The Impact of Climate and Land-use Change on Groundwater Flooding

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In areas dominated by aquifers, water emerging from the subsurface can inundate regions for periods of up to several months. Estimating the effect changes in climate and landuse may have on the frequency of these flood events will help determine suitable mitigation strategies.

Previous studies have made attempts at applying output from Global Climate Models to numerical groundwater models. However, the focus of these studies has largely been the impact on low flows/ drought conditions. In addition, few have explicitly taken into consideration the modulating effect of surface hydrology on the subsurface.

The aim of the research is to link atmospheric, hydrological and hydrogeological models together. This 'meta model' can then be used to run UKCIP scenarios of socio-economic and climate change. Ensemble outputs from the model will be used to assess the impact such changes might have on the frequency of dangerously high groundwater levels.

Weather data for climate change scenarios is provided by EARWIG (Environment Agency Rainfall and Weather Impacts Generator). This data is interfaced with a distributed recharge model developed in ArcGIS. This representation of surface hydrology is coupled with a 3D groundwater flow model in order to estimate future groundwater time series. Integrated modelling like this will help improve understanding of the risk of groundwater flooding at the catchment scale.

Investigation into the Potential Impacts of Climate Change on Groundwater Extremes for a 'Model' Chalk Catchment

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The River Lavant is a chalk intermittent stream in the South Downs, West Sussex. Over the past 15 years, exceptionally heavy and prolonged rainfall events have caused river flows to exceed the capacity of the culverts under Chichester resulting in extensive flooding. Conversely, there have also been a number of droughts in the chalk catchments in the South Downs over the last 30 years. Future climate change scenarios predict that by 2100, summers will be drier and winters wetter. Rainfall events during the winter recharge months will be more intense over shorter periods of time. Consequently, there is a need to examine how climate change will impact on the frequency and magnitude of groundwater flooding and droughts in the chalk catchments such as the Lavant.

The behaviour of the catchment has been modelled using a 'leaky aquifer' conceptual model using climate data dating back to 1855. Model performance was been assessed on both streamflow at the Graylingwell gauging station, just upstream of Chichester, from 1970 and groundwater levels at various long period observation wells, including Chilgrove House. Investigations of climate change impact were investigated using present and future input drivers derived from the EA's climate impacts methodology, EARWIG. Comparing proportional changes, the analysis of the resulting groundwater levels and stream flow time series for the future climate change scenarios of the Lavant catchment show an increase in the frequency and magnitude of drought events, especially when associated with the high emissions scenario. By contrast, the results indicate that the frequency of groundwater induced flood events will decrease over the coming century.

Modelling Groundwater Flooding: Is Good Enough Good Enough Or Grounds For Complacency?

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The numerical simulation of groundwater flooding is increasingly necessary as the problem is gaining recognition from government bodies and the regulator, and climate change may bring more extreme events. However producing a suitable simulation of groundwater flooding involves many technical challenges. The timescale of the development of the flood can be short, recharge must be correctly calculated, the unsaturated zone must be considered as well as the "usual" suitable simulation of the saturated zone. The latter requires appropriate simulation of absolute as well as relative values, since the timing and extent of the water table reaching the ground surface must be reproduced well. All these factors combined with data scarcity makes simulation of groundwater flooding difficult. Using examples of recent modelling of flooding in superficial deposits in Scotland the development of a suitable modelling approach is illustrated. The modelling approach allowed the assessment of the impact of a flood alleviation scheme on a groundwater system with existing groundwater flooding problems. Groundwater models need to "know" where the ground surface is; this is undertaken by post-processing. The engineering scheme will result in standing water behind a bund and this needed to be simulated. Whilst this approach produced a viable solution, it highlighted issues for further research. These questions are being addressed in the NERC funded FREE project, which is examining groundwater flooding in the Pang and Lambourn catchments, Berkshire. Initial findings from this work are presented to demonstrate a more comprehensive groundwater flooding modelling system.

Groundwater Flooding In The Chalk: The Role Of The Unsaturated Zone

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The emergence of flood water from sub-surface permeable strata has, historically, been rare in England. However, major groundwater flooding occurred in the winter of 2000/1 in Chalk catchments in south east England (particularly the Pang) and Northern France. Studies suggest that the flooding was caused by expansion up the valleys of the area where the water table intersects the ground. Moreover, the rainfall that caused this unprecedented flooding was only exceptional on a two-year timescale, reflecting the importance of antecedent conditions. However, other observations, notably following the very intense rainfall events in summer of 2007, suggest that a water table which is tens of metres below the surface can respond very rapidly to rainfall events. This non-linear behaviour is typically attributed to the dual permeability nature of the Chalk unsaturated zone. We have developed a two-dimensional (in depth and length), dual permeability, numerical model which couples the unsaturated and saturated zones of the Chalk. This model has been applied along an approximate groundwater water flow line, from the interfluve to the river in the Pang catchment, Berkshire UK. Extensive unsaturated/saturated zone instrumentation has been installed, which can be used to test and condition the model. We present findings from this model in relation to the transmission of large rainfall events of differing intensities and duration through the Chalk unsaturated zone, and the corresponding water table response.

The Unsaturated Zone Of The Chalk, The Key To The Aquifers Response To Extreme Events

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Chalk catchments are prone to long-lasting groundwater floods and are resilient to droughts. Evidence from laboratory results and Chalk borehole and river hydrographs has previously suggested that storage in the unsaturated zone of the Chalk sustains river discharge during droughts and prolongs groundwater flooding events.

The primary objectives of the EU INTERREG IIIA funded project, FLOOD1, were to develop unsaturated zone monitoring techniques, and to understand the hydraulic behaviour of water flow in the unsaturated zone which leads to triggering of groundwater flood events. To this aim boreholes at two research sites, one near Brighton in the South Downs, and one near East Ilsley in the Berkshire Downs were instrumented with deep borehole tensiometers that continuously monitor matric potential at multiple intervals in the unsaturated zone.

Observations from wire-line CCTV surveys have been integrated with borehole geophysics to provide the geological context for matric potential data. Together these data sets reveal that differences in the sedimentary composition and structural evolution of Chalk catchments control recharge processes, and, therefore, the response of the catchments to extreme events.

At the East Ilsley site, where marl horizons are less developed and the Chalk less weathered, recharge to the water table continues throughout summer and autumn. Such year-round drainage, is not always accounted for in numerical models, but is key to sustaining the water resources of the Chalk. At the Brighton site, where marls are well developed and the Chalk more weathered, a multi-layered unsaturated zone develops as successive marls impede draining water. Matric potentials are close to zero throughout much of the unsaturated zone and smaller fractures are saturated. A tipping point is reached and rapid drainage occurs to the water table when the air entry pressure of larger fractures is exceeded.

An Early Warning System For Groundwater Flooding In The Chalk

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FLOOD1, a joint project between BRGM, the University of Brighton and the BGS, was implemented under the INTERREG IIIa initiative of the European Union to develop appropriate early warning systems for groundwater flooding in Chalk catchments. It was developed following the particularly severe groundwater floods of the winter of 2000-01 and focussed on flooding in the Patcham area of Brighton and in the Somme Valley of northern France. Research sites were set up to the north of Brighton and in the Hallue sub-catchment of the Somme. An additional site was established at East Ilsley in the Pang Valley of the Berkshire Downs.

This paper describes the early warning system that was developed for the Patcham area of Brighton which, within the context of the available data, provides a fit-for-purpose methodology for forecasting groundwater flood events in the Chalk. One that is capable of operating within a longer timescale than had previously been possible.

The methodology involves a set of nested models based on the research carried out in FLOOD1 and previous understanding of the hydrogeology of the Chalk. It must be pointed out that the methodology has not been tested on a real flooding event as no groundwater flooding has yet occurred in either of the two UK FLOOD 1 research catchments following its development. It should also be recognised that the early warning system as described does not include specific trigger levels to initiate either the next step of the methodology or promulgation of warnings of varying severity. Such trigger levels will be developed through experience of use of the system.

Analysis And Modelling Of Groundwater Floods In Fractured Chalk Following Extreme Rainfall Events

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Following the dramatic flooding in the Somme river basin (France) during the 2001 Spring, an experimental site was installed for the monitoring of the unsaturated fractured Chalk formation overlying the Chalk aquifer (FLOOD 1 project). The aim of this continuous monitoring, was to understand how the fractured vadose zone close to saturation reacts to long extreme rainfall events by increasing dramatically its hydraulic conductivity, as the fractures become conductive, leading to preferential flows which transmit quickly the recharge to the aquifer and generate floods. The water content was monitored to a depth of 8 metres and the matrix pressure from the ground surface down to the water table, 23 metres below. The measurements were carried out during more than three years in natural conditions except for two periods of heavy artificial recharge similar to extreme rainfall events. The gathered data appeared to be unique over such a depth range and of very high quality. All the available measurements were used to establish a vertically discretized flow model, based on Richards equation, calculating the water flow from the rainfall over the ground surface down to the saturated aquifer. The MARTHE code, which models the unsaturated-saturated continuum, was first used and, as expected, could not reproduce the high saturations periods. The model constitutive relations, permeability-saturation and retention-saturation were then both modified in order to integrate the increase in the permeability near saturation and the extra available porosity. The model was then able to accurately reproduce the water contents and the pressures at all depths during the whole monitored period, including the artificial recharges, making it possible to estimate the local aquifer recharge. The computed recharge appeared to be realistic as it enabled to simulate closely the monitored aquifer level. The model was then used for extrapolation with long meteorological data, including flood periods, to calculate the corresponding aquifer recharges.

Groundwater And Flooding In Oxford

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The city of Oxford is situated within a narrow valley in the Upper River Thames catchment. Although much of the city sits above the current floodplain of the River Thames, approximately 3600 properties in Oxford are located within the 1% floodplain envelope. The city suffers from recurrent floods, most recently in December 2000, January 2003 and July 2007. The July 2007 flood, a 1 in 20 year event, impacted over 200 properties. A significant number of these properties were affected by flooding from rising groundwater which was either the sole cause of flooding or the initial cause prior to inundation from fluvial waters.

The British Geological Survey is undertaking a jointly-funded, collaborative project with the Environment Agency, linked with the Oxford Flood Risk Management Study, to assess the role of groundwater in flooding in Oxford. This addresses both the role of groundwater during flooding but also the implications of flood mitigation measures on the groundwater system outside of flooding periods so that, for example, the impact of these measures on groundwater-dependent ecosystems can be assessed. The study has built on extensive monitoring that had already been undertaken in the Oxford area to assess the impact of gravel extraction and river abstractions on groundwater levels beneath the Special Area of Conservation within the Thames floodplain to the north of Oxford. The study has also been aided greatly by the monitoring data collected during the July 2007 flood.

The study has provided insights into the groundwater flow system in general in the alluvial aquifer underlying the Oxford floodplain, and the relative response of groundwater levels during flood events to direct rainfall and subsequent heightened river levels. In addition, groundwater flooding risk has been mapped. The results have informed flood risk management approaches being considered by the Environment Agency for the city.

Groundwater Flooding Experience, Thames Region Winter 2000/01

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Flooding issues are very high profile at the moment. Recent events have led to a new Defra strategy on flooding, Making Space for Water, and many recommendations from the Pitt Review. Groundwater flooding is included in both of these documents and so we will illustrate the groundwater flooding that occurred in Thames Region during the winter of 2000/01 to provide a real example of an event that needs to be monitored and managed.

The rainfall of winter 2000/01 and subsequent recharge to aquifers in Thames Region exceeded all previously recorded quantities for a similar period in most areas. As a result, the groundwater levels, particularly in the Chalk aquifer, rose to the highest recorded levels. Extensive groundwater flooding occurred, mainly in the upper, normally dry, valleys on the dip slope of the Chalk escarpment. We show what happened in Thames Region and how the groundwater information was evaluated to assess the risk of there being further groundwater flooding the following year.

A Probabilistic Groundwater Flood Map for the Unconfined Chalk Aquifer

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As observed during the 2000/01 winter, some areas of the UK are at significant risk from flooding from groundwater. Here we present a methodology for deriving probabilistic flood risk envelopes for the unconfined Chalk, which outcrops across much of England from Yorkshire to the Solent, an area of about 10,000km^2 (the eastern fringes of the Chalk are confined under a layer of impervious glacial material and are therefore not included in the mapping although artesian conditions in the confined chalk could lead to surface flooding from groundwater sources on a localised basis).

In all data from 850 groundwater boreholes have been utilised. Frequency analyses of annual maximum groundwater levels from the longest and most complete records have been used to calculate the T-year return period groundwater surface at these key locations, whilst their correlation with seasonal water level profiles at nearby boreholes having shorter or partial records have allowed the T-year levels at those points to also be derived. A final step is the spatial interpolation of the groundwater surface between known values based on a 5m resolution DTM.

Based on this approach flood risk maps have been produced for 75, 100 and 200-year return period events. In each case the map delineates those areas that are at a lower elevation than the groundwater surface and are therefore at risk from groundwater flooding.

Our analysis has indicated relatively little risk of groundwater flooding in the Yorkshire and Lincolnshire Wolds, whilst the North and South Downs, the Chilterns and the Salisbury Plain have the most extensive flood envelopes. In total an area 2400km^2 in extent is at risk during the 100-year event. Our analysis also suggests that the extensive groundwater flooding observed during the 2000/01 winter generally relates to an event of return period between 100 and 200-years.

Mechanisms And Indicators Of Groundwater Flooding In The Lincolnshire Chalk: A Case Study Following Extreme Rainfall In Summer 2007

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Groundwater flooding occurred at the base of a Chalk catchment near Barrow-on-Humber (North Lincolnshire) following torrential rain in June 2007. Although the flood waters receded after 14 days, flooding recurred in January 2008. Concerns were raised by local residents that the summer flooding had washed away clays that had previously prevented discharge from the emergent spring. Therefore, there was concern that flooding would become more frequent. A detailed analysis of available hydrometric data, including 15-minute logger records from three nearby observation boreholes, and recharge modelling was undertaken to investigate. The summer flooding was determined to be the result of two successive heavy rainfall events. 110 mm rain fell between 16th and 19th June, which cancelled out the established soil moisture deficit (SMD) and caused groundwater levels to rise by about 1 m. Subsequently 121 mm rain fell between 23rd and 25th June and groundwater levels rose by over 13.1 m at a rate of 0.32 m/hour. Flooding ensued on the 27th June. Bypass recharge is insignificant in this catchment because even heavy rainfall fails to generate a hydrograph response following several weeks of dry weather. Therefore, the presence of a SMD significantly mitigates the risk of groundwater flooding despite the high infiltration capacity of the Chalk. Based on a qualitative chronology of the flood event provided by observers, flooding indicator levels were proposed for two observation boreholes. These indicator levels were used to evaluate hydrographs from the January floods: indicator levels were exceeded at both boreholes during the flooding event. This suggests that the hydrogeology of the system was not changed by the summer flooding and gives confidence in the applicability of simply derived indicator levels to groundwater flood warning systems.

The Effect Of Recovery From Drought On Chalk Groundwater Quality

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The Chalk is an aquifer which can vary between flood and drought conditions within a few years. This might be expected to result in changes in the groundwater quality of spring outlets as they wax and wane in discharge, with possible implications for ecological status etc. To assess the potential for this, a catchment monitoring study was initiated in the autumn of 2006 at the end of a period of drought that had seen hosepipe bans applied in many parts of SE England. Samples from springs and boreholes across two selected catchments (Pang and Lambourn) were periodically measured for a range of hydrogeochemical parameters until spring 2008, when recovery was deemed to be complete. This presentation is based on an initial consideration of the results and their significance.

Groundwater Level Forecasting During Drought Periods

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After two dry winters followed by intensely hot summers, water companies in southern England, East Anglia and the Midlands were concerned that a third dry winter in 2006/2007 would result in a decline in groundwater levels to depths never encountered before and thus result in an inability to maintain groundwater supplies.

Planning for a third dry winter is commonly accepted in the water industry as the key to managing drought. Anglian Water Services (AWS) required a drought-forecasting tool for the prediction of groundwater levels at its 26 drought-vulnerable sources. The prediction would run through to the end of the 3rd dry winter followed by a simulated subsequent hot summer. The simulation would help form drought management plans in the event of further drought conditions, an important decision making procedure for all water companies.

The Groundwater Level Forecasting Tool, based on historical groundwater levels at representative observation boreholes during previous droughts, was used to predict future trends. The method was subsequently compared with real data and the outputs from groundwater models. This proved that the forecasting tool was better at predicting water levels than other more expensive alternatives.

Development of Methods for Drought Prediction and Planning for South East Water

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As drought conditions develop water companies and the Environment Agency implement Drought Plans, which describe the monitoring, management, communications and intervention measures required to maintain public water supply and protect the environment. Most companies consider future drought conditions over periods of 3 months to 2 years using scenarios based on past droughts ("what if" conditions are like 1944, 1976, 1995..) or simple percent reductions in rainfall.

A pilot study undertaken by HR Wallingford and Aquaterra for South East Water (SEW) explored new methods for deriving drought scenarios that considered current climate and recharge conditions as well as historical climate information. The study aimed to demonstrate how models developed for climate change impact assessments could be used for drought planning and management.

The project included three components: development of a tool for deriving rainfall scenarios; refinement of groundwater models originally used for climate change impact assessments for estimating levels and source Deployable Outputs (DOs) and integration of models within a conjunctive use (AQUATOR) model, including a supply-demand balance and 'traffic light' warning system. One of the main innovations in the project was the further development of conceptual groundwater models that linked predicted levels at observation boreholes to DO at sources so that 'DO time series' could be used in the water resources zone model.

The methodology was illustrated for part of SEW's Water Resource Zone 2 located near Lewis in Mid Sussex focusing on the Ouse/South Downs Chalk for the 2004 to 2006 drought, which included two consecutive dry winters and resulted in drought permits and order applications throughout the South East of England. The case study showed that the modelling system would have provided an early indication of reductions in groundwater and reservoir yields, with associated probabilities, and helped water resource managers make planning and operational decisions during the drought.