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PILOT DESCRIPTION AND ASSESSMENT

Hull & East Riding chalk aquifer (United Kingdom)

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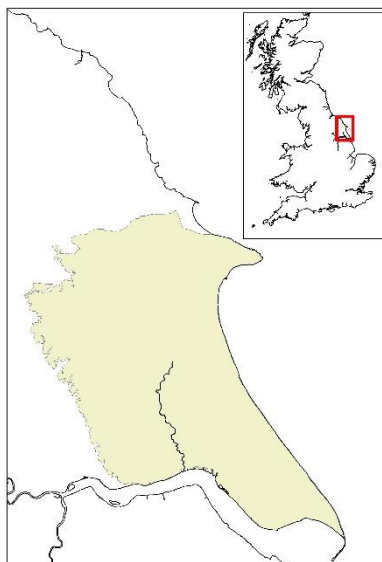
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LIST OF ABBREVIATIONS & ACRONYMS

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1 EXECUTIVE SUMMARY

Pilot name	Hull and East Riding	
Country	United Kingdom	
EU-region	North-western Europe	
Area (km ²)	2040	
Aquifer geology and type classification	Cretaceous Chalk (dual porosity aquifer)	
Primary water usage	Drinking water / Industry/ Irrigation	
Main climate change issues	Slight increase in winter and summer recharge due to rainfall increase with a risk of groundwater flooding. However, future temperature predictions indicate a higher increase in evapotranspiration compared to the rainfall increase.	
Models and methods used	Index methodologies to assess aquifer vulnerability to saline intrusion	
Key stakeholders	Government. Research institutes. Water companies.	
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Seawater intrusion is not generally reported as a major issue in the UK, despite the long coastline length. Nevertheless, a screening approach based on the Catchment Data Explorer database (<https://environment.data.gov.uk/catchment-planning/>), developed by the Environment Agency for the implementation of the Water Framework Directive (2000/60/EC) and on Water Quality Archive (<https://environment.data.gov.uk/water-quality/view/landing>), was employed to identify specific groundwater bodies prone to seawater intrusion problems.

Following the above procedure, the Hull and East Riding groundwater body, which belongs to East Yorkshire Chalk formation, was identified as an appropriate pilot area. The Hull and East Riding groundwater body extends over an area of 2040 km². The hydrogeological conditions are mainly unconfined although may vary to semiconfined or confined in certain parts of the aquifer. Transmissivity values in the area exhibit a large spatial variation and the groundwater system receives most of its recharge from rainfall. The area has a coastline length of approximately 80 km.

Although saline intrusion affects the background chemistry in the Yorkshire Chalk, it is believed that the saline groundwater in this area is rather an old stable body of water according to previous studies (University of Birmingham, 1978, Smedley et al., 2004). In overall, the current groundwater abstraction schemes in the area do not seem to have an impact on the existing saline front as only a small percent of total recharge is being abstracted and further monitoring suggests that the saline front remained static despite the changes in the mixing zone between freshwater and saline water.

However, a model of seawater intrusion has not been previously developed in the area while the identification of those parts of the present aquifer system that might be more prone to saline intrusion could provide additional information about the general status. Given that existing information for the area under study suggests that the saline front is generally static over long periods of time, the use of sharp interface models was selected as an appropriate modelling approach. Furthermore, due to the large spatial scale of this pilot area, the sharp interface assumption provided a computationally efficient model to assess the seawater intrusion status without additional requirements for field data collection.

Different modelling scenarios were investigated based on historical and future climate recharge variations that were averaged over long time periods. The results obtained from the simulation with the sharp interface model are in good agreement with the existing known status of saline intrusion in the area. The simulation outputs also showed that the location of the freshwater/saltwater interface remains mainly unaffected in several parts of the aquifer, despite the different distribution of applied recharge. However, it was observed that for some parts of the aquifer system the location of the simulated interfaces may vary up to 700 meters, depending on the recharge scenario. In overall though, small percentage differences were obtained from the calculation of the total freshwater area for each recharge scenario. This implies that at least for the future climate scenarios investigated here, no significant changes are expected to the available freshwater area, based on the results from the sharp interface model.

Furthermore, by using the widely applied GALDIT vulnerability method an effort was made to identify the most vulnerable parts of the Hull and East Riding groundwater body to saline intrusion. Based on this preliminary investigation, a moderate to high vulnerability was observed in the upper north-eastern part of the aquifer near Bridlington and close to the Humber estuary near Kingston Upon Hull.

Future investigations in the area using more advanced seawater intrusion models, such as variable density flow and solute transport models, along with further analysis of existing data and use of updated versions of the GALDIT method, may provide additional information for possible saline intrusion problems. Nevertheless, the sharp interface model developed for this area and the use of the GALDIT vulnerability method delivered a practical computational tool to assess the status of seawater intrusion in a systematic and efficient manner. These modelling tools could provide further assistance to deal with uncertainty aspects and groundwater management practices in the area regarding the problems of saline intrusion.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The present document reports the TACTIC activities regarding the Hull and East Riding groundwater body in UK. The pilot area is part of the East Yorkshire Chalk aquifer. The main land use activities in the area is agriculture, animal farming and some manufacturing and food processing industries. Average annual rainfall in the area ranges somewhere between 600 mm to over 750 mm. The hydrogeological conditions in the East Yorkshire Chalk are mainly unconfined although they may vary to semiconfined or confined in certain parts of the aquifer. Different degrees of fracturing and matrix properties exist which form a complex geological environment of mainly two porosity regimes with values greater or less than 30%. Transmissivity values in the area exhibit a large spatial variation ranging from $100 \text{ m}^2\text{d}^{-1}$ to values greater than $10000 \text{ m}^2\text{d}^{-1}$. The thickness of unsaturated zone in the Yorkshire Chalk may vary from less than 10 m to over 120 m in certain regions. The groundwater system receives most of its recharge from rainfall during the first quarter of the year. The length of the coastline in the Hull and East Riding groundwater body is approximately 80 km.

The overall objective of this study is to assess the status of seawater intrusion in the Hull and East Riding groundwater system given available field data as well as via modelling and mapping tools which are considered suitable for the large spatial scale of this pilot area. As groundwater management schemes over the last 30-40 years have controlled further encroachment of seawater in the area, focus is given here on modelling the impact that different recharge scenarios may have on the extent of seawater intrusion. Thus, long-term averaged recharge periods either based on historical data or future climate scenarios are employed to simulate any

changes in the status of seawater intrusion in the area. The information generated through this investigation using mathematical models of seawater intrusion could be usefull to identify those parts of the aquifer that might be more vulnerable to seawater intrusion problems.

3 PILOT AREA

Seawater intrusion (SWI) is not reported as a major issue for UK coastal aquifers, due to the existing hydrological and geological conditions, as well as, due to groundwater abstraction policies imposed since 1970s (Environment Agency, 2006). However, by using a systematic approach, specific groundwater bodies prone to SWI problems were identified along the UK coastline. This screening approach was based on the Catchment Data Explorer database (<https://environment.data.gov.uk/catchment-planning/>), developed by the Environment Agency for the implementation of the Water Framework Directive (2000/60/EC), and it was used to retrieve information about the status of groundwater bodies in the UK. Furthermore, the Water Quality Archive (<https://environment.data.gov.uk/water-quality/view/landing>) was also utilized as a repository of water quality measurements around England for coastal and estuarine waters, rivers, lakes, ponds, canals and groundwater. Water quality measurements were available for the years 2000-2018. Both platforms provide free access to the relevant data. Based on quantitative and qualitative criteria five groundwater bodies were initially selected as potential pilot areas. The associated shapefiles of each groundwater body were then utilized to estimate the availability of monitoring points for chemical components related to salinity, as well as, of borehole data.

Following the above procedure, Hull and East Riding groundwater body, which belongs to East Yorkshire Chalk formation, was identified as an appropriate pilot area given the availability of groundwater quality and borehole data, the coastline length and the existence of a fully developed groundwater flow model by Environment Agency. The East Yorkshire Chalk constitutes a significant source of groundwater supply for the development of industrial and agricultural activities in the area, as well as, for drinking purposes (Gale and Rutter, 2006). Over the past decades, the saline groundwater in the area was mostly attributed to SWI from the Humber Estuary, as a result of uncontrolled pumping (Foster et al., 1976). Increased Cl concentrations in pumped groundwater support this assumption, however, the saline front in the area is considered stable due to groundwater management practices (Chadha, 1986). By using the methodologies proposed in this work package, our intention is to characterize the status of the selected pilot area in terms of SWI and compare with the existing known conditions.

3.1 Site description and data

3.1.1 Location of the pilot area and SWI problems

The Hull and East Riding groundwater body is part of East Yorkshire Chalk aquifer that extends from Flamborough Head southwards to the Humber Estuary. The length of the coastline is approximately 80 km and the area of the groundwater body is estimated to 1967.32 km². The major towns are situated on the coast of Humber and North Sea where the main SWI problems exist due to over-abstraction. Of particular interest, is the coastal aquifer part in the Hull area along the Humber estuary. In the past, over-exploitation of groundwater, mainly from industrial boreholes close to the estuary, resulted in increased salinity. Detailed studies in the early 1970s investigated the potential to control SWI along the Humber Estuary in the Yorkshire Chalk aquifer (Foster and Milton, 1976). A numerical flow model was also developed in the mid-1990s, which covered the whole of the Yorkshire Chalk, and a more recent numerical flow model was also built (ESI 2013) with updated climate and hydrogeological information.



3.1.2 Topography

The East Yorkshire Chalk topography includes impressive cliffs in the coast round Flamborough that exceed 100 m in height, while ground surface elevations in the overall area range from zero to approximately 250 m OD as shown below in Figure 1.

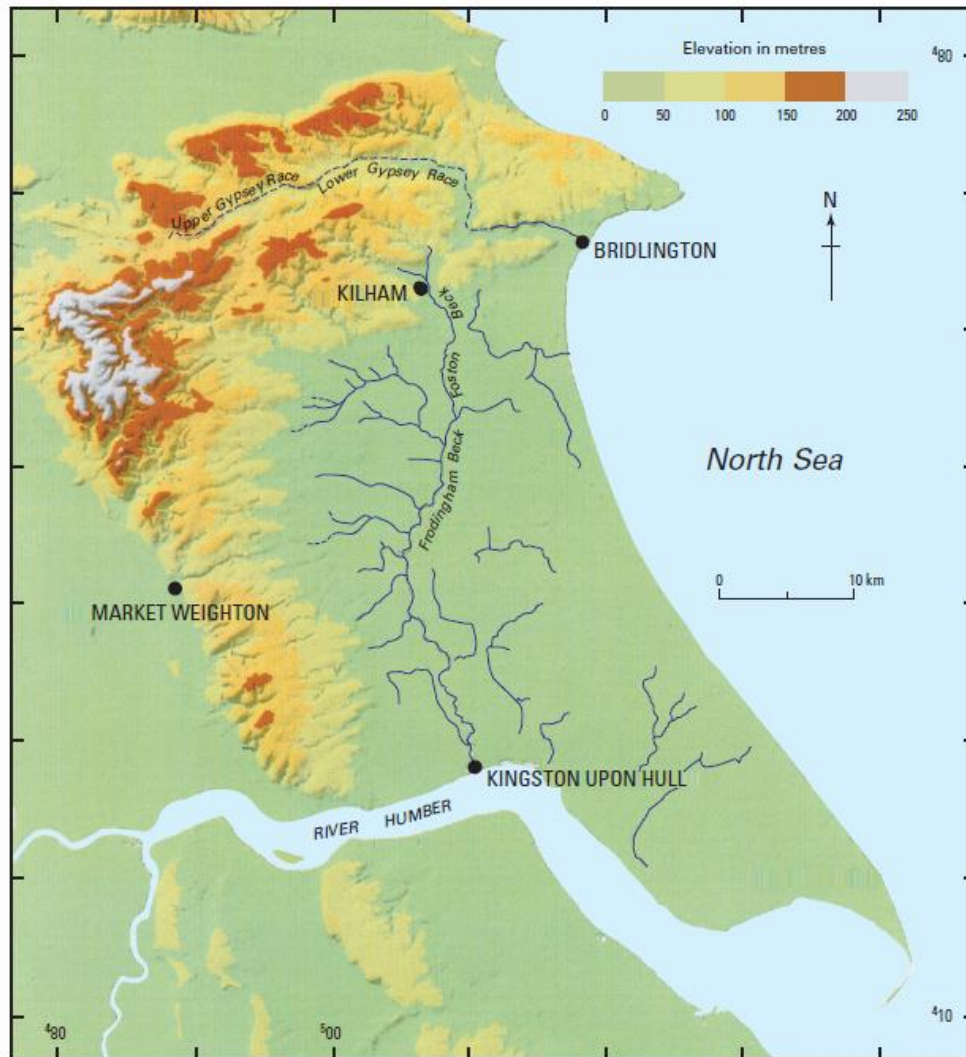


Figure 1. Topography map over the East Yorkshire Chalk (Gale and Rutter, 2006)

The Chalk is buried beneath Quaternary deposits and Holocene coastal and marsh sediments. A network of dry valleys exists across the Wolds and there is little surface drainage on the outcrop. Significant flows occur only in the Gypsy Race along the Great Wold Valley. When groundwater levels are high enough, the Gypsy Race runs along the entire length of the valley while at times of lower groundwater level the flow is increasingly intermittent. The entire Wold Valley becomes

dry in the late summer or in extended periods of drought. Springs rise in the lower reaches of the dry valleys and the tributaries of the River Hull are formed due to flow over the glacial drift.

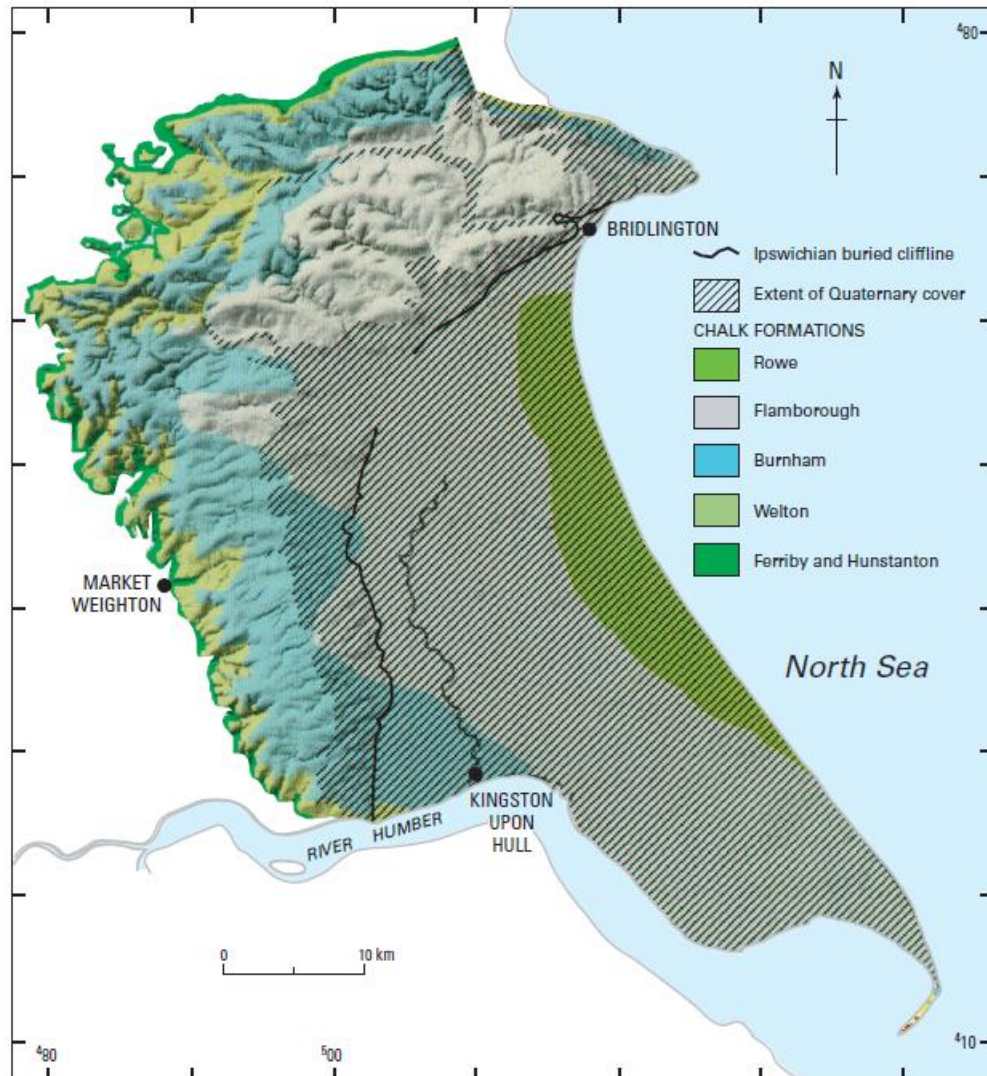


Figure 2. Geological map for the East Yorkshire Chalk (Gale and Rutter, 2006)

3.1.3 Land use

The main land use activity in the area is agriculture, focusing on arable production such as wheat and barley. Grassland comprises about 15% of arable land, oilseed rape (7%) the remainder being sugar beet, potatoes, vegetables, peas and beans. Set-aside land amounts to some 10% of the arable land cover in the Etton and North Newbald catchments. Animal farming is also important, particularly in parts of the upland Wolds where the terrain is steeper. Manufacturing is mostly related to those areas where urban centres exist, such as Hull, with food processing industry being the dominant activity. The various land use activities are depicted in Figure 3.



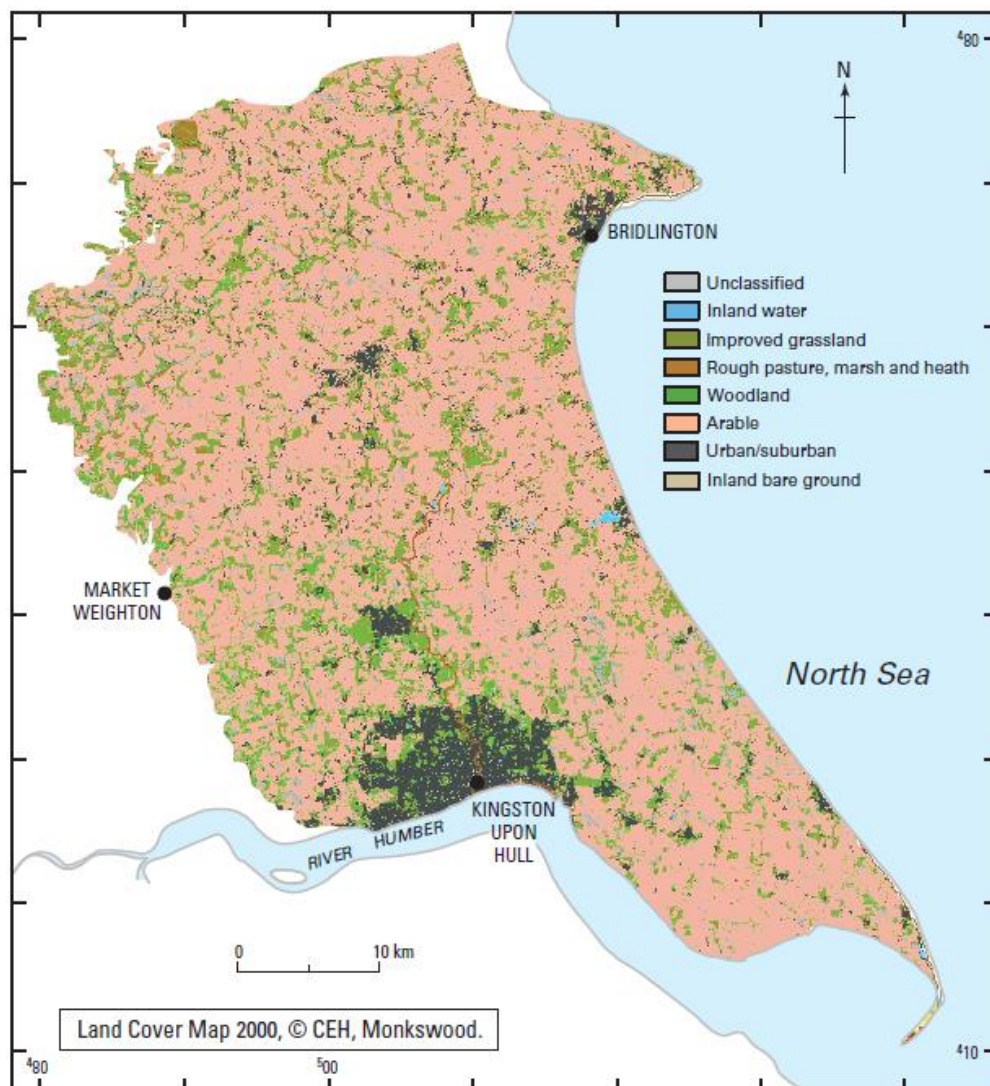


Figure 3. Map of land use over the East Yorkshire Chalk (Gale and Rutter, 2006)

3.1.4 Rainfall

Average annual rainfall in the area ranges from below 600 mm on the low-lying Holderness area to over 750 mm over the highest parts of the Wolds (Figure 4). Daily rainfall raster data (1×1 km) are available from the Centre for Ecology and Hydrology (CEH). Spatially distributed daily rainfall data are available starting from 1961 to 2016 (CEH). Projected (future) values of rainfall data are also available by the work of UKCP09 (Prudhomme et al., 2012; Murphy et al, 2007; Jenkins et al., 2009; Murphy et al, 2009).

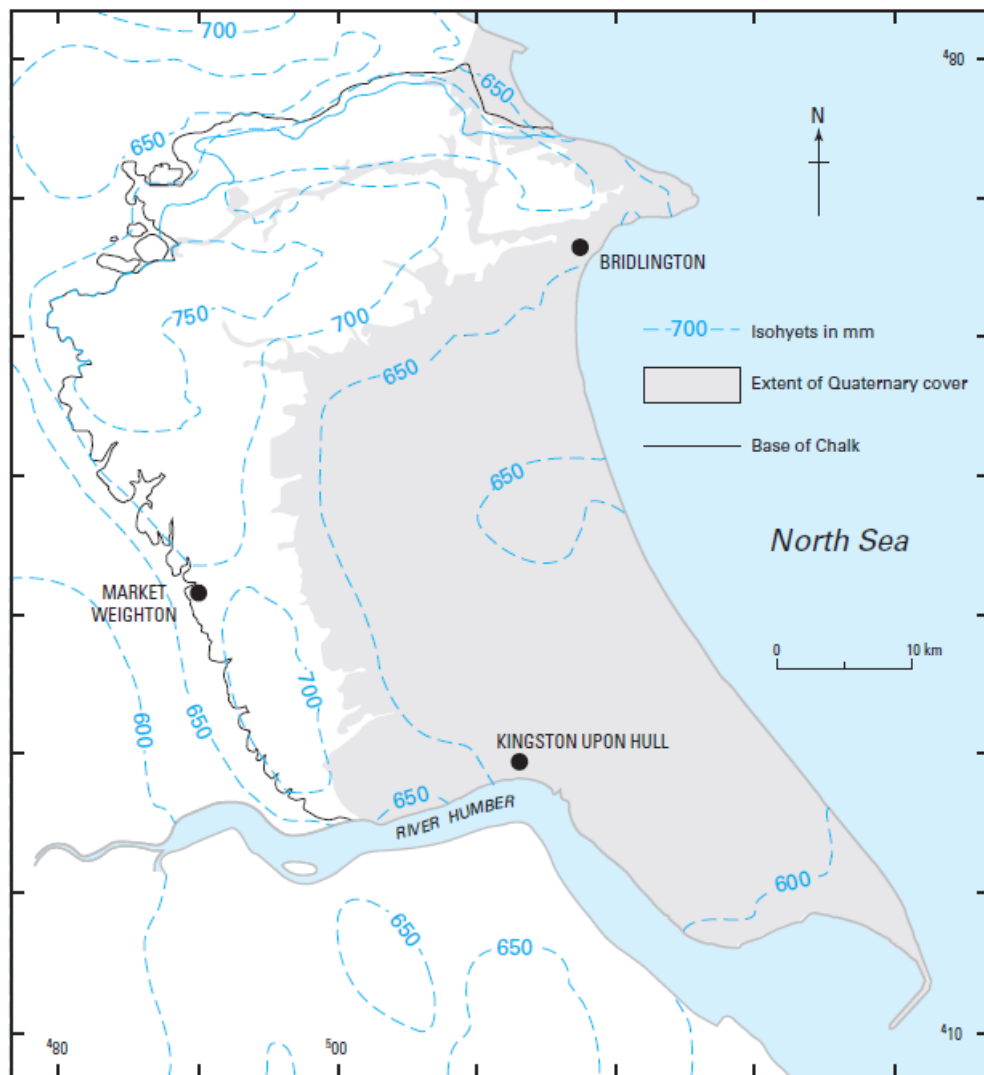


Figure 4. Spatial distribution of rainfall in the East Yorkshire Chalk (Gale and Rutter, 2006)

3.1.5 Potential evaporation

The annual potential evapotranspiration (PE) in the pilot area exhibits an average of approximately 600 mm. Monthly PE raster datasets (40 × 40 km) are available through the Met Office Rainfall and Evaporation Calculation System (MORECS), from the Met Office of the UK (Hough and Jones 1997). Figure 5 shows the distributed annual average potential evaporation data. Higher PE rates are observed to the south-southeast part of the area along the Humber estuary, while lower PE rates are observed to the middle and northeast regions.

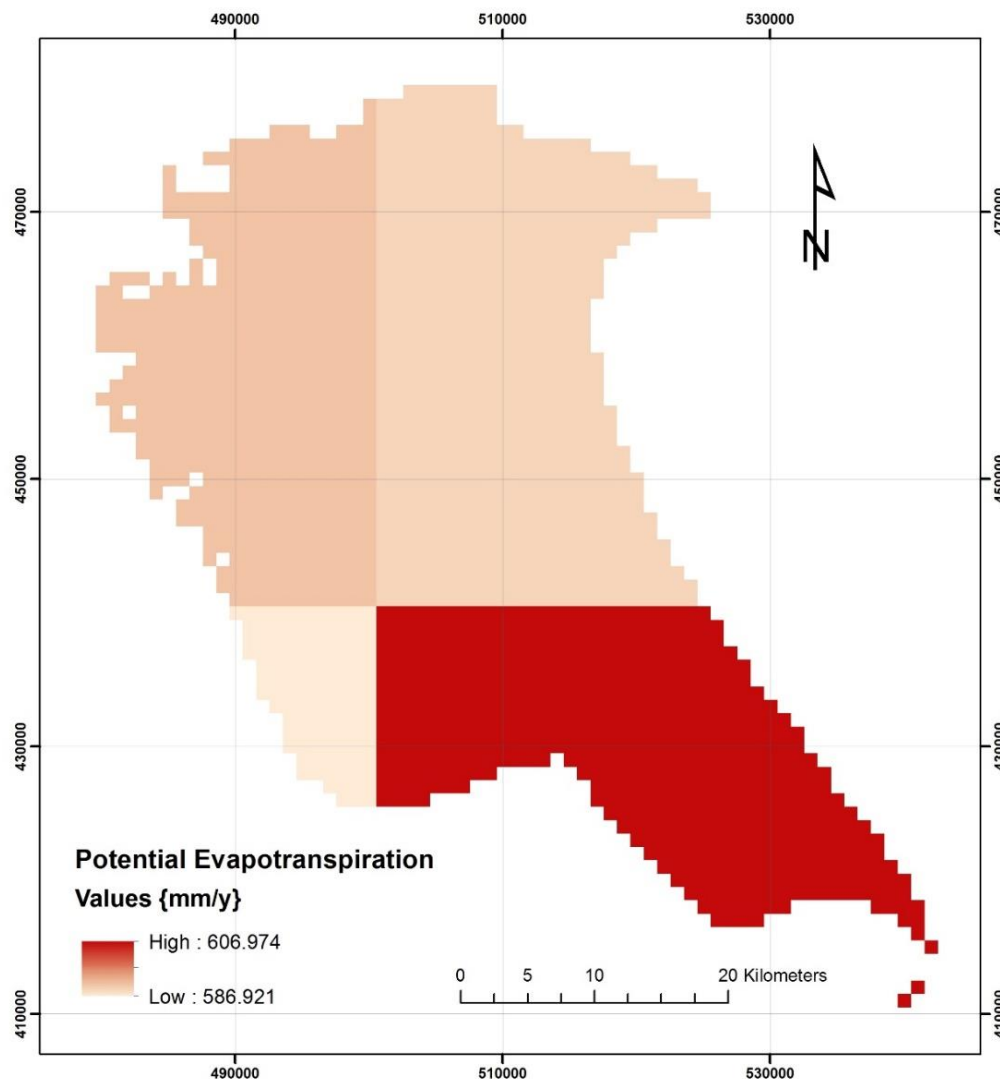


Figure 5. Spatial distribution of potential evaporation in the East Yorkshire Chalk

3.1.6 Recharge

The groundwater body in the pilot area receives most of its recharge from rainfall during the first quarter of the year. Nevertheless, the recharge process of the Chalk aquifer is generally a combination of complex flow regimes varying in timing and amount. The different rates of effective rainfall infiltration may be also affected by the presence or absence of Quaternary deposits in the surface strata. Several approaches have been applied to estimate recharge in the area. The standard Penman soil-water balance approach has been used by Environment Agency for recharge estimation. Other alternative recharge estimation approaches in the area are discussed by Rushton and Ward (1979), by Aspinwall (1995) while recently a distributed rainfall-runoff model was applied in the area to estimate recharge (ESI, 2013).

3.1.7 Hydrogeology

The aquifer properties of the East Yorkshire Chalk exhibit dissimilarities with southern England chalks due to different degrees of fracturing and matrix properties, which in turn, has an impact on the aquifer flow and transport capabilities. Two porosity regimes have been mainly identified in the chalk of Yorkshire with values greater or less than 30%. Transmissivity values in the pilot area exhibit a large spatial variation ranging from $100 \text{ m}^2\text{d}^{-1}$ to values greater than $10000 \text{ m}^2\text{d}^{-1}$ as observed south west in distances less than 10 km from the Humber estuary (Figure 6). High transmissivity values of $8000 \text{ m}^2\text{d}^{-1}$ have also been reported in the Wold Valley, northeast of the pilot area, in a study from the University of Birmingham (1985).

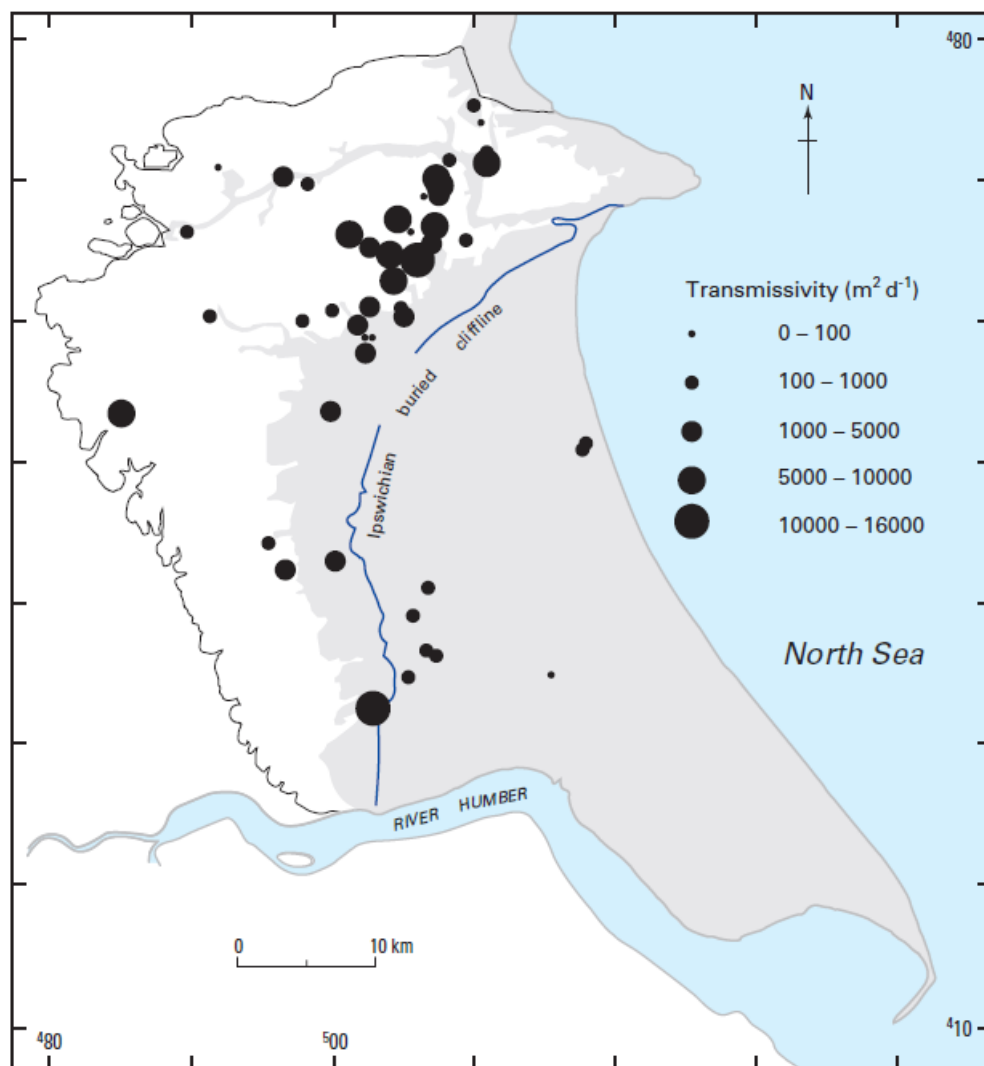


Figure 6. Spatial distribution of transmissivity values in the East Yorkshire Chalk (Gale and Rutter, 2006)

The hydrogeological conditions in the East Yorkshire Chalk vary from unconfined across the Wolds, through semiconfined conditions in the Hull catchment, to confined Chalk underlying Holderness. The latter, due to the restriction of groundwater movement and poor water quality is not being used as an aquifer. The thickness of unsaturated zone in the Yorkshire Chalk may vary from less than 10 m to over 120 m in certain regions.

The regional groundwater flow is mainly oriented along the dip of the Chalk with the major groundwater divide approximately following the line of the Chalk escarpment. The discharge of chalk groundwater takes place mainly to the North Sea, either on the beaches, or below low tide level (Foster and Milton, 1976). A network of dry valleys exists across the Wolds since the water table rarely intersects the ground surface. Just south of the Chalk outcrop, some springs occur which flow over the glacial deposits and form tributaries of the River Hull.

3.1.8 Groundwater levels

There is a network of approximately 220 boreholes in the pilot area, which monitors groundwater levels in the East Yorkshire Chalk. The longest record is Dalton Holme since 1889. Seasonal head variations are small in the confined aquifer, but may reach 30 m in the unconfined aquifer. Smaller fluctuations of approximately 10 m have been recorded in the dry valleys (Robertson, 1984). Highest groundwater levels are recorded north west of the pilot area whereas groundwater levels in the coastal aquifer body close to Humber estuary are round zero m OD.

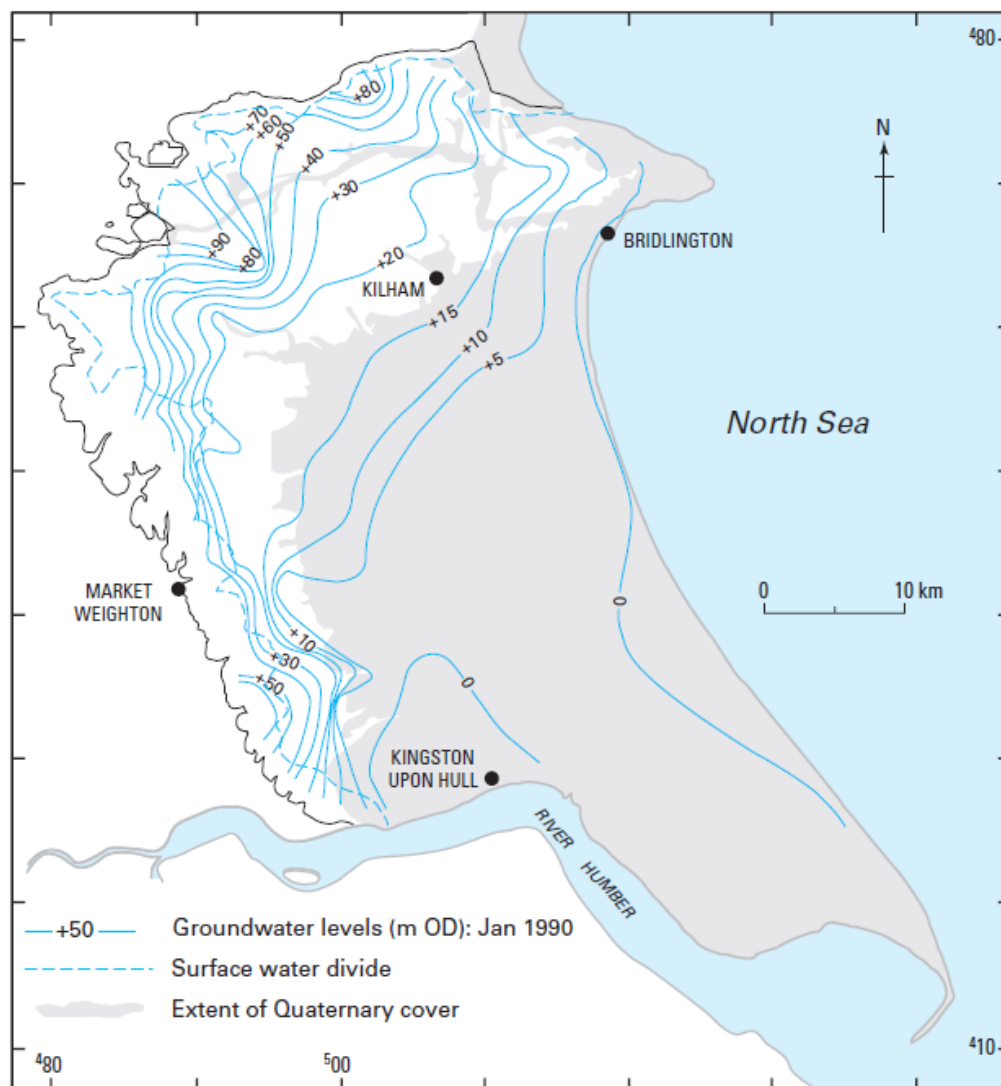


Figure 7. Spatial distribution of groundwater levels in the East Yorkshire Chalk (Gale and Rutter 2006).

3.1.9 Groundwater abstraction

The amount of groundwater extracted is significant in both the confined and unconfined aquifers in the area. The majority of abstraction boreholes is located in a north–south line through Driffield and Beverley and their main major licensed abstractor within the area is Yorkshire Water Services Ltd (Aspinwall and Co., 1995a). The aquifer over-exploitation for many years resulted in SWI problems in the Kingston-upon-Hull and Holderness areas, from the Humber Estuary (Foster and Milton, 1976; Chadha, 1986). It is thought that before 1976 the total groundwater abstraction in the Kingston-upon-Hull area was in excess of the estimated annual recharge for more than 70 years.

In general, it is estimated that the current total abstraction from the Chalk is only 14% of the total recharge. It is noted that in the Hull area, which is of specific interest due to the proximity with the Humber estuary, groundwater has been extensively exploited for public water supply with indicative abstraction rates exceeding 20 MI d^{-1} .

3.1.10 Groundwater quality and SWI

Saline intrusion is one of the main factors that affect the groundwater chemistry in the Yorkshire Chalk. Increased salinity has been observed in the confined aquifer close to the coast in the low-lying Holderness area with electrical conductivity measurements up to 17 mS cm^{-1} . However, the saline groundwater in this area is rather an old stable body of water while in the Hull area is more likely that salinity originates from a mixture of old and modern water (University of Birmingham, 1978, Smedley et al., 2004). Despite that relatively high Chloride concentrations have been recorded in the low-lying confined aquifer of the Chalk, it is not believed that this is the result of mixing with modern seawater (Figure 8).

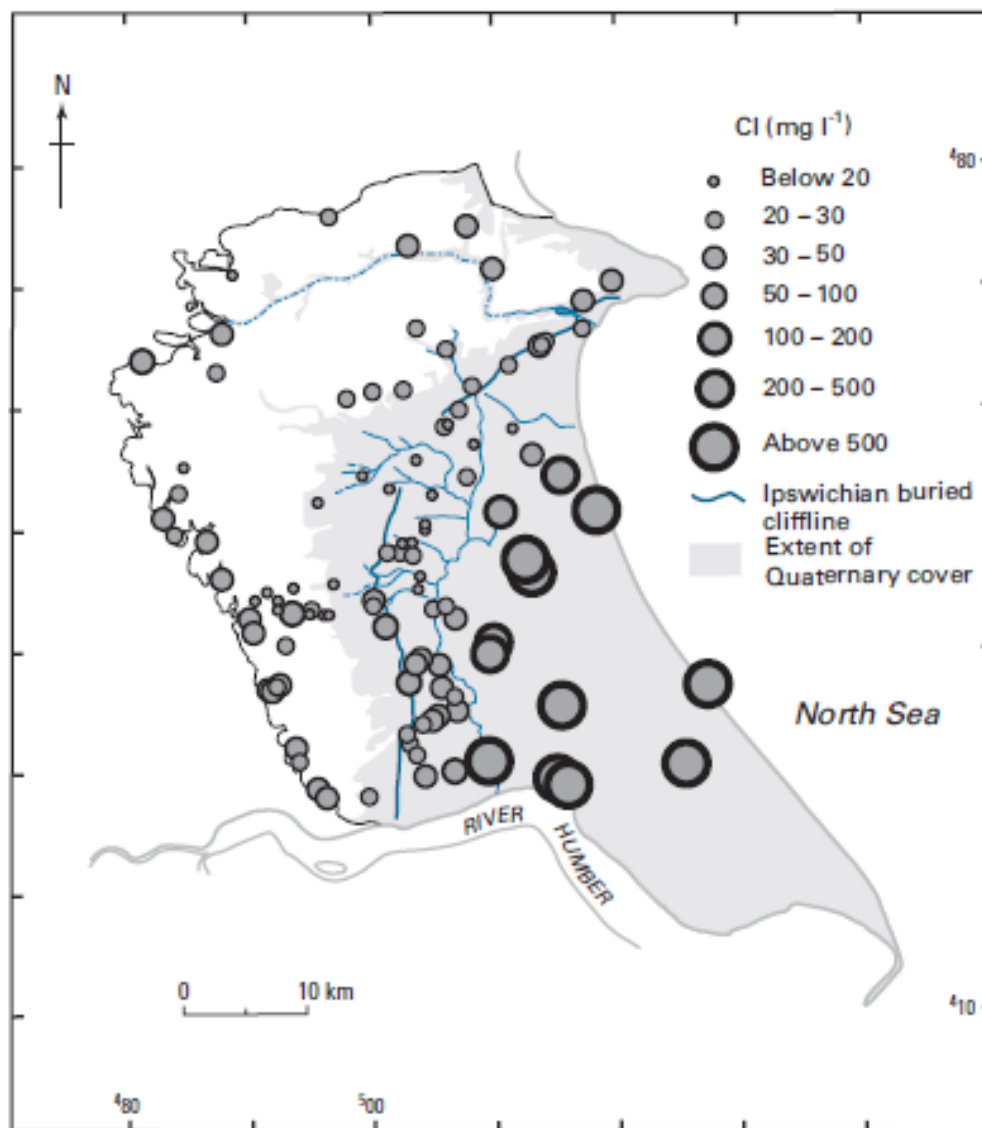


Figure 8. Spatial variation of Chloride concentrations in the groundwater of the East Yorkshire Chalk (Gale and Rutter, 2006)

Due to intensive pumping in the area, the piezometric surface was lowered down to more than 10 m below OD in some parts, allowing saline water to advance inland into the aquifer (Figure 9). Groundwater abstraction from the Chalk aquifer in Yorkshire is estimated around 38×10^3 m³ per year (Aspinwall, 1995a). However, further monitoring suggested that the saline front remained static despite the changes in the mixing zone between freshwater and saline water.

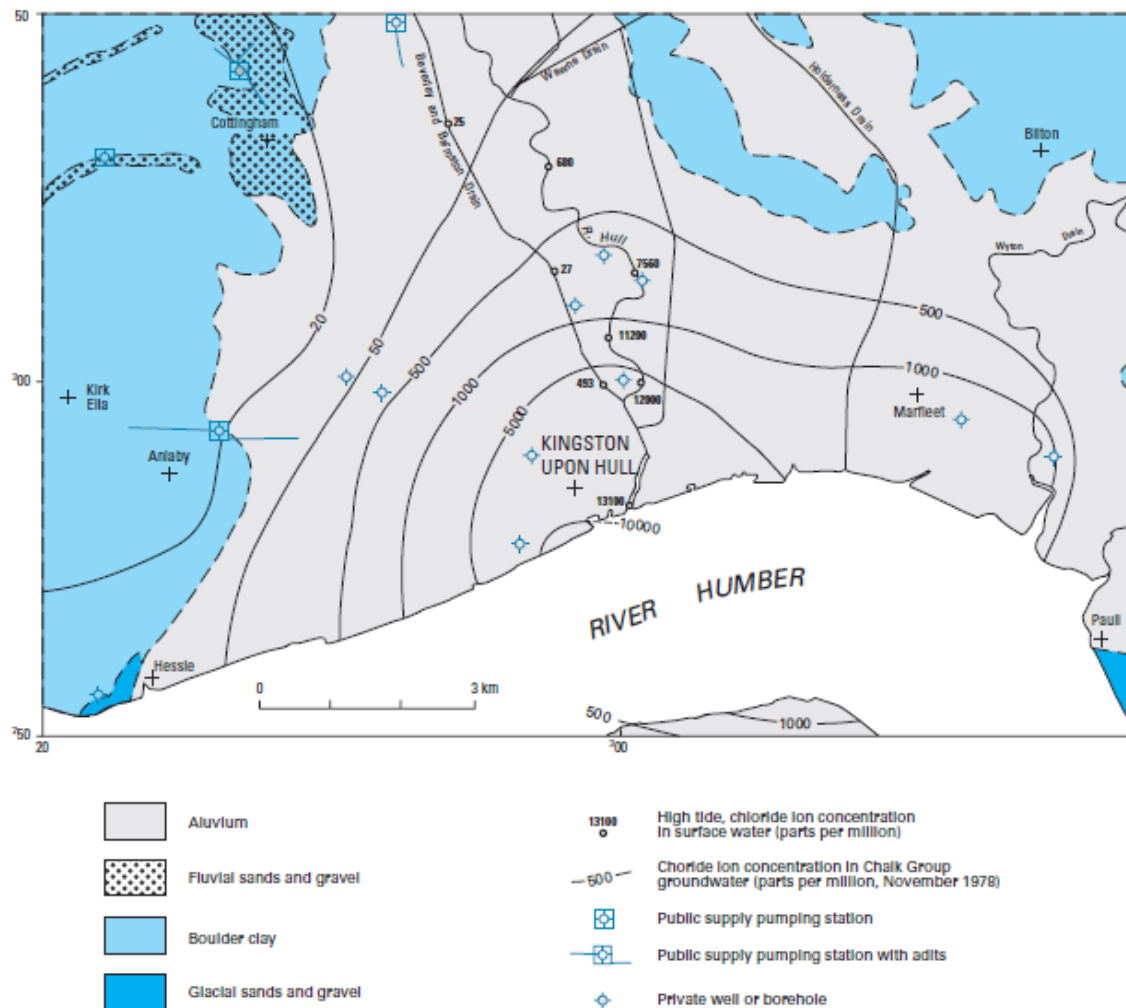


Figure 9. Extent of SWI in the Kingston-upon-Hull area (after IGS, 1980).

3.2 Climate change challenge

The assessment of impacts of climate change in the pilot area produced ambiguous results in the past since the predicted small increase in recharge may be offset by increased evapotranspiration (Gale and Rutter, 2006). Recently, the British Geological Survey (BGS) with the support of the Environment Agency (EA) BGS have undertaken a study to investigate the impact of climate change on groundwater resources using the distributed recharge model ZOODRM (Mansour and Hughes, 2018). Potential recharge values for Great Britain (England, Scotland and Wales) are produced using rainfall and potential evaporation data from the Future Flows Climate datasets (11 ensembles of the HadCM3 Regional Climate Model or RCM). This study has shown that generally the recharge season appears to become shorter, but with greater amount of recharge “squeezed” into fewer months. This conclusion is aligned with the European Environment Agency map that describes the expected climate change across the different areas in Europe (Figure 10). Impacts of climate change in the pilot area, regarding SWI, should be further investigated.

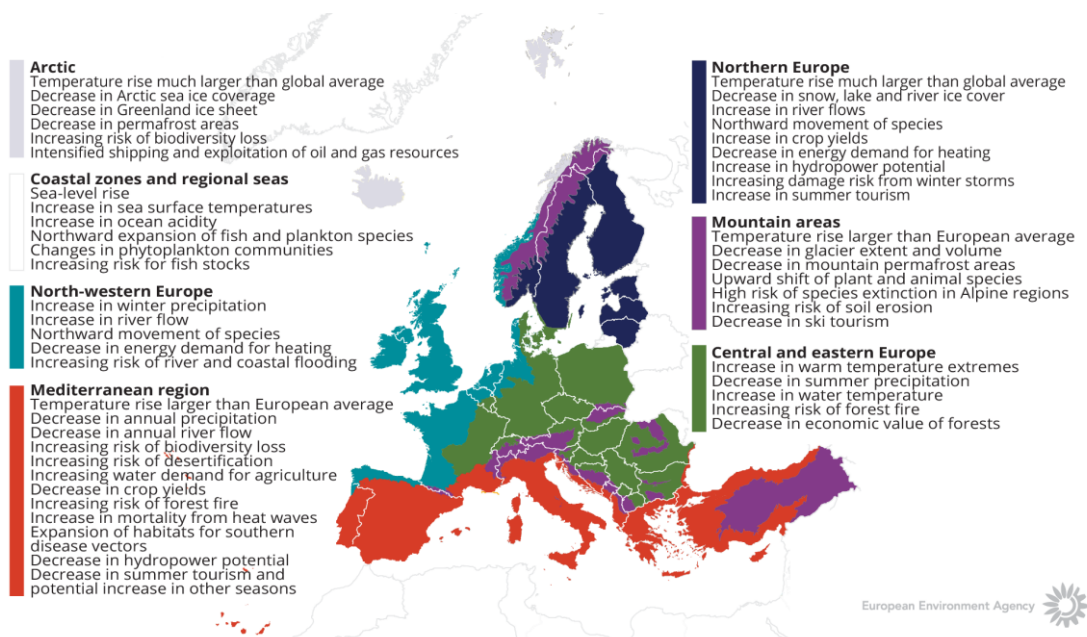


Figure 10. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

The mathematical modelling of a Sea Water interface (SWI) is mainly based on two different conceptualizations of the freshwater and saltwater interactions. Variable density flow and solute transport models describe the formation of a transition zone between freshwater and saltwater, controlled by hydrodynamic dispersion mechanisms, and provide a more realistic representation of coastal aquifer flow processes. A coupled system of nonlinear partial differential equations is solved by using numerical codes, for example SUTRA (Voss, 1984), SEAWAT (Guo and Langevin 2002), or FEFLOW (Diersch and Kolditz 2002). Variable density flow and solute transport modelling is a high-fidelity approach in representing the dynamics and mixing of freshwater and saltwater in coastal aquifers (Werner et al. 2013). However, the application of these numerical models in regional-scale coastal aquifers might not always be straightforward due to a combination of computational challenges and spatial distribution of field data (Sanford and Pope 2010).

Another modelling approach for SWI is based on a simplification of the coastal aquifer flow where the dispersion zone is idealized as a sharp interface. It is considered as a reasonable approximation of regional coastal aquifer flow where the dispersive zone is expected to be narrow compared to the spatial scale of the area under study (Mantoglou et al. 2004). Due to the large spatial extent of the present pilot area, a sharp interface model has been employed to simulate SWI. A parsimonious SWI model was selected, based on the single-potential formulation of Strack (1976). It is suitable of providing a rough approximation of the SWI status for this pilot area within minimum computational effort. The sharp interface model of Strack (1976) is based on the Ghyben-Herzberg relation and Dupuit approximation and neglects density variability in space as well as mixing between freshwater and saltwater. The saltwater is assumed static and aquifer flow is assumed horizontal and steady-state. The depth of the interface is estimated using the Ghyben-Herzberg approximation which assumes that horizontally flowing freshwater floats above static saltwater (Essaid 1986). It is noted that sharp interface models might overestimate the extent of seawater intrusion, particularly under pumping conditions (Dausman et al. 2010; Llopis-Albert and Pulido-Velazquez 2014; Christelis and Mantoglou 2016).

Figure 11 illustrates vertical cross-sections of both confined and unconfined coastal aquifers where a sharp interface is assumed to separate freshwater from saltwater. Two distinct zones are developed. In zone 1, a confined (upper view) or an unconfined (lower view) aquifer flow is depicted whereas in zone 2 a freshwater lens floats above the static saltwater. Fresh groundwater is also pumped in zone 1.

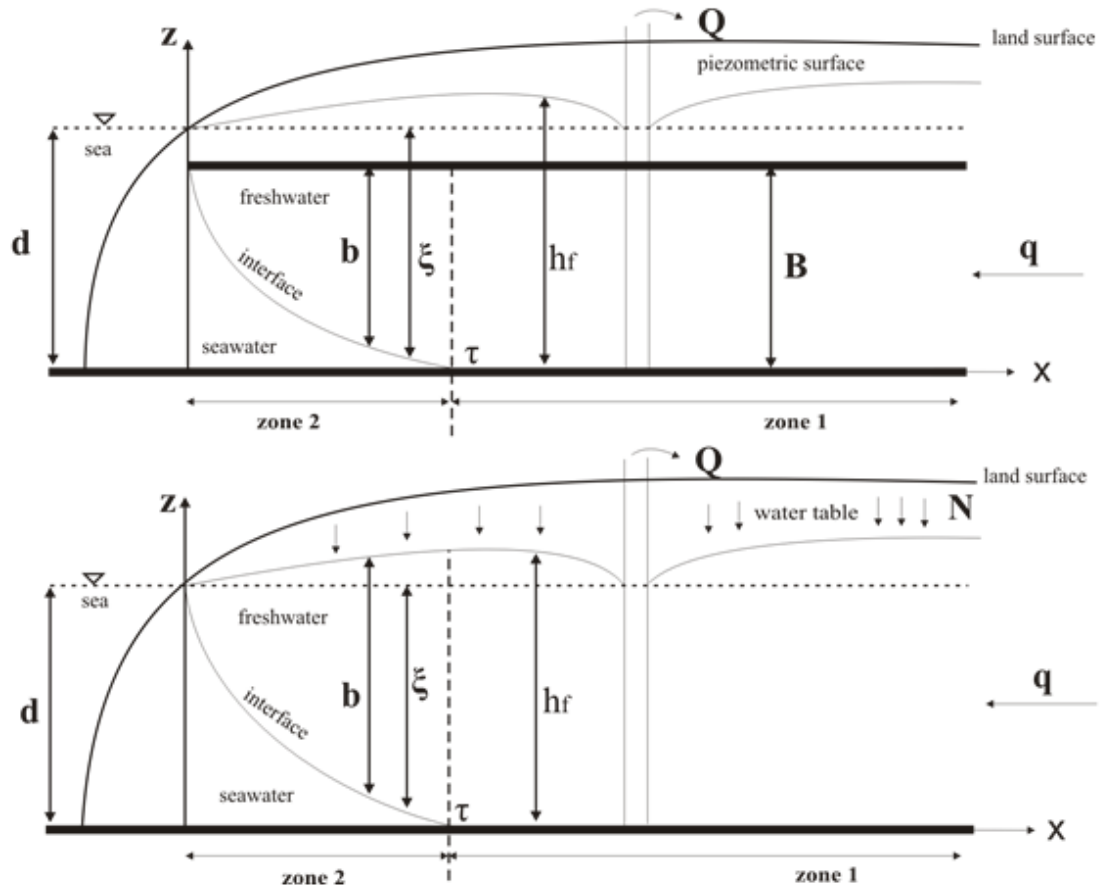


Figure 11. Schematic vertical cross-sections of a confined (upper figure) and an unconfined (lower figure) coastal aquifer, based on the sharp interface approximation (source: Christelis 2021).

Variable d [L] represents the depth from sea level to the aquifer base and variable $\xi(x, y)$ [L] represents the freshwater depth from sea level to the interface. At point τ the interface intersects the base of the coastal aquifers. This point is usually called “toe” of seawater front and indicates the inland intrusion of seawater. A freshwater discharge volume rate per unit width of aquifer q $\left[\frac{L^3}{LT}\right]$ can be introduced in the model to represent inland recharge.

For the case of confined flow, variable $b(x, y)$ [L] is the thickness of the confined flow region and in zone 1 equals B [L], that is, the aquifer thickness defined by the two confining boundaries. In zone 2, $b(x, y) = \xi(x, y) - (d - B)$. For the case of unconfined flow, $b(x, y)$ [L] is the total freshwater depth and in zone 1, $b = h_f$ while in zone 2 $b(x, y) = h_f - d + \xi(x, y)$. Variable $h_f(x, y)$ [L] is the freshwater head with reference to the impermeable aquifer base. In the case of the unconfined aquifer, a groundwater recharge rate N $[LT^{-1}]$ can be also applied to replenish the aquifer.

The Ghyben-Herzberg formula relates the hydraulic head $h_f(x, y)$ and depth $\xi(x, y)$ via the saltwater/freshwater density ratio $\varepsilon = \frac{(\rho_s - \rho_f)}{\rho_f}$ according to: $\left(\frac{1}{\varepsilon}\right)(h_f - d) = \xi(x, y)$. The following differential equations govern the aquifer flow in the confined and the unconfined case (Strack 1976; Mantoglou et al. 2004):

$$\left. \begin{aligned} \frac{\partial}{\partial x} \left(K \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(K \frac{\partial \phi}{\partial y} \right) - Q(x, y) &= 0, & \text{confined interface flow} \\ \frac{\partial}{\partial x} \left(K \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(K \frac{\partial \phi}{\partial y} \right) + N - Q(x, y) &= 0, & \text{unconfined interface flow} \end{aligned} \right\} \quad (1)$$

where $\phi [L^2]$ is the flow potential and $K [LT^{-1}]$ is the aquifer's hydraulic conductivity. The distributed pumping rate $Q(x, y) [(L^3 T^{-1}) L^{-2}]$ is $Q(x, y) = \sum_{j=1}^M Q_j \delta(x - x_{wj}, y - y_{wj})$ where (x_{wj}, y_{wj}) are the coordinates of pumping wells $j = 1, \dots, M$ with rates Q_j and $\delta(x - x_{wj}, y - y_{wj})$ is the Dirac delta function. In the case of confined aquifers, the flow potential is defined as (Bear et al. 1999):

$$\left. \begin{aligned} \phi &= Bh_f + \frac{\varepsilon B^2}{2} - (1 + \varepsilon)Bd & \text{zone 1} \\ \phi &= \frac{1}{2\varepsilon} [h_f + \varepsilon B - (1 + \varepsilon)d]^2 & \text{zone 2} \end{aligned} \right\} \quad (2)$$

while in the case of unconfined aquifers the flow potential is expressed as (Bear et al. 1999),

$$\left. \begin{aligned} \phi &= \frac{1}{2} [h_f^2 - (1 + \varepsilon)d^2], & \text{zone 1} \\ \phi &= \frac{(1 + \varepsilon)}{2\varepsilon} (h_f - d)^2, & \text{zone 2} \end{aligned} \right\} \quad (3)$$

At the location of the toe, the flow potential is calculated based on the following equations for each coastal aquifer type (Mantoglou 2003):

$$\left. \begin{aligned} \phi_{toe} &= \frac{\varepsilon}{2} B^2, & \text{confined aquifer} \\ \phi_{toe} &= \left[\frac{\varepsilon(\varepsilon + 1)}{2} \right] d^2, & \text{unconfined aquifer} \end{aligned} \right\} \quad (4)$$



4.1.1 Climate data

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Inter-comparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5° global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (e.g. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected between 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature were calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact on the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp6p0	noresm1-m
	"Wet"	rcp4p5	miroc-esm-chem
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp8p5	miroc-esm-chem



4.2 Tool(s) / Model set-up

The flow equations presented in Equation 1 can be solved numerically using a groundwater flow code to account for coastal aquifers of irregular shape. Here, the groundwater model version of MODFLOW-2005 (Harbaugh, 2005) was utilized to solve the flow equations based on a block-centered finite-difference numerical scheme. Unconfined and steady-state, two-dimensional coastal aquifer flow conditions were simulated using a spatial discretization of $\Delta x = \Delta y = 500m$. A simplified river flow network was included in the model, given the availability of existing data for river stages in the pilot area. Spatially distributed hydraulic conductivity and recharge values were used as inputs to the model to simulate the extent of seawater intrusion in the area. A single simulation run requires approximately 0.17 seconds which is indicative of the very low computational cost associated with this sharp interface model.

In particular, the impact of several recharge scenarios on the extent of SWI was investigated. As discussed previously, this particular sharp interface model assumes steady-state flow conditions and thus all recharge maps were averaged over specified time periods. First, a baseline simulation was performed using the long-term average of a historical recharge calculation of 50 years produced using the UK national scale model (Mansour et al., 2018). Then, the 50 years of historical recharge were disaggregated into five decadal recharge periods to investigate for possible differences in the simulated SWI extent. Finally, the future recharge values estimated using the UK national scale recharge model and the change factors of the four selected climate scenarios presented in Table 1, were applied in the SWI model to assess their effect on the simulated location of the freshwater/saltwater interface in the pilot area.

4.3 Model calibration

The historical recharge values applied to simulate the groundwater potentials for the baseline case are obtained from the work published by Mansour et al. (2018). In this work a national scale recharge model was calibrated by comparing the simulated long-term average overland flows to the observed ones at selected gauging stations located at major rivers. Figure 12 shows a Q plot for the simulated vs observed long term average runoff values at the selected gauging stations. The estimated recharge values are also compared with recharge values estimated using other tools and by other researchers and governmental bodies such as the Environment Agency.

The values of the hydraulic parameters, mainly the hydraulic conductivity, are obtained from an ongoing research project called Hydro-JULES. This a research program supported by NERC National Capability funding (Grant number: NE/S017380/1) to the Centre for Ecology & Hydrology (CEH), British Geological Survey (BGS) and National Centre for Atmospheric Science (NCAS). Under this work a numerical groundwater model is developed for the Chalk aquifer which covers the Humber estuary. A stochastic approach was used to produce a spatially distributed map of the hydraulic conductivity values. In this approach, hydraulic conductivity data available across the Chalk aquifer were interpreted stochastically to produce a large number of statistically acceptable hydraulic conductivity maps. These are then processed using the numerical model. Simulated and observed groundwater levels at selected observation boreholes are compared and a selected number of best performing models are selected. Finally, and to address the uncertainty associated with the used data and the stochastic approach, maps showing the 25th, mean and 75th percentile hydraulic conductivity values and obtained from the



hydraulic conductivity maps are produced. In this work, the spatially distributed mean hydraulic conductivity values are used to investigate the saline intrusion in the aquifer.

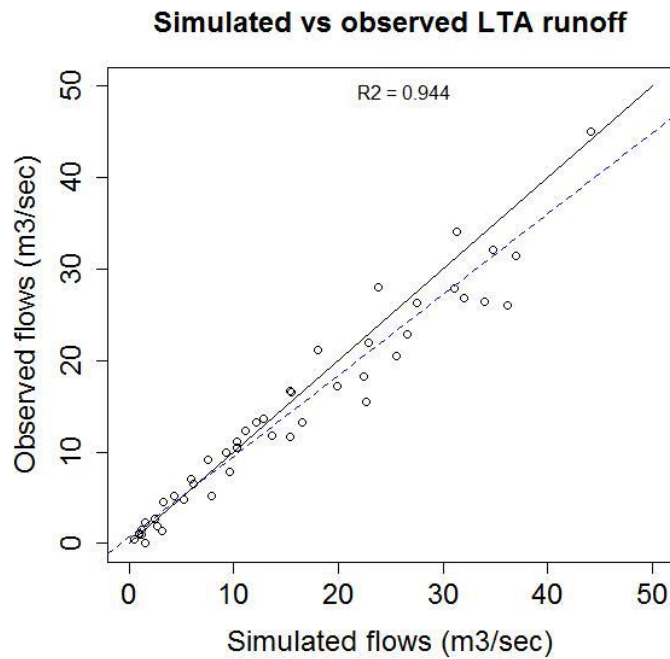


Figure 12 Q plot for the simulated vs observed long term average runoff values at the 56 gauging stations shown in **¡Error! No se encuentra el origen de la referencia.** after Mansour et al. (2018)

5 RESULTS AND CONCLUSIONS

5.1 Saline intrusion using the historical long-term average recharge values

Initially, SWI was simulated for the case of a long-term average recharge input distributed spatially in the area. Figure 13 presents the specific contour which corresponds to the flow potential of the interface location as calculated by equation 4. The sharp interface approach separates the aquifer into a freshwater zone (the area indicated by Zone F in Figure 13) and into a saltwater zone (the area indicated by Zone S in Figure 13).

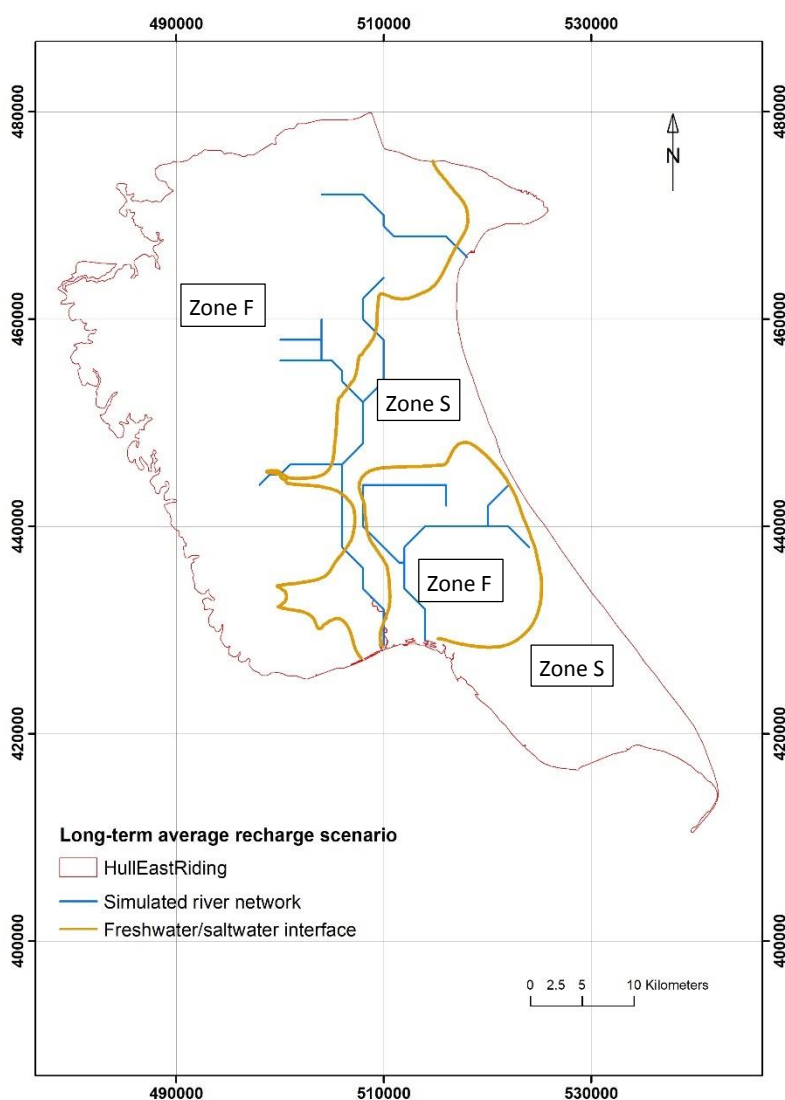


Figure 13. Baseline scenario presenting the simulated intrusion of seawater for a long-term average recharge of 50 years period

In overall, the simulated interface reasonably approximates the distribution of chloride data shown in Figure 8. The saltwater intruded area simulated by the sharp interface model, mostly



encompasses the quaternary cover of the aquifer where, according to Figure 8, increased chloride values have been recorded. From a qualitative point of view, the model appears to reproduce well the status of SWI based on the historical chloride data which are indicative of saline groundwater in the area along the coastline and inland (Figure 14).

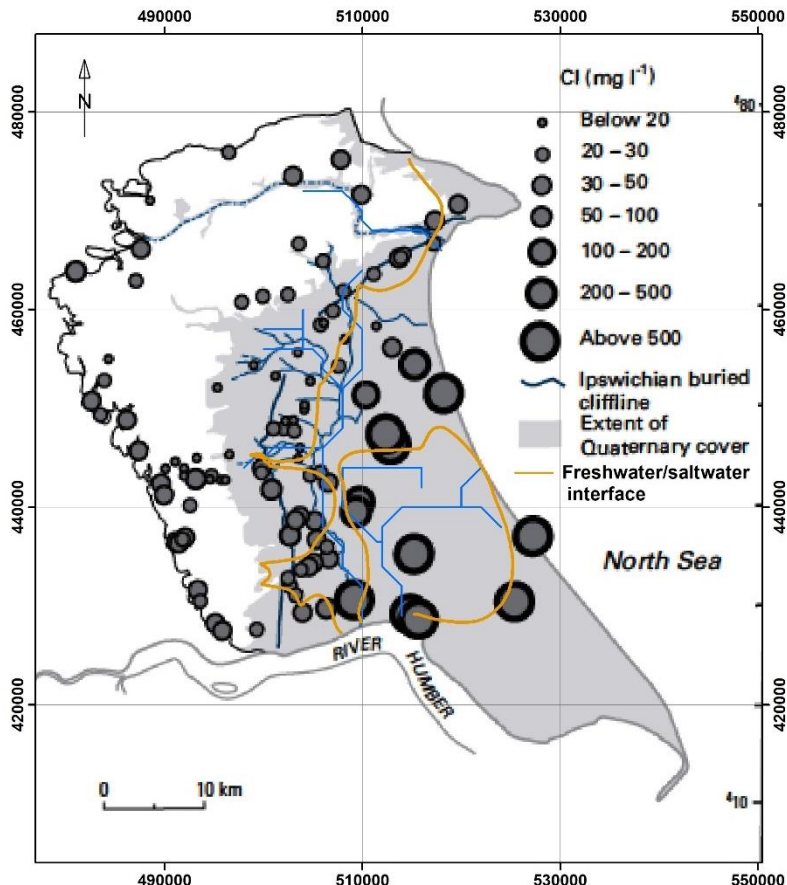


Figure 14. The freshwater/saltwater interface plotted on top of the available chloride map of figure 8.

5.2 Variation of saline intrusion on a decadal basis

Next, the simulated interfaces are presented based on the time-averaged decadal recharge periods (Figure 15). Results show that by simulating different historical recharge periods the extent of seawater intrusion exhibits a similar pattern for all of these periods. However, the differences among the interface locations may range from as low as 10 meters up to 700 meters, depending on which part of the Hull and East Riding groundwater body is considered. For example, large differences are observed in the upper north-eastern part near Bridlington and close to the Humber estuary near Kingston Upon Hull.

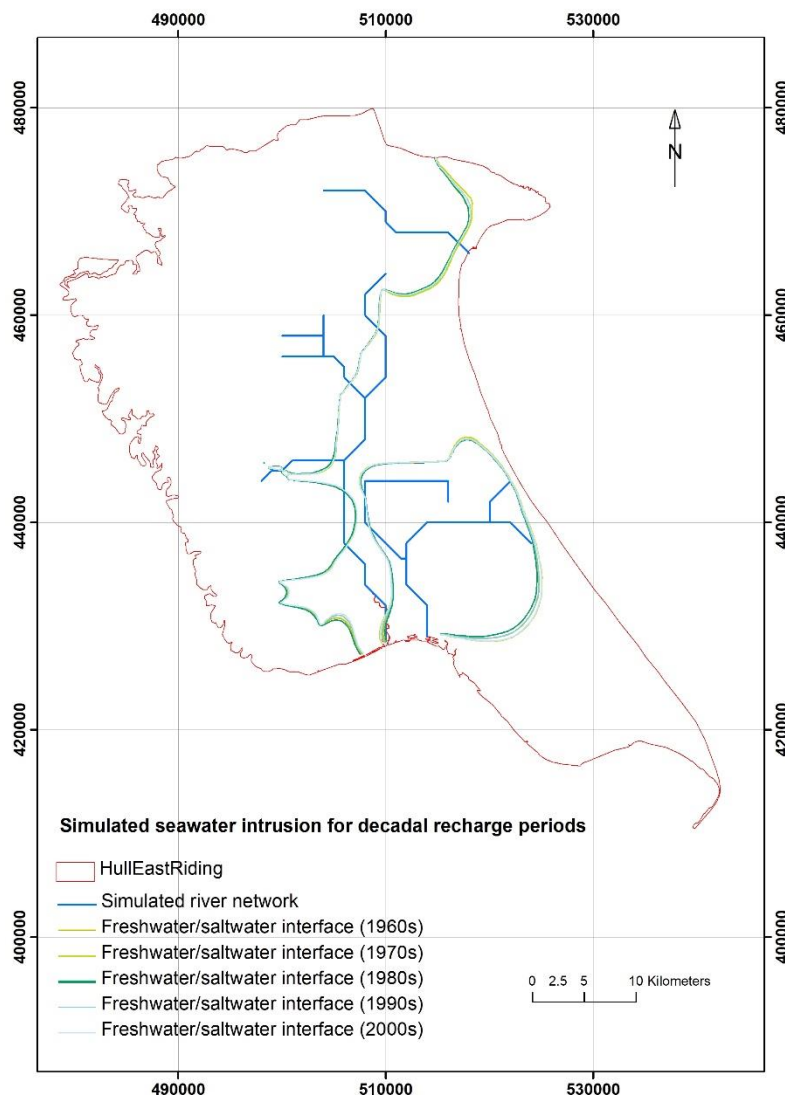


Figure 15. Location of freshwater/saltwater interfaces for 5 different decadal recharge periods.

Another metric to quantify the differences among the decadal recharge periods is to calculate the freshwater area as this is separated from the saltwater intruded area using the simulations with the sharp interface model. The results demonstrate that the recharge period from 1980-1990 (i.e. 1980s), had a smaller calculated freshwater area than the other periods with a 1.8% difference from the corresponding freshwater area obtained from the baseline simulation. This is attributed to the reduced recharge during that period which is 11.74% less than the long-term average recharge.

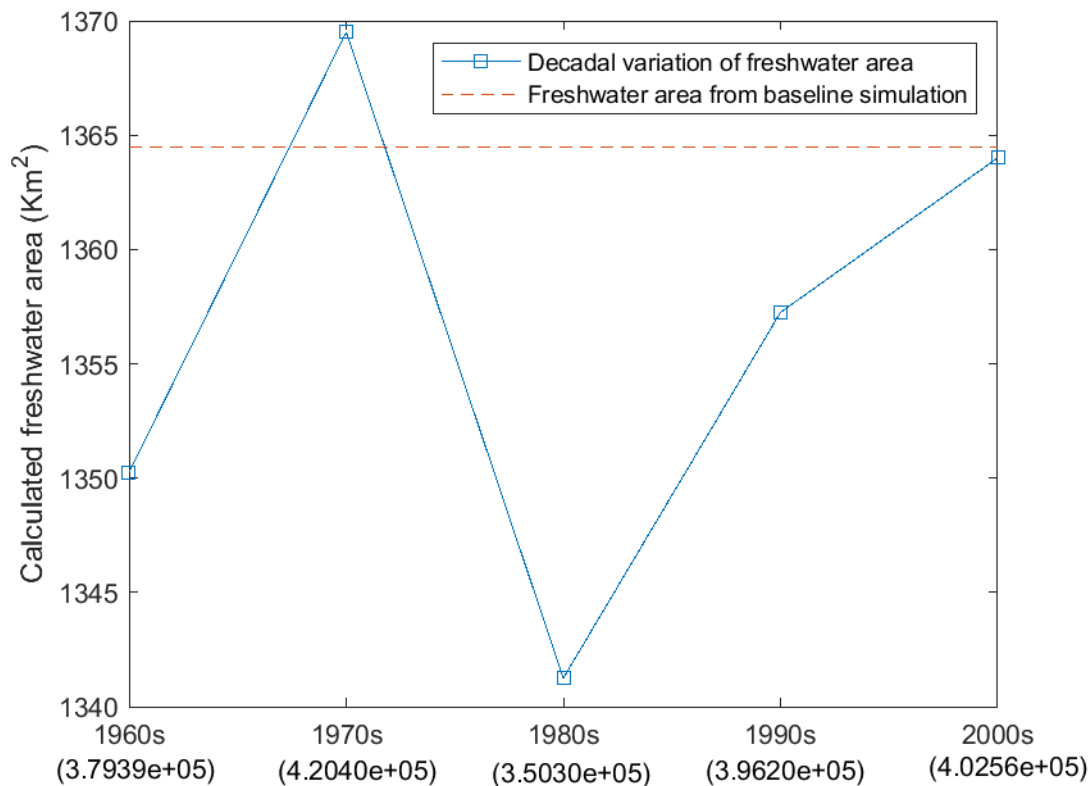


Figure 16. Calculated freshwater area for the 10-year averaged periods between 1960s-2000s. In parenthesis is the total groundwater recharge (m³) applied in the SWI model.

5.3 Saline intrusion under future climate scenarios

A set of four SWI simulations were also performed to assess the impact of future climate recharge projections on the interface position. The recharge inputs for each SWI simulation are based on the climate scenarios presented in Table 1. As it is shown in Figure 17, there are parts of the aquifer where the simulated interfaces are close to each other while the range of these distance differences may vary from 30 meters to 760 meters. Apart from the total recharge input applied in the SWI model, the interface location in the area also depends on local hydraulic conductivity and local river network features. Thus, a decrease or an increase in total recharge is not always the major factor to trigger a smaller or larger extent of seawater intrusion as demonstrated by the simulated interfaces. However, it is observed that in the case of the 3-degree “Wet” climate scenario, the recharge input has a significant impact on the simulated extent of seawater intrusion. The interface line corresponding to this scenario (3 degree “Wet” in Figure 17) remains always closer to the coast boundary compared to the other interfaces.

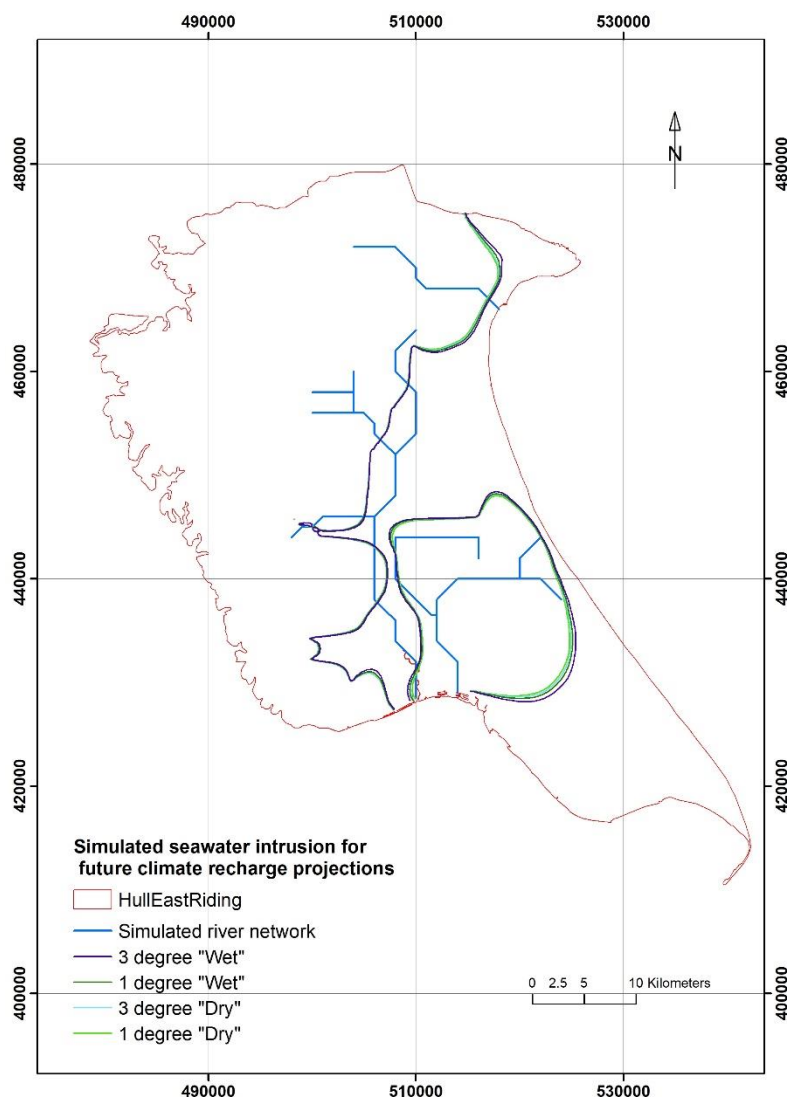


Figure 17. Location of freshwater/saltwater interfaces for the four climate scenarios.

The freshwater areas were also calculated for the climate scenario simulations. The impact of the 3-degree "Wet" climate scenario on mitigating seawater intrusion is evident by providing the largest freshwater area. Interestingly, the 3-degree "Dry" climate scenario provided a slightly larger freshwater area than the 1-degree "Dry" climate scenario which contradicts to the hypothesis that the former is a drier scenario than the latter. This could be attributed to that the 3-degree "Dry" scenario may include short-period high intensity rainfall storms that generate large amounts of recharge and compensate for the dry periods. This could be more extreme in the 3-degree "Dry" than in the 1-degree "Dry" climate scenario yielding a long-term average recharge that is slightly higher.

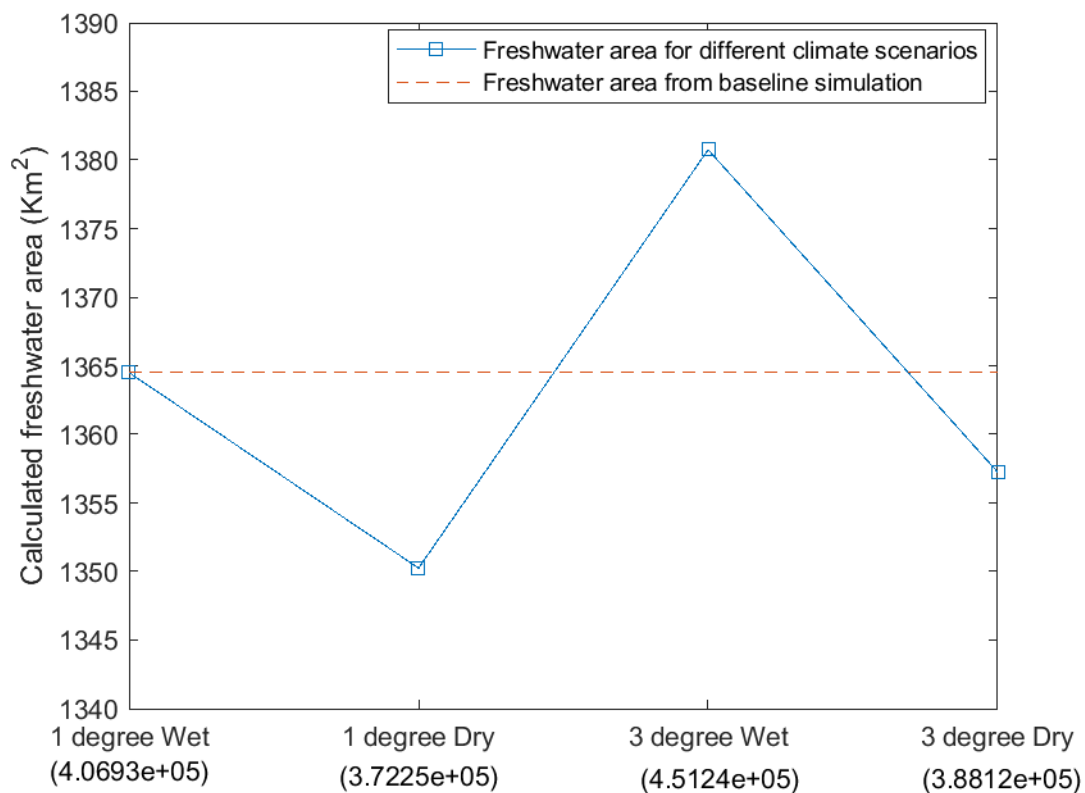


Figure 18. Calculated freshwater area for the different future climate recharge projections. In parenthesis is the total groundwater recharge (m³) applied in the SWI model.

5.4 Assessment of saline intrusion vulnerability using the GALDIT method

One popular approach to assess the vulnerability of a coastal aquifer to seawater intrusion is the GALDIT method (Lobo-Ferreira et al. 2005), an index-based ranking approach which provides a practical tool to map those parts of an aquifer that are more prone to the encroachment of seawater (Recinos et al. 2015). Enhancement of the currently available data, mostly regarding salinity levels in the area, might lead to a different interpretation of the seawater intrusion vulnerability in the area. Nevertheless, the method identified certain areas which appear to have moderate or high vulnerability score and further modelling analysis and data collection could provide insights regarding the seawater intrusion status for future groundwater management.

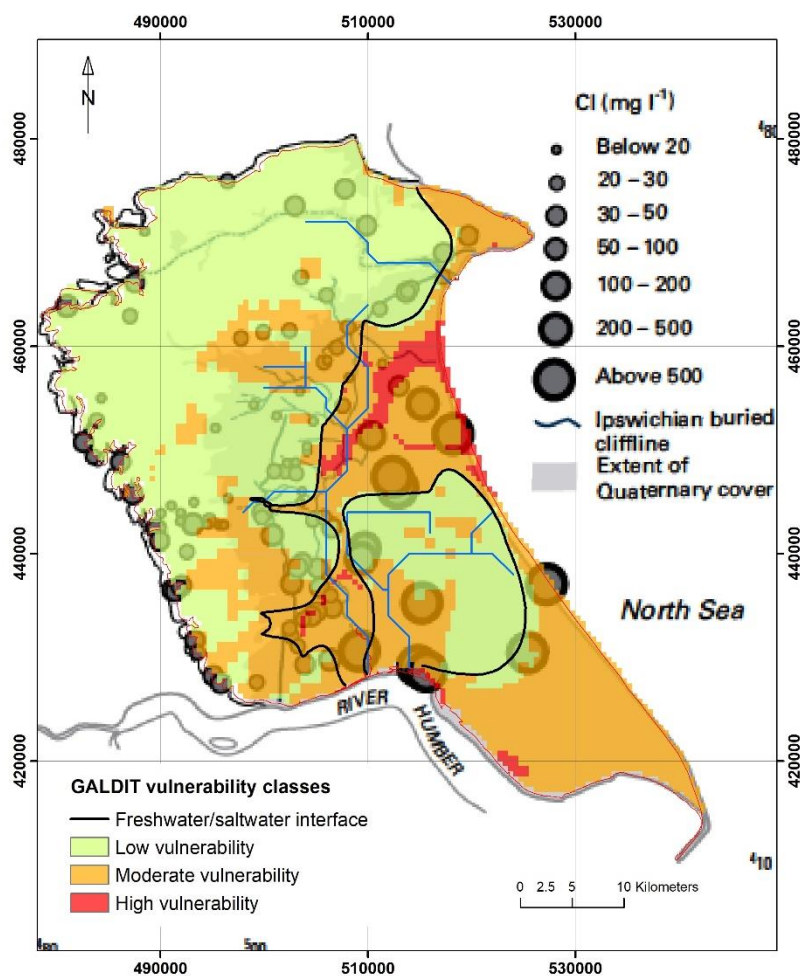


Figure 19. Characterization of the vulnerability of the pilot area to seawater intrusion based on GALDIT method.

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