo-Triassic Sandstones appears to have no reported incidences.

It could be expected that the Chalk of Yorkshire, Humberside and Lincolnshire, where exposed, would react in the same way as that in the south of the country. However, generally fewer flooding reports were received. Where the Chalk is unconfined it typically has a seasonal range of up to 30m and like that of southern England is dissected by dry valleys and associated springs. However, in contrast to the southern Chalk formations, this Chalk is reportedly much harder and has a much higher transmissivity (Allen *et al*, 1997). The aquifer may thus behave in a manner more similar to other major aquifers than to southern Chalk, with more rapid drainage and attenuation of heads when high recharge rates occur. It can be concluded then, that with the slightly less extreme rainfall and a more highly transmissive aquifer with, in many places glacial drift covering, that the northern Chalk outcrops were slightly less vulnerable in 2000/01 than the southern Chalk.

### ***Topography and Drainage***

Groundwater flooding occurs when groundwater levels rise sufficiently high to reach the ground surface and, for whatever reason, the local drainage network is unable to cope with the volume of water. These areas are typically in the headwaters of the ephemeral drainage system and, in a typical year, are usually some considerable distance from the seasonal watercourses. Flooding was also reported at lower elevations in river valleys largely as a result of the groundwater flow rate exceeding the channel capacities. Where channels seldom flow there has been the tendency for them to become neglected or small bridges to properties built over them with insufficient capacity. Infilling of these local drainage paths is also a common phenomenon. Detailed surveys of dry valleys and the seasonal migration of the

head of winterbournes and points of emergences were beyond the scope of this study.

### 2.5.2 Mapping Groundwater Flooding

Areas subject to groundwater flooding result from an interplay between hydrogeological characteristics, topography and anthropogenic factors. Whilst the flooding experienced in 2000/01 was relatively widespread in southern England many of the contributing factors to the degree and precise location of flooding were caused by local factors superimposed on the regional picture. In many locations, flooding was exacerbated by ephemeral streams having being neglected and local drainage channels constricted by either poor maintenance or development. However, the overriding control on the vulnerability to flooding in 2000/01 was the manner in which the permeable catchments responded to the exceptional antecedent conditions and heavy rainfall of 2000/01.

Several reports are available documenting the location of groundwater flooding as experienced in 2000/01. These cover areas ranging from individual villages (Halcrow, 2001), to aquifer units (Chiltern Society) and region wide (Robinson *et al*, 2001). However, with the exception of Robinson *et al* (2001) they are generally reports of flooding locations rather than detailed explanations of physical processes.

Finch *et al* (in press) investigated the spatial distribution of groundwater flooding in the Pang catchment (Berkshire) during 2000/01. Using a combination of aerial photography, flow measurements and water temperature analysis, Finch was able to explain the occurrence of flooding on the basis of the regional groundwater flow directions and the presence of locally important preferential flow lines. It is not possible to replicate work of this detail to identify flood prone areas in all permeable catchments although it clearly provides insights into the controlling factors and the relationships between regional and local scale influences. At a regional scale, the British Geological Survey (BGS) mapped flood risk areas in the Chalk using relatively detailed groundwater contours and showing those areas where maximum groundwater levels were within 5m of the surface (Mckenzie, pers com). This preliminary study was based on a single estimate of the range in groundwater levels and took no account of superficial deposits. However, it is our understanding that this work is currently being refined.

Two different approaches have been taken in this present study with regard to the mapping of areas vulnerable to groundwater flooding. The first identifies those locations where groundwater flooding has been reported since 1994. The second method is more predictive and aims to identify those areas which would be first affected if groundwater were to rise sufficiently close to the surface to cause problems. This latter series of maps does not imply that flooding will be a problem. As described above, the location and degree of flooding is dependent on local factors that cannot be incorporated on a national assessment of potential vulnerability to groundwater flooding. This series of maps is indicative only and provides a summary of areas which could be affected if a combination of conditions led to exceptionally high groundwater levels in the underlying aquifers.

#### **Mapping Areas of Reported Groundwater Flooding**

The first series of maps document all reported incidents of groundwater flooding in recent years during the winters of 1994-95, 2000-01 and 2002-03. Those areas that experienced flooding in the exceptionally wet winter of 2000-01, as indicated on the maps, will again be vulnerable in subsequent winters if groundwater rises to the same level and effective remedial measures have not been put in place. These

maps clearly show the regional distribution of flooding but also the impact of local factors – some areas experiencing different degrees of problems.

These maps are largely based on records kept by the Environment Agency of reports made by the public of groundwater flooding. As such they are only really a sample of occurrences as discussed previously.

Despite the limitations of the data, the occurrence maps clearly show the spatial distribution of the incidents of groundwater flooding. Each symbol on the map shows the occurrence of at least one report of flooding. However, particularly in the Chalk of southern England, the symbol can refer to many reports or even an entire village. It has not been possible given the form in which the data was supplied to always be sure of the number of properties affected. However, Tables 2-A and 2-B provide details of reports of groundwater flooding as received from the Environment Agency.

Environment Agency Area number	Environment Agency Region	Environment Agency Area	1994/95	2000/01	2002/03	Totals
1	North West	Northern	-	-	-	0
2	North West	Central	-	-	-	0
3	North West	Southern	-	-	-	0
<b>North West Region Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
4	North East	Northumbria	-	-	-	0
5	North East	Dales	-	-	-	0
6	North East	Ridings	-	6	-	6
<b>North East Region Total</b>			<b>0</b>	<b>6</b>	<b>0</b>	<b>6</b>
7	Midlands	Upper Severn	-	-	-	0
8	Midlands	Upper Trent	-	-	-	0
9	Midlands	Lower Trent	-	-	1	1
10	Midlands	Lower Severn	-	-	-	0
<b>Midlands Region Total</b>			<b>0</b>	<b>0</b>	<b>1</b>	<b>1</b>
11	Anglian	Northern	-	3	-	3
12	Anglian	Central	-	11	-	11
13	Anglian	Eastern	-	-	-	0
<b>Anglian Region Total</b>			<b>0</b>	<b>14</b>	<b>0</b>	<b>14</b>
14	Thames	West	-	77	20	97
15	Thames	North East	-	9	5	14
16	Thames	South East	-	110	21	131
<b>Thames Region Total</b>			<b>0</b>	<b>196</b>	<b>46</b>	<b>242</b>
17	South West	Cornwall	-	-	-	0
18	South West	Devon	-	-	-	0
19	South West	North Wessex	-	-	-	0
20	South West	South Wessex	7	9	22	38
<b>South West Region Total</b>			<b>7</b>	<b>9</b>	<b>22</b>	<b>38</b>
21	Southern	Hampshire	19	70	45	134
22	Southern	Sussex	-	-	20	20
23	Southern	Kent	-	34	2	36
<b>Southern Region Total</b>			<b>19</b>	<b>104</b>	<b>67</b>	<b>190</b>
<b>Environment Agency England Total</b>			<b>26</b>	<b>329</b>	<b>136</b>	<b>491</b>

Table 2-A Reported occurrences of groundwater flooding from hard rock aquifers

Environment Agency Area number	Environment Agency Region	Environment Agency Area	1994/95	2000/01	2002/03	Totals
1	North West	Northern	-	-	-	-
2	North West	Central	-	-	-	-
3	North West	Southern	-	-	-	-
<b>North West Region Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
4	North East	Northumbria	-	-	-	-
5	North East	Dales	-	-	-	-
6	North East	Ridings	-	-	-	-
<b>North East Region Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
7	Midlands	Upper Severn	-	-	-	-
8	Midlands	Upper Trent	-	-	-	-
9	Midlands	Lower Trent	-	-	-	-
10	Midlands	Lower Severn	-	-	-	-
<b>Midlands Region Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
11	Anglian	Northern	-	-	-	-
12	Anglian	Central	-	-	-	-
13	Anglian	Eastern	-	1	2	3
<b>Anglian Region Total</b>			<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>
14	Thames	West	-	5	-	5
15	Thames	North East	-	10	70	80
16	Thames	South East	-	203	117	320
<b>Thames Region Total</b>			<b>0</b>	<b>218</b>	<b>187</b>	<b>405</b>
17	South West	Cornwall	-	-	-	-
18	South West	Devon	-	-	-	-
19	South West	North Wessex	-	-	-	-
20	South West	South Wessex	-	-	-	-
<b>South West Region Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
21	Southern	Hampshire	-	-	-	-
22	Southern	Sussex	-	-	-	-
23	Southern	Kent	-	2	-	2
<b>Southern Region Total</b>			<b>0</b>	<b>2</b>	<b>0</b>	<b>2</b>
<b>Environment Agency England Total</b>			<b>0</b>	<b>221</b>	<b>189</b>	<b>410</b>

**Table 2-B** *Reported incidences of groundwater flooding from superficial deposits*

### ***Spatial Distribution of Reported Flooding***

The map in Appendix B Occurrence/National/1 shows the location of reported flooding for England as a whole from permeable catchments. It is immediately evident that there is a clustering of incidents in the south and east of the country. Map Occurrence/National/2 shows the incidents of reported flooding from valley and terrace gravels. The Environment Agency recorded a large volume of calls from the public reporting flooding from this source within Thames Region. It has not been possible to investigate the exact causes or to assess whether the problem exists in other parts of the country.

Maps Occurrence/6 to 23 in Appendix B show the distribution of reported flooding for each Environment Agency Area. Where there have been no reports of flooding within an Environment Agency Area, the Area map has not been produced. Whilst the data is considered to be an underestimation of the number of properties flooded, the maps are considered to be a reasonable representation of the geographical extent of the flooded areas. Reference to the underlying geology clearly shows that the reported occurrences of groundwater flooding are almost entirely confined to the Chalk outcrop and, within the Chalk, to that of southern England.

The Environment Agency report on groundwater flooding (Water Resource Situation Report, 2001) summarises the number of properties flooded throughout England. In March 2001, Southern Region was reported to have 60 properties flooded and in Thames Region the number of flooded properties ran into the 'low hundreds'. In addition South West Region reported 200 properties (pers comm), the Halcrow Report (2002) reported that over 700 properties in Hampshire were affected in some way by groundwater flooding and 60 properties were affected in North East Region. Taking into account the variable format in which flooding was documented and the degree of under reporting it is estimated that around 2000-3000 properties were affected by groundwater in 2000/01. In addition to this numerous roads and under ground services were disrupted.

### **2.5.3 Mapping Areas Potentially Vulnerable to Groundwater Emergence**

The second series of maps - the potential Groundwater Emergence Maps (GEMs) in Appendix C, identify those parts of England where, in exceptionally wet winters, groundwater levels could be expected to be at or close to the ground surface. Where possible these maps have been calibrated on the ground truth observations made in the winter of 2000-01. Where no flooding was reported, or information was not made available, the maps indicate estimated areas based on anticipated groundwater levels using relevant aquifer properties. The GEMs do not imply flooding per se, only that groundwater would emerge at the surface first within the indicated areas. The impact of groundwater being at or close to the surface is largely dependent on its frequency of occurrence. Those areas that have groundwater near the surface on an annual basis, would normally have drainage systems adapted to the annual flow range experienced. It is in those areas, normally at the upper reaches of the catchment that experience high groundwater only very rarely, where problems of flooding are most likely to be experienced. Typically, drainage paths in these areas will be poorly defined and unable to cope with the flow, and cellars and basements may flood from seepage. Within the zones identified the following impacts are possible:

- *Emergence of new or rarely experienced springs;*
- *Migration of stream sources high into the headwaters;*
- *Emergence of water into underground structures;*

- Emergence of water at the surface;
- Flooding of properties;
- Local drainage network overwhelmed by rate of flow;
- Large areas of standing water;
- Surcharging sewer network;
- Failure of electricity supplies;
- Inundation of roads, restricting vehicle movements and deterioration of the surface cover; and
- Damage to crops.

The groundwater emergence maps are composite maps. They are constructed according to the availability of required information. Where there are numerous reports of groundwater flooding and groundwater contour data is available, mapped areas are calibrated on observations. Where there are no reports of flooding, or no data is available, the mapped areas are based on regional groundwater movements only. Where no groundwater contours are available or the aquifer is of local significance only, the Base Flow Index derived from the Hydrology Of Soil Types (BFIHOST) classification colour coded network gives some indication as to the proportion of flow derived from baseflow. These three scenarios are summarised in Table 2-C.

Scenario	Availability of Data	Method Employed
Flooding reported	Groundwater contours available	Identified areas defined by observed flooding and calibrated.
No flooding reported or no data supplied	Groundwater contours available	Identified areas based on generalised aquifer properties.
Flooding or no flooding reported	No groundwater information available	River network classified by BFIHOST identifies vulnerable areas.

**Table 2-C Mechanism used for identifying areas potentially vulnerable to groundwater emergence**

Areas prone to groundwater emergence have been identified, where possible by reference to the underlying depth to groundwater. Previous studies (McKenzie, pers. comm.) have mapped areas in the southern Chalk with groundwater within 5 m of the surface. However, applying this same threshold at a national scale to aquifers with disparate properties (storage) would be misleading. To achieve national coverage it has been necessary to consider the properties of each aquifer and define an appropriate expected rise in groundwater levels under wet winter conditions.

The Environment Agency and British Geological Survey (BGS) made groundwater contours available to the study for all major aquifer units of England. The majority of the data (supplied by BGS) was in the form of metres or feet above Ordnance Datum. This has been converted to depth below ground surface (in metres) using the Centre of Ecology and Hydrology (CEH) digital terrain model (IHDTM) (Morris and Flavin, 1990) as supplied by Defra, comprising ground level contours at 2m intervals. Ideally, groundwater contours representing the groundwater conditions of the spring of 2001 would be used however, these data was not available and constructing such a data set was beyond the scope of this study. The areas covered by the data supplied represent different years and seasons, the majority of

which are for periods when the groundwater levels could be considered to be average or below average. This reflects the emphasis on which groundwater data is generally of interest i.e. monitoring for low flows and water resource utilisation. Table 2-D provides details of the source of the data, the period they represent and additional notes.

Area covered	Source	Period
Cambridge / Maidenhead	BGS	Autumn 1976
Carmenellis	BGS	September 1985
Clwyd/Cheshire	BGS	1977 – 1986
East Yorkshire	BGS	July 1976
Hampshire	BGS	October 1973
Kent	BGS	Pre 1970
NE Anglia	BGS	1968 – 1974
NE Lincolnshire	BGS	1976
NE Midlands	BGS	1970 – 1980 for Limestone and 1978 for Sandstone
South Downs	BGS	October 1973
SE Anglia	BGS	August and September 1976
SW Chilterns	BGS	August 1976 Chalk, Pre 1978 for Corallian
SW Minor Aquifers	BGS	January 1977 for Triassic, 1973 – 1980 for Permian
South Yorkshire	BGS	1969 – 1980
Wessex	BGS	September 1975
Thames Region	EA	Unknown - high levels
Hampshire & IOW*	EA	1976

*Note. \*BGS version used for Hampshire. Since this analysis was undertaken groundwater contours depicting high water levels have become available in Southern Region.*

**Table 2-D Source and date of groundwater contour data**

To overcome the limitations imposed by the varying nature of the groundwater contour data and to ensure the properties of aquifers are properly considered, each aquifer unit, and where necessary, sub-units have been mapped separately. Whilst the overall approach has been the same throughout the country, data limitations have meant that modifications to the approach have been made as best fits the situation. Consequently, the confidence that can be placed on the maps will vary from area to area. In order to provide an indication as to the reliability of the maps, they have been ranked from 1 to 3 where 1 represents a high degree of confidence in the mapped area. In this case, good quality data exists with sufficient observations being available to allow good calibration and verification of the mapped area resulting in a high degree of confidence in the results. Conversely, a score of 3 indicates a lower than average degree of confidence because of geological complications or lack of data for calibration and verification. A score of two indicates

a situation between 1 and 3 where either data are available but are of unreliable quality or that hydrogeological conditions lead to a high degree of uncertainty.

In those areas where flooding has been experienced in the winter of 2000-01, the locations of reports of groundwater emergence have been identified in a number of headwater locations. These may be stream headwaters or flooding reports. Emphasis was placed on identifying those at the highest elevations. Where available, the corresponding Environment Agency depth to groundwater contour at these points has been noted and an appropriate contour selected to represent these observations. This contour is then taken to have represented the zero depth to groundwater in the spring of 2001. The area falling within this contour area is then defined as vulnerable to groundwater emergence as it is assumed that in the winter of 2000-01 the depth to groundwater at these headwater locations was at or near to zero. This methodology effectively raises the groundwater grid as a horizontal plane by x m whereas in reality the groundwater gradients would also rise. The effect of this is to produce a slightly wider zone of emergence than would be anticipated in the lower reaches of the catchments. Each aquifer has been calibrated separately and, where possible, the aquifer has been calibrated in one area and tested on a separate area to ensure known areas of groundwater emergence are appropriately mapped.

In those parts of the country where no reports of flooding were made in the recent past (2000-01), there is no readily available means of calibrating the groundwater contours for a wet winter. With the exception of a few Areas, the Environment Agency do not routinely record the location of seasonal spring sources. Whilst groundwater borehole levels would be of assistance, unfortunately the analysis of sufficient data on a countrywide basis is beyond the scope of this study. Marsh and Dale (2002), tabulate the average annual groundwater rise experienced in 2000/01 for a number of boreholes considered representative of the major aquifers. This table, reproduced in summary here, (Table 2-E on next page) has been used in this study to identify appropriate levels by which to raise the groundwater contours to simulate the 2000-01 winter period. As with the previous case, the selected contour enables an area to be defined in which, in an exceptionally wet winter, groundwater would be expected to be at or close to the surface. Again, the maps do not imply flooding –the drainage network may have sufficient capacity to accommodate enhanced flow rates from the aquifers or the transmissivity of the aquifer is such that the lag in the system attenuates extremes. In areas of uncertainty, two zones have been identified (typically at 2 m and 10 m). The lower of the two is that considered to be most probable in a wet winter. The second provides an upper band and is there to show the sensitivity of the mapped zone to changes in the selected contour. It is not suggested that the higher of the two contours would be possible under the current climatic regime. In several cases even the 2m increase is considered to be unlikely due to the hydraulic properties of the aquifer units, however the digital terrain model contours are at 2m intervals and therefore a smaller increase would not be consistent with the data sets.

This methodology assumes an unconfined aquifer in which water levels are free to rise or fall. To avoid raising the groundwater in those parts of an aquifer that are confined, reference has been made to the BGS digital classifications of solid geology and drift deposits. Those aquifers overlain with clay, till, boulder clay or less permeable silt have been excluded from the zones of groundwater emergence (Table 2-F on next page). Using aquifer vulnerability maps may have been more definitive than identifying impermeable drift, but, these were not available in a suitable format within the time required. It is considered that, within the mapping scale adopted, major occluding drift has been included.

Well site	County	Aquifer	First year	Mean annual range (m)	Rise winter 2000/01 (m)
Wetwang	N. Yorks	Chalk	1971	8.7	17.3
Redlands Hall	Cambs	Chalk	1963	8.5	17.9
Compton	E Sussex	Chalk	1894	20.8	39.7
Stonor	Bucks	Chalk	1961	7.5	19.8
Lime Kiln	Dorset	UGS	1969	0.8	1.6
Llanfair DC	Gwynedd	PTS	1972	0.7	1.1
Heathlanes	Shrops	PTS	1971	0.5	2.1
Nuthalls Farm	Staffs	PTS	1974	0.5	0.8
Peggy Ellerton	Yorks	MLS	1968	1.2	1.3
Alstonfield	Derbys	CLS	1974	30.6	45.7

Note: UGS, Upper Greensand; PTS, Permo-Triassic Sandstone; MLS, Magnesian Limestone; CLS, Carboniferous Limestone

**Table 2-E Groundwater Levels 2000 –01**

Classification	Geology	Definition
Solid Geology	CLAY,CLGR,CLLI,CLRK,C LSA, CLSI,CLSS	Predominantly clay deposits
Solid Geology	MDST	Mudstone
Drift Geology	SICL,SIGR,SILT,SIMD,	Predominantly silt deposits
Drift Geology	CLAY,CLGR,CLSA,CLSI,C LSS	Predominantly clay deposits

**Table 2-F Superficial deposits used to identify confined areas of aquifers**

There are some locations, mainly consisting of minor aquifers, where groundwater level data are unavailable or, in many cases, groundwater levels are not monitored. To ensure comprehensive coverage of all areas with the potential to cause groundwater flooding the Base Flow Index derived from the Hydrology Of Soil Types (BFIHOST) classification has been applied to the CEH rivers network.

This approach enables the proportion of flow derived from baseflow (stored or slowly released water/groundwater) to be assessed. Simply, the greater the proportion, the greater the propensity to flood from this stored water. The GEMs all show BFIHOST classified according to four categories. Those with a baseflow in excess of 0.9 (90% flow) being heavily dominated by baseflow and typically being Chalk fed. The next two categories are less dominated by baseflow with proportions of 80% and 70%. All other rivers are shown as blue and indicate those rivers in which baseflow does not play a major part in the flow regime. Those sections of rivers coloured grey are unclassified and arise from a poor fit between the rivers network and the BFIHOST network. As the proportion of baseflow drops, the more flashy the flow regime becomes and it would be expected that surface runoff floods become dominant. Whilst the coloured rivers do indicate the proportion of baseflow on the established rivers, it is the minor rivers upstream that are the most vulnerable. However, displaying the more detailed drainage path network is inappropriate at this scale of mapping.

### ***Explanation of BFIHOST***

The BFI derived from the Hydrology of Soil Type (HOST) classification of UK soils has been used in this study to identify those rivers and drainage paths where baseflow is the dominant contributor to the total flow. A high baseflow index indicates a greater propensity to flood from groundwater. The derivation of BFIHOST and the underlying soil classification system are explained in detail in Boorman *et al* (1995). The conversion of the BFIHOST from gridded format to catchment values is described in volume 5 of the Flood Estimation Handbook (Bayliss, 1999)

BFIHOST was chosen as a means of depicting permeable catchments as it provides national coverage of all drainage paths, classified according to the proportion of the flow derived from baseflow. Whilst baseflow estimated from soil properties is inevitably generalised it does enable those drainage paths and rivers with high baseflow to be identified. It cannot, for example, represent subsurface differences in transmissivity between valleys and interfluvies in Chalk areas and so at a local scale generalisations are evident. It also does not distinguish between water released from major or minor aquifers or from land drainage of heavy soils. For the purposes of this study BFIHOST is used to characterise drainage networks by their baseflow component at a national scale and has proven to be sufficiently accurate for this purpose.

BFIHOST varies from 1.0 to 0.17 with an index close to 1.0 being typical of drainage from Chalk and 0.17 from very responsive impermeable catchments such as clay. Map Aquifers in Appendix D shows BFIHOST for all drainage paths with a catchment area in excess of 0.5km<sup>2</sup>. This network extends well beyond the recognisable surface drainage system and, in catchment headwaters will represent only local low points rather than channels. Drainage paths have been supplied by CEH from the Integrated Hydrological Digital Terrain Model (IHDTM) – details of which are described in Morris and Flavin (1990). The IHDTM was produced by interpolating Ordnance Survey panorama data and river heights, both from 1:50,000 scale maps. The interpolation method produces a terrain surface with most height values on the resulting 50 m grid within +/- 2 m of the true value. In the predictive GEMs, BFIHOST has been used to classify the CEH river network to again indicate the baseflow component of the recognisable river network.

### ***Limitations and assumptions***

Having described the methodology used in generating the GEMs, it is appropriate to detail the limitations and assumptions that have had to be made in the process.

The major limitation of all the predictive maps is that of scale. They are all based on assumptions made in one area and superimposed on adjacent areas. It is clear that local characteristics, particularly in the Chalk, can have a direct influence on the location and severity of groundwater emergence. Ideally, those locally important features would be incorporated into the maps – certainly many of the Environment Agency hydrogeologists know the peculiarities of their valleys and reaches in terms of stream source migration and spring emergence. However, a national study can only give a broad-brush approach to identifying areas with groundwater close to the surface.

The methodology is heavily reliant on the groundwater contour data. Unfortunately, at the time of writing virtually no background information detailing the methods used to define the contours or the number and location of water level readings was

available. For the purposes of this study it has had to be assumed that not only are the groundwater contours accurate but that the patterns are permanent. It assumes that the summer pattern is maintained throughout the full range of groundwater levels. This is clearly not the case and it is expected that heads and gradients could change and groundwater catchments could change shape and size both throughout the season and from year to year.

Aquifers, or parts of aquifers, that are confined have been eliminated from the mapped areas. It is assumed that an aquifer is confined if solid geology or drift geology indicates an impermeable covering. In practice, particularly on the edge of the confined area there are zones of greater or lesser confinement. It has not been possible to delineate confined aquifers on a case by case basis nor assess the degree of confinement.

The location of stream sources and the selection of reports of flooding used for calibration purposes are open to error, as it is believed that the data sets supplied are not comprehensive.

It should also be noted that the CEH river network supplied by Defra for this study is an older version than that currently held by CEH. The more recent version has a denser river network than that shown for the North West Region. In the version used here the North West has a lower drainage density shown than the rest of the country. As it is the more minor rivers that are of interest and these are not represented, some headwaters of high BFIHOST may be omitted in the North West maps. However, we do not anticipate that many high baseflow rivers occur in the northern part of the North West Region and those that do will be very localised. We anticipate the deduced network density will lead to an underestimate of the high baseflow network in the south of the Region.

#### **2.5.4 Groundwater Emergence Maps**

##### **Comments on Individual Groundwater Emergence Maps**

Although the predictive model has been well calibrated against the observed groundwater flooding events for the Chalk aquifers, the applicability of this approach to the other major aquifers is less certain. Table 2-G below presents comments on the results of the predictive modelling and the applicability of the approach for each of the individual maps.

Map no	Region	Area	Comments
1	North West	Northern	Predominantly an area of low BFI. Some baseflow dominated streams in the Permo-Triassic sandstones on the eastern boundary and coastal strip. No reports of groundwater flooding although pumping of groundwater from deep pits in coastal sandstone has been reported.
2	North West	Central	Small area identified in quaternary sands and gravels aquifer. It is considered unlikely that water levels could rise by even 2m. No reports of flooding received. Confidence level set at 3 indicating insufficient information available to confirm mapped area. Just north of this area there are some rivers with relatively high baseflow components suggesting some groundwater flooding potential in headwaters. Note reduced density of drainage network shown on this map compared to the rest of England.
3	North West	Southern	Relatively large area defined by raising groundwater levels by 2m in the Bunter sandstones. This area is low lying and poorly drained. No reports received of groundwater flooding and BFIHOST classification shows rivers are not strongly baseflow dominated. Note reduced density of drainage network shown on this map compared to the rest of England.
4	North East	Northumbria	BFIHOST classification of rivers shows rivers are not baseflow dominated. No reported groundwater flooding and area not considered to be at risk of flooding from groundwater sources. Note that the drainage network is incomplete in the north of the Area.
5	North East	Dales	Raising groundwater levels by 2m shows some restricted areas with groundwater near to the surface. This is a complex area of limestones and shales forming minor aquifers. These areas have a very restricted range of groundwater fluctuation. York is known to experience high groundwater levels however no reports of flooding from this source were reported in 2001.
6	North East	Ridings	Chalk area on east coast clearly shows potential for groundwater levels to rise close to the surface. Some reports of flooding in 2000/01 although too few to be fully confident in mapped zone.
7	Midlands	Upper Severn	Area of complex geology including water bearing Permo-Triassic sandstones. No groundwater contour data available. Only small reaches of minor tributaries show base flow dominance. No reported groundwater flooding.
8	Midlands	Upper Trent	Area of complex geology including water bearing sandstones. No groundwater contour data available. Only small reaches of minor tributaries show base flow dominance. No reported groundwater flooding.
9	Midlands	Lower Trent	Groundwater contours available for the Bunter sandstones and Magnesium limestones, both of which show restricted annual variation in groundwater levels. No reports of groundwater flooding received. BFIHOST clearly shows baseflow dominated rivers on western edge of aquifer.
10	Midlands	Lower Severn	This Area is largely covered by Lias clay and thus the rivers have low BFIHOST values. A small area of Jurassic limestone to the south is drained by high baseflow streams. However, no groundwater contour data is available. No reported groundwater flooding.

Map no	Region	Area	Comments
11	Anglian	Northern	Chalk aquifer in which groundwater level rise based on a restricted number of reports of groundwater flooding. Good agreement with high BFI Host rivers.
12	Anglian	Central	A complex map based on three groundwater contour data sets. BGS Cambridge/Maidenhead area calibrated on reports of groundwater flooding - some beyond Area boundary. In BGS SE Anglia area a few reports of flooding although considered to be a reasonable representation of area vulnerable to groundwater rising close to the surface. The BGS NE Anglia area is less certain due to more complex geological conditions and no reported observations of groundwater flooding.
13	Anglian	Eastern	BGS NE Anglia area composed of unconsolidated crag in which groundwater levels are unlikely to rise beyond the 2 m shown. The 10 m envelope, covering a much larger area highlights the relatively flat terrain and thus the sensitivity to contour selection. Greater confidence is placed in the BGS SE Anglia area comprising Chalk and calibrated on reported observations of flooding (note these lie within the same aquifer block but beyond the Area boundary). To the very south of the map, no groundwater contours are available and BFIHOST classification suggests no propensity to flood from groundwater.
14	Thames	West	Northern sector comprises the oolitic limestone of the Cotswolds. No reported groundwater flooding in recent years although rivers draining the aquifer areas experienced record high flows in the spring of 2001 for prolonged periods. This is a typical response for this type of aquifer which shows only small fluctuations in water levels. The Chalk aquifer to the south shows a good fit with the reported flooding.
15	Thames	North East	Chalk area overlain in the north eastern areas by drift deposits of varying thickness. Zone vulnerable to groundwater emergence based on reported observations of groundwater flooding. Areas in the southernmost part of the map are river valley gravels. The extent of the emergence zone is over-estimated in these areas and needs further refinement based on local aquifer properties.
16	Thames	South East	Emergence zone running south west to north east across map reflects the Chalk of the North Downs and is considered to be a reasonable interpretation based on observations. However, the area of Greensand outcrop to the south needs further refinement using a reduced rise in groundwater levels. Note the large number of reported groundwater flooding incidents outside the emergence zones. These are believed to arise from flooding from superficial deposits of valley gravels. The actual cause of flooding in these areas is more localised – note the BFIHOST does not suggest a tendency to high baseflows. However, there is obviously a large population affected and further investigations are required.

Map no	Region	Area	Comments
17	South West	Cornwall	Rivers in this area have low baseflow components reflecting the impermeable nature of the geology. Groundwater contours were supplied for an area of a minor aquifer of unconsolidated weathered granite. Groundwater levels are unlikely to rise as much as the 2 m shown due to the high permeability and porosity characteristics of such localised deposits and this is born out by the lack of reported incidences.
18	South West	Devon	Minor local aquifers with very restricted annual fluctuation in groundwater levels. No reported incidences of groundwater flooding although river classification shows importance of baseflow component. Note presence of a few baseflow dominated rivers in coastal zone south of limit of groundwater data.
19	South West	North Wessex	Very small area of Chalk on western boundary of BGS South West Minor Aquifers shows restricted area with groundwater near to the surface although no reported flooding incidents. Some scattered baseflow dominated rivers visible within the area but no reported problems.
20	South West	South Wessex	Map generated from two groundwater contour maps. The western sector had only one report of groundwater flooding – a single property in 1994/5, details of which are sparse. Consequently this map is based on raising the groundwater contours by 10 and 20 m and has been allocated a low (3) confidence limit. The eastern sector is well calibrated based on a large number of reported incidents and is considered to have a confidence level of 1.
21	Southern	Hampshire and Isle of Wight	Large number of reports of groundwater flooding from the Chalk aquifer. Map calibrated on observations. Some outlying observations beyond the defined zone suggest local influences on groundwater emergence. Note no river network or groundwater contours available for the Isle of Wight. No reports of groundwater flooding in the Isle of Wight.
22	Southern	Sussex	Potential emergence zone based on reported observations of groundwater flooding. Confidence level 1 assigned to the potential emergence zone.
23	Southern	Kent	Potential groundwater emergence zone based on reported incidents of groundwater flooding from the Chalk. Note some reports for areas to the south of the envelope of groundwater contours. These are believed to arise from localised minor aquifer units and are located close to high baseflow streams.

**Table 2-E Comments on individual Groundwater Emergence Maps**

### **General conclusions on predictive maps**

The predictive GEMs indicate the areas of England which would be the first to flood if groundwater rose to, or close to, the surface. The most extensive areas identified are entirely confined to the Chalk. The high number of reported incidents of flooding in and downstream of Chalk catchments in the winter of 2000/01 confirms that these potential flood envelopes are associated with a real risk of flooding. All other areas identified are generally of restricted geographical extent and have a higher degree of uncertainty attached.

The mapped areas fall into two categories. Those in which calibration was possible against reported incidents of flooding occurring in 2000/01. These areas are almost entirely confined to the Chalk aquifers of southern and eastern England. Here the analysis shows that extensive areas are vulnerable to groundwater emergence. As expected, the vulnerable areas are in the valleys of ephemeral and perennial streams but also in the headwater extensions of these streams into areas where surface water is very rarely seen. In a winter with water levels similar or higher than those witnessed in 2000/01 these same areas will be expected to experience groundwater at or close to the surface again. Given the heterogeneous nature of Chalk it could be argued that predictions cannot be made between areas and this is substantiated to a degree by the findings of Finch *et al* (2003) in the Pang catchment study and Robinson *et al* (2001). However, at the scale presented the areas defined can clearly be considered as having the potential for groundwater to emerge and cause the disruption seen in 2000/01

The second category of areas identified as likely to have groundwater at or close to the surface in a winter at least as wet as 2000/01 are more uncertain. In these areas no reports of groundwater flooding were received and it is our understanding that on the whole few would be expected given the properties of these aquifers. In these areas, the groundwater contours have been adjusted by the expected maximum range appropriate for each aquifer type in relation to the season of the contour data. In many instances the adjustment has been by only 2m – the minimum possible with the techniques used. A low degree of confidence can be placed on these mapped areas (as indicated on the maps). They are predictive and would benefit from refinement using more localised information. However, the maps show where groundwater is predicted to be at or close to the surface under high groundwater conditions and will be of value for planning purposes.

Each vulnerable zone has, attached to it, an indication showing the degree of confidence that can be placed on the zone. In all cases, these should be borne in mind when interpreting the maps.

It has not been possible to assign return periods to the vulnerable zones defined. Those maps depicting the exposed Chalk aquifers of southern England are calibrated on the 2000/01 events and are calibrated on documented stream sources and reports of flooding. It is therefore not unreasonable to assign the maps in these areas to the return period of the 2000/01 event if it is ever calculated. However, all other maps whilst calibrated to the water levels of 2000/01 are less certain as, in many cases no reports of flooding were received.

#### **2.5.5 Property Count**

Table 2-H and the Properties/Aquifer Map in Appendix D summarise the number of properties located on the major aquifers of England. This is based on a simplified geology map. It takes no account of whether or not the aquifer is confined, of the

aquifer storage properties and does not include minor aquifers (hence the zero for Cornwall). Property locations have been taken from the OS Address Point database. This database includes all residential and business properties defined by the Royal Mail postcode address files combined with OS digital map databases. Details of the database can be found on the Ordnance Survey web site. The count is based on the aquifer units and Environment Agency areas hence the colour changes at Area boundaries.

<b>Environment Agency Region</b>	<b>Environment Agency Area</b>	<b>Number of Properties</b>
Anglian	Central	315,220
	Eastern	193,289
	Northern	519,179
<b>Anglian Region Total</b>		<b>1,027,688</b>
Midlands	Lower Severn	75,861
	Upper Severn	220,412
	Lower Trent	367,791
	Upper Trent	352,294
<b>Midlands Region Total</b>		<b>1,016,358</b>
North East	Dales	413,138
	Northumbria	161,515
	Ridings	321,910
<b>North East Region Total</b>		<b>896,563</b>
North West	Central	241,049
	Northern	76,970
	Southern	988,846
<b>North West Region Total</b>		<b>1,306,865</b>
Southern	Hampshire & IOW	123,615
	Kent	307,322
	Sussex	276,289
<b>Southern Region Total</b>		<b>707,226</b>
South West	Cornwall	0
	Devon	134,772
	North Wessex	144,022
	South Wessex	105,450
<b>South West Region Total</b>		<b>384,244</b>
Thames	North East	441,777
	South East	252,074
	West	273,388
<b>Thames Region Total</b>		<b>967,239</b>
Welsh Region	Northern Area	60,769
<b>Environment Agency England Total</b>		<b>6,366,952</b>

*NB Property numbers shown above are totals by Environment Agency Area lying on all major aquifer types. The Properties/Aquifer Map in Appendix D indicates a larger set of numbers of properties by both Area and aquifer type.*

**Table 2-H Number of properties located on major aquifers**

The location of properties on permeable strata does not give a good measure of vulnerability to groundwater flooding. Aquifers may be confined or groundwater may be many meters below the ground surface and never likely to approach the surface.

Whilst the most vulnerable properties are those located close to ephemeral streams within the permeable areas, major flooding has also arisen in the areas downstream of major aquifers – in the surrounding plains. The most prominent example is Chichester located on the River Lavant that drains the Chalk aquifer of the South Downs. It is also worth mentioning that, with the exception of a few urban areas such as Salisbury and Winchester, settlements on the Chalk aquifers of Southern England, tend to be small and scattered. There are, however, several large urban areas located on rivers draining aquifers but remote from the aquifer itself most notably, Louth and Chichester.

Despite these limitations, the Properties/Aquifer Map in Appendix D and the accompanying Table 2-H do provide some insight into the property density and thus the population within permeable catchments. This map can be refined further by counting only those properties located in the zones identified by the predictive modelling as being vulnerable to groundwater emergence. The previous section describes the process in which areas of England were identified as likely to have groundwater at or close to the surface. It is the number of properties lying within these zones that are most vulnerable. Counting only properties in these zones eliminates those located on high ground where groundwater is many meters below the surface and also those on confined aquifers. It is also allows aquifer properties to be incorporated. The blue zone is calibrated for each aquifer type to allow for the typical range in water level movement to be incorporated. Table 2-I and the Properties/GWZones Map in Appendix D provide a summary of the number of properties located in areas in which groundwater is predicted to be at or close to the surface in a winter with water levels similar to those experienced in 2000/01. In those areas where two envelopes of groundwater emergence have been made, comprising usually a 2 m and 10 m rise, only the smaller 2 m envelope has been used in the property count. It should be noted that in those aquifers where the seasonal fluctuation is very small a 2 m rise – the minimum contour interval – has been used. In many cases this will still result in an overestimation of the vulnerable zone.

Environment Agency Region	Environment Agency Area	Number of Properties
Anglian	Central	168,729
	Eastern	94,352
	Northern	99,715
<b>Anglian Region Total</b>		<b>362,796</b>
Midlands	Lower Severn	0
	Upper Severn	0
	Lower Trent	58,133
	Upper Trent	0
<b>Midlands Region Total</b>		<b>58,133</b>
North East	Dales	4,554
	Northumbria	0
	Ridings	87,055
<b>North East Region Total</b>		<b>91,609</b>
North West	Central	7,896
	Northern	0
	Southern	101,231
<b>North West Region Total</b>		<b>109,127</b>
Southern	Hampshire & IOW	43,837
	Kent	118,474
	Sussex	83,481
<b>Southern Region Total</b>		<b>245,792</b>
South West	Cornwall	16,304
	Devon	50,084
	North Wessex	2,410
	South Wessex	55,223
<b>South West Region Total</b>		<b>124,021</b>
Thames	North East	249,595
	South East	370,223
	West	95,620
<b>Thames Region Total</b>		<b>715,438</b>
Welsh Region	Northern Area	7,804
<b>Environment Agency England Total</b>		<b>1,714,720</b>

*NB This table indicates the number of properties which would be impacted first by groundwater emergence if groundwater levels were to rise to exceptionally high levels in these areas, it does not imply likelihood of groundwater emergence or flooding.*

**Table 2-1 Properties located within emergence envelopes on predictive GEMs**

The figures in Table 2-1 are clearly well in excess of those reported to have actually flooded during the winter of 2000/01 (Section 2.2) even if a reasonable allowance is made for under reporting. The figures produced here indicate the number of properties within the zones of predicted groundwater emergence and not specifically those predicted as vulnerable to flooding. Many local factors contribute to whether a property will flood not least local drainage and the exact location of the property. Local factors cannot be incorporated into the analysis at this scale of mapping.

It should be noted that this count of properties only includes those major aquifers in which groundwater levels were made available. Omitted from this property count are those areas with minor aquifers of local importance. However, these are unlikely to have the capacity to cause problems to a large number of properties. Finally, there

are some areas of the country where rivers have been identified as having a high baseflow component (identified by the BFIHOST river colouring) that are not included in the property count. These rivers are generally fairly isolated from the known aquifers and from other rivers with high baseflows. In many cases the high baseflow index will be depicting slow release of water from heavy soils rather than groundwater. Future developments of this work would be to delineate groundwater prone areas along the course of these rivers. However, this is really a local refinement and it is not considered that they will make a large difference to the results.

The property count figures can be refined further by eliminating those properties located within the 1 in 100 year fluvial floodplain that are already included in the Environment Agency's Indicative Floodplain Maps (IFM). Correspondence between the two sets of maps is very good allowing those areas falling outside the 100 year fluvial floodplain to be identified. As expected, the resulting areas are seen to fall either side of the defined flood plain and in the headwater extensions of the rivers. Table 2-J indicates the number of properties that lie within the zone vulnerable to groundwater flooding that fall beyond the fluvial flooding zone. The properties / Non IFM map in Appendix D shows the groundwater emergence zones with the IFM envelopes removed.

Table 2-J shows that the total property count is reduced by 112,855 properties leaving some 1.6 million properties in the groundwater emergence zones. Of these, approximately 382,000 properties are located on the exposed Chalk outcrops of southern England (Kent, South Wessex, Sussex, Hampshire and Thames West Area) – areas shown to be most vulnerable in 2000/01 as a result of the nature of the aquifers properties.

The property count calculations are based on the zones identified in the groundwater emergence maps. The figures should be considered within the limitations and caveats placed on those maps.

Environment Agency Region	Environment Agency Area	No. of properties outside IFM envelope	Difference from all properties in groundwater emergence zones.
Anglian	Central	163,907	-4,822
	Eastern	88,728	-5,624
	Northern	94,586	-5,129
<b>Anglian Region Total</b>		<b>347,221</b>	<b>-15,575</b>
Midlands	Lower Severn	0	0
	Upper Severn	0	0
	Lower Trent	52,761	-5,372
	Upper Trent	0	0
<b>Midlands Region Total</b>		<b>52,761</b>	<b>-5,372</b>
North East	Dales	3,216	-1,338
	Northumbria	0	0
	Ridings	74,714	-12,341
<b>North East Region Total</b>		<b>77,930</b>	<b>-13,679</b>
North West	Central	7,896	0
	Northern	0	0
	Southern	97,494	-3,737
<b>North West Region Total</b>		<b>105,390</b>	<b>-3,737</b>
Southern	Hampshire & IOW	41,392	-2,445
	Kent	116,439	-2,035
	Sussex	79,974	-3,507
<b>Southern Region Total</b>		<b>237,805</b>	<b>-7,987</b>
South West	Cornwall	15,499	-805
	Devon	49,526	-558
	North Wessex	2,398	-12
	South Wessex	53,091	-2,132
<b>South West Region Total</b>		<b>120,514</b>	<b>-3,507</b>
Thames	North East	219,239	-30,356
	South East	341,840	-28,383
	West	91,511	-4,109
<b>Thames Region Total</b>		<b>652,590</b>	<b>-62,848</b>
Welsh	Northern	7,654	-150
<b>Environment Agency England Total</b>		<b>1,601,865</b>	<b>-112,855</b>

**Table 2-J Properties located within emergence envelopes on predictive GEMs but outside the national fluvial 1 in 100 year envelope**

## 2.6 Impact of Groundwater Flooding

There are a number of physical, economic and social impacts that result from groundwater flooding events some of which are common to fluvial flooding and others unique to groundwater flooding.

### 2.6.1 Long Duration of Flooding

During groundwater flooding events, property, land, roads and services are “under water” for long periods of time with significant physical, economic and social

consequences that are described below. Compared to fluvial events where floodwater dissipates in a few hours or at the most a day or two, groundwater flooding can be present for periods of up to many months. The maximum known period in England is six months (Orpington) and in France is three years (Abbeville). This long duration of inundation increases the level of impact compared to fluvial flooding.

## **2.6.2 Physical Impacts**

### ***Property***

The damage to property is of a different type to that normally associated with fluvial flooding. In groundwater flooding events the water usually emerges relatively slowly so that the force and the velocity of the floodwater can be much less than occurs at times of fluvial flooding. However the majority of the flow is not contained in a restricted channel or floodplain as it generally occurs where there is no established drainage path and only shallow gradients.

Nevertheless, the persistence of the floodwater flow can have a deleterious impact upon the fabric of a property. In many cases, the properties are old structures that are situated in a dry valley or relatively close to a source of water such as a shallow well, which had a water table close to the ground surface. They do not benefit from modern construction methods in that they would originally have had thin un-reinforced floor slabs that were waterproofed with tarred paper or similar short-lived materials. Generally, these older properties had floors at ground level with low ceilings. Modernisation has sometimes involved the lowering of floors to obtain extra headroom exacerbating the flood risk.

Properties that are subjected to groundwater inundation for long periods can suffer damp penetration to the extent that they become structurally unsafe and require significant structural repairs or even demolition. This has occurred in both Hampshire and Oxfordshire.

The other effects on property are similar to those experienced with fluvial flooding and include damage to plasterwork, floors, power supplies and electrical equipment.

### ***Agricultural Land***

In agricultural areas the occurrence of groundwater flooding does not usually have a significant impact upon the farming community but in the 2000-01 event water levels were very high over a long period causing a more pronounced impact than usual. In the Yorkshire Wolds there were incidents of large-scale market gardening enterprises being affected that employed several hundred staff and suffered extensive damage and loss of income. It should be noted that this is believed to have arisen from poorly designed boreholes becoming artesian and flooding the local area.

In Wiltshire, during the same winter, water levels rose sufficiently high to flood barns and damage agricultural machinery.

### ***Communications***

In many villages in the Chalk countryside the roads follow the line of the valley with houses situated on either side. It was quite common in the winter of 2000/01 for the

groundwater flood to flow down the roads and cause deterioration to the road top surface and sub-base due to erosion and hydrostatic uplift pressures.

### ***Sewer Backflows***

The surcharging of sewers by floodwater can cause backwater flows of untreated sewage into properties and as many of the older properties have cellars, this impact can be particularly damaging and unpleasant. Portable toilets had to be installed in some villages, sometimes for many weeks, when sewers were overwhelmed by groundwater. Some villages, we are led to understand, were close to being evacuated in early 2001.

### **2.6.3 Social Impacts**

With the long duration of groundwater flooding houses can become uninhabitable for long periods of time without such ground-floor facilities as kitchen, toilets, power and heating. Roads can be closed for several weeks, which prevents people from leaving their properties. Workplaces, shops, and schools may become inaccessible thereby affecting the normal way of life and means of employment.

## **2.7 Public Perception**

### **2.7.1 Understanding the Process**

There is a considerable public misunderstanding regarding groundwater flooding in urban areas and to a lesser extent in rural areas. For example in South London in 2000-01 when groundwater flooding occurred well within the urban environment there was a lack of understanding both within the public community and the Local Borough Council. Some of this could be attributed to the rarity of the event but mostly it was derived from a lack of knowledge of the ground formations and the previous natural drainage system that existed prior to urbanisation and subsequently replaced by sewers and culverts.

In the rural communities there is a greater awareness of the local water environment and its character and behaviour. Nevertheless the onset of groundwater flooding in the 1990s came as a surprise as many people were not aware of previous similar events.

### **2.7.2 Education**

In the Thames, Southern and South West Regions, the Environment Agency has undertaken a programme of educating and advising the local communities through parish council meetings of the causes, effects, protection and warning measures relating to groundwater flooding. Some of these topics are similar to those pertaining to fluvial flooding but the ability to plan in advance of groundwater flooding and to install protection measures can reduce the anxiety that most people have in regard to flood events.

### **2.7.3 Responses to Groundwater Flooding**

An important aspect in improving the public perception of groundwater flooding issues is the ability to demonstrate a programme of planned responses at the national, regional and local levels. In this way those affected or at risk will know who to contact and what to expect in the event of flooding.

Planned responses to groundwater flooding can be considered under three categories; prevention, mitigation (protection) and warning (or prediction). These are considered in the following sections although, where measures fall in more than one category they have not been repeated.

## **2.8 Prevention of flooding**

This section covers those responses broadly aimed at preventing the water discharging from permeable catchments from causing flooding. Typically this involves maintaining the water courses, culverts drains etc in good condition.

### **2.8.1 Ditches and Drains**

In previous sections, reference was made to the frequency of groundwater flooding and to the absence of flooding for up to 33 years in some parts of southern England between 1960 and 1993. During this period, ditches and drains fell into disrepair and were not capable of containing the flood flows that they may have been designed for. Culverts and bridge openings would similarly have not been maintained thus creating bottlenecks and flow restrictions.

### **2.8.2 Road Drainage**

Because of the restricted width of village streets the capacity to transmit water down the roads can be limited especially when the road-side drainage has been poorly maintained. During recent floods it was observed that the continual resurfacing of roads had elevated the surface to such an extent that it had become higher than the floor level of adjacent houses and shops with the consequence of water flowing down roads being discharged into properties.

## **2.9 Flood Mitigation**

Individuals with practical experience of groundwater flooding and organisations with experience of fluvial flooding provide advice on flood alleviation methods. Most notably, advice is available from research institutes, from water, engineering, construction and building industry advisory offices (such as CIRIA and BRE) and from the Environment Agency area offices.

Many of the fluvial flood mitigation measures are applicable to groundwater flooding although because groundwater flooding has a shallower depth of floodwater, a lower flow velocity and, earlier warning, some measures are more appropriate than others. Consequently the principal means of protection are:

- *Removal of possessions, goods and materials from flood-prone areas;*
- *Construction of diversion works;*
- *Improvement of capacity of local drains and ditches;*
- *Large-scale flood schemes;*
- *Groundwater pumping; and*
- *Property improvements.*

### **2.9.1 Removal of Possessions, Goods and Materials**

Experience gained from a number of flood events in the last 10 years has provided people living in flood-prone areas with experience to adapt to the frequent risk of flooding. These changes have brought about a different attitude in regard to the use

of cellars for living accommodation and storage and even the need to provide temporary living accommodation on the first floor.

At the time of an incipient flood there will be a set of procedures that suit individual cases and with a flood warning period of about two weeks sufficient time may be available to remove all possessions, goods and materials to safe levels.

### **2.9.2 Improvement of Capacity of Local Drains and Ditches**

During the period between the 1960s and the 1990s when there had been no significant groundwater flooding events, local drainage systems had been neglected and routine maintenance and repair works had not been undertaken by the respective local councils. Consequently, when the floods occurred, the drainage system did not have the capacity to convey the floodwater and where there were blockages, floodwater was diverted to nearby properties.

In many cases, even if the local drainage system were operating properly, it would not have the capacity to convey the groundwater flood flows as the design capacity of the system is usually for a local short-term rainfall event of a high frequency. In those areas susceptible to groundwater flooding, consideration would have to be given to increasing the capacity of the local drainage system.

### **2.9.3 Large-scale Flood Defence Schemes**

To provide protection for the larger communities or groups of neighbouring communities an option may be the provision of large-scale flood defence works that could include one or more components such as channel diversion works, flood relief channels and washlands. Such schemes would be expensive and technically difficult. Any such schemes would have to meet Defra's scheme assessment guidelines and demonstrate an appropriate benefit/cost ratio.

### **2.9.4 Diversion Works**

The construction of diversion works by means of a temporary or permanent channel is an option that has been adopted for individual properties or a group of properties. During the 2000-01 groundwater event two diversion schemes were constructed for individual villages in South Oxfordshire (Hampstead Norreys and Great Shefford) with assistance from the Environment Agency and in 1998 a large diversion channel was constructed by the Environment Agency to divert groundwater induced floodwater in the River Lavant around Chichester in West Sussex.

### **2.9.5 Groundwater Pumping**

The use of large-scale emergency groundwater pumping schemes has often been postulated as a means of lowering groundwater levels. However, the volume of water that would have to be removed and disposed of to protect a reasonably sized area is well beyond the feasible pumping capacity. Moreover, pumps would have to be run continuously for many months and the water discharged at a downstream location without increasing the fluvial flood risk.

In a couple of instances, the Environment Agency has requested that public water supply boreholes be operated outside their licensed amounts in order to control water levels during flood events. However, there is a lack of evidence available to judge the effectiveness of this solution which is limited by the location of suitable

pumping sites, the installed capacity of the pumps and the legal and financial arrangement that have to be in place.

The West Berkshire Groundwater Pumping scheme was operated in 2000/01 to alleviate flooding in the village of Hampstead Norreys. It is difficult to assess the effectiveness of the pumping and Environment Agency personnel are divided over how effective it actually was.

Pumping from individual properties by means of suction pumps is a common means of locally lowering groundwater levels, but there are many restrictions regarding the method of disposal and there is always the possibility of creating an inconvenience on neighbouring property.

### **2.9.6 Property Improvement Measures**

A number of advisory services provide guidance in regard to suitable modifications that would afford a variety of levels of protection from groundwater flooding.

They include the following remedies:

- *Floor raising by jacking or relaying;*
- *Installation of slab floors and up-stands;*
- *Installation of damp-proof courses;*
- *Tanking; and*
- *Construction of a sump and installation of a pump.*

### **2.9.7 Temporary Protection Measures**

Most groundwater flooding protection consists of walls of sandbags and large capacity suction pumps but a difficulty arises in regard to discharging the water as most means of disposal either are not allowed or a consent is required. Discharges on to road surfaces in the winter are not permitted by Highway Authorities because of the risk of icing.

### **2.9.8 Damage, Property Values and Insurance Cover**

#### ***Damage***

During recent groundwater flooding events some unpublished information regarding property damage particularly in the Hampshire area has become available. Repair costs are very variable ranging from minimal costs to as high as £70,000 for a single household. A report commissioned by the Environment Agency (Halcrow, 2002) concluded that the average consequential loss per property associated with internal flooding is £10,000 per property (based upon the FLAIR (FHRC, 1990) methodology, adjusted to 2001 prices and assuming property flooding to a depth of 0.1 m with a ground floor area of 100 m<sup>2</sup>).

#### ***Property Values***

As a result of recent and frequent groundwater flooding events, properties situated in flood prone areas are believed to have become blighted with values falling by 10% to 15% (pers. comm.). As a result, property owners are becoming less willing to discuss the history of flooding of their property.

*Insurance Cover*

From brief enquiries made for this study it appears that most households have insurance cover for the risk of damage from groundwater flooding and payments have been received in respect of recent flood events. However it appears that premiums are rising.

Information obtained from the Association of British Insurers (ABI) indicates that most of their members would be of the opinion that, in terms of insurance cover, there is a distinction between unexpected groundwater flooding and progressive groundwater flooding. The former is perceived as an insurance peril and the latter is not, although, the Financial Services Ombudsman reserves the right to assess each case on its merits.

Owners of property that suffer from groundwater flooding as defined in this study could be covered by insurance for such losses as the peril is sudden and temporary. Those that suffer from rising groundwater in conurbations or mining areas would not have this benefit as the peril can be foreseen. Nevertheless there may be exceptions to each case and insurance companies may attach exclusions to individual policy contracts.

**2.10 Flood Warning**

The slow build up of groundwater levels and the subsequent emergence allows a longer period for prediction and warning than that possible with fluvial flooding.

The recent completion of a five-year programme involving the construction of a network of groundwater observation boreholes across most of the Chalk regions of southern England has improved the dataset. The installation of data loggers and telemetry makes it possible to monitor and record groundwater levels at 15 minute intervals and transmit the data to the Environment Agency offices.

This monitoring system is used for the purpose of flood warnings. The Environment Agency's South Wessex and Hampshire area offices have installed transmitters that can automatically disseminate groundwater level information by phone, email or internet to interested parties.

The process of flood warning currently employed in South Wessex involves parish councils communicating with the Environment Agency through volunteer flood wardens and deputies. Similarly, in Hampshire the process is undertaken through community catchment liaison groups managed by parish councillors.

A line of communication has been established, in both cases, between the Environment Agency and the local community which is based upon the following procedures:

- *An Environment Agency quarterly newsletter that includes general information regarding recent rainfall amounts, present groundwater levels and sometimes a short-term forecast of rainfall amounts;*
- *An Environment Agency autumn newsletter that includes similar information to the quarterly newsletter but provides graphs of recent and long-term average, maximum and minimum groundwater levels and rainfall at selected local sites together with a prognosis of future weather conditions;*
- *If a pre-determined trigger level as derived from the flood predictor models is attained at an observation borehole site then a two week state of*

*preparedness will be instigated termed a flood watch or flood threshold (similar to that being used for fluvial events);*

- *When the onset of groundwater flooding is imminent a flood warning situation will be issued (similar to that being used for fluvial events); and*
- *Operation of the Floodline call centre (similar to that being used for fluvial events).*

Throughout the period prior to a flood event a set of action plans will be instigated to provide protection to those at risk of from flooding.

### **2.10.1 Flood Preparedness**

Monitored boreholes and groundwater prediction models allow early warning of anticipated flooding to be made by the Environment Agency. This enables the flood plan, a list of procedures to be carried out prior to flooding, to be activated. The flood plan specifies preparatory work including the clearance of drainage obstructions and the delivery of flood protection equipment.

Nearer the anticipated time of the flood a second action plan is instigated which completes the mobilisation to site and installation of flood protection equipment and facilities by local district councils, the emergency services and the Parish Council.

### **2.10.2 Informing the Public**

A number of stakeholders including Borough Councils, District Councils, Water Companies, Emergency Services and the media issue guidelines to the public through their websites, call centres and enquiry services. The guidelines provide advice on actions to be taken in the event of a flood and whom to contact in cases of emergency.

Borough Councils and District Councils have declined to provide this project with information on their flood action plans and their advice to the public on protecting their property.

### **2.10.3 Recommendations for a Groundwater Flood Warning Procedure**

Following a number of structured interviews held with selected Environment Agency Area staff a recommended procedure for groundwater flood warning and planning has been prepared and is included in Appendix G. This proposed procedure incorporates the most appropriate elements of a number of courses of action many of which are included in fluvial flood action plans.

## **2.11 Flood forecasting**

This section considers the appropriateness of existing flood forecasting techniques for groundwater flooding situations. Existing techniques range from simple spreadsheet models to complex groundwater simulation models although their application to flood conditions is at an early stage of development.

Based on a knowledge of the behaviour of the Chalk aquifer in their local area, the Environment Agency offices in the Thames, Southern and South West regions have each built their own simplified groundwater level prediction models. These enable them to predict the emergence of water at different spring-line elevations based upon the change of groundwater storage volumes in response to different rainfall scenarios. From a knowledge of the individual Chalk “blocks” in their region,

hydrogeological characteristics of the aquifer can be incorporated and the results calibrated on field observations.

With the implementation of telemetry to observation borehole networks there is now greater data availability and subsequently enhanced opportunities to actively respond to changing water levels.

Several Environment Agency Areas have developed complex groundwater models. However, the main driver for creating these models has been for water resource monitoring with special emphasis on low flows. It is our understanding that these models are generally calibrated on periods when groundwater levels are low and perform poorly at exceptionally high groundwater levels. In the Chalk aquifers this is considered to be a result of the normally unsaturated zone having very different transmissivity to the zone within the normal range of groundwater fluctuations. Calibrating these models with the emphasis on high groundwater levels may produce a new generation of groundwater flooding prediction models.

Bloomfield *et al* (2003) report on a statistical method that has been used to robustly predict minimum groundwater levels. The technique is shown to work on three different aquifer types with predictions within 10% of the true groundwater level for drought periods. It seems that this technique may have some value in predicting maximum groundwater levels under different rainfall scenarios and appears to work on relatively short term borehole records.

### **2.11.1 Indicative Floodplain Maps**

The Environment Agency has produced Indicative Floodplain Maps (IFMs) for all main rivers in England, which are publicly available through their internet site. The IFMs are based on a combination of detailed modelling, historical events, Environment Agency observations and broad brush modelling. In some cases detailed flood envelope maps are available which delineating the extent of floods for a range of return periods. These maps have been prepared by the Environment Agency and are used by their development control officers and by District Council planning officers to control development in areas liable to flooding.

Similar statutory maps do not exist for areas susceptible to groundwater flooding but it is understood that informal maps are currently used in some Environment Agency Area offices to minimise the risk of new properties being constructed within vulnerable areas. Although current legislation does not provide for groundwater flooding to be incorporated within the planning process, it is understood that some area offices believe that under Planning Policy Guidance (PPG) Note 25 there is such a provision. It is not known at present whether the present review of PPG 25 will encompass groundwater flooding.

Construction of new housing developments in Pilton and Farringdon in Hampshire on greenfield sites during the 1990s which were subject to severe groundwater flooding in 2000-01 has highlighted the need for indicative groundwater flood maps to be produced. The recent collection of data regarding groundwater flooding and the commissioning of aerial surveys will assist in this process.

### **2.11.2 Catchment Flood Management Plans**

A programme of Catchment Flood Management Plans (CFMPs) has recently been initiated by Defra and the Environment Agency in England and Wales. It is recommended that groundwater flooding, at a catchment scale, is investigated in vulnerable catchments through the CFMP programme.

### **2.12 Summary**

In recent winters there has been a sequence of groundwater flooding events of long duration and high frequency that have affected land, property and services in locations spread across central, southern and eastern England. Information regarding these events is of poor quality even though many communities were affected for periods of between 4 and 6 months as no statutory agency is responsible for recording these events.

Data and reports regarding groundwater flooding and rising groundwater were gathered from a wide range of sources but principally from the Environment Agency through records and anecdotal information. From questionnaires sent out to the 23 Environment Agency area offices in England, by staff in the Hampshire and IOW Area Office, and subsequent telephone interviews by Jacobs staff, a database of recent groundwater flooding events was compiled representing the geographic distribution of reported incidences of the floods that occurred in the winters of 1994-95, 2000-01 and 2002-2003. The details of these flood occurrences have been mapped according to the date.

The overriding characteristics of the spatial and temporal distribution of groundwater flooding presented in Section 2.3 are that the flooding occurred:

- *Almost wholly on the surface outcrop of the Chalk aquifer;*
- *During a prolonged period of high rainfall; and*
- *When groundwater levels in most aquifers were at higher than average levels.*

Although the reported groundwater flooding is strongly associated with the Chalk it is important to note that flooding did not occur at every location on the Chalk that a simple rise in groundwater level across the whole aquifer would predict. This indicates that the precise nature of groundwater flooding across the Chalk was affected by local variations in a number of factors, which may include:

- *Details of rainfall distribution;*
- *Recharge characteristics of the interfluvial Chalk blocks;*
- *Degree of karstification in the Chalk;*
- *Chalk permeability and porosity profiles in the valley bottoms; and*
- *Buffering effects of any overlying low permeability drift deposits.*

It is clear that the particular nature of the dual porosity present in the Chalk is a potential explanation as to why groundwater flooding is almost wholly associated with this aquifer. The precise mechanisms for flooding at different locations on the Chalk, however, can only be identified by a site by site consideration of a number of factors.

Although groundwater flooding is virtually unrecorded in major aquifers other than the Chalk it is possible that this may relate to a lack of reporting or other factors

such as regional meteorological variations at the time. It is therefore possible that these aquifers could cause groundwater flooding if a certain combination of climatic and hydrogeological conditions were to occur. Further work beyond the scope of this study is needed to clarify the likelihood of such flooding.

To assess the possible extent of groundwater flooding a theoretical approach was necessary and therefore a simple predictive model was generated for this study that could produce vulnerability maps across England. These maps have been produced for each of the Environment Agency's administrative areas taking into account the physical characteristics of the soils, the underlying rocks, the topography, the drainage network, groundwater levels and climate together with population distribution data. The model has been built upon a set of very detailed physical databases with soil, bedrock, topographic and groundwater elevation with population data to the level of post-code addresses.

For aquifers other than the Chalk the vulnerability maps present an indication of the areas which would first be impacted by emerging groundwater if exceptionally high groundwater levels were to occur. In some cases the rises in groundwater necessary for this to happen are considered highly unlikely due to the specific hydraulic characteristics of the aquifers in question and this is noted on the relevant maps.

Within the model, groundwater contours for the Chalk have been elevated to represent exceptionally high groundwater levels equivalent to those of the wet winter of 2000/01. A digital terrain model was used to identify those areas where groundwater could be expected to be at or near to the ground surface and therefore delineate those areas that are at risk of future flooding. The areas have been calibrated and verified using records of flooded properties and spring locations. The calibration exercise has provided considerable confidence in the method adopted as an area wide overview.

Due regard has been paid to aquifer properties at a regional scale although it is recognised that local hydrogeological and hydraulic factors, particularly in the Chalk, can be very influential in determining where inundation might occur.

## 3 Rising Groundwater in Major Conurbations

### 3.1 Introduction

There are presently two types of rising groundwater issues that are causing concern in large urban areas:

- *The rise of groundwater at shallow depths either in superficial deposits or in the bedrock that is caused by leakage into the ground from water mains, foul sewers, storm water drains or culverted watercourses which is not included in this study; and*
- *Groundwater rebound within a deep groundwater-bearing formation (aquifer) following a reduction in long-term groundwater abstraction.*

The former mechanism is present in many cities and extensive studies are presently being carried out primarily because of the possible impact on public health from a range of biological and chemical contaminants that are being mobilised by groundwater flow.

The latter mechanism, which is described in this report, has a range of possible impacts that could affect the built and the natural environment. Although the rise of groundwater from deep levels may be associated with water quality issues these are not regarded as being injurious to public health but result from mineralogical changes in the water as it migrates through different rock horizons. Nevertheless some risks do exist when the water reaches shallower depths and comes in contact with contaminated land, waste sites and landfills.

Rising groundwater has become a problem in a number of cities that were founded and developed on major aquifers. The presence of a reliable groundwater supply from springs, then wells and then boreholes initiated and subsequently was an important aspect in the growth of urban environments and in many places provided the opportunity for industrial development and population growth. This led to a rapid increase in the amount of water abstracted from the aquifers that lay beneath the expanding conurbations in the late 19th century as technological developments took place in the installation of deep wells and the construction of water storage and distribution systems. For nearly a century, the effect on the aquifers by this development was not assessed and abstraction continued unabated.

Water levels continued to fall and it was not until the early 1980s that it became apparent that water levels had begun to rise and if the rise were to continue then there might be some significant consequences. The conurbations had grown in size and had become industrialised resulting in the lowering of water tables until the 1960s when industrial decline commenced and water levels began to rebound towards the original levels.

### 3.2 The Cause of Rising Groundwater in Conurbations

Rising groundwater beneath conurbations in England came to the attention of the public in the early 1980s when concern began to be expressed regarding the rebound of water levels beneath London and Birmingham and other cities. This rebound coincided with the reduction of groundwater abstraction for industry that commenced in the 1960s when the industrial base of the large cities began to

decline. This reduction had not been offset by an expected large rise in abstraction for public water supply which had only risen modestly.

There were very few observation boreholes that were not affected by pumping whose records could be relied upon to measure the rates of rise in each of the cities. Those measurements that were available indicated that the rates of rise would impact upon the built environment above the water table in about 10 to 50 years depending upon the city and the type of underlying aquifer.

The impacts that caused most concern were those that might affect the structural integrity of buildings with deep foundations and the ingress of water into buried structures such as tunnels and deep communication conduits.

In 1989 a report was published on rising groundwater in London (Simpson *et al*, 1989), which revealed that the rate of rise of water was significant and it then became apparent that groundwater conditions in other cities had to be examined. A number of scientific papers were written on the topic and conferences were convened because of the added anxiety that no legislation existed to deal with such a problem and there did not appear to be a government authority that had any powers to provide a solution. A report was published on Birmingham in 1993, (Knipe *et al*, 1993), but since then there has been a dearth of published information concerning other cities that had been previously identified as having a rising groundwater problem.

### **3.3 The Potential Impacts of Rising Groundwater in Conurbations**

The rise of groundwater in conurbations is considered to have a number of impacts that are generally grouped into those that might have an engineering impact and those that might have an environmental impact. The impacts that could result from rising groundwater have been identified by Johnston (1993) and Simpson (1993) and are listed below.

#### Engineering Impacts:

- *A reduction in bearing capacity of both shallow and deep foundations;*
- *The development of uplift pressures under foundations and floor slabs;*
- *Swelling and heaving of clays;*
- *Expansion of fill materials;*
- *Leakage into basements and service ducts;*
- *Compaction and settlement of loose materials;*
- *Increased loads on retaining walls and basement wall structures;*
- *Solution of minerals and an increased potential for chemical attack on buried structures;*
- *The possible trapping or displacement of hazardous gases; and*
- *The increased need for drainage and the potential for instability of excavations and temporary works.*

#### Environmental Impacts:

- *Previously immobile organic and inorganic contaminants present in the sub-surface resulting from historical industrial use can be mobilised causing groundwater pollution problems. This situation can occur as groundwater rises into previously unsaturated and contaminated land. The risk of harm to human health and the environment can be significant;*

- *Where the groundwater table can reach the surface either through the absence of an overlying confining stratum or where the aquifer is overlain by permeable materials, drainage may become a problem with flooding and, in susceptible areas, an increased risk of polluting surface watercourses; and*
- *The establishment of near-surface groundwater levels could also affect the efficacy of highway drainage systems.*

In the early 1990s no one authority in the UK had statutory responsibility for dealing with rising groundwater levels or for the problems that they may cause. In the case of London the National Rivers Authority (NRA) agreed to monitor the situation but stated that they had no direct responsibility for the consequences.

### **3.4 Present Situation**

It was reported in 1990, (Brassington, 1990), that there were a number of conurbations including London, Birmingham, Liverpool, Manchester, Coventry and Nottingham, together with other sites such as industrial parks and coastal locations where rising groundwater was taking place. This paper has been used as the starting point for this present study as there was no up-to-date information available from literature searches and the Environment Agency had no database on this topic.

It was therefore necessary to obtain information from individual people at the Environment Agency by contacting each regional office and then each area office to identify where rising groundwater was occurring and what measures were being implemented to remedy the situation

Brassington identified 15 sites in England that were experiencing a significant rise in groundwater at that time as shown in Table 3-A and of these the majority have since been monitored by the Environment Agency and a management strategy put into place to maintain water levels at a satisfactory level.

A list of the sites, allocated by Environment Agency region, is shown in Table 3-A and a detailed description of the situation in each conurbation is given below. This may not represent a complete list of all the sites with rising groundwater problems but it contains all the sites that have been brought to the attention of the study team during discussions with each of the regional Environment Agency offices.

For each of the sites identified by Brassington, a check has been carried out with senior staff at each of the Environment Agency's regional offices to ascertain their present conditions. The results of the survey indicate that of all the sites, Doncaster is the only one where a problem still exists and this is currently being examined by both the Midlands and North East Regions with the assistance of a large-scale EU funded groundwater quality study.

The map of Rising Groundwater in Conurbations (in Appendix E) indicates the relationship of the affected major conurbations to the underlying geology. Although requested, no information was forthcoming regarding the extent or scale of rising groundwater in major conurbations. Likewise, a search of the literature failed to find a reference to the number of properties affected or the geographical extent of the problem.

The results of the survey of present conditions are presented in the following sections by Environment Agency Region. There are no reported cases in North East or South West Regions.

Location and aquifer	Extent of rise in groundwater levels	Reduction in abstraction	Problems caused by rising groundwater levels	References
1. London: Chalk and London Tertiaries	Rise from -85m in 1965 to -65m in 1986 in the Trafalgar Square observation borehole	A fall from a peak of 230 MI/d in 1940 to 118 MI/d by 1982	Ground uplift caused by elastic heave and swelling in clays; rise threatens to flood the underground railway system and the basement of many buildings; the stability of building foundations is also endangered.	Marsh and Davies Wilkinson Connorton Simpson et al.
2. Tilbury: Chalk	Only minor changes in groundwater levels as dewatering pumping in quarries has been continuous	Groundwater pumped to dewater extensive chalk quarries	Abandoned quarries used for industrial development and housing need continuous pumping to prevent flooding	Anglian Water
3. Northfleet: Chalk	Approx. 1.5m between 1970-86; 8.7 MI/d 1986 mainly due to saline intrusion problems	Industrial abstraction 60 MI/d 1960 (reduced extent of rise in levels)	Increased pumping to dewater quarries	Southern Water
4. Fawley (Hants): Bagshot Sands	Recovery ranges 15-45 m depending on location over the period 1950-85	4.5 MI/d 1950; zero 1981	None known	Southern Water
5. Birmingham: Permo-Triassic Sandstone	Between 5-10m from 1971-87	45.2 MI/d in 1967; 14.1 MI/d in 1986	Flooding of factory basements reduced by dewatering boreholes; minor problems inside tunnel and other basements	Severn -Trent Water Lloyd and Lerner
6. Wolverhampton: Permo-Triassic Sandstone	18 m between 1973 and 1987	Cessation of major industrial abstraction of more than 20 MI/d after a factory closer	None known	Southern Water
7. Coventry: Coal measures	Not measured but effect known to be local	Shut down of one abstraction well (figures not available)	Minor flooding in one housing estate	Severn -Trent Water
8. Nottingham: Permo-Triassic Sandstone	3 m between 1965 and 1987	26.7 MI/d in 1965; 14.5 MI/d in 1986	Flooding in Basements of some city centre shops and in caves which are a tourist attraction	Severn - Trent Water Wilkinson

Location and aquifer	Extent of rise in groundwater levels	Reduction in abstraction	Problems caused by rising groundwater levels	References
9. Trafford Park, Manchester: Permo-Triassic Sandstone	Rises of about 15 m between 1970 and 1986	29 MI/d in 1960; 8 MI/d in 1986	None known	Ellins
10. Liverpool: Permo-Triassic Sandstone	2.5 m between 1975 and 1985	45 MI/d in 1963; 10 MI/d in 1984	Flooding in rail tunnels and building basements	Brasington and Rushton Rushton et al. Quirk
11: Beverley: Chalk	Not measured	Reduction in industrial abstraction by 50%	Minor flooding of agricultural land and properties	Yorkshire Water
12: Doncaster: Permo-triassic	Not measured	Considerable reduction in groundwater abstraction during the late 1970s	Sewer flows increased as groundwater intercepted	Yorkshire Water
13: Ipswich: Chalk	Not measured	Industrial groundwater pumping reduced by 3 MI/d 1967-87 because of saline intrusion	Flooding in cellars associated with groundwater: no known problems with chalk aquifer	Anglian Water
14: Braintree: Chalk	15-20m between 1978 and 1988	7 MI/d in 1978 and 1.6 MI/d in 1985	None known	Anglian Water
15: South Essex: Chalk	13.5m between 1975 and 1988	Reduction of 14 MI/d in abstraction of public water supply and abandonment of boreholes because of saline intrusion	No problems	Anglian Water

**Table 3-A Case histories of rising groundwater levels in England (after Brassington 1990 )**

### **3.4.1 Rising Groundwater in Thames Region**

#### ***London***

Groundwater has been rising since the 1960s in response to a reduction of industrial abstraction in the deep basin of the Chalk aquifer, which is overlain principally by London Clay and at present is largely under-drained. This rise presents potential problems for building structures in the London Clay as pore water pressures rise within it. In considering the engineering implications, it is the reduction in effective stress in the London Clay as the groundwater level attempts to rise above the Chalk which provides the greatest threat to foundation integrity. Other potential problems include damage and instability caused by differential movements, seepage and water ingress and possible chemical attack on buried steel and concrete.

Although the basin extends from the Chilterns in the north to the North Downs in the south, which constitute the principal recharge areas, the rising groundwater problem is restricted to the confined central London area.

A group of stakeholders appointed a technical group to monitor and study the problem in order to obtain a solution and GARDIT (General Aquifer Research, Development and Investigation Team), was established which reports annually. The latest report (Environment Agency, July 2003) states that groundwater levels in the central cone of depression have been falling in central London for nearly three years thus indicating that groundwater levels are being controlled.

This stabilisation has largely been achieved through the local water companies following a policy agreed with the Environment Agency to balance abstraction with recharge whereby the abstractions are being used to provide local public water supplies and recharge water to neighbouring depleted Chalk aquifer basins (Environment Agency, 2003). This arrangement is obtained by mutual agreement with no enforcement placed upon the Water Companies.

### **3.4.2 Rising Groundwater in Midlands Region**

#### ***Wolverhampton***

Rebound is complete and water levels have stabilised below ground surface at an elevation at which they are not considered to present a problem.

#### ***Birmingham***

The principal aquifer underlying Birmingham is the Permo-Triassic sandstone which underlies the city and the surrounding district. Overlain by varying deposits of fill and superficial drift materials, the groundwater levels can rise almost unobstructed to a new equilibrium. Historically the groundwater table in the Aston and Witton areas, along the Tame Valley and at the boundary of the Birmingham fault was near or at the surface with free flowing springs in places.

The concern regarding rising groundwater was the risk of water ingress into basements and damage to building fabric where structures are founded on drift deposits and fill materials. In these instances the bearing capacity could be reduced by water rising into previously dry material. Also, it was considered that in areas of high groundwater levels, the repair and maintenance of existing underground structures and the construction of new underground structures would be more difficult and costly.

Since the early 1990s a programme of groundwater monitoring has taken place and a water resources management strategy involving the Environment Agency and Severn Trent Water has largely controlled the problem of rising water and groundwater levels in the sandstone beneath the city have stabilised.

However, in the city centre deep excavations have encountered groundwater during the recent re-construction of the Bullring area. Also some cellars in the tower blocks of the new Bullring are suffering from water ingress.

In the Aston and Whitton area on the edge of Birmingham close to the River Tame groundwater levels have risen significantly since the late 1980s and early 1990s with water entering cellars. In order to maintain lower levels water is now being abstracted and pumped to the river.

### ***Coventry***

The groundwater situation is complex with extensive geological faulting and frequently occurring horizontal bands of mudstone. It is believed that groundwater may be rising in some parts following a significant reduction in groundwater abstraction for industrial purposes. This rise only began three years ago and future monitoring will identify whether or not this trend is likely to continue.

### ***Nottingham***

Rising groundwater is believed to be causing the flooding of cellars and caves following a curtailment of Public Water Supply (PWS) abstractions because of water quality problems. Some of the flooding of cellars may be attributed to broken water pipes or leaking sewers but the majority appears to result from the ingress of groundwater. The Environment Agency is not engaged in any remedial action but provides advice on the tanking of cellars and the installation of sumps.

### ***Doncaster***

It appears that groundwater levels are rising but the distribution and the extent of higher levels are not well mapped as both industrial and PWS abstractions have recently declined. The latter have been reduced because of the concern that the Environment Agency had regarding falling groundwater levels based upon their groundwater model predictions for the aquifer. However, at present the PWS boreholes are not fully operational because of operational difficulties and the presence of localised groundwater contamination. The land is low lying and flat and the local Internal Drainage Boards (IDBs) have recently reported 12 flooding incidents.

## **3.4.3 Rising Groundwater in North West Region**

### ***Liverpool***

In 1990 rising groundwater was reported to be causing flooding of the underground railway in the centre of the city following the reduction of groundwater abstraction (Brassington, 1990). A number of studies were undertaken and a permanent abstraction system in the Permo-Triassic Sandstone was installed by Railtrack to provide a remedy to this problem. Water levels are continuing to rise gradually in the north-eastern part of the city but no risk has yet been attached to this rise.

### ***The Wirral***

Large-scale groundwater abstraction from the Permo-Triassic Sandstone has been taking place for several years in the east in the industrial belt alongside the Mersey estuary. The area has relatively low relief and there is a history of large-scale abstraction with a significant potential for saline intrusion from the estuary. However groundwater has been rising rapidly since 1986 in the centre along the low ridge of West Wirral in a largely rural area with scattered villages but levels are not yet approaching the ground surface (ESI, 2001).

### ***Manchester***

The Trafford Park area has a history of heavy abstraction from the Permo-Triassic Sandstone which caused falling water levels and the upconing of deep connate water. Recent reductions in abstraction have produced a rise in groundwater levels. In central Manchester water levels have also risen in response to reduced abstraction but have now stabilised with some discharge occurring to surface watercourses. (ESI, 2001). High water table levels in overlying silty drift deposits may also cause problems in this area.

### ***Fylde***

Rises within the Permo-Triassic sandstone of 15 m in the area on the eastern industrial outskirts of Preston have been observed over the last 20 years in response to reduced industrial abstractions. However, there are no reported problems associated with this rise.

## **3.4.4 Rising Groundwater in Southern Region**

### ***Brighton-Worthing Coastal area***

A policy of managed abstraction has been adopted by the Water Companies to reduce the rise of sea water intrusion into the Chalk aquifer by the introduction of a winter/summer pumping regime. This involves pumping inland during the summer and near the coast during the winter in order to maintain chloride concentrations of mixed supplies at a prescribed level. A small (2 m) rise of groundwater has taken place but this is regarded as insignificant given the current depth to groundwater.

### ***North Kent (including North Fleet)***

Extensive planned dewatering is taking place to control potential rising groundwater where large-scale Chalk quarries previously existed and extensive retail parks have now been built.

### ***Fawley***

Groundwater levels in the Bracklesham Group have stabilised following closure of the power station.

### **3.4.5 Rising Groundwater in Anglian Region**

#### ***Ipswich***

Reductions in groundwater abstraction for public water supplies have caused a small rise in groundwater levels but these have stabilised and are not reported to be causing any problems.

#### ***Tilbury***

Small rises in groundwater levels following cessation of the dewatering of Chalk quarries has not caused any problems because of the confined nature of the Chalk in this area.

### **3.5 Rising Groundwater in Coastal Areas**

In the 1990s there were a number of reported incidences of groundwater rising in response to the cessation or reduction of groundwater abstractions pumping in coastal areas. The changes in the pumping regime had taken place in order to curtail the ingress of saline water into boreholes located close to the sea and coastal estuaries.

As a result of these actions groundwater levels began to rise and there was a risk of cellars becoming flooded in built-up coastal areas in Essex and Suffolk but it now appears that this flooding has not occurred due to the improved management of groundwater abstractions.

### **3.6 Summary**

When rising groundwater began to occur in some of the major conurbations, it was not clear how the problem would be managed and by whom. Fortunately, detailed studies were initiated by groups of stakeholders that identified the causes and the remedies with solutions being brought about largely through water resources management partnerships between the Environment Agency and the Water Companies. In a few conurbations, the causes and the remedies are still being examined but generally rising groundwater is being effectively managed with the exception of some city centres where shallow permeable deposits have groundwater levels at or near ground-level such as west and central London and central Birmingham.

## 4 Rising Groundwater in Mining Areas

### 4.1 Introduction

There are two types of mine in England that are reported to be at risk from rising groundwater, coal mines and metal mines. The cause has been the large-scale closure of the coal mines that took place in the early 1990s and the progressive abandonment of metal mining that has taken place over the last 40 years. Today there are few metal mines that are operating or have recently been closed but in regards to coal-mining there are a number of very large coal-fields that have been closed in the last few years with others that may close in the next few decades.

### 4.2 The Cause of Rising Groundwater in Mining Areas

The closure of a mine and the cessation of water pumping from the mine results in the re-saturation of the mine void by water. The rate at which the mine becomes flooded is controlled principally by the rate of inflow/outflow, the source of inflow and the residual mine void.

Water inflow to a mine comes mainly from three sources: mine entries, permeable strata adjacent to mine workings and shallow mine workings.

Water inflows from shafts or adits can be very variable depending on the nature of the strata that the mine entry has to pass through and the sealing of the shaft or adit wall. The inflow from shafts or adits is generally a constant flow that will only reduce once water levels in the mine recover to the level of the inflow, i.e. near surface. Should there be a deterioration of the shaft or adit lining, increased inflows can occur. Filling a shaft or adit does not stop these inflows, this is only achieved by the construction of a seal or plug in the shaft in impermeable strata below the level of inflow. The quality of water that inflows to a mine from shafts or adits is generally good.

Water inflows to a mine from permeable strata adjacent to the mine workings usually comprise the majority of the inflow to a deep mine. There are two principal factors affecting the rate of inflow, namely the type of mining and the size, number and permeability of the adjacent aquifers and intervening strata. Faulting and fracturing of the strata either naturally or by the movement associated with mining will affect the rate of water flow into a mine. In many mines in the UK the rate of water inflow is proportional to the area of total extraction in the mine because it is controlled principally by the permeability of the Coal Measures strata between the source and the mine opening. Water inflows from adjacent strata decrease in volume as the mine becomes re-saturated and the pressure difference between the water in the mine and the pressure in the aquifer decreases. This reduction in water flow into a mine results in a gradual slowing of mine water recovery with time, assuming the volume of the mining void is evenly distributed with depth. The recovery of water levels in a mine is therefore usually quite rapid in the period immediately following mine closure becoming gradually slower with time. However, interactions between connecting mines and between shafts can result in complex water movement.

The quality of the water flowing into a mine from adjacent aquifers can vary enormously depending on the depth and type of aquifer. For example deep Coal Measure sandstone aquifers may have chloride levels up to 200,000 mg/l.

The other principal source of water entering the deep mines is from old shallow mine workings. This flow again tends to be a constant flow until mine water levels have recovered to near surface. In many mining areas these shallow mine waters were, and in some cases still are, pumped to prevent uncontrolled inflows to the deeper modern mine workings.

### **4.3 The Potential Impacts of Rising Groundwater in Mining Areas**

The possible impacts of rising groundwater in mining areas has been categorised in a research and development report on predicting mine water rebound that was prepared for the Environment Agency (Younger and Adams, 1999) which identified flooding risks as well as a number of environmental risks primarily relating to water quality.

The impacts that were identified are:

- A *Surface water pollution*
- B *Localised flooding*
- C *Temporary loss of dilution in surface waters*
- D *Over-loading and clogging of sewers and sewage treatment works*
- E *Pollution of overlying aquifers*
- F *Temporarily accelerated mine gas emissions*
- G *Risk of subsidence*
- H *Impingement of landfills*

This present study has only addressed the impacts of localised flooding (B) and the indirect risk of flooding from subsidence (G) from the list above and has selected data from Younger and Adams's report to provide an indication of the flooding impacts for those coalfield areas shown on the Mining/National Map in Appendix F. Because the report was based upon data collated in 1998, the authors have kindly agreed to update their findings to present conditions and these results are tabulated in Table 4-A and listed in relation to Environment Agency regions.

Table 4-A indicates certain characteristics of the rising groundwater conditions as listed below:

- *Whether or not the mine is operating (in the latter case dewatering is continuing);*
- *The possible impacts that could exist if no implementation scheme were implemented; (as listed above)*
- *The anticipated severity of the impacts (on a scale of 1 to 5 with 5 being the worst);*
- *The anticipated volume of water that would be discharged at the surface (1 is < 50 l/s; 2 is 50 – 100 l/s; 3 is > 100 l/s); and*
- *The stem understanding in terms of knowledge (1 to 5 with 5 being the best), whether or not there is a prevention scheme in place and if so the organisation that is responsible (Y = Yes; N = No; NA = not applicable; TBA = to be announced (a plan is currently under preparation); the organisation: CA = Coal Authority; EA = Environment Agency; MC = Mining Company.*

(Included in Table 4-A is the only metal mine, South Crofty, that may have a potential impact on the environment and which is discussed in the following section.)

Environment Agency Region	Coalfield Area/Mine	Current Status (Feb 2004)	Possible Impacts without Prevention Scheme	Anticipated Severity of Impacts (1-5, 5 the worst)	Anticipated Volume of Water (1-5, see notes)	System Understanding (1-5, 5 the worst)	Prevention Scheme in Place?
Southern	Kent	Rebound Complete	E	1	1	2	N
Midlands	Warwickshire	Rebound & Dewatering Underway	A, E	3, 3	2	2	N
	Leicestershire	Rebound Complete	A, B	3, 2	2	3	N
	Staffordshire	Rebound Underway	A, B, E	2, 1, 1	3	3	Y,CA
	Asfordby	Rebound Underway & Complete	E	1	1	3	N
	Nottinghamshire	Dewatering Underway	A,C, E	2,3,5	3	3	N, TBA
	Derbyshire	Rebound Underway	A, E	1,3	1	2	N, TBA
	North West	West Cumbria	Rebound Underway & Complete	A, E	3, 2	3	2
Lancashire		Rebound Underway	A, B, E	3, 4, 3	3	4	N, TBA
North East	South Yorkshire	Rebound & Dewatering Underway & Complete	A, B, E, F, G	3,1,3,3,1	3	2	N, TBA
	West Yorkshire	Dewatering	A	4	2	3	Y, CA
	Doncaster District	Dewatering	A, B ,E, F, G	3, 1,3, 3, 1	3	2	N
	Selby Complex	Dewatering	E	2	2	2	N, TBA
	Durham Coalfield	Dewatering	A, B, C, E, F, G, H	4, 1, 3, 3, 2, 2, 2	3	4	Y,CA
	South Tyneside	Rebound & Dewatering Underway	A, B, E	3, 2, 1	?	1	N
	Blenkinsopp Drift	Rebound Underway	A	3	?	3	Y,CA
	S Northumberland	Dewatering	A, B	3,2	2	4	Y,CA
	Ellington	Dewatering	A, B	3,2	2	4	Y, CA/MC
Whittle-Shilbottle	Dewatering	A, B	5, 2	1	4	Y, CA/EA	

**Table 4-A Characteristics of rising groundwater conditions in selected mining areas**

To validate these findings a number of checks were made with Environment Agency staff at regional level, the Coal Authority senior development officer and representatives from their consultants. It was agreed that this list was the most appropriate representation of present conditions for a scoping study.

From these discussions it was learnt that all of the listed sites are being monitored in terms of groundwater levels and a number of models are in place to forecast the future rise of water levels based upon historic records. Generally it is assumed that the rate of rise is exponential with time as is the case with groundwater recovery from a single abstraction well and this is because the area around the mine behaves as an aquifer would around a well. This assumption is realistic provided that the water level observations are representative of the blocks being examined.

In more complex environments, typically deep extensive mines, the rebound has to be modelled to incorporate the large complex void of the individual levels, the shafts and adits as well as the ponds on the surface, the latter often comprising several impoundments and interconnecting drainage systems. Additionally these models are also used to predict water quality conditions under a range of scenarios.

One of the major factors affecting the accuracy of the predictions of the rate of rise of rising groundwater is the estimation of the void created by the mine workings and the degree of collapse that may have occurred since closure took place.

In general terms the residual volume of the mine that is flooded by the inflows of water is dependent on the type of mining and the nature of the strata adjacent to the workings. British Coal used a factor of 10% of the coal extraction to calculate void space for areas of total extraction. However this factor is now considered to probably be too low given that not only the void space left by the coal extraction but also any natural porosity in strata adjacent to the mine workings also has to be re-saturated (pers. comm.). Calculation of residual void based on known recovery rates and inflows suggest that in many cases the residual void left after total abstraction of an area of coal is more like 20% of the original extraction.

#### **4.4 The Present Situation**

The residual body of the Coal Board, the Coal Authority is responsible for monitoring rising groundwater and the Environment Agency reviews the results through a formal dialogue with the Authority. Under the new Water Act, which is expected to be enacted soon, the Coal Authority “may take such action as it considers appropriate (if any) for the purpose of preventing, mitigating the effect of, the discharge of water from a coal mine into or on any land or into any controlled waters.”.

Unfortunately, it has not been possible, given the scale of this study, to quantify the geographical area prone to flooding from mine water.

#### **4.5 Rising Groundwater in Metal Mines**

There have been recent incidences of rising groundwater emerging at ground level and causing a major environmental impact principally because of the water quality issues rather than the flood issues such as occurred at Wheal Jane in Cornwall in 1997 (Bowen *et al*, 1998). When this study commenced it was believed that there were three metal mines that should be examined under this study but it is now apparent that only one mine, the South Crofty tin mine may pose a risk to the environment but a flooding risk from rising groundwater is not anticipated.

## **4.6 Summary**

In regard to rising groundwater in mining areas, the principal concern has been the impact of the discharge of acid mine drainage on the water environment in respect of river water quality and the local ecology. However, flooding resulting from discharges issuing from the mines or by mine subsidence has been identified as an issue that needs to be addressed and the Coal Authority has established a national monitoring programme and is examining a large number of case studies in agreement with the Environment Agency. This work has the objective of forecasting the rate of rise of groundwater, the possible points of emergence and the likely flooding risks. Some of the disused mines have already begun to discharge and some are forecasted to discharge in 20 or more years time. Of the few mines that are operating, the majority are deep mines and consequently there is sufficient time available to instigate effective control measures.

In recent years concerns have been expressed regarding rising groundwater from metal mines but remedial measures are now in place at all the larger sites with the Environment Agency taking over the responsibility of managing the site in some instances.

## 5 Synergy with Water Resources and Source Protection

### 5.1 Groundwater Flooding in Permeable Catchments

Groundwater flooding events appear to occur predominantly in areas where there is a large fluctuation from year to year of the elevation of groundwater emergence. Thus when groundwater storage levels are high, groundwater flooding occurs and when groundwater storage levels are low, low flows in rivers occur. Thus, in Chalk-fed rivers there is a propensity for both extreme events which can be a result of the over-year storage characteristics of the Chalk aquifer that are described in Section 2.3. This large groundwater reservoir that is present in the more extensive Chalk blocks could provide a potential for the over-year management of water resources providing a solution to the problems of both groundwater flooding and low flows. However it should be noted that the volumes of water involved are very large which may render such management impractical.

The current large-scale groundwater modelling of Chalk regions across Southern England such as the Test, Itchen, Mimram, Colne, Kennet and North Kent models is being undertaken because of the need to provide water resources management tools as part of the Catchment Abstraction Management Strategy (CAMS) process as well as low flow investigations as part of the Restoring Sustainable Abstraction Programme (RSAP).

These drivers could be harmonised thereby enhancing the synergy of groundwater flooding and water resources management.

However, from a water quality point of view there is an increased risk, during periods of high groundwater levels, of aquifers being polluted as groundwater emerging at the surface can become polluted and as it infiltrates back into the ground it can have the potential to pollute a valuable water resource. If this process were to occur within source protection zones then the recent increase in the frequency of groundwater flooding could have a pronounced effect on public water supplies which are predominantly located downstream of groundwater emergences although, in some cases they may be protected by confining layers.

### 5.2 Rising Groundwater

There are a number of very important issues associated with rising groundwater in urban areas and in mining areas.

The initial concern that was expressed in regard to rising groundwater in conurbations was the possible impact upon deep engineering structures such as deep foundations and tunnels but it has since been realised that there are other issues such as the flooding of cellars and services. These possible impacts can be classified as engineering impacts but there are also potential environmental impacts that merit attention. These latter impacts result from the migration of a wide range of pollutants that are mobilised by rising groundwater and originate from a variety of sources such as landfills, waste tips and sewers.

In the case of rising groundwater from mine closures there are potential engineering risks associated with subsidence and flooding as well as possible environmental risks resulting from Acid Mine Drainage (AMD), gas emissions, saturation of mineral

workings and landfills and contamination of overlying aquifers that are used for public water supply.

Many of these potential environmental risks originating from rising groundwater may have an impact on areas designated Source Protection Zones (SPZ). These SPZs were designated on the basis of three zones radiating from a source and defined in terms, respectively, of the travel times of pathogens, chemicals and recharge water. They were established in the early 1990s using a standardised approach that was based upon a steady state aquifer model.

Since that date, the occurrence of rising groundwater in conurbations has been recognised and the wide spread closure of coal mines and the abandonment of metal mines has taken place.

In the light of these events it would appear to be prudent to instigate a review of the delineation of SPZs that was undertaken over ten years ago.

### **5.3 Summary**

Current large-scale groundwater models of Chalk regions across Southern England are being developed by the Environment Agency to provide water resources management tools as part of the Catchment Abstraction Management Strategy (CAMS) process. Low flow investigations are also being undertaken as part of the Restoring Sustainable Abstraction Programme (RSAP). These initiatives provide an opportunity to assess whether practical solutions are possible to alleviate the risk of groundwater flooding which are consistent with water resource management objectives.

The key issues relating to water resources regarding rising groundwater both in conurbations and mining areas concern water quality. It is possible that Source Protection Zones for groundwater abstractions in areas of rising groundwater need to be reviewed to ensure that the underlying assumptions have not changed since 1990 when they were defined.

## 6 Conclusions and Recommendations

### 6.1 Conclusions

This report has documented the findings of a scoping study commissioned by Defra's Flood Management Strategy Unit to provide information on the scale, distribution and nature of groundwater flooding in England. The findings will feed into the ongoing exercise to develop a new Government Strategy for Flood and Coastal Erosion Risk Management in England.

It has covered the eight key tasks as set out in the Project Specification:

1. *A literature review of major conurbation groundwater management to identify the scale of the problem.*
2. *Review reports and investigations on flooding in permeable catchments.*
3. *Identify generic causes of groundwater flooding.*
4. *Provide maps of susceptible areas to groundwater flooding at a suitable scale for national assessment.*
5. *Quantify the scale and general likelihood of groundwater flooding in terms of the number of properties, density, area of land or other suitable measures.*
6. *Consider the range and applicability of potential preventative measures and flood forecasting techniques that may be suitable for promoting in a strategy.*
7. *Consider the synergy with water resources and source protection issues and areas where knowledge in these areas may contribute to the understanding of groundwater flooding.*
8. *Public perception of groundwater flooding.*

The main conclusions from each section of the report are detailed herein.

#### **Groundwater flooding from permeable catchments**

This study has investigated non-fluvial flooding arising from the natural process of groundwater emergence from permeable hard rock aquifers. During the winter of 2000/01 exceptionally high rainfall totals caused unprecedented rates and volumes of recharge in many areas. In those aquifers unable to transmit the water rapidly to the fluvial network, very high groundwater levels built up and caused groundwater flooding. This event has been analysed as part of this study to assess the scale, extent, and frequency of the flooding and to consider the appropriateness of the response measures.

Questionnaire surveys, interviews with Environment Agency hydrogeologists and reviewed reports enabled a database of groundwater flooding locations to be assembled for the whole of England for the events of 1994/95, 2000/01 & 2002/03. However, no single authority has the remit to document groundwater flooding and whilst some Environment Agency Area Offices collated detailed information it is our assessment that the figures severely underestimate the number of properties affected in 2000/01. Data collated from the Environment Agency suggests that around 500 properties were affected however it is estimated here that the figure is more likely to be 2-3000 properties. In addition, numerous roads and underground services were affected by flooding.

It appears from the literature survey that return periods for the flooding, or more generally for groundwater levels, have not been calculated. However, records from

observation boreholes show that water levels were, in most cases, the highest on record. Records generally extend back 40 years but even in longer records the levels are unprecedented. For example, at Chilgrove groundwater levels in 2000/01 exceeded any recorded in a record extending back 167 years. The rainfall that caused the recharge has been analysed more thoroughly in the literature and for the 3 months starting in September 2000 is estimated to have a return period in excess of 200 years. However, less extensive groundwater flooding appears to occur fairly regularly in some locations with some Environment Agency staff citing a frequency of around every 7 years.

From our analysis groundwater flooding was found, not unexpectedly, to be almost entirely confined to the Chalk aquifers of England and only those in which there are no overlying drift deposits. The ratio of granular flow to fissure flow that characterises the Chalk aquifers makes them particularly efficient at building up groundwater heads. During the winter of 2000/01 groundwater levels in the exposed Chalk were such that new or “forgotten” springs developed and dry valleys flowed for the first time in living memory. In other aquifers the effects of high recharge are more clearly evident in the flow records from the rivers draining the aquifers rather than from exceptionally high groundwater levels. Here the aquifers are more able to transmit the recharge to the river network although some more localised flooding was reported from the Greensand and may have occurred to a limited extent in other aquifers. Other aquifers have a greater propensity to store the water with minimal short term fluctuations evident in the level records.

Flooding was generally reported to be in the valleys of ephemeral streams and in what are usually dry valleys. In many cases flooding was exacerbated by the local drainage network being overwhelmed by the volume of water, either because it exceeded channel capacity or because the channel had been neglected, built over or constricted.

Two series of maps have been developed as part of this study. The first documents all reports of flooding collated from the Environment Agency and other authorities and clearly shows that the distribution is largely concentrated in the south of England. It should be reiterated that this is not considered to be a comprehensive record of groundwater flooding occurrences, but it does give a good indication of the geographical extent. A simple model has been developed to create the second series of maps- the Groundwater Emergence Maps (GEMs), providing an objective indication of those areas with potentially high groundwater levels. For these maps, those areas of the country with groundwater levels close to the surface in 2000/01 have been identified using a digital terrain model and groundwater elevations. The model has been calibrated on 2000/01 stream sources, flooding reports or groundwater levels, whichever is appropriate for each aquifer. This series of maps show those areas of the country in which groundwater is close to the surface in a winter at least as wet as that of 2000/01. It does not infer flooding per se – only that groundwater could be sufficiently close to the surface to cause flooding, pending local conditions. It should be noted that these maps were developed at an Environment Agency Area scale. Local geology, drainage and developments could not be incorporated in the analysis and are major influences which would more closely define the occurrence of flooding.

Estimates have been made of the number of properties that fall within the vulnerable zones identified from the GEMs. In total 1.7 million properties fall within the area defined as having groundwater close to the surface in an exceptionally wet winter. Some areas defined as vulnerable to groundwater coincide with those areas defined as vulnerable to fluvial flooding as delineated by the Environment Agency’s IFMs.

Removing the IFM areas from the GEMs reduces the property count to approximately 1.6m. This study indicates that only the Chalk is particularly vulnerable – approximately 382,407 properties are located within the Chalk of southern England.

Groundwater flooding causes the same problems to properties as those of fluvial flooding although the flow rate is generally lower and the water often, although not always, cleaner. However, groundwater flooding is persistent and generally lasts for longer durations causing additional structural problems to properties and more severe disruption to residents.

A number of measures have been adopted by Environment Agency Area Offices and local authorities in those parts of the country where groundwater flooding was experienced during 2000/01. These comprise of:

- Clearance and maintenance of ephemeral streams;
- Groundwater level monitoring systems;
- Groundwater flooding warning systems; and the
- Re designation of ordinary watercourses to Critical Ordinary Watercourses (COWs).

This study has reviewed the options available to prevent, mitigate and forecast groundwater flooding. It is unlikely, given the volumes of water involved, that anything other than very local alleviation of groundwater levels can be achieved by pumping from groundwater. However, to some extent, flooding can be prevented by maintaining ephemeral and rarely flowing watercourses. Mitigation measures have generally proven to be more effective and include the diversion of watercourses, construction of new watercourses and the pumping away of surface water. Forecasting of groundwater flooding is in its early stages of development and currently relies on borehole trigger levels calibrated on the occurrence of flooding nearby. There appears to be some potential to calibrate groundwater models to simulate high water levels and run scenarios based on predicted rainfall.

The public appear to be less clear on the characteristics of groundwater flooding than they are of fluvial flooding. Many of those affected by the 2000/01 floods found it difficult to understand the cause of the flooding (partly due to the lag between rainfall and local groundwater response) or appreciate its likely duration and the difficulties involved in alleviating the situation. The lack of public awareness may have arisen because previous campaigns have concentrated on fluvial flooding. However, there also appears to have been a loss in community knowledge about the locations vulnerable to groundwater flooding as a result of the extended period prior to 2000 when no groundwater flooding occurred. The lack of perception of the risk of groundwater flooding has allowed relatively recent developments to take place in inappropriate locations.

### **Rising groundwater in major conurbations**

Rising groundwater under urban conurbations is caused by an entirely anthropogenic effect resulting from the cessation of over abstraction. Since abstraction from groundwater reduced, as a result of changes in industrial processes, groundwater levels gradually tend towards their natural levels. In many places underground structures were built during times of low groundwater levels and have since become vulnerable as the groundwater levels rebound. Generally speaking, in the past, management of rising groundwater levels has largely been undertaken by stakeholders. However, the GARDIT programme in London (an

agreement between stakeholders) has largely enabled water levels under London to be managed.

This report has identified those major conurbations subject to rising groundwater and details the measures being taken to remedy the problem.

### **Rising groundwater in mining areas**

The cessation of pumping of water from abandoned metal and coal mines has been identified as a cause of both groundwater rebound and subsequent environmental pollution from poor water quality. The Coal Authority is responsible for monitoring rising groundwater levels in coal mines, with the Environment Agency reviewing the situation through formal dialogue. Under the new Water Act the Coal Authority may, if appropriate, take action to prevent or mitigate the effects of the discharge of water from coal mines. This study presented an updated situation report on the characteristics of rising groundwater in coal mines. Rising groundwater in metal mines is identified as only being a problem in South Crofty tin mine where the quality of the water is of concern rather than any flooding implications.

### **Consider the synergy with water resources and source protection zones**

Current large-scale groundwater models of Chalk regions across Southern England are being developed by the Environment Agency to provide water resources management tools as part of the Catchment Abstraction Management Strategy (CAMS) process. Low flow investigations are also being undertaken as part of the Restoring Sustainable Abstraction Programme (RSAP). These initiatives provide an opportunity to assess whether practical solutions are possible to alleviate the risk of groundwater flooding which are consistent with water resource management objectives. Given the timing of groundwater flooding from permeable catchments and the volumes of water involved it is unlikely that problems can be resolved by management of groundwater levels.

## **6.2 Recommendations**

The following section details recommendations, in order of priority, corresponding to section headings.

### **Groundwater flooding from permeable catchments**

1. The predictive maps produced as part of this study provide an indication of those areas in which groundwater is at or close to the surface in an exceptionally wet winter. However, these are based on Environment Agency Area scale generalisations. Groundwater flood risk maps, particularly for areas of Chalk outcrops, should be produced and used to influence planning decisions. This would then be in line with the Environment Agency's IFMs for the fluvial floodplains. To produce groundwater flood risk maps, local details of flood extents and flood cause need recording and analysing in a systematic manner at an appropriate scale of detail. The frequency of flooding from groundwater sources needs further investigation in order to assign a return period to any future flood risk maps but also to enable cost-benefit analysis of any remediation schemes.
2. A flood management process similar to those available for fluvial and coastal flooding should be put in place at the national, regional and local

levels. Included in this should be a public awareness and education programme, particularly in those areas most at risk. It is recommended that CFMPs incorporate groundwater flooding processes and, for those catchments deemed to be at risk, a single government authority is given responsibility for its management.

3. Whilst groundwater flooding appears to be a phenomenon of Chalk, further work is needed to assess the potential for all other aquifer types to respond in the same way. It should be possible to simulate the hydrological conditions required to cause flooding from these non Chalk aquifers and assign a probability to the likelihood of such an event occurring. A limited number of reports of flooding came from Greensand areas suggesting that this aquifer may be vulnerable and if recharge had been any greater more widespread flooding could have occurred.
4. Groundwater flooding events tend to persist for many weeks or months and as such can give rise to greater financial and social costs than those occurring as a result of fluvial flooding. In the light of this, criteria used to assess the property damage resulting from groundwater flooding need to be reviewed.

#### **Rising groundwater in major conurbations**

5. Many of the current ongoing solutions are based on the goodwill of the parties involved, which is clearly a potential risk for the future. Ideally, formal agreements between stakeholders should be implemented and until then, the situation monitored.

#### **Consider the synergy with water resources and source protection zones**

6. Groundwater flooding should be incorporated in the CAMS process and Restoring Sustainable Abstraction Programme (RSAP).
7. Source Protection Zones for groundwater abstractions in areas of rising groundwater need to be reviewed to ensure that the underlying assumptions have not changed since 1996 when they were defined.

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*SITE No.3 ST MARY BOURNE, BOURNE RIVULET.*

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*SITE No.5 PENTON MEWSEY.*

*SITE No.6 APPLESHAW, ANTON.*

*SITE No.7 HATHERDEN, ANTON.*

*SITE No.8 PITTON.*

*SITE No.9 NETHER WALLOP, WALLOP BROOK.*

*SITE No.10 KINGS SOMBORNE, SOMBORNE STREAM.*

*SITE No.11 DEANE.*

*SITE No.12 WHERWELL, TEST.*

*SITE No.13 BARTON STACEY.*

*SITE No.14 PRESTON CANDOVER.*

*SITE No.15 WINCHESTER, HARESTOCK ITCHEN.*

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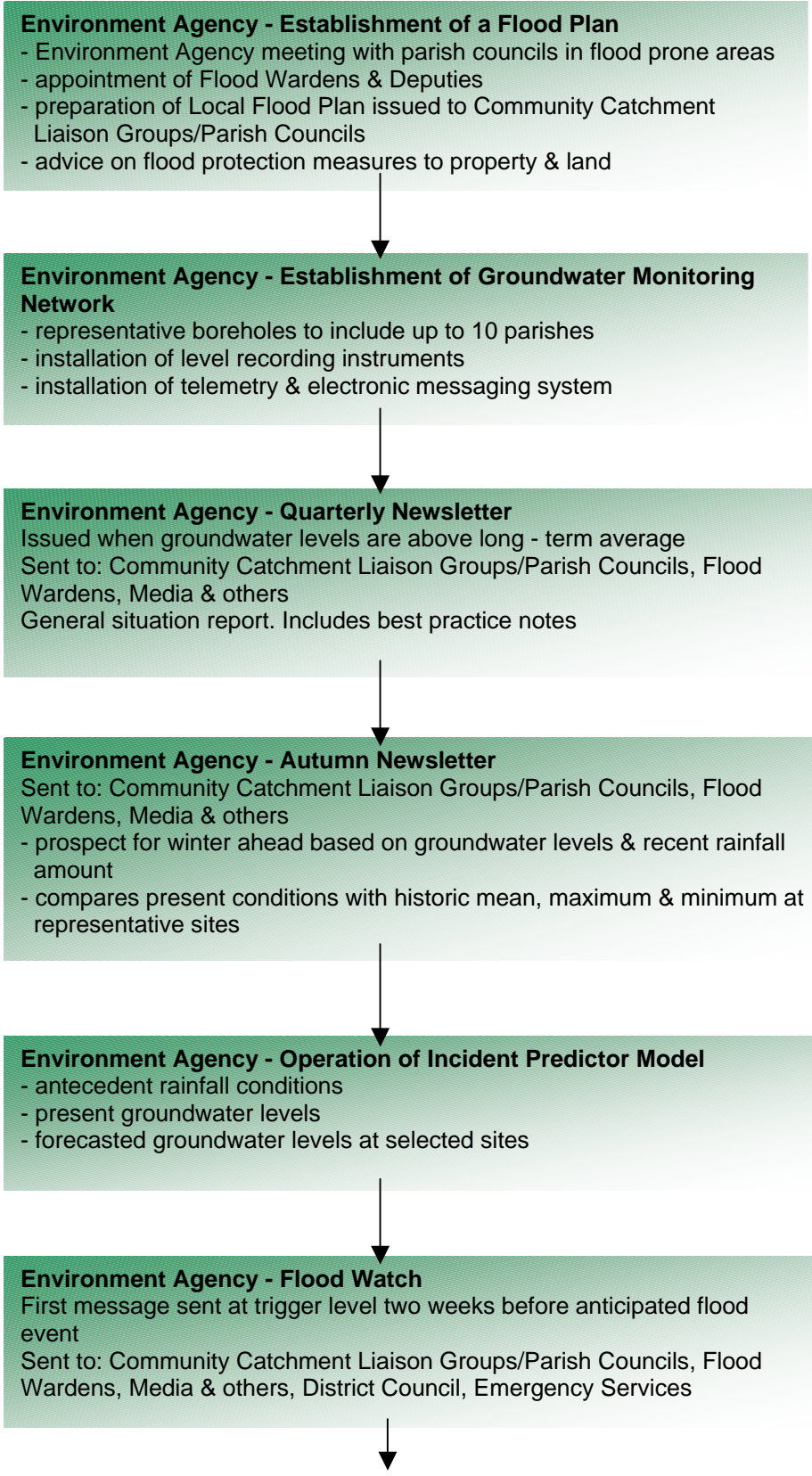
## Appendix A - List of Consultees

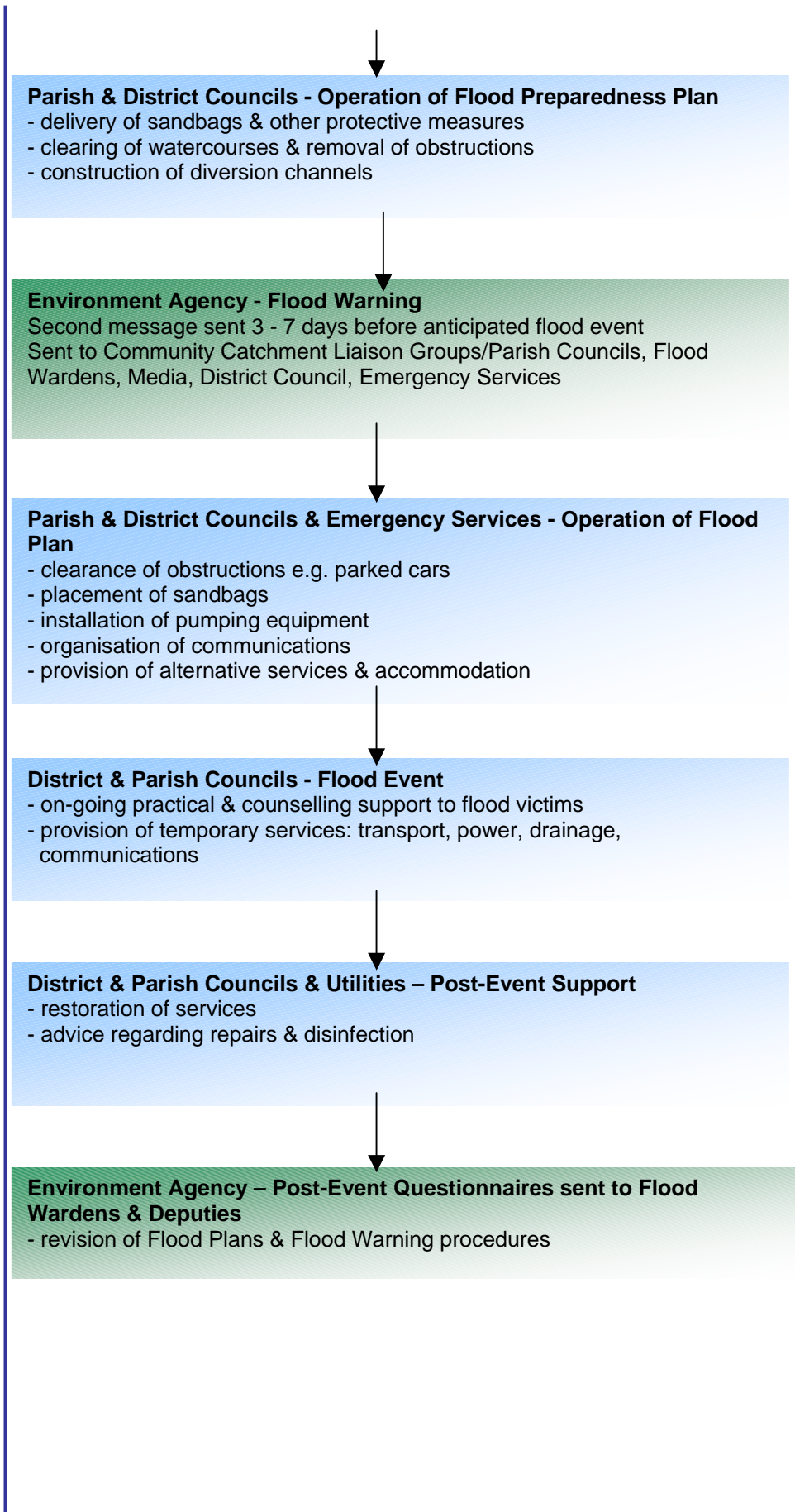
Environment Agency  
Association of British Insurers  
British Geological Survey  
Centre for Ecology and Hydrology - Wallingford  
Centre of Air, Water and Soil Science  
CIRIA  
Coal Authority  
Fire Service  
GARDIT  
Geological Society  
Halcrow  
Highways Authority  
ICE  
Local Authorities  
National Farmers Union  
National Flood Forum  
Peter Brett Associates  
University of Newcastle  
University of Southampton

**Appendix B - F**

**These Appendices are contained in Volume 2.**

**Appendix G - Proposed Procedure for Groundwater Flood Warning**





**Appendix H - CD**