# Revised approach for the calculation of groundwater flooding annual average damages

## Establishing a probability-based relationship for groundwater flooding

## Flood Hazard Research Centre

## Report prepared for Lincolnshire County Council

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Middlesex University

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## Executive Summary

Project Groundwater Greater Lincolnshire, as part of the Department for Environment, Food & Rural Affairs (Defra) and the Environment Agency (EA) Flood and Coastal Resilience Innovation Programme, seeks to enhance understanding and resilience to groundwater flooding. Existing economic appraisal methodologies and datasets within the Multi-Coloured Manual (MCM) are predominantly tailored to fluvial, pluvial, coastal flooding. The Flood Hazard Research Centre (FHRC) delivered a scoping report to Lincolnshire County Council (LCC) in July 2023, highlighting the need for groundwater-specific appraisal methodologies. A significant gap was identified regarding methods for estimating Expected Annual Damages from groundwater flooding due to the different flood mechanisms and impacts compared to other flood types.

This report outlines key considerations for developing a probability-based relationship for groundwater flooding, focusing on different types of groundwater flooding relevant to proposed Lincolnshire case study areas (Grimsby, Scopwick, Barton/Barrow-upon-Humber). Traditional methods such as the development of a probability-discharge relationship, as done for fluvial flooding, are not applicable due to the lack of discharge record data for groundwater events. Instead, the use of groundwater borehole levels (annual maximum level) has been identified as a more suitable dependent variable, though difficulties such as limited data and non-stationary time-series data due to changing abstraction rates exist.

Flood duration has been identified as a critical variable for evaluation of economic damages. Groundwater flood frequency analysis must therefore consider the likelihood of prolonged periods of high groundwater levels. This report considers that this may be addressed through the use of a Standardized Groundwater Flood Index (SGFI) or using maximum winter effective rainfall data to develop discrete event probability curves.

The final proposed approach for estimation of the frequency of groundwater flooding involves defining a benefitting area, identifying a relevant borehole and establishing the relationship between the receptors at risk and the borehole, and conducting a frequency analysis to establish event probabilities. The feasibility of this proposed approach will be further investigated and discussed for the selected case study areas within the second phase of this project. As groundwater flooding contexts and mechanisms vary, the approaches used for economic appraisal are also likely to be adapted to the context. Groundwater appraisal will likely require significant local survey and expertise to fully define the most suitable approach for each study area.

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# 1. Introduction

Project Groundwater Greater Lincolnshire, undertaken as part of the Department for Environment, Food & Rural Affairs (Defra) and the Environment Agency's (EA) Flood and Coastal Resilience Innovation Programme, has ambitious plans to better understand groundwater flooding and enhance the resilience of communities. Achieving increased community resilience to groundwater flooding necessitates further consideration of the economic and financial benefits of the avoidance of flooding through the implementation of different risk management options. Existing appraisal flood damage and loss data widely used in the assessment of the benefits of flood risk management options are available from the Multi-Coloured Manual (MCM) suite of methodologies and data. Whilst these data may be applied to all types of flooding, so far, the supporting evidence and assumptions are typically aimed at coastal, fluvial and pluvial flooding with very limited attention or insight given with respect to groundwater flooding, meaning that these data may not be the most accurate in that respect. More widely, actual and potential damage and loss attributable to groundwater flooding is limited and therefore requires further attention and investigation.

The Flood Hazard Research Centre (FHRC) delivered a scoping report (Hardman *et al.*, 2023) to Lincolnshire County Council (LCC) in July 2023 which identified a number of key focus areas to progress the development of groundwater specific appraisal methodologies. A significant gap was identified regarding the approach to estimation of expected annual damages (as a key risk metric) due to the inherent differences in flood mechanisms and impacts from groundwater as opposed to fluvial, pluvial, and coastal flood types. This formed the main deliverable of *Task 1 'Exploring the state and nature of groundwater flooding'*.

FHRC held sessions with a number of UK consultancy companies that specialise in groundwater flood risk and modelling including JBA, Jacobs, GeoSmart, Atkins, WSP, and BGS. The aim of these sessions was to help gain insight into how industry approaches to groundwater modelling vary, and to help develop the thinking around a suitable approach to the estimation of annual damages based on discussion around the characteristics and mechanisms of groundwater flooding. FHRC presented slides to show initial thinking around the topic and to help initiate discussion. The complexities and issues surrounding this topic were discussed to guide the consideration of suitable approaches for loss estimation.

The report will first explore different types of groundwater flooding relevant for this project, and then will evaluate the feasibility of different existing methods to establish a probability-based relationship. Further scoping of additional case studies was also discussed within sessions. **Appendix A** details the full list of case studies that are currently being considered for further work within this project. **Appendix B** provides insight into the agricultural considerations of groundwater flooding and scopes further potential case studies.

## 2. What is groundwater flooding?

Basic terminology surrounding groundwater flooding is considered here in order to draw together standardised definitions for use within groundwater flooding economic appraisal guidance. British Geological Society provides terminology and definitions for general groundwater and hydrogeology concepts (BGS, 2024a; BGS, 2024b) which have been applied to the flooding context in this report.

Groundwater flooding is typically split into three categories based on the hydrogeological setting of the area and the mechanism by which the groundwater leads to impacts. **Table 2-1** provides definitions of the three types of groundwater flooding.

This report will consider high groundwater level in bedrock aquifers and high spring flow groundwater flooding scenarios as these are the most applicable to the Lincolnshire hydrogeological setting and associated LCC case study areas. Groundwater flooding impacts related to sea-level and saltwater intrusion have not been considered in this report. **Table 2-2** provides a summary of our understanding at this stage of the project of the potential impacts that can occur due to these two types of groundwater flooding scenario.

*Table 2-1: Definitions of the three overarching types of groundwater flooding*

| Groundwater flood mechanism | Definition / Description | Duration | Source |
|---|---|---|---|
| Permeable Superficial Deposits (PSD) | 'This mechanism of groundwater flooding is associated with shallow unconsolidated sedimentary aquifers overlying non-aquifers. These aquifers (typically sand and gravel) have a relatively high permeability, are often in good hydraulic connection with the adjacent watercourse and can have groundwater levels close to the ground surface.' (ESI, 2016)<br>When river levels rise, groundwater that cannot discharge to the flooded river may back up and lead to additional flooding. Water moving through the ground may emerge at locations behind flood defences unless these have been designed to seal off the aquifer. | Flooding in these systems can be relatively short and generally comparable in duration to the associated fluvial flooding. | BGS, 2024a; ESI, 2016 |
| High groundwater levels in bedrock aquifers | 'Bedrock flooding, also referred to as clearwater flooding, is associated with the rise of the water table in permeable bedrock aquifers in response to long periods of high rainfall conditions. Flooding is enhanced | Groundwater recharge in aquifers occurs most during the winter season and can lead to elevated groundwater levels that last months. | BGS, 2024a; ESI, 2016 |

| | | | |
|---|---|---|---|
| | by antecedent conditions of high groundwater levels.' (ESI, 2016) | | |
| High spring flow | 'Spring lines are likely to occur at the outcrop boundary of a permeable formation with an underlying low permeability formation. Chances of spring occurrence are higher on the hill side down dip of the aquitard, in the direction of groundwater flow. Permanent springs are more likely to occur on the dip slope of valley sides and water will generally be discharged to the nearby watercourse.' (ESI, 2016) | Groundwater recharge in aquifers occurs most during the winter season and can lead to elevated groundwater levels that last months. High spring flow scenarios will typically occur when groundwater levels in the bedrock aquifers reach peak levels. | BGS, 2024a; ESI, 2016 |

*Table 2-2: Types of groundwater flooding impact and their relevance to the existing Lincolnshire case study areas and other potential case studies (a code is attributed to each case study in appendix A such as Sc: Scopwick, Lh: Lincoln Hillside avenue, Gr: Grimsby, Bb: Barton/Barrow upon Humber, Bo: Bourne)*

| | **High spring flow 1** | **High groundwater level (bedrock) 2** | | |
|---|---|---|---|---|
| **Scenario** | Spring emergence (1) | Elevated water table level above ground (2a) | Elevated water table level below ground (2b) | Elevated water table level below ground (chronic groundwater rise) (2c) |
| **Impact mechanisms and characteristics** | A rise in the water table leading to spring emergence. This causes surface water flooding and impacts assets and infrastructure in the same ways as pluvial/fluvial flooding and the cases of mismanaged boreholes and artesian effects can lead to local flooding.<br>Generally low flood depth | A rise in the water table over ground flooding land uses. | A rise in the water table below ground impacting underground assets and infrastructure.<br>Rising damp can lead to direct damage to foundations, basements, underground assets (mould, lateral pressure).<br>High groundwater can cause blocking of sewer systems (e.g. leading to toilets being unable to flush). | Semi-permanently risen groundwater levels (for example, due to reductions in local abstraction over time) leading to loss of original land-use function and subsequent land-use change over time (e.g. loss of allotments to wetlands, constraints to new development, degradation of local sewer systems).<br>Seasonal |
| **Likely flood duration; existing MCM duration** | Days; Short / Long | Weeks; Long / Extra-Long | Weeks to Months; Duration not currently considered within MCM | Seasonal, Chronic; Duration not currently considered within MCM |

| | | | | |
|---|---|---|---|---|
| **Metric** | mAOD / flood depth above ground level<br>Flow, contribution to SW flooding<br>Duration | mAOD above ground level<br>Duration | mAOD below ground level<br>Duration | Years until land-use change |
| **Case study (see Appendix A for reference code)** | Lh, Bo | Gr, Bb, Sc | Gr, Bb, Bo, Sc | Gr, Bb, Sc |
| **Integration into MCM** | Traditional MCM depth/damage curve approach could be utilised. Green *et al.* (2006) discussed the suitability of existing MCM data for this purpose however this study is old and new evidence needs gathering. | | ***New to MCM*** | |

High spring flow results in overland flows and therefore flooding on the surface, this type of groundwater flood has the potential to be appraised using traditional MCM methods such as depth/damage curves. **Figure 2-1** illustrates the formation of a spring line and the emergence of groundwater due to the presence of an impermeable layer, for example, as is seen at Lincoln, Hillside Avenue where the road is situated along the spring line.

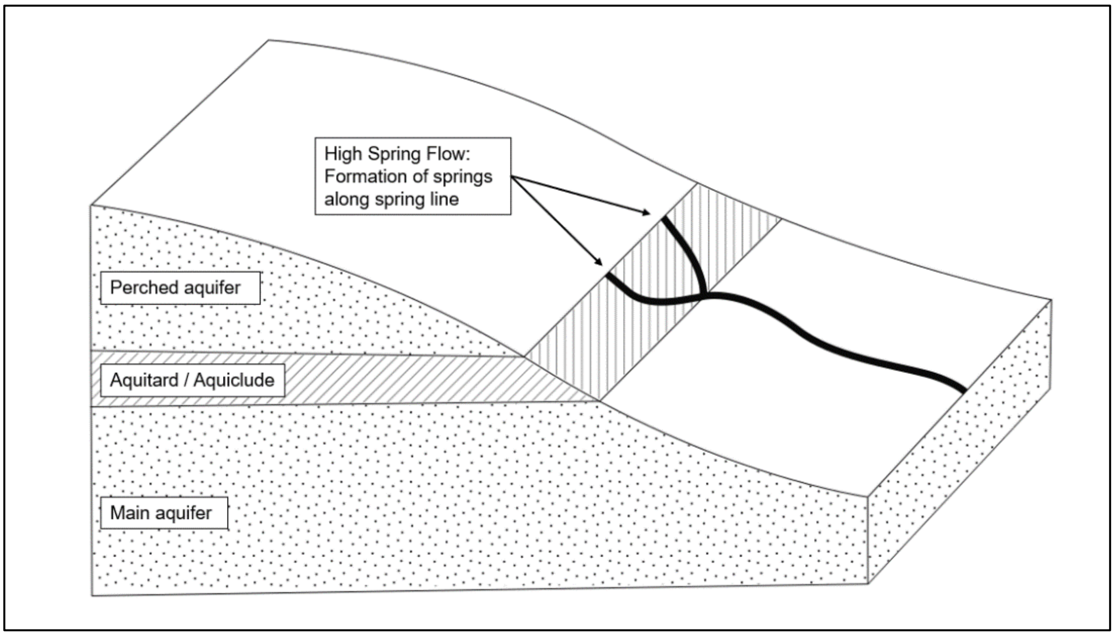

*Figure 2-1: Schematic illustrating the formation of a spring line due to a change in geology from a permeable to impermeable layer as is seen at Lincoln, Hillside Avenue where the road is situated along the spring line*

High groundwater level (bedrock) largely comprises of impacts to assets below ground due to the elevated water table. There are two possible impact scenarios relating to this type of groundwater flood, the first is a generally seasonal rise of the water table leading to impacts to assets, whilst the second is a chronic or semi-permanently risen water table that contributes to land-use change within an area to accommodate for this long-term impact. **Figure 2-2** shows a schematic of an area local to a chalk stream in which groundwater rise causes direct flooding to basements and infiltration into local sewer systems leading to blockage (Type 2a and 2b), for example as experienced in Scopwick. **Figure 2-3** illustrates how groundwater can rise from the chalk aquifer through the sand and gravel layer or via a borehole (Type 2a and 2b) due to an artesian condition, for example as is observed in Grimsby.

Seasonal high groundwater levels are of particular concern in the rural context. Groundwater levels and the incidence of water logging are a major determinant of agricultural land use due the effect of excessively wet soils on crop production and the bearing capacity of soils for field machinery and/or grazing livestock. The groundwater levels and associated soil water relations are also critical for target natural habitats and species. Groundwater management interventions can be prescribed to deliver specific agricultural and conservation management outcomes as detailed in **Appendix B**.

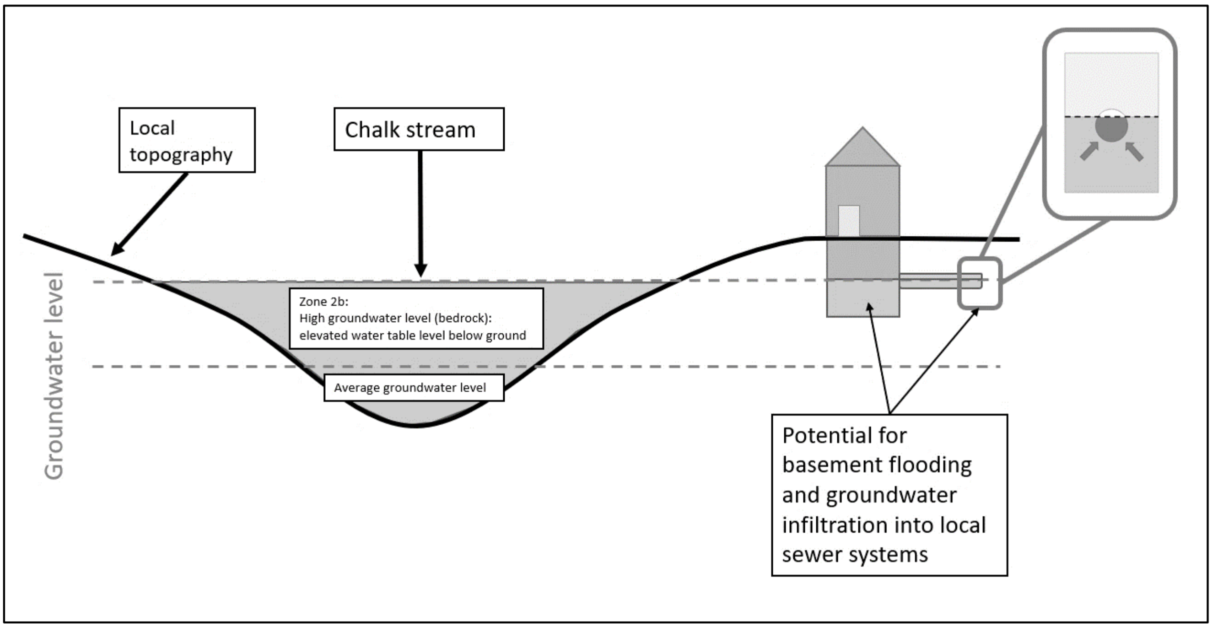

*Figure 2-2: Example of how higher chalk bedrock groundwater levels can impact basements and local sewer systems (e.g. as in Scopwick)*

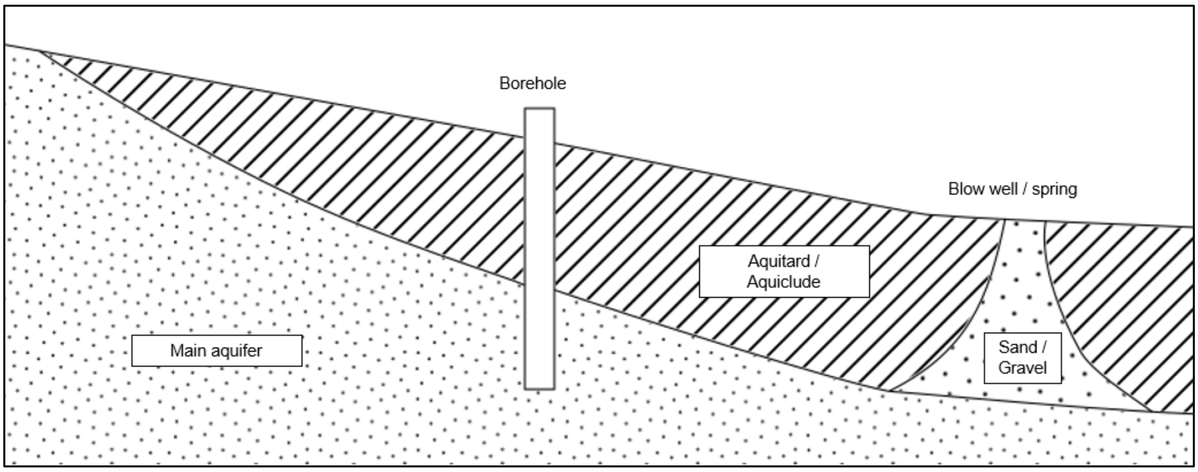

*Figure 2-3: Example of groundwater flooding pathways via artesian conditions in boreholes or sand/gravel deposits*

Areas that are susceptible to elevated groundwater tables are also susceptible to impacts driven by groundwater levels that are seen to be consistently elevated (chronically risen groundwater). This can be due to a number of reasons including the influence of climate change leading to increased rainfall and rising sea levels; it may be areas that have been drained or pumped historically resulting in the disappearance of natural ponds and wetlands. Chronic groundwater rise can lead to impacts including necessary land-use change, development constraints, and degradation of assets as they are exposed to increased vulnerability often beyond their design standards (e.g. degrading underground infrastructure (sewers, boreholes); urban land-use change; basement dry rot and mould; long term road diversions or abandonment). As **Table 2-2** notes, the MCM does not currently consider this kind of long-term impact from groundwater rise in urban environments, however, it is possible to apply already existing concepts provided in MCM Chapter 9 (Agriculture).

Groundwater flooding may contribute to overland extreme flood events (surface, fluvial). Significant groundwater flooding may occur in some locations every year. This is the result of rainfall percolating into the geological substructure, filling it, and discharging water lower down to flood properties there. For a 5 to 10-year probability event, the groundwater flooding may be slightly more serious, with a longer duration of groundwater flooding but not necessarily greater flow volumes at any one time. If the same area experiences a 100-year storm event in terms of rainfall, then obviously it will trigger the same percolation of water into the geological substructure, and discharge out lower down. However, the process is likely to be dominated more by overland flow of the very severe rainfall, to which the groundwater flow adds only a small proportion. In such cases, the appraiser should refer to the traditional MCM economic appraisal approaches.

## 3. Establishing a probability-based relationship for groundwater flooding

Typically, an appraiser will follow a number of stages in order to estimate benefits due to flood risk management (Penning-Rowsell *et al.*, 2013). The process involves defining the maximum extent of future flooding, identifying the different receptors at risk and their vulnerability, assessing the hazard characteristics for different return periods, and calculating Expected Annual Damages (EAD) and comparing costs of mitigating options and resulting benefits. EAD is a probabilistic model of the annual likelihood of phenomena (probability of exceedance) and the damages expressed in monetary term associated with their consequences. The methodology for the estimation of the benefits for fluvial flooding (**Figure 3-1.D**) is well-defined in the Multi-Coloured Manual and primarily requires the consideration of discrete flood events defined by their return-periods (e.g. 5-year, 10-year, 25-year, 75-year, 100-year, 200-year return-periods). Probability of discrete events should be established using a relevant dependant variable of the phenomena; such as discharge flow for fluvial flooding or rainfall event intensity and duration for surface flooding. As such, the typical approach to determine the probabilities of different magnitude fluvial events is based on a frequency analysis of annual maxima of river discharge (Robson and Reed, 1999). Similarly, for pluvial flooding, an equivalent process can be carried on a series of annual maxima daily rainfall (Viavattene *et al.*, 2022; Vargas Godoy *et al.*, 2024). Hardman *et al.* (2023) identify a first significant difficulty for appraisal in groundwater flood risk areas; i.e. the estimation of discrete events related to groundwater flooding as neither short rainfall events or flow can be considered as a dependant variable. This section aims to establish the feasibility of existing approaches to address this gap.

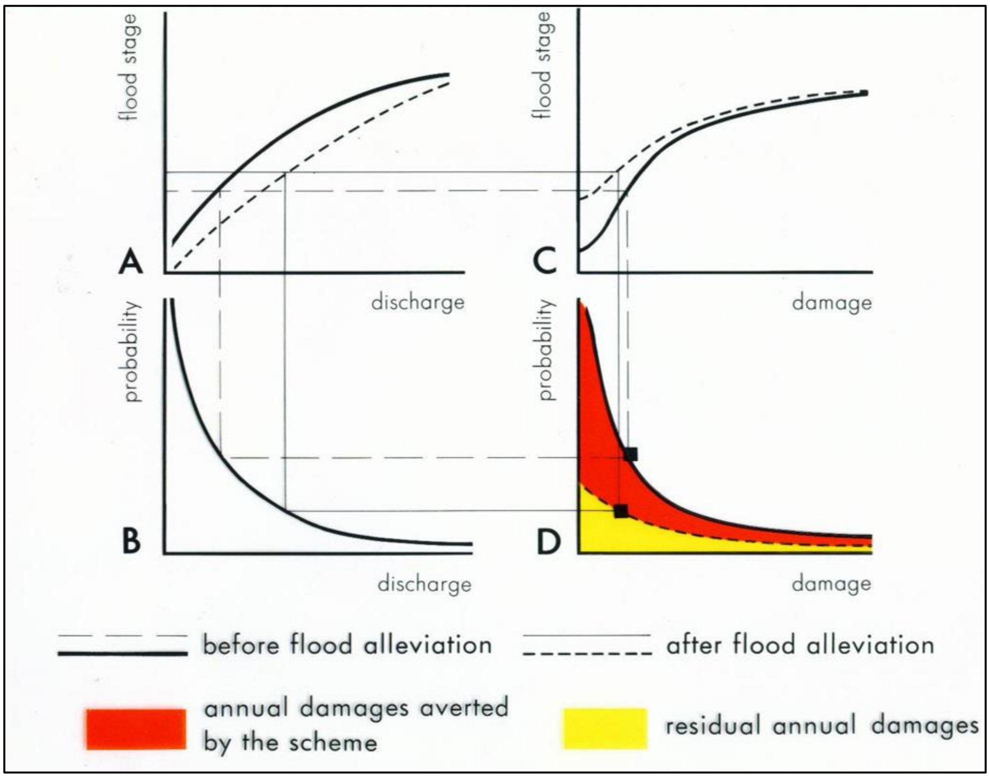

*Figure 3-1: Calculation of annual average flood losses (Penning-Rowsell et al., 2013)*

## 3.1. Borehole data

A frequency analysis of annual maximum groundwater levels (mAOD) can be carried out to develop probabilistic function (Coda *et al.*, 2023; Morris *et al.*, 2015; Furst *et al.*, 2015). Morris *et al.* (2015) performed a process and successfully developed growth curves using level data from four observation boreholes from Buckinghamshire and West Berkshire. They carried out an extreme value frequency analysis on borehole level annual maxima. The shape of the four growth curves present an inflection point generally between a 1 in 2-year to a 1 in 5-year return period, and then a plateau for less probable events. Similar curves are observed in the work done by Coda *et al.* (2023) and were also discussed in the sessions with groundwater modellers. The presence of a plateau is generally indicative of when an aquifer could be considered 'active', and therefore flooding of type 1 or 2a may occur. It was noted that it is common to have small variation in groundwater level between different probability events when the level is constrained by boundary conditions (contribution to river, spring flow).

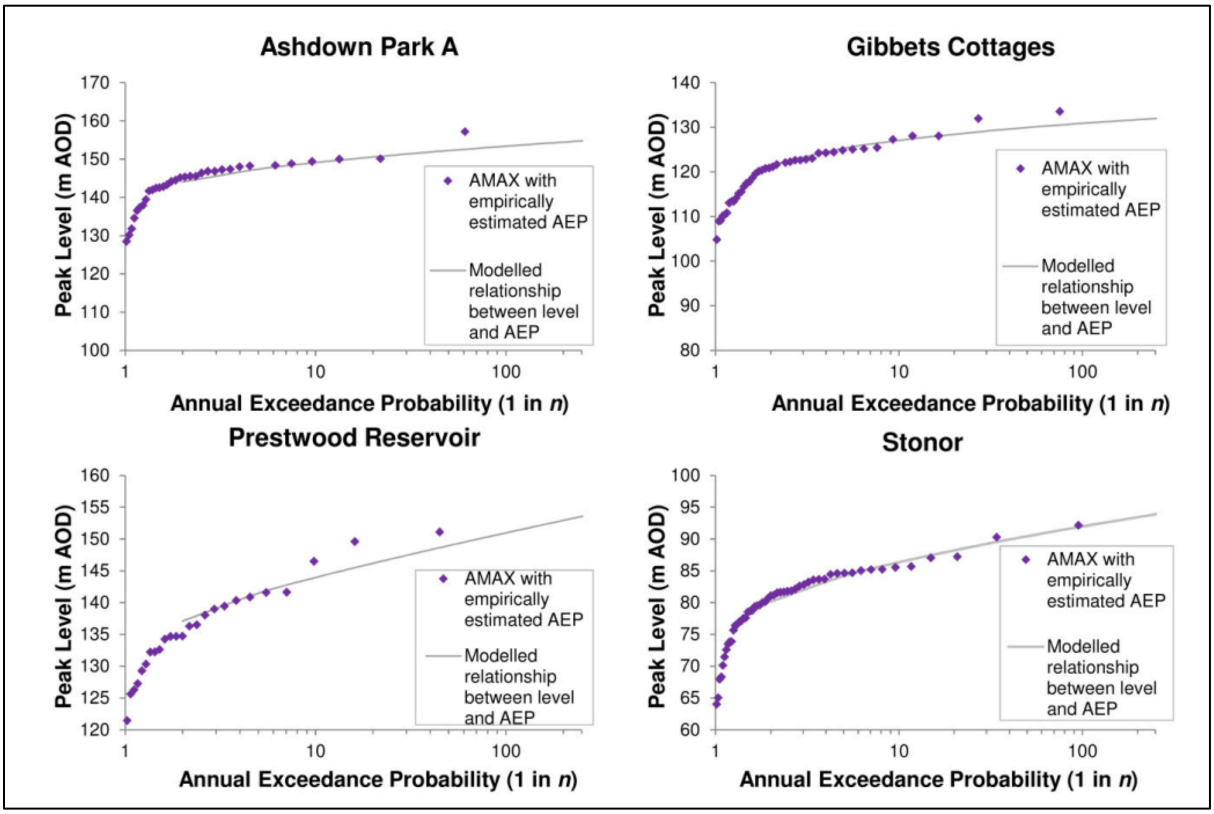

*Figure 3-2: Examples of growth curves developed by Morris et al. (2015)*

Potential deficiencies with most borehole annual maxima time series and other groundwater level data available may, however, limit the possibility to develop growth curves for specific locations at risk (Morris *et al.*, 2015; Furst *et al.*, 2015). These findings are also in agreement with the discussions with groundwater modellers during the workshop sessions.

There is generally not a long enough time-series of data to confidently associate a probability to larger and more rare events. Morris *et al.* (2015) noted that the timeseries data from all four individual boreholes was insufficiently long to confidently provide frequency estimates and, as such, they had to use additional data from donor boreholes to provide realistic frequency estimates. Furst *et al.* (2015) also addressed the problem of short time series of data by adopting a regional frequency analysis based on the assumption that nearby selected boreholes values are similar statistically.

Estimated groundwater levels for ranges of probabilities can be clustered especially when using annual maxima provided by a borehole located in a valley as the groundwater will either be controlled by artesian conditions, or flooding will occur, and as such recorded levels will not vary greatly between different estimated event probabilities. A borehole located within an interfluvial zone will be able to provide the best range of levels between low and high probability events due to its location higher up within a catchment, however flooding in these areas is not generally experienced and therefore using groundwater levels and events based on these data may also not be fully representative of the flooding that will occur lower down within the catchment area. Interpolation is then required to establish the relationship between water table level at the borehole level and the risk areas. Kriging techniques or a hazard model can be used for the interpolation (Furst *et al.*, 2015, Coda *et al.*, 2023).

Groundwater abstraction rates are variable over time, and typically have been historically higher than in the present day due to industrial pumping. This variability introduces non-stationarity into the system, meaning that historic conditions, trends, and baselines may not apply to current or future data. Consequently, borehole records influenced by these human activities may not accurately represent the current state of an aquifer. Non-stationarity makes it challenging to attribute a probability to different groundwater levels based on historical data alone. Only a part of the borehole annual maxima series may then be considered to represent stationary time series (Furst *et al.*, 2015).

For fluvial flooding the discharge-flood stage function is relevant as the key factor in the flood stage-damage function relates to the flood depth (depth-damage curves for assets). For groundwater flooding, groundwater emergence typically results in low flood depths but for longer periods of time (weeks to months), the duration being then a key factor to integrate in the economic analysis. As a result, the probability of the phenomena should also indicate the probability of a long period of high ground water level. The maximum mAOD series provides a probability of reaching a certain level ('active' / flooding), yet this does not necessarily reflect the duration of high groundwater level. Existence of plateau in borehole time-series data also represent limitations in the frequency analysis. It is, therefore recommended here to better consider maximum duration above a minimum mAOD value in the analysis rather than the annual maximum groundwater levels. In catchment water resource management, the seasonal or annual shape of the borehole hydrograph of an unconfined aquifer can be used for estimating the net recharge of the aquifer for a recharge period (Hiscock & Bense, 2021). From an annual water balance equation perspective, it can be considered that the total effective precipitation equals the total river baseflow minus artificial abstractions (Hiscock & Bense, 2021). It can therefore be assumed that groundwater flooding can be related to greater annual/seasonal recharge and a possible approach is to develop a Standardized Groundwater Flood Index (Ascott *et al.*, 2017) for extreme value frequency analysis (Figure 3-3). The minimum mAOD value should be defined in regards to the expected risk area's groundwater level zones (levels at which groundwater flood types 1, 2a, 2b, 2c are expected to occur). An alternative in the use of borehole time series data is to consider rainfall data series to estimate annual exceedance probability of maximum winter recharge of the aquifer.

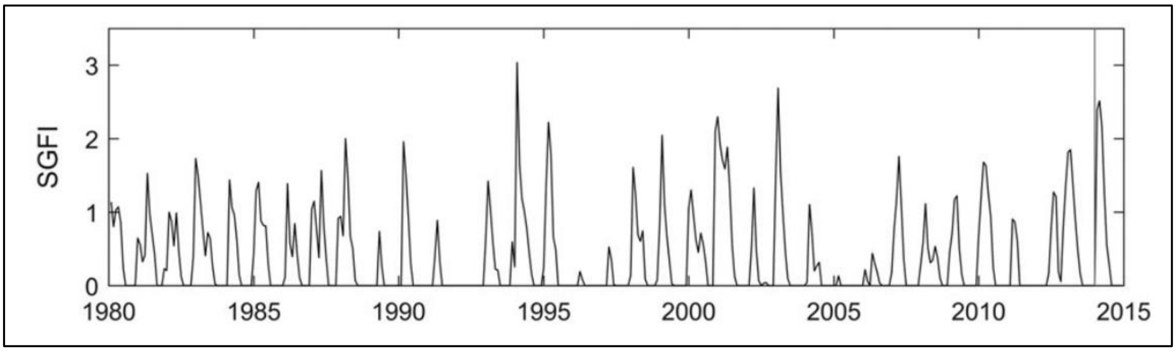

*Figure 3-3: Extract from Ascott et al. (2017) showing an example of a SGFI derived from observed groundwater level time series*

## 3.2. Seasonal rainfall analysis

As previously mentioned, the annual effective precipitation equals the total river baseflow minus artificial abstractions. Groundwater aquifers in the UK typically recharge during the winter season (September to April) with maximum recharge in December, January, and February, when rainfalls exceed evapotranspiration and soils are saturated over a long period of time (Hughes *et al.*, 2011; Jimenez-Martinez *et al.*, 2015). The difference in the winter rainfall against the seasonal average recharge in an area could be used to establish the annual exceedance probability. Hughes *et al.* (2011) established that the accumulated effective rainfall over a period of three months for the Pang and Lambourn catchments in UK could provide an indication of groundwater flooding likelihood (Figure 3-4). Jimenez-Martinez *et al*. (2015) also used effective rainfall to predict groundwater flooding in a chalk aquifer in the South of England. In order to model groundwater flooding from a chalk aquifer in the Somme Valley, Pinault *et al.* (2005) had to consider long-term precipitation to better represent non-linear processes associated with micro and macro-pores phenomena. Their approach stresses the importance in certain contexts of successive wet winter and accumulation of water volume in the aquifer. The approach involves stochastic models with different rainfall generators including short-term (maximum 10-day rainfall in mm) and long-term variance (2-year intervals) precipitation and provides a relationship between return period and maximum annual flow.

A frequency analysis on winter rainfall events and their accumulated effective precipitation would need to be carried out to determine the likelihood of groundwater levels reaching certain water table levels and leading to certain durations of groundwater flood scenarios (1, 2a, 2b, 2c). The probability associated with accumulated precipitation of winter rainfall could then be directly related to the duration of groundwater flood scenarios and an annual average damage could be determined based on this relationship. In addition, it may be necessary to consider successive wet winters and antecedent conditions leading to more extreme groundwater flood events.

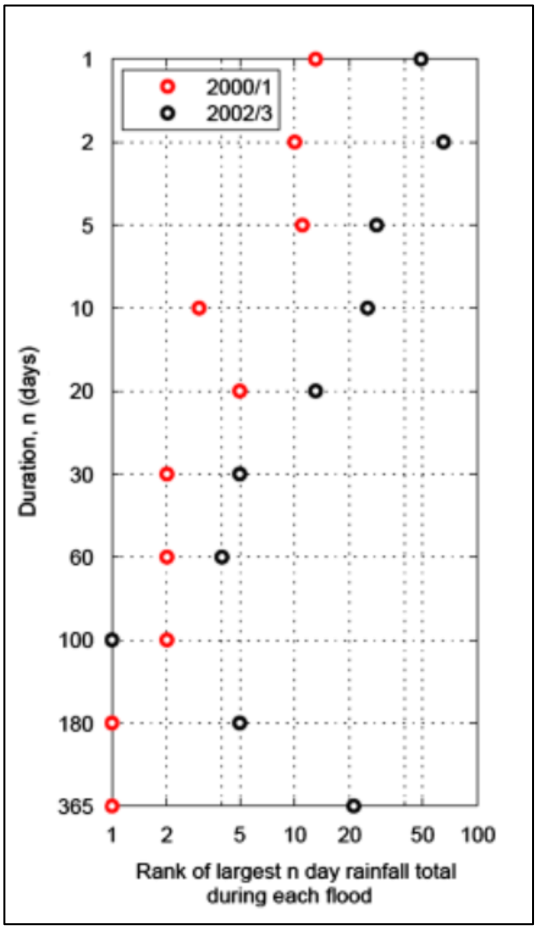

*Figure 3-4: Example of relationship between n days accumulated effective rainfall and rank of flood event (Hughes et al., 2011)*

# 4. Conclusion

This report aimed at exploring the feasibility of existing approaches to develop discrete event probability curves for chalk groundwater flooding. The MCM recommends developing a probability-discharge relationship for fluvial flooding. This approach is not applicable for most types of groundwater flooding as discharge information is not generally recorded.

It has been shown that groundwater borehole levels (annual maximum level) provide the best dependant variable for attributing probability to groundwater flooding events, however, different limitations are often present (limited time series data, changes in abstraction rates, artesian conditions). These limitations may be overcome in certain cases by combining borehole observations from different locations.

Flood duration has been established as a key factor to evaluate economic damages. For the purpose of an economic appraisal, annual maxima level does not suffice to differentiate between extreme events. As a result, the probability of the phenomena should also indicate the probability of a long period of high groundwater level. A possible approach is to develop a Standardized Groundwater Flood Index for extreme value frequency analysis. The minimum mAOD value should be defined in regards to the expected risk area's groundwater level zones**.** An alternative approach is to use maximum winter effective rainfall (mm per year) to develop discrete event probability curves. It is expected that the probability curve will be a plateau curve shape.

The following steps should be considered in order to estimate the frequency of groundwater flooding for a benefitting area:

- Step 1: Define the benefitting area and the expected type of groundwater flooding;
- Step 2: Define minimum mAOD for active groundwater level threshold (1, 2a, 2b) in benefitting area;
- Step 3: Identify all boreholes in the catchment area and select reference borehole;
- Step 4: Define relationship between mAOD in benefitting area and mAOD at reference borehole;
- Step 5: Borehole frequency analysis to determine event probabilities using SGFI;
- Step 6: If borehole frequency does not allow for establishing discrete event probabilities, the seasonal accumulated effective rainfall should be used to evaluate groundwater flooding probability.

The feasibility of this proposed approach will be investigated and discussed for the selected case study areas within the second phase of this project. It should be noted that groundwater flooding contexts and mechanisms vary greatly and as such the approaches used for economic appraisal are also likely to vary greatly. Groundwater appraisal will require significant local survey and expertise to fully define the most suitable approach for each study area.

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## Appendix A – Case Study Characteristics Matrix

| *Case study area* | *County* | *Type(s) of groundwater flood impact mechanism* | *Known impacts* | *Mitigation* |
|---|---|---|---|---|
| Lincoln, Hillside Avenue | Lincolnshire | High spring flow | Spring emergence from the fronts of local properties leading to frequently wet pavements, roads, and pathways. Water causes slippery algae growth on pavements. Water flows downhill into adjacent property; however, no high flood depths or damage to property has been recorded. | None yet established |
| Grimsby | | High groundwater level (bedrock) - Elevated water table below ground (chronic groundwater rise) | Long-term high groundwater levels experienced at Saltings Allotments leading to unusable land and potential change of land-use into wetlands.<br>Properties with timber floors have had to have replacement flooring. Some properties have been demolished and rebuilt due to long-term subsidence issues.<br>Subsidence is occurring in some roads, properties, and footpaths. | Historic groundwater abstraction local to Grimsby has traditionally led to lower groundwater levels. Anglian Water are investigating the potential for increasing abstraction at Little Coates, however if groundwater is over-abstracted there is a risk of saltwater intrusion due to Grimsby's coastal location. |
| Barton-upon-Humber | | High groundwater level (bedrock) - Elevated water table below ground<br>High spring flow | Multiple areas of groundwater flooding have been found including the football and cricket pitch, and areas in the centre of town. | Barton-Upon-Humber has reported historical flooding events which were mitigated against previously by groundwater abstraction taking place by the water companies/industrial uses. A loss of abstraction licences due to policy changes within the EA has meant the risk of groundwater flooding has returned to Barton-upon-Humber. |
| Barrow-upon-Humber | | High groundwater level (bedrock) - Elevated water | Barrow-upon-Humber has previously suffered from groundwater flooding due to spring activation. | The spring activated groundwater flooding was previously mitigated against by works from the local council, but due to the uniqueness of the chalk streams, an assessment of groundwater in the area |

| | | | | |
|---|---|---|---|---|
| | | table below ground<br>High spring flow | | is required to ensure if further springs appear they do not impact the chalk stream habitat. |
| Scopwick | | High groundwater level (bedrock) - Elevated water table below ground<br>Elevated water table level below ground (chronic groundwater rise) | Seasonally elevated groundwater levels cause water to infiltrate into sewers leading to toilets being unable to flush.<br>It is thought that rising groundwater levels over time have potentially led to degradation of the local sewer system. Flooding incidents have reportedly become more common since 2012. | Anglian Water have relined sections of the local sewer system however groundwater impacts are still occurring. |
| Bourne | | High groundwater level (bedrock) - Elevated water table below ground | The Lincolnshire Limestone is strongly confined and leading to artesian pressures on the groundwater system.<br>Rural boreholes occasionally flood local land and contribute to flows in local land drainage systems.<br>In the town of Bourne there is one borehole that was found within a suburban garden that has caused flooding to garden and adjacent road. | |
| Chalfont St Peter | Buckinghamshire | High groundwater level (bedrock) - Elevated water table below ground (leading to sewer flooding) | Flooding to the full length of the high-street leading to widespread business disruption.<br>Sewer flooding due to surface water and groundwater infiltration leading to contamination of flood waters above ground. | |
| Pang Valley | West Berkshire | High groundwater level (bedrock) - Elevated water table below ground. | Seasonally elevated groundwater rises from the underlying chalk aquifer.<br>Basement flooding and flooding of agricultural land are common. | |

| | | | | |
|---|---|---|---|---|
| Lambourn Valley | | High spring flow<br>High groundwater level (bedrock) - Elevated water table below ground. | Spring flows often flood roads.<br>Contaminated flood water due to groundwater entering sewer systems and leading to flooding from manholes.<br>Potential for groundwater to flood agricultural land. | |
| Oxford | Oxfordshire | High groundwater level (bedrock) - Elevated water table below ground.<br>PSD flooding | Urban area with cases of basement flooding.<br>Gravel aquifer is hydraulically linked to the river and groundwater flooding is often linked with fluvial flooding. | |

# Appendix B – Groundwater flooding and the implications for agricultural land use and productivity in England and Wales

**Joe Morris (July 2024)**

## Background and summary of key points

Seasonal high groundwater levels and excessive soil wetness are of particular concern in the rural context. The unprecedented wet winter of 2023/24 resulted in severe waterlogging and impeded drainage of agricultural land that has affected national food production and farm incomes (ECIU, 2024).

Groundwater levels and the incidence of water logging are a major determinant of agricultural land use due to the negative effects of excessively wet soils on crop production and the bearing capacity of soils for field machinery and/or grazing livestock. Groundwater modelling, combined with the analysis of impacts on land use and crop and livestock yields, can support the economic assessment of options for groundwater management on farmland.

Groundwater flooding on agricultural land in one location (on-site) often interacts with ground and surface flooding on another (off-site). Agricultural land can act as both as a *pathway* and as a *receptor* for groundwater flooding. It can act as a *provider* of Flood and Coastal Erosion Risk Management (FCERM) services through managed groundwater storage to alleviate flooding elsewhere. Agricultural land has also been a *recipient* of FCERM services through public investment in land drainage infrastructure over many years.

Groundwater levels and associated soil water relations are critical for target natural habitats and species, including wetland management options taken up by farmers that can simultaneously provide FCERM services.

Groundwater management interventions can be prescribed to deliver specific agricultural and conservation management outcomes. Groundwater levels, waterlogging and associated drainage conditions are important 'antecedents' that affect the cost of surface flooding on farmland when it occurs. These factors are already included in the MCM appraisal methods for Agricultural Flood Risks Management. The link between groundwater flooding on farmland and off-site effects, including the effects on the built environment, are not explicitly considered in MCM at the moment.

Lincolnshire contains large areas of prime agricultural land of national strategic importance, much of it dependent on FCERM infrastructure, especially in the fenlands and coastal margins. In the Lincolnshire fens, regionally high seasonal water tables associated with climate change could lead to increased groundwater flooding (waterlogging) of agricultural soils in the absence of mitigation measures. On higher ground, the management of agricultural water tables may help to alleviate surface and groundwater flooding elsewhere, either by improving the movement of water through soils or by facilitating temporary soil water storage, depending on context.

Preliminary discussions with Internal Drainage Board (IDB) Chief Technical Officers in the Lower River Witham (Lincoln to Boston) identified groundwater flooding on farmland during the wet winter of 2023/24 that resulted in surface and groundwater problems in adjacent built areas. It is proposed to work with the IDBs in the study area to explore the links between groundwater flooding on agricultural and built property for selected case study sites.

### Agricultural groundwater flooding

In the agricultural context, groundwater flooding concerns the degree and duration of water saturation of the soil profile, notably the root zone that lies between the surface and a depth of about 0.5m to 0.7m. Ground water levels and height of the saturated zone are determined by precipitation, evapotranspiration, soil type, depth to the impermeable layer, water levels in adjacent water bodies, and other site conditions, including interventions such as artificial field drainage that affect the movement of water through the soil profile.

Groundwater management is a key component of agricultural land drainage that seeks to reduce the potential constraints on land use imposed by excessive soil water, while ensuring there is sufficient 'available water' to support crop growth. Excess water inhibits root growth and dryness inhibits water uptake.

The incidence of groundwater flooding is incorporated in the criteria for Agricultural Land Classifications (ALC) that denote the agricultural suitability and relative advantage of land according to climatic, site and soil properties (Defra, 2024). ALC Grades 4 and 5 may be impeded by seasonal groundwater flooding that affects land use suitability and potential.

### Agriculture's role in groundwater flooding

Groundwater flooding can be considered within a source-pathway-receptor framework (Figure 1). Waters from sources with potential to cause flooding to move through surface and groundwater pathways to impact on assets that lie above, at or below the land surface thereby potentially resulting in loss and damage. Surface and groundwater flood pathways are interconnected to varying degrees according to context, particularly topography and soils.

Groundwater flooding attributes are similar to those used to describe surface flooding, with greater emphasis in the urban context placed on the duration of a groundwater flooding event than is usual for surface flooding[1]. Groundwater flooding may contribute to surface flooding where the saturation of soils prevents or slows the movement of excess surface water into the soil profile, and/or site conditions mean that excess groundwater emerges to the surface.

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[1] By comparison, the duration of both surface and groundwater flooding are critical for agricultural land use.

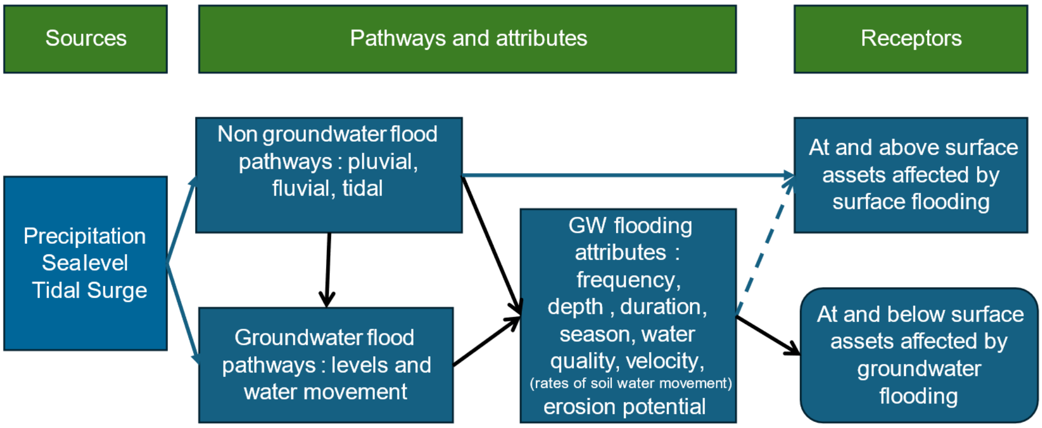

**Figure 1: General source-pathway-receptor framework for groundwater flooding**

The general framework in **Figure 1** fits the agricultural case. As discussed below, agricultural land use and production are particularly sensitive to groundwater flooding. Agricultural surface and groundwater flooding are closely linked. Agricultural land that is subject to frequent (low return period) flooding, typically on floodplains or coastal margins, is commonly subject to seasonal groundwater flooding in the absence of control measures. Elsewhere, avoidance of groundwater flooding and water logging are prerequisites for productive farming. Indeed, flood protection for agriculture in the UK was historically subsumed under the wider concern for 'Land Drainage'. For land subject to less frequent flooding, waterlogging of soils usually continues well beyond the recession of floodwaters, often requiring restorative measures and delay of subsequent field operations.

Agricultural land has a diverse role in flood risk management (Hess *et al.*, 2024), not least for groundwater flooding. Agricultural land can act as *pathway* for groundwater flooding by contributing to surface flooding with consequences both on- and off site, as referred to above. Agricultural land is also a *receptor* for groundwater flooding, whether due to groundwater movement from elsewhere, or where regionally high-water table levels lead to increased water levels in ditches and rivers and hence higher retained field water levels.

Furthermore, agricultural land can act as *provider* and as a *recipient* of FCERM services with respect to groundwater flood risk management. As a provider, agricultural land can be managed to provide groundwater storage to avoid or delay surface flooding off-site, possibly linked to wetland management options in floodplains. As a recipient of FCERM services, publicly funded investments in field and arterial drainage and pumping are justified for water table control and the avoidance of groundwater flooding on farmland.

Climate change has potential to modify the interactions and roles for groundwater management on agricultural land. Wetter warmer winters are likely to exacerbate groundwater flooding, while hotter drier summers will require groundwater conservation. Farmers will need to adapt to greater variability in seasonal groundwater conditions and available soil water.

The case studies to be developed for the Lincolnshire Study will explore these processes and relationships, as well as strategies for addressing groundwater flooding issues on agricultural land.

### The drainage status of agricultural land and associated groundwater flooding

Land drainage and associated waterlogging conditions as they affect the productivity of agricultural land are determined by field water table levels and the degree of soil saturation during critical periods of the farming calendar.

A distinction can be made between the effect of saturation of the total root zone (usually to a depth of 0.5 m to 0.7 m) on crop yields and the effect of saturation at the soil surface that reduces the bearing capacity of soils for grazing animals and field machinery. The latter is commonly associated with relatively impermeable clay soils that are liable to surface damage and compaction (‘poaching’) when saturated. Poaching may or may not be associated with generally high-water tables. Poaching can exacerbate surface flooding by preventing soil water percolation.

As such, ‘poaching’ is a major influence on land use where, for example, clay soils are unsuited to the heavy field machinery required for arable cropping. Distinguishing surface poaching from groundwater flooding may be important in some circumstances.

### Groundwater flooding and agriculture: MCM methods for appraisal

Groundwater flooding effects on agricultural land as a *receptor* are included in the methodology for the Appraisal of Flood Risk management for Agriculture in Chapter 9 of the Multi-Coloured Manual (MCM) and Handbook (MCH), together with estimates of production loss and asset damage, as explained below. The identification of field drainage conditions is an important step in the appraisal of flood risks on farmland. The costs of surface flooding events (£/ha) are likely to be greater on well-drained soils compared to poorly drained soils because land use is generally and yields are not constrained by waterlogging.

The impact of surface flooding *on farmland* due to run-off from waterlogged soils is covered in the existing MCM methodology for agricultural appraisal. The appraisal of groundwater flooding on farmland as a *pathway* is not explicitly considered. Neither are management options on agricultural land to deliver off-site flood alleviation benefits, including Natural Flood Management (such as soil conservation) and engineered solutions (such as enhanced arterial drainage).

Estimation methods for groundwater flooding and associated waterlogging used in MCM are summarised below.

### Estimating the effects of groundwater flooding on agriculture

The effect of drainage/groundwater status on agricultural land use and productivity can be determined on a seasonal timescale (spring, summer, autumn) according to the number of days that the water table lies within given bands of depth from the surface. Drawing on research literature (Hodgson *et al.*, 1976) [2] and field observations (Dunderdale and Morris, 1996).

**Table 1** shows the association between agricultural drainage conditions (classed as good, bad, very bad), agricultural productivity (classed as normal, low, very low), and the percentage of the total days

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[2] Hodgson, J.M. (ed) 1976 for example produced VI classes of increasing order of soil wetness. Durations (days) of water logging per year occurring within 0.7 m of the surface were prescribed for Classes I to III. For classes IV to VI durations were prescribed for periods with the water table lying within 0.7m depth and also within 0.4 m depth. These classes of soil wetness and waterlogging were interpreted to help derive the three classes of drainage conditions based on seasonal water table heights reported here.

in a specified seasonal period that field groundwater levels lie within given ranges for naturally draining sites and for sites with piped subsurface field drains. For most agricultural situations, spring is the most critical period for water level control.

**Table 1: The link between agricultural drainage, groundwater flooding, land use and yields in England and Wales.**

| Agricultural drainage condition | Agricultural productivity class | Depth to water table from surface | % of days in a period when the water table lies within specified range from surface | Typical freeboard* in water-courses for natural drainage (and piped field drains) |
|---|---|---|---|---|
| **Good**: 'rarely wet' | **Normal,** no impediment imposed by drainage | 0.5 m or more | At least 80% of days at or greater than 0.5m | 1 m sands to 2.1 m clays (0.2 m below outfalls) |
| **Bad:** 'occasionally wet' | **Low**, reduced yields, reduced field access and grazing season | 0.3 m to 0.49 m | At least 50% of days greater than 0.3 m (and < 80% of days are at > 0.5 m) | 0.7 m sands to 1.9 m clays (temporarily submerged outfalls) |
| **Very bad**: 'commonly or permanently wet' | **Very low**, severe constraints on land use, much reduced yields, field access and grazing season: mainly wet grassland | Less than 0.3 m | At least 50% of days less than 0.3 m | 0.4 m sands to 1 m clays (permanently submerged outfalls) |

*Freeboard is the mean difference (m) between ditch/river water levels and adjacent land level. Table based on Table 9.2 in the Multi-Coloured Handbook, Chapter 9 (Morris, 2024)

### Financial and economic impacts of agricultural groundwater flooding

The effect of groundwater flooding on agricultural productivity classes can be expressed in financial and economic terms (**Table 2**). It is unlikely that arable crops would be grown where groundwater flooding is persistent and drainage is 'very bad'. The incidence of waterlogging critically affects grassland management and the type and profitability of livestock systems (**Table 2**).

**Table 2: The financial implications of field drainage conditions and groundwater flooding in England and Wales**

| **£ 2024 Values** | **Field drainage conditions and associated groundwater flooding** | | |
|---|---|---|---|
| | **Good** | **Bad** | **Very Bad** |
| **Arable** | | | |
| Yield as % of 'good' category | | | |
| Winter wheat and barley | 100 | 80 | 50 |
| Spring wheat and barley | 100 | 90 | 80 |
| Oil seed rape | 100 | 90 | 80 |
| Potatoes, Peas, Sugar beet | 100 | 60 | 40[1] |
| Wheat financial gross margin £/ha/year | £1,200-£1,500 | £800-£1,000 | £330-£430 |

| **Grassland** | | | |
|---|---|---|---|
| Typical nitrogen use kg N/ha/year | 150 - 200 | 50 – 75 | 0 - 25 |
| Grass conservation | 2 cut silage | 1 cut silage or graze | 1 cut hay or graze |
| Typical stocking rates; Livestock units/ha/year | 1.7 - 2.0 | 1.2 - 1.4 | 0.7 - 1.0 |
| Typical livestock type | Dairy, intensive beef and sheep | Beef cows, 24-month beef, sheep | Fattening of ‘store’ cattle, and sheep |
| Financial gross margins £/ha/year (after forage costs) | £2,200-£3,000 (dairy)<br>£600-£950 (intensive beef/sheep) | £430-£630 | £250-£430 |
| Days reduction in grazing season compared to ‘good’ category | none | Spring: 14 to 21<br>Autumn: 14 to 21 | Spring: 28 to 42<br>Autumn: 28, no stock out in winter |

Based on Table 9.3 in in the Multi-Coloured Handbook, Chapter 9 (Morris, 2024)

### Indicators of groundwater flooding problems

The extent and severity of groundwater flooding can be obtained from farmer assessments of seasonal soil wetness and the effects on land management decisions and outcomes. In addition to observations on land use, the presence and impacts of groundwater flooding can be observed by *plant-based indicators* such as stunted or discoloured crop, by *site-based indicators* such as surface damage by tractor wheels and livestock, and evidence of shortened grazing periods; and by *soil-based indicators* such as surface gleying and mottling, undecomposed organic matter and ‘slumped’ structureless soils.

### Groundwater modelling at the field level

Modelling (**Figure 2**) can assess the impacts of river and drainage system maintenance strategies on ground water levels, drainage status and farming productivity (Hess *et al.*, 1989; Youngs *et al.,* 1989). Water table height above the impermeable layer, and hence the propensity for groundwater flooding, is estimated from rainfall, evapotranspiration, water levels in the adjacent ditch/river, soil conditions and field drainage systems whether natural or piped. The proportion of the controlled area that falls under different classes of drainage status can be ascertained. Water table levels in fields served by artificial underdrainage depend on adequate outfalls for drainage pipes into ditches and rivers and the avoidance of submergence.

A non-steady state version was used to model water table height and drainage status throughout the year (Morris and Sutherland, 1993; Dunderdale and Morris, 1996). It is possible that this field scale modelling approach could use the outputs from regional groundwater modelling to assess the impacts on agriculture of raised water levels in ditches and rivers at the landscape scale.

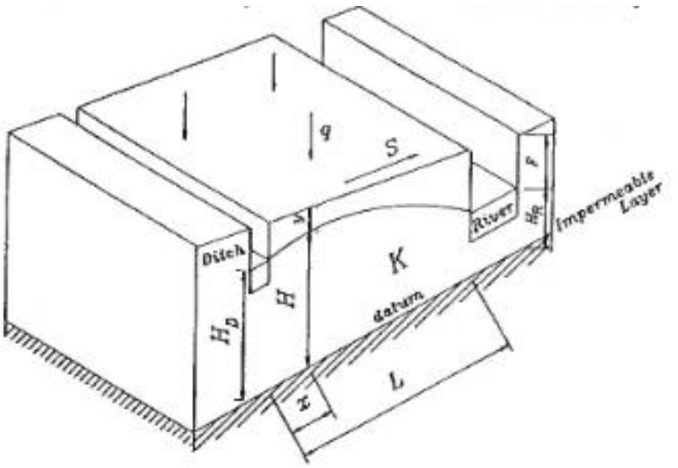

**Figure 2: Steady state water table model showing the effect of ditch and river water levels on water table levels in adjacent fields for natural (non-artificially) drained soils (Hess *et al.*, 1989)**

Notes to Figure 2: K is the saturated hydraulic conductivity of the soil and q is the average daily rainfall. S is the land slope and F is the freeboard at the River. y is depth to the water table at any distance x from the ditch. H and L refer to various height and length dimensions.

**Groundwater management responses and evaluation**

Depending on the cause of agricultural groundwater flooding, management responses have variously involved surface flood control, field and arterial drainage, and the pumped evacuation of excess seasonal water (**Table 3**). Responses may also include actions to retain groundwater levels during water deficit periods, implying that an integrated approach is required to water level management in farmed areas, including crop and field management decisions by farmers.

A particular concern here is with the climate change induced effects of (i) seasonally high regional water tables and the on-site effect on farmland drainage conditions and productivity and (ii) the increased probability of off-site flooding due to the long duration saturation of agricultural soils.

The methods outlined above can help to evaluate the costs and benefits of alternative strategies for the management of groundwater flooding on agricultural land, both as pathway and a receptor, including consideration of on-site and off-site effects.

**Table 3: Causes and possible treatment of groundwater flooding on agricultural land**

| Cause | Response | Comment |
|---|---|---|
| Surface flooding | Flood alleviation | Saturation of soil profile continuing after recession of flood waters |
| Seepage | Interception | Groundwater ingress from adjacent areas onto farmland, possibly adjacent wetland sites |
| High regional water table | Improved arterial drainage and field drainage, including pumping. Adaptive farm management practices to cope with increased seasonal (winter/spring) wetness | Linked to climate change, requiring increased capacity in agricultural drainage infrastructure, and possible change in farming practices. High seasonal (manly winter) water tables reduce buffering effects of agricultural land, potentially increasing surface flooding on-and off-site |

| | | |
|---|---|---|
| Impermeable soil layer, perched water tables | Field drainage and secondary treatments such as subsoiling | Often associated with waterlogging (*poaching*) of the surface layers; not treatable in some cases |
| Saline intrusion/groundwater quality | Abstraction controls, groundwater recharge | Potential risk in coastal areas associated with seasonally variable groundwater levels |

**Groundwater flooding and management for Nature Conservation**

The principles of groundwater management also apply where the purpose is to achieve conservation habitat outcomes, guiding seasonal maximum and minimum water table levels (**Figure 3**). Uncontrolled groundwater flooding can compromise environmental objectives. Elevated seasonal regional water tables and the use of wetlands for temporary seasonal surface and groundwater flood storage may not necessarily align with the management objectives of nature sites for breeding waters, species rich pastures and controlled 'conservation' grazing (Morris *et al.*, 2000; 2005).

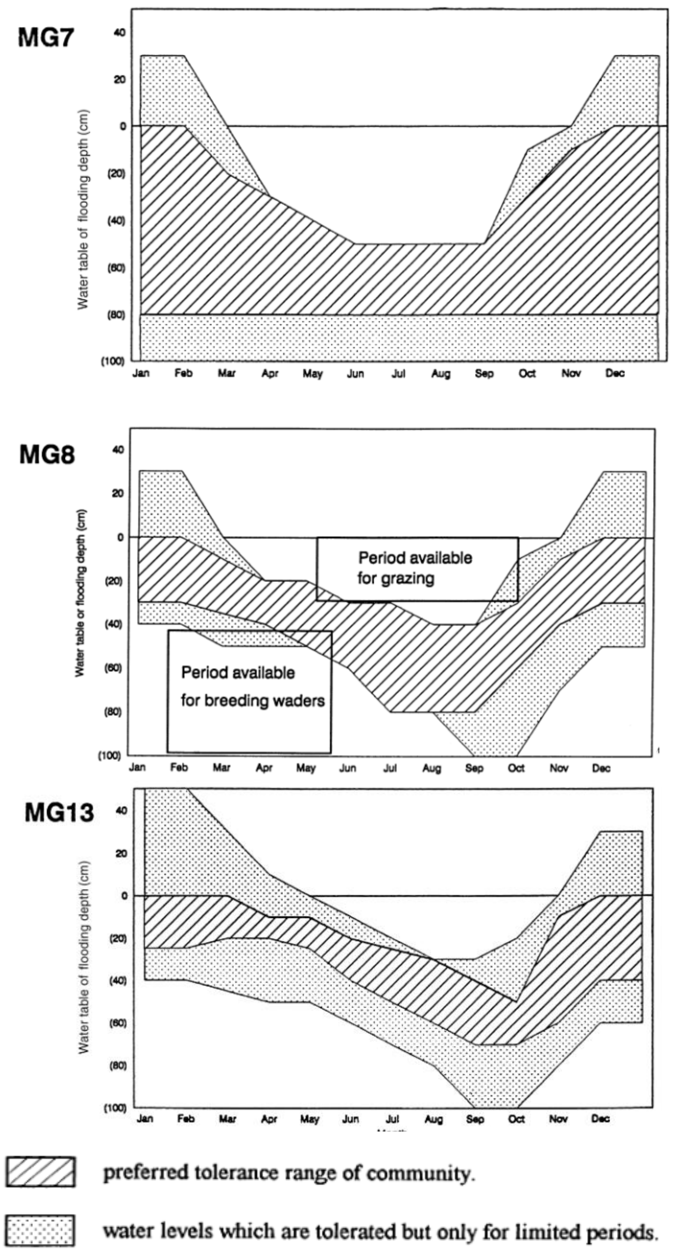

**Figure 3: Seasonal water regime requirements, surface flooding and/or water table heights for selected plant communities: MG7 agriculturally productive grassland, MG8 species rich flood pasture/meadow and MG 13 species poor inundation grassland (suited for breeding waders) (Morris *et al.*, 2000)**

### Implications for Lincolnshire

Lincolnshire contains regionally and national significant agriculture assets that are important for national food security. Relatively large areas of ALC Grade 1 and 2 land, including large areas of low-lying fenland, are supported by FCERM infrastructure and services.

Groundwater management, including the control of groundwater flooding (waterlogging), is a key component of agricultural land management in Lincolnshire, reflected in the major investments in land drainage infrastructure and the operations of Internal Drainage Boards (**Figure 4**).

**Figure 4: Arterial drainage in the Lower Witham, Lincolnshire, 2023 (Morris)**

The links between groundwater and surface flooding in the rural context are complex and evident in the Lincolnshire case. Agricultural land can be a pathway for off-site surface flooding as well as receptor for groundwater flooding due to seasonally raised regional groundwater and ditch/river levels associated with climate change. The latter can increase groundwater/waterlogging problems on farmland and/or increase the cost of drainage solutions.

Problems associated with raised ditch and groundwater levels were identified by farmers in a recent strategic assessment of the Lower Witham Flood Risk Management Strategy (Morris, 2023). Failure to maintain adequate land drainage standards through water table control and the avoidance of groundwater flooding could lead to major shifts in agricultural land use, reverting to the less intensive cropping and grasslands evident in the period before investment in flood protection and land drainage, especially the Lincolnshire fenlands.

Preliminary discussions with the Chief Technical Officers in the Black Sluice and Witham 4th Internal Drainage Board (IDB) areas occupying the floodplain and fenland areas of the Lower Witham River (Lincoln to Boston) identified groundwater interactions between farmland and adjacent built property, particularly during winter 2023/24. It is proposed to identify case study sites within the IDB controlled areas where groundwater flooding on agricultural land has also affected built property, infrastructure and services. Appraisal methods and data will be developed for the case study site(s), linked to MCM methods. Simultaneously, potential participants to represent rural groundwater management issues will be identified for the proposed Project Workshop in September/October 2024.

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