Briefing note for Defra:

The contribution of groundwater to flood risk in Britain

Introduction

The role of groundwater in flooding in the UK is not widely understood. This briefing note provides a summary putting the significance of groundwater into the context of flood risk overall.

GeoSmart published the first groundwater flood risk map of Britain in 2014 and for the last ten years has been building a database of groundwater flood events alongside the development and calibration of more advanced models. Our latest model incorporates flood routing of emergent groundwater and flood risk estimates at property level and nationally for mainland Britain.

The outputs are used by our FloodSmart Analytics model alongside financial loss analysis to provide an integrated hydrological and loss modelling system that quantifies the effect of all four main flood mechanisms (surface water, groundwater, rivers and coastal) on a common scale of flood risk and average annual losses from flooding under current and future climates. Findings are summarised in this note to demonstrate the role of groundwater within the broader context of flood risk overall.

What is groundwater flooding?

Groundwater flooding is the emergence of water into buildings and infrastructure and at the surface due to unusually high groundwater levels following high rainfall or high river levels. Following its emergence above ground, groundwater flooding can also lead to significant runoff, to impact property downstream.

Groundwater flooding occurs when sub-surface water emerges from the ground at the surface or into Made Ground and structures. This may be as a result of persistent rainfall that recharges aquifers until they are full (known as bedrock flooding); or may be as a result of high river levels, or tides, driving water through near-surface deposits (known as permeable superficial deposit flooding)

Summary of main groundwater flood mechanisms

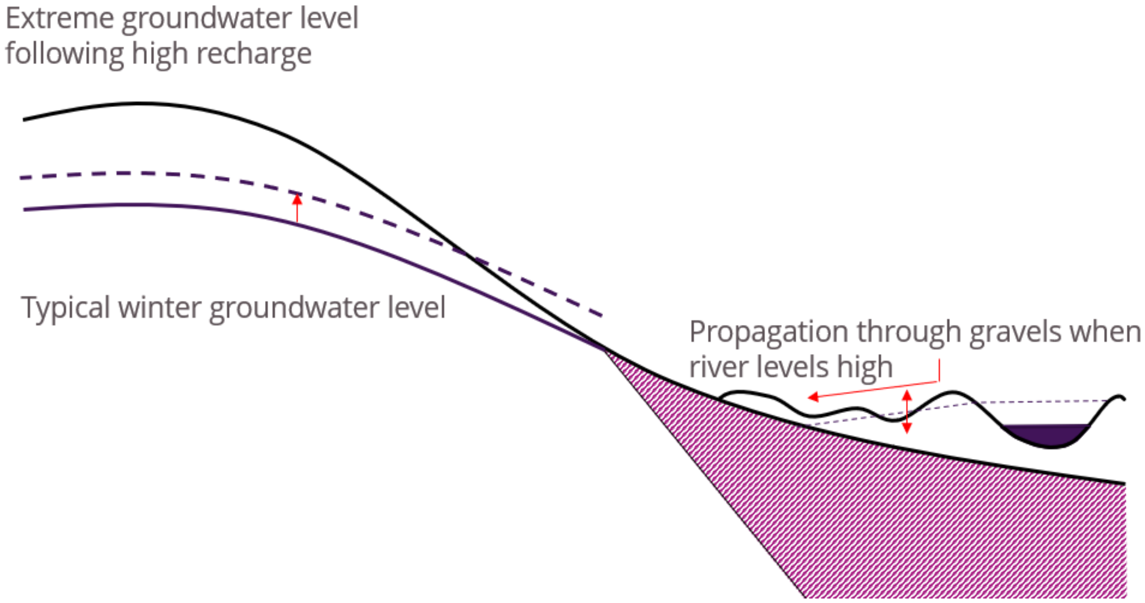

Figure 1.
Cross section illustrating bedrock flooding and permeable superficial deposit flooding concepts

Groundwater flooding is characterised by:

- Water flows to the surface or into basements, services ducts and other subsurface infrastructure rising up through floors or directly from the ground. This may be seen as diffuse seepage from the ground, as emergence of new springs or as an increase in spring flows.
- Flooding may last a long time compared to surface water flooding, from weeks to months. Hence the amount of damage that is caused to property may be substantially higher. Likewise closures of access routes, roads, railways etc. may be prolonged, with serious consequences to communities and business interruption.
- Flooding may occur with a long delay after periods of high rainfall rather than immediately during storms.
- Emergent groundwater may be relatively clean compared to muddy fluvial flood waters, but contamination by sewers and brownfield sites poses additional hazards.
- Groundwater flooding or a shallow water table prevents rainfall infiltration and increases the risk of surface water flooding. This means that many surface floods are actually driven by groundwater conditions. But consideration of surface water in isolation and lack of evidence for groundwater conditions leads to incorrect analysis of overall causes.

Groundwater flows very slowly compared to surface runoff and groundwater flood events are often of very long duration compared to other types of flooding. The graph in Figure 2 shows groundwater levels near Bramdean in East Hampshire where the duration of flooding from the Chalk aquifer typically lasts several months. Compare this to the River Severn at Bewdley (for example) where even the most extreme flooding typically lasts less than a week.

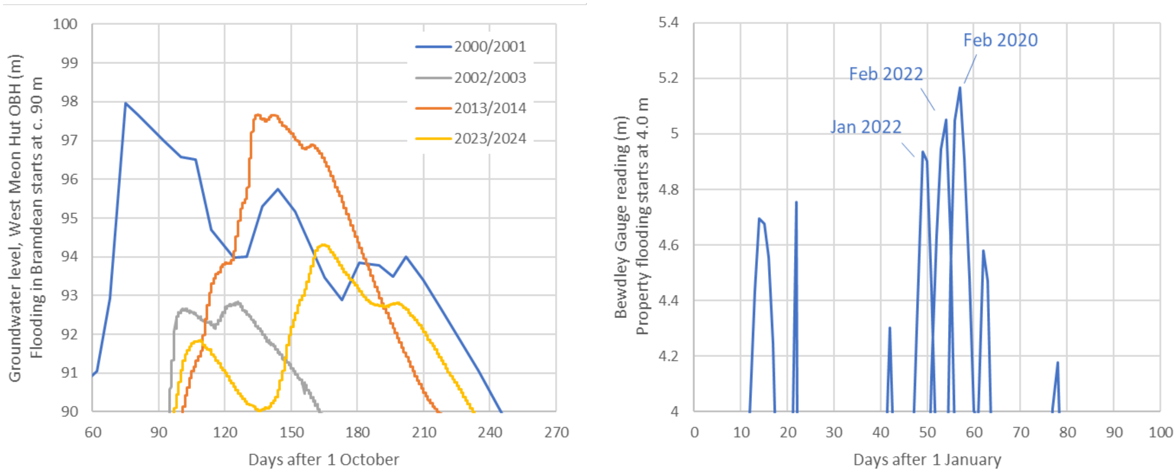

Figure 2.
Graphs illustrating typical responses of groundwater levels and river levels indicative of flooding duration

Taking an example from the Chalk areas of Kent, this report from February 2014 is illustrative of the long duration impacts of groundwater flooding:

Mark Douch, the Environment Agency's flood and coastal risk manager, said:

'It will take Kent a large part of 2014 to fully recover from another wet month.You are looking at a period of months, especially for the areas of Kent that have chalk-based catchments.It could take until April or May until those areas are fully out of risk, and that is still dependent on dry weather."

Figure 4. Groundwater flooding during February 2014 from the Chalk aquifer in Kent

What is the wider role of groundwater in flooding?

Groundwater is a critical part of the water cycle; it provides 30% of England's water supply and supports about 50% of flows in rivers. It is what keeps rivers flowing between rainfall events.

Groundwater discharge to rivers ("baseflow") increases when water tables are high, and this makes future river flooding more likely (high baseflow is a primary cause of river flooding[1]).

High water tables and groundwater flooding also increase the risk of surface water flooding (flash flooding) because saturated ground does not allow infiltration. This increases surface runoff and ponding in such areas, and surface water flooding can combine with runoff of emergent groundwater in compound events.

Groundwater flow is slow and following periods of high water tables, the recession of groundwater can take weeks or months. These processes drive longer term flooding events which significantly increase damaging consequences.

Groundwater also interacts with the sea, contributing to flooding on the coast and along estuaries, where it causes damage due to flows beneath coastal defences. Flows beneath coastal defences present an increasing threat to coastal towns and cities due to rising sea levels.

High river levels also drive groundwater flooding beyond the river banks, which may occur even when rivers do not overtop their banks. Flows beneath river defences present an increasing threat to many towns due to the effects of more extreme rainfall due to climate change.

As we can see therefore, groundwater and its interactions with other flood sources are central to driving flood risk, and particularly lead to extended duration and consequently increased damage.

Traditionally flood hydrologists focus on the surface flows, but it is helpful to recognise flood risk within a different paradigm. Generally inland flooding results from two independent events, with the first forming the antecedent conditions for the second, and the likelihood of a flood is most often based on a joint probability:

1. High rainfall onto soil and recharge into aquifers create antecedent conditions for flooding by priming catchments with saturated ground and high baseflow in rivers;
2. Subsequent significant rainfall events lead to river and flash flooding.

There can be several weeks between these events. Recognising such interactions can bring much earlier visibility on future flooding events of national significance.

[1] Wouter R Berghuijs and Louise J Slater, Groundwater shapes North American river floods. Environ. Res. Lett. 18 (2023) 034043

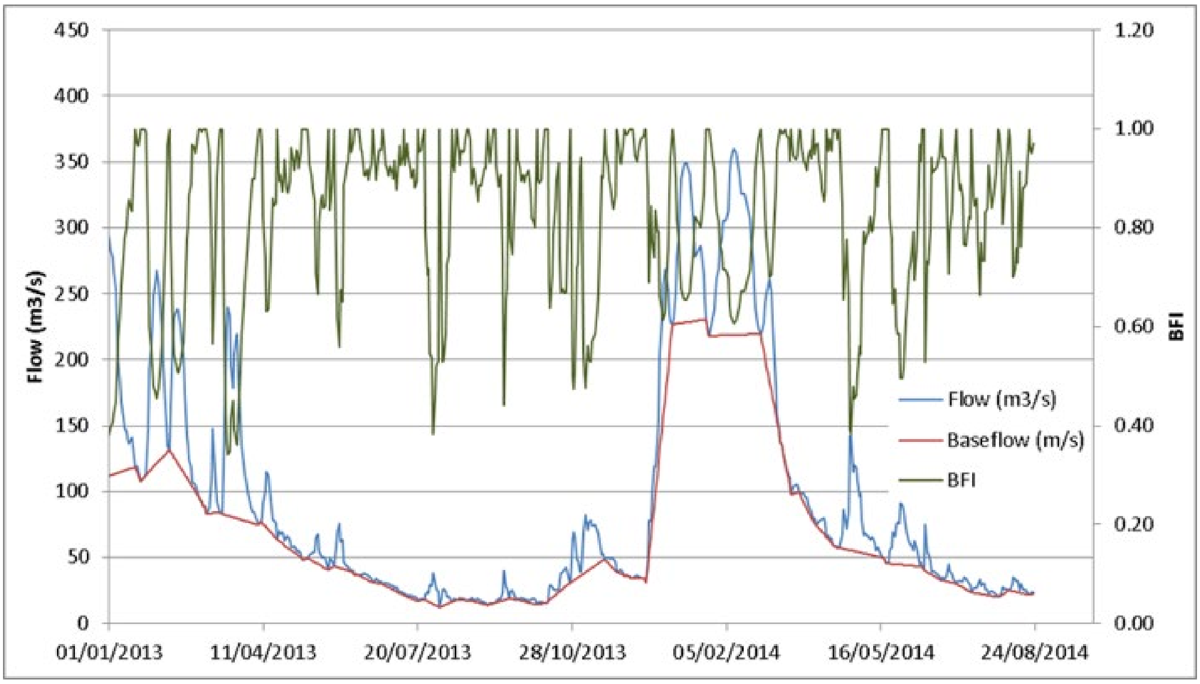

Figure 5.
Naturalised flow of the River Thames at Kingston. Baseflow separation shows the extreme groundwater discharge ("baseflow") driving river flooding in February 2014

Groundwater flooding impacts property and communities every year but it can also be a primary cause of extreme **low probability, high consequence events** on a national scale. Such compound events are significantly more likely given increased climate volatility and could coincide to cause catastrophic flooding events.

Unfortunately there is very little monitoring of groundwater at a scale and frequency needed to protect individual communities and this means that major flooding events have occurred with little warning. For example, the flood events of February 2014 caused serious disruption and damage but the regulatory structure is not conducive to catchment monitoring of groundwater so only a few days warning was achieved even though a suitable forecasting system could have predicted flooding events a month ahead.

The example shown below illustrates how groundwater forecasting provides several weeks advance notice of groundwater flooding and the creation of antecedent conditions for subsequent increased likelihood of river flooding.

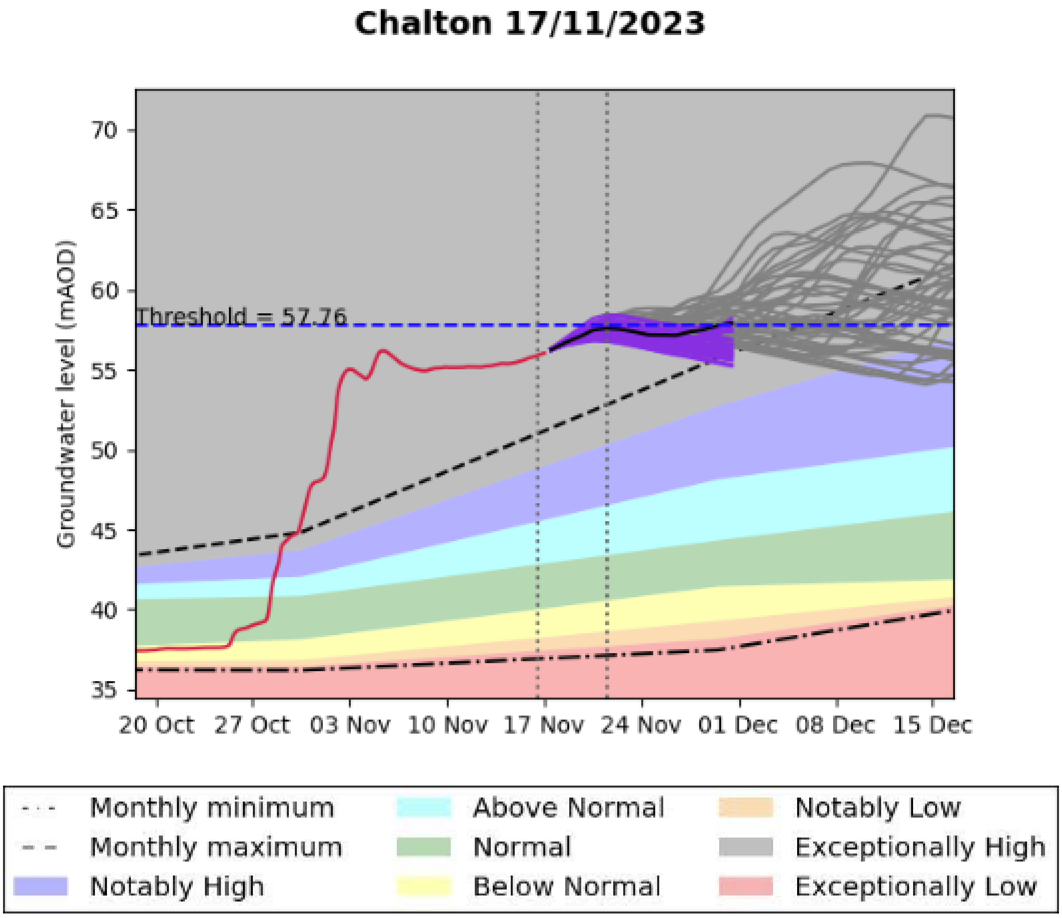

Figure 6.
GeoSmart groundwater forecast

Notes: The figure displays the GeoSmart groundwater level forecast for the Charlton borehole in the South Downs on 17 November 2023. The red line indicates actual groundwater levels over the past month, while the black and purple lines represent forecasted levels for the next two weeks. These forecasts are generated by our groundwater model using meteorological predictions. The grey lines depict a more extended forecast based on historical rainfall. Background colours show the borehole's groundwater levels as 'Exceptionally High,' 'Notably High,' etc, according to Environment Agency definitions.

Estimating number of properties at risk and financial losses

Over the last ten years GeoSmart has developed a new model to quantify risk from all four sources of flooding and their interactions and the table below summarises national residential property flood risk in Britain to put flood sources into context and illustrate the scale of the problem.

GeoSmart FloodSmart Analytics results summarizing residential property in Britain at risk of flooding from all main sources, and % contribution to average annual losses

Flood Source	% of GB residential properties within areas at risk based on UPRN data	Average annual loss % contribution	% of properties where losses exacerbated by groundwater
Fluvial (river flooding) - defended	1.8%	23%	78.7%
Groundwater*	3.2%	13%	100%
Surface water flooding	14.5%	53%	15.0%
Coastal flooding – defended	0.5%	11%	16.2%

Groundwater flooding does not impact all properties within risk zones because it is often mitigated by building design or natural and artificial drainage systems which act to lower water tables

It can be seen that groundwater leads to more annual losses than coastal flooding, and is also a central factor priming catchments for more significant damage from rivers, surface water and the sea. These losses do not include the wider business interruption and community impacts or economic consequences, which are generally higher too in a groundwater-dominated catchment.

Floods with a groundwater component often impact property and infrastructure on a very localised scale. They also have different characteristics and need different mitigation strategies.

Our results highlight the vital need for more localised and property level risk data to be taken into consideration in land use planning and in particular also informing flood resilience plans to meet flood risks due to accelerating changes in climate.

GeoSmart's national flood risk assessment shows that the risk of flooding is of particular concern in relation to typical brownfield sites and commercial properties, where flood risk is 50% higher than the average for homes. Such sites are also twice as likely to suffer from groundwater flooding due to locational factors for many old industrial sites.

Comparison with other relevant estimates

ESI Technical Note (2016).

In 2016 ESI estimated that 570,000 properties in England are at risk from groundwater flooding (the Environment Agency published a review of this note[2]).

[2] ESI Groundwater Flooding Note: Technical review by Environment Agency published December 2016 (created in discussion with experts from the Environment Agency, the British Geological Survey and the Flood Forecasting Centre)

GeoSmart's current results suggest that about 770,000 properties are at risk - slightly higher than the 2016 estimate. These latest results come from a more sophisticated groundwater model that predicts groundwater flood routing (rather than just emergence zones in the previous work) and also benefit from property data for actual locations (not available to the previous work).The new estimated groundwater flood risk results from this new more sophisticated analysis are considered more accurate and replace these previous estimates.

British Geological Survey

A detailed review[3] of the number of properties at risk from groundwater was undertaken by the British Geological Survey, with input from the Environment Agency, following the flooding events of 2014. This yielded an estimate that between 1.1M and 1.3M properties are at risk of groundwater flooding in England (about 23% of flood risk properties), of which 1M lie within areas that are also at risk of flooding from rivers or the sea.

By comparison, the GeoSmart results suggest 16% of flood risk properties (some 30% less than the BGS estimate) are at risk from groundwater flooding. Of these 164,000 may be only at risk from groundwater (The BGS equivalent estimate for this component was similar, with a range of 122,000 to 290,000 properties).

Environment Agency

In its annual report for England reported 2015 to 2019[4], the Environment Agency quoted the BGS range for groundwater only properties but omitted the other 980,000 properties at risk of groundwater flooding that lie within rivers and sea flood zones. This unfortunately gave the mistaken impression that groundwater was about 4% of the problem instead of the BGS reported 23%.

In their most recent report[5] for 2023 the Environment Agency did not present any estimate but instead reported that:

"Due to the complexity and nature of groundwater flooding, we are not able to assign a likelihood to it."[6]

Climate Change Committee

In previous work for the Climate Change Committee[7] more significant groundwater flooding was recognised, with estimates closer to the range quoted by ESI, BGS and GeoSmart (see Figure 6).The authors then concluded that:

"High susceptibility to shrink-swell subsidence and groundwater flooding were the hazards that consistently returned the highest levels of exposure for England's infrastructure.

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3 http://nora.nerc.ac.uk/510064/

4 https://www.gov.uk/government/publications/flood-and-coastal-risk-management-national-report/flood-and-coastal-erosion-risk-management-annual-report-1-april-2018-to-31-march-2019

5 https://www.gov.uk/government/publications/flood-and-coastal-risk-management-national-report/flood-and-coastal-erosion-risk-management-report-1-april-2022-to-31-march-2023#current-risk-and-investment

6 https://www.gov.uk/government/publications/flood-and-coastal-risk-management-national-report/flood-and-coastal-erosion-risk-management-report-1-april-2022-to-31-march-2023

7 https://www.theccc.org.uk/wp-content/uploads/2014/07/5-MCR5195-RT003-R05-00.pdf

assets… In general the next level of exposure of the hazards assessed was flooding from the rivers and the sea or from surface water"

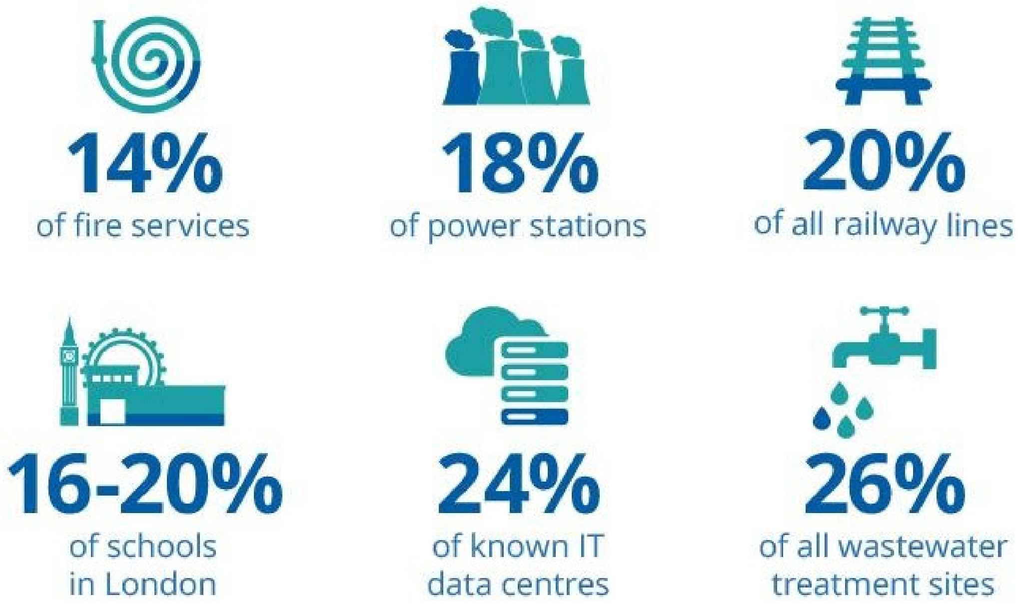

Figure 7.
UK infrastructure at risk from groundwater flooding[8]

The above error in the Environment Agency annual reports was repeated in the latest work of the Climate Change Committee[9], which also reports that 122,000 to 290,000 properties are at risk from groundwater.

Lead Local Flood Authorities and the use of Environment Agency Areas Susceptible to Groundwater Flooding (AStGWF) maps

The impression that groundwater is a very minor problem was also promoted by an unfortunate choice of schema for "Areas susceptible to groundwater flooding" AStGWF maps published by the Environment Agency and widely used by LLFAs for Flood Risk Assessments.

On 29 March 2014 we wrote to the Environment Agency with findings from a review concluding that such maps were leading to genuinely high risk areas being classified as low or negligible risk, and recommended that use of such data be discontinued. The schema was widely used to classify groundwater flood risk in relation to what % of each 1km square was within groundwater susceptibility areas.

Narrow high risk zones typically less than 300m wide pose the biggest groundwater flood risks in England. Many of the flood risk assessment reports for LLFAs (eg Maidstone

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[8] HR Wallingford. Indicators to assess the exposure of critical infrastructure in England to current and projected climate hazards, 2014

[9] https://www.ukclimaterisk.org/publications/technical-report-ccra3-ia/#publication-downloads

Borough Council) mistakenly classified the highest risk areas as negligible or low risk because the classification scored according to whether hazard extended over more than 50% of the 1km square (Figure 7 illustrates).This schema was therefore totally unsuitable for the nature of the risk and not consistent with normal risk screening principles

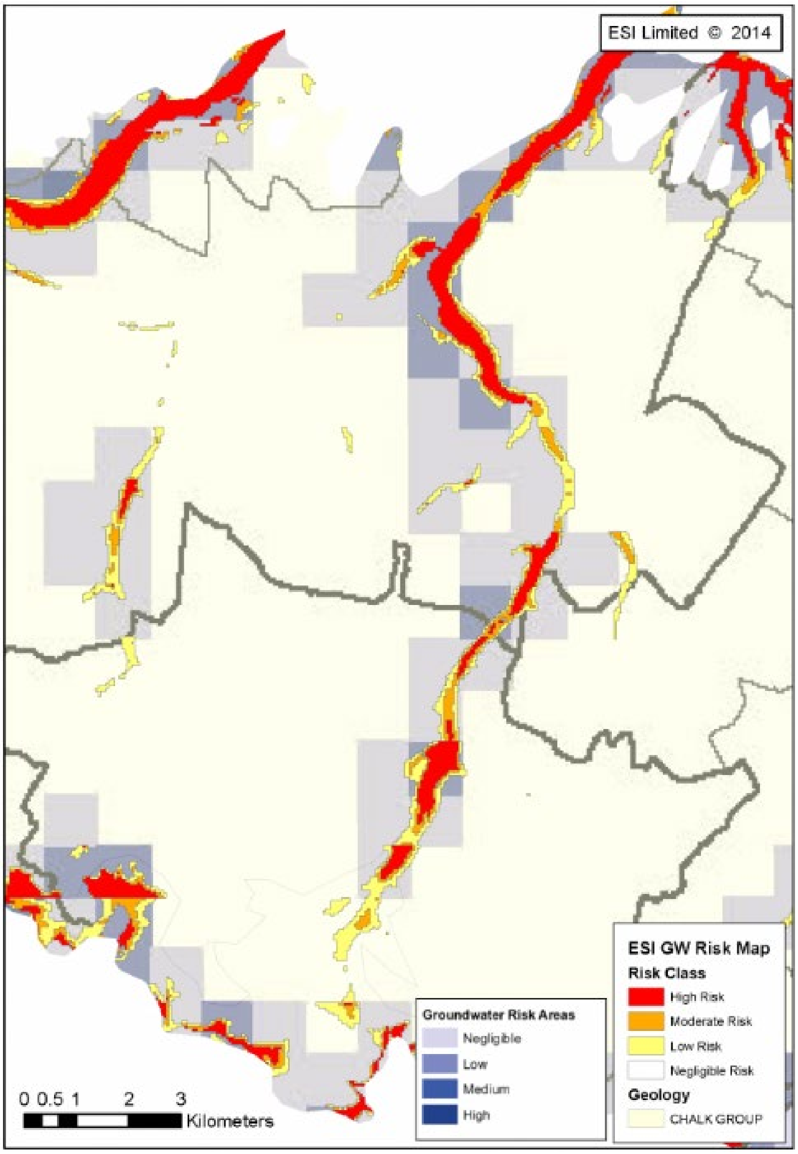

Figure 8.
Example AStGWF risk areas compared to groundwater flood risk areas mapped by GeoSmart's GW5 flood risk map.

Flood risk management

The reality is that groundwater is one of the most significant natural perils in the UK and there is evidence available quantifying the likelihood and consequences of groundwater flooding. From a risk analysis point of view complexity adds uncertainty and this contributes to the overall risk. Within a suitable risk management framework there are always trade-offs between tiers of risk assessment and their data requirements and costs.

It is important to understand the contribution made by groundwater flooding directly to national flooding losses and number of homes and businesses impacted, and that of the other main flooding sources.

Groundwater does not act alone, instead forming a central component of the catchment flow system and the baseflow in rivers. It is therefore vital that flood risk management is undertaken on a catchment basis.

It is our perspective that sensitivity analysis considering parameter uncertainty helps to prioritise further investigation and more detailed risk modelling. This is consistent with Government guidance[10] and provides a suitable framework for devising an appropriate flood risk management strategy.

The Flood and Water Management Act 2010 incorrectly set out that groundwater flooding is 'Local Flooding' and passed responsibility for risk management to the Lead Local Flood Authorities.

There are serious consequences arising from the lack of national flood risk management in relation to groundwater that is a consequence of the FMWA.

Lack of focus and attention to this issue has led to a 'rivers-centric' approach which has led to 1M homes at risk from groundwater flooding being lost from the national overview of groundwater flood risk, with consequent perceptions widely held that groundwater is not a significant problem.

The risk from groundwater is highly localised and subject to some parameters that remain uncertain so cannot be included in relevant risk models and maps. However, risk maps such as those available from GeoSmart[11] provide a useful preliminary risk screening tool. Depending on the results and sensitivity of planned use, more detailed and site specific risk assessment is often required as development projects proceed.

Implications for flood risk management

Flood risk is not only a function of location and likelihood, but also of the characteristics of the flooding, its duration, and how to manage it. Flooding may occur by overtopping of river banks or flash flooding, but thereafter may become a groundwater dominated event with long duration and significantly increased damage in areas with significant groundwater influence.

The FWMA introduced a divided regulatory regime which inappropriately labelled groundwater 'Local Flooding', and management of flood risks was assigned to the Lead Local Flood Authorities (LLFAs).**As stated above, it is not correct to define groundwater flooding as Local Flooding and dividing a single catchment flow system between two different regulatory bodies** is having significant adverse consequences, preventing an adequate approach to flood risk management nationally.

[10] https://www.gov.uk/government/publications/guidelines-for-environmental-risk-assessment-and-management-green-leaves-iii

[11] https://geosmartinfo.co.uk/risk-management-for-financial-services/floodsmart-analytics/

One casualty of this approach is lack of recognition of the role of groundwater driving increased damage and community disruption from river, surface water and coastal flooding where these interact. The damage to UK plc is very significant.

Over the years since the Pitt Review[12] of the 2007 floods, groundwater scientists have developed a much clearer understanding of the role of groundwater in flooding, and specialists such as GeoSmart have published maps, data and forecasts to help inform those managing the risk.

The recent results from modelling and research offer new insights. Recognition of the flooding characteristics is key to designing suitable mitigation strategies. Those areas where river and surface water flooding are subject to the influence of groundwater need different management response to those occurring in low permeability catchments.

Given the lack of national attention to this significant hazard there has been little systematic investigation nationally. The findings presented here are very preliminary and subject to significant uncertainties. A systematic review is necessary to increase confidence and further confirm the role of groundwater in flood risk.

Conclusions

It is clear that groundwater is a significant source of flooding that causes disproportionately more harm than other sources of flooding in many cases by direct emergence into property and infrastructure, and has long duration effects that multiply community disruption and economic damage.

It is also clear that seeking to analyse and regulate groundwater flood risk as a separate problem to river, surface water and coastal flooding processes is unhelpful. Groundwater is the underlying factor that drives most river flooding in permeable catchments. Assessment and management of the hazard on a catchment basis is essential.

Understanding the surface/subsurface interactions in a holistic catchment analysis will provide a more rigorous and appropriate framework to complete the flood risk assessment we need for planning and land use decision-making for the UK. This approach will also help to improve forecasting, event response and resilience.

[12] Pitt, M. 2008. Lessons learned from the 2007 floods. Defra/CLG, UK.