Late Holocene Relative Sea-Level Change and the Implications for the Groundwater Resource, Humber Estuary, UK

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Abstract

This thesis presents new late Holocene relative sea-level reconstructions in the Humber Estuary, and examines the relationship between sea-level change and the salinisation of the groundwater resource.

Relative sea-level reconstructions were produced using lithological and biostratigraphical analyses from two sites. Single and multi-proxy transfer functions were developed using diatom and foraminifera training sets from three sites in the Humber Estuary, with the multi-proxy transfer function providing the best performance. However, the application of the transfer functions was limited by the availability of modern analogues and generally poor preservation of microfossils.

Eight new sea-level index points were produced, providing constraints of relative sea-level change between 4022-1470 cal years BP. The reconstructions were consistent with existing data, offering new constraints for the previously identified expansion and contraction of estuarine conditions during the late Holocene. In the outer estuary, two sea-level index points provided a record for an expansion between 3395-3227 cal years BP not previously constrained by sea-level index points. In the inner estuary, the sea-level index points indicated an expansion of estuarine conditions at 4022 cal years BP. Two of the points now provide the youngest constraints for the inner estuary.

Multiple sea level and groundwater abstraction scenarios for time periods in the past and future were undertaken using a numerical model. These determined the contribution of sea level and abstraction to changes in the groundwater and saline intrusion; sea-level rise increased saline waters within the aquifer, and abstraction induced additional saline intrusion. Future sea-level rise will also result in an increase in aquifer salinity. A lack of data and consensus over the current conditions of the aquifer and groundwater was identified, with significant further research across multiple disciplines required for sustainable management and use of the groundwater resource.

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Author’s Declaration

I declare that the work contained in this thesis is my own original work and has not been submitted for any other degree at this, or any other, University. All sources and data from other authors that are referred to are acknowledged at the appropriate point and listed in the references.

1. Introduction

Rising sea levels are a key concern around the globe due to both the direct and indirect effects on coastal regions and resources. For example, rising sea levels can result in an increased frequency of coastal storms, floods, and coastal erosion, damaging and disrupting coastal urban populations, properties and infrastructure (Dawson *et al*., 2016; de la Vega-Leinert & Nicholls, 2008; Wong *et al*., 2014). Such effects are particularly challenging due to large populations inhabiting coastal regions, and the continuing growth of these exposed populations (Pelling & Blackburn, 2014; Wong *et al*., 2014). In the context of coastal aquifers, rising sea levels can result in potential salinisation and changes to the groundwater, and this can result in particular concerns over the consequences this may have on the groundwater systems and their use as a water resource, including the preservation of potable and plentiful water supplies (Ferguson & Gleeson, 2012; Masciopinto & Liso, 2016; Wong *et al*., 2014). Understanding the effects of future sea-level changes, however, is dependent upon an in depth understanding of past sea-level changes, as it allows the determination of trends and rates of change.

This thesis establishes a high resolution record of relative sea-level change for the last c. 3000 years for two locations in the Humber Estuary. These data are used to investigate changes to the groundwater in the local aquifer due to sea level and abstraction, through the use of an existing numerical model of the aquifer. The results are used to evaluate the application of palaeo sea-level methods in an estuarine environment to reconstruct Holocene sea level, as well as the implications of sea-level change for the groundwater resource. This in turn can be used to inform future research and sustainable groundwater management to safeguard the groundwater resource.

This chapter summarises the context and justification for this thesis, and outlines the key research aims and objectives.

1.1. Sea-Level Change and the Implications for the Humber Estuary

Estuaries are important features to study due to the multiple interactions between terrestrial, fluvial and coastal-marine processes functioning at varying scales, as well as the natural functions they perform in terms of ecosystems, flood control and available resources. In the context of the Humber Estuary, resources exploited include potable water from the Chalk aquifer. This groundwater resource is potentially vulnerable due to the impacts of climate change and sea-level rise.

The Humber Estuary is a macrotidal funnel shaped coastal plain estuary located on the eastern coast of England, and forms part of the southern boundary between the counties of Yorkshire and Lincolnshire (Figure 1.1). The intertidal portion of the estuary extends approximately 60km, but the sub-tidal extent reaches 140km inland through the main contributing rivers, the River Ouse and River Trent (Jickells *et al.*, 2000; Long *et al.*, 1998). It is the largest estuarine system in England, with a catchment area of 26,109km^2, covering approximately 20% of England (Environment Agency, 2009; Jarvie *et al.*, 1997; Jickells *et al.*, 2000).

Despite several studies of Holocene relative sea level along the Humber Estuary (e.g. Dinnin & Lille, 2005; Long *et al.*, 1998; Metcalfe *et al.*, 2000; Shennan *et al.*, 2003; 2006), there is a significant absence of high resolution data for the latter part of the Holocene, particularly the last 3000 years, with just one sea-level index point representing the last millennia (Long *et al.*, 1998). During the Holocene, sea level increased at a rate of c. 3.9mm a^{-1} between c.7500-4000 cal years BP, and slowed to c. 1mm a^{-1} over the last 4000 cal years BP (Long *et al.*, 1998). At present there is a trend of rising sea levels in the region, with tide gauge data from Immingham, in the outer estuary, showing a rate of 0.64±0.38mm a^{-1} from 1960-2006 (Woodworth *et al.*, 2009). This trend is predicted to continue, with estimates of net sea level rise for the northeast of England increasing from 2.5mm a^{-1} for the period 1990-2025 to 7.0mm a^{-1} 2025-2055 (Gehrels & Long, 2008).

No single microfossil proxy has been found to provide a continuous record of Holocene sea-level change for the Humber Estuary (e.g. Long *et al.*, 1998; Metcalfe *et al.*, 2000), and this may also be the case when establishing a record of change for the last c. 3000 years. The identification of sites that preserve a suitable and undisturbed record of late Holocene sea-level change is particularly challenging due the history of land reclamation and management along the estuary, however their discovery creates a unique opportunity to constrain relative sea level during the late Holocene.

As with other UK estuarine systems (e.g. Thames, Mersey), the Humber Estuary is a highly modified, urbanised and industrial landscape, and as such the utility of palaeo sea-level methods is restricted, particularly due to the lack of saltmarsh and wetland environments remaining within the estuary. It is necessary, therefore, to assess the methods and techniques that are used to ensure the reliable reconstruction of former sea levels. Based upon their application in the Humber Estuary, the use of palaeo methods and techniques, such as microfossil analysis, sea-level index points and transfer functions, must be reviewed in terms of their suitability for producing reliable relative sea-level reconstructions in a modern estuarine environment.

The production of new high-quality Holocene relative sea-level data will aid the understanding of the evolution of the estuary and its sea-level history; it will also assist in understanding present sea-level changes in the estuary and determining possible future trends. Palaeo data is also useful for validating our understanding and constraining models that are used for predicting future trends. It will benefit the understanding of not only the Humber Estuary, but also for the wider eastern UK coast and North Sea Region. Determining late Holocene relative sea-level change on the Humber Estuary is therefore important from a scientific perspective, in terms of understanding sea-level changes and rate of changes that have, and may occur, but also from a management perspective of protecting the land, and resources, exploited around the estuary.

The relative sea-level changes that have occurred in the estuary are important to understand because of the implications on the groundwater resource that is utilised to the north of the estuary by the local water company, Yorkshire Water, and to enable appropriate and sustainable practice and management, of both the groundwater resource and water supplies. Groundwater is abstracted as a source of potable water from boreholes in the Chalk aquifer in close proximity (<5km) to the Humber Estuary. There is a complex relationship within, and between, groundwater and estuarine coastal processes, and the risk of possible changes in the flows, pressures and salinity of the groundwater source needs to be investigated in the context of changing sea levels. The relationship requires a consideration of both the sea-level history of the estuary, as well as the groundwater characteristics of the surrounding region.

Sea-level rise has caused an increased salinisation of coastal aquifers (e.g. Anderson & Al-Thani, 2016; Moore, 1999; Vafaie & Mehdizadeh, 2015; Wassaf & Schüttrump, 2016). The effects of groundwater use, the movement of groundwater in the aquifer, and the potential influence of sea-level change on the salinity of water abstracted are, therefore, important to assess and consider to enable appropriate use and resource management. This directly links the sea-level reconstructions to management issues, informing the planning and management policies of an industrial organisation.

Multidisciplinary approaches, as well as collaborations, are becoming increasingly critical to ensure the accurate and suitable application and dissemination of knowledge and data. From a Quaternary science perspective, this includes considering how environmental reconstructions can be directly used to inform current environments, but also considering the indirect influences on different environmental settings (e.g. sea level and groundwater), and the implications these changes may have in terms of anthropogenic use and resources. This research will demonstrate how 'traditional' sea-level data can be linked to groundwater research, to investigate and to manage groundwater resources.

To summarise, there is a scarcity of late Holocene sea-level data for the Humber Estuary that this research addresses by producing new late Holocene relative sea-level data. It assesses the applicability of palaeo sea-level methods within an estuarine environment and examines the localised interactions of sea level and groundwater, and the implications that sea-level change and abstraction have on the commercial and sustainable abstraction of groundwater.

1.2. Research Aims and Objectives

To undertake the research, three aims were established, each with a series of objectives that address and contribute to that aim. The aims and objectives of the research are:

1. To assess the validity of palaeo sea-level techniques in a modern estuarine environment.

- Identify suitable palaeo study sites that retain an undisturbed late Holocene record.
- Assess the preservation of microfossils within the sedimentary record.
- Establish a contemporary training set of diatoms and foraminifera from remaining modern saltmarshes within the estuary, and the relationships of the proxies to the modern environment.
- Develop single proxy and multi-proxy transfer functions of varying scale using the new training sets and existing UK scale training sets.
- Evaluate the suitability of the developed transfer functions for application to the palaeo records to reconstruct relative sea level.

2. To reconstruct and elucidate the late Holocene relative sea-level history of the Humber Estuary.

- Produce new relative sea-level data for the Humber Estuary.
- Apply the selected transfer functions to the fossil assemblages of the palaeo sequences to produce a continuous record of relative sea-level change, and establish sea-level index points for the dated horizons.
- Integrate the reconstructions of relative sea level from the palaeo sites with existing records and understanding of Holocene relative sea level and environmental change in the Humber Estuary.
- Evaluate the methods utilised and the reconstructions of sea levels produced.

3. To examine the interactions of groundwater and sea level between the Humber Estuary and an adjacent groundwater abstraction site.

- Assess the current understanding and conceptual models of the hydrogeology of the Springhead source and adjacent Humber Estuary.
- Run groundwater scenarios based on the different sea level and abstraction conditions at different time slices (past (3000, 2000 and 1000 years BP), present conditions, and future (year AD 2100) conditions using an existing numerical model of the East Yorkshire Chalk aquifer.
- Evaluate the groundwater conditions from the modelling, and the relationships between sea-level changes, groundwater abstraction and saline intrusion, and the future implications for the groundwater resource.

1.3. Summary

In this project, relative sea-level reconstructions for the last c. 3000 years in the Humber Estuary were produced through the application of detailed lithological and biostratigraphical analyses of sites within the estuary. An evaluation of the methods employed was undertaken. Critical to achieving this was the identification of sites with a suitably undisturbed and well-preserved sedimentary record. In addition to this, a numerical model of the regional aquifer was utilised to examine the relationship of the local groundwater and sea-level change. The Holocene data was used to examine the relationship of sea level and groundwater through the late Holocene, as well as various scenarios considering groundwater abstraction and possible future sea-level rise. The project employed a multi-disciplinary approach, whereby a traditional Quaternary sea-level reconstruction project was considered in the wider context of hydrogeology and resource management disciplines.

2. Estuaries and Sea-Level Change

The following chapter provides a context for estuarine environments, and explains the concepts and drivers of sea-level change, focussing on the history of sea-level change around the UK since the last glacial period to present. An overview of sea-level reconstruction, along with the various methods and proxies that can be utilised to interpret and reconstruct sea-level change are described.

2.1. Estuaries

Estuaries are located in coastal regions, and can be considered as a "semi-enclosed coastal body of water which has free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard, 1967, p3). Alternative definitions also acknowledge that the opening to the sea can either be permanent or periodic (Day, 1980; 1981). Primarily, estuaries feature salinity differences and mixing processes (Fitzgerald *et al.*, 2014; Hansen & Rattray, 1966; Pritchard, 1967), and can be considered as transitional zones of terrestrial freshwater environments and coastal marine environments (Fitzgerald *et al.*, 2014; Hansen & Rattray, 1966; Montagna *et al.*, 2013). The interaction of climate, continental geology and tidal regime make all estuaries physically different and unique (Montagna *et al.*, 2013).

Estuaries experience tidal fluctuations, with rapid variations in the current velocity through the tidal cycle (Bird, 2008; Fitzgerald *et al.*, 2014). The morphology of the estuary reflects the adjustment between the volume of water moved by tidal oscillations and the capacity of its channels and creeks, with the tidal prism representing the volume of water within the estuary between high and low tide (Bird, 2008; Fitzgerald *et al.*, 2014). As such, estuaries can be classified on the basis of tidal range (micro- meso- or macrotidal estuary), and tides are a significant forcing factor to consider in the evolution of the estuary (Montagna *et al.*, 2013).

The development, evolution and morphology of estuaries are controlled by a number of hydrodynamic processes other than tidal range though. These include physical processes such as tidal currents, wave action and river flow, chemical processes, such as flocculation, and biological processes, such as saltmarsh development, as well as changes in sea level, sediment supply and anthropogenic activities (Bird, 2008; Fitzgerald *et al.*, 2014; Hansen & Rattray, 1966). These processes can be spatially and temporally variable and complex (Bird, 2008; Fitzgerald *et al.*, 2014). Estuarine boundaries can be classified based upon the penetration of saltwater upstream into the estuary, measured by salinity levels and seawater dilution (e.g. Hansen & Rattray, 1966; Pritchard, 1967).

Alternatively the limits may be considered based upon the extent of tidal oscillations, the transition from marine and estuarine sediments to fluvial sediments, or upon the morphology of the bordering coastline (Bird, 2008; Day *et al.*, 1989; Elliott & McLusky, 2002). Estuaries are therefore unique features with inter-estuary variability, complex interactions between terrestrial and coastal environments, as well as sea level, and should be considered on a site-specific basis.

Within estuaries, a saltwater wedge is formed due to saltwater being denser than fresh river water, and this directly influences accumulation of sediments (Bird, 2008; Fitzgerald *et al.*, 2014). As marine water penetrates an estuary it forms an underlying saltwater wedge flowing upstream, over which fresh river water flows downstream, and can create strong stratification, but the waters can also become well mixed (Bird, 2008; Fitzgerald *et al.*, 2014; Hansen & Rattray, 1966; Montagna *et al.*, 2013). These variable water density flows can result in fine grained sediment that is transported out to sea by the freshwater being carried back into the estuary by the bottom currents of the salt wedge, and the accumulation of coarser sediments upstream beyond the salt wedge limit (Bird, 2008). These trends of flow through the tidal prism also shift in dominance depending on whether there is an incoming or outgoing tide (Bird, 2008; Fitzgerald *et al.*, 2014). The currents that pass through the mouth of an estuary are dependent upon the volume of water that enters and leaves through the tidal cycle, and this also determines the estuary discharge and flow velocities (Bird, 2008), again demonstrating the significance that tidal and sea-level changes have in an estuarine environment.

The salinity and mixing of water within estuaries can also influence sedimentation, whereby the meeting of positively and negatively charged particles within fresh and saltwater mix and attract, resulting in the flocculation of clay and increased sedimentation (Fitzgerald *et al.*, 2014). The estuarine turbidity maximum represents the location with high suspended sediment concentrations and the area in which clay particles or flocs rapidly settle. This region therefore has increased sedimentation and is often located within the inner estuary, with varying sediment concentrations depending on the estuary setting and tidal amplitudes (Fitzgerald *et al.*, 2014).

In funnel-shaped estuaries, such as the Humber, the flow of currents is further complicated through the Coriolis force, driving the in- and out-flows to flow in opposite directions (Bird, 2008; Fitzgerald *et al.*, 2014). The mixing of fresh and saline water and salinity distribution can also be modified on a localised scale by turbulence, strong winds and river flood events (Bird, 2008; Fitzgerald *et al.*, 2014). Active sedimentation is a key feature of coastal plain estuaries, whereby the area drowned by relative sea-level rise is progressively infilled by sediments. Sediment delivery can help build and stabilise wetlands and tidal flats, though the supply of sediment and accumulation can be forced by a variety of catchment, estuarine, marine and anthropogenic factors (Bird, 2008; Fitzgerald *et al.*, 2014; Montagna *et al.*, 2013; Olsen *et al.*, 2007), with resultant sediment sequences offering an insight into historical changes of the morphology of the estuary as well as sea-level changes.

As well as the main channel itself, the configuration of estuaries comprises several additional geomorphological components. At low tide, smaller ebb and flood channels are often revealed within the main channel (Bird, 2008). The larger tidal current shapes the position and dimensions of these, and their configuration can change rapidly (Bird, 2008), demonstrating the dynamic nature of estuaries. The shores of the estuary extend from the low spring tide level across the intertidal zone to the high spring tide level (Bird, 2008). The intertidal zone generally comprises the transition from sandflats, mudflats, shoals and bars, to saltmarshes or mangrove swamps (Bird, 2008; Fitzgerald *et al.*, 2014). The limit of the spring high tide is often represented either by the presence of a beach or transition to terrestrial vegetation (Bird, 2008).

Saltmarshes are generally fronted by the intertidal sand- and mudflats, with gentle slopes of vegetation with small cliffs subject to wave action and tidal channels, and are dissected by tidal creeks (Allen, 2000; Allen & Pye, 1992). The landward margin comprises a transition through freshwater swamps to land vegetation (Bird, 2008). Saltmarshes can change and migrate in response to relative sea-level changes along estuaries, and as such can provide a record of past marsh position in the tidal frame and sea-level change. The varieties of components present that provide habitats within estuaries, such as mudflats and saltmarshes, contributes to them being biologically rich and productive environments (Cooper, 1999).

2.2. Sea-Level Change

Sea-level change is a consequence of numerous factors acting at global, regional and local scales, incorporating terrestrial and marine influences, and at varying temporal scales (Gehrels & Long, 2008; Horton, 2007; Khan *et al.*, 2015a; Kopp *et al.*, 2015; Long, 2003; Rovere *et al.*, 2016; Figure 2.1) Contributing factors to sea-level change include ice sheet growth and decay, plate tectonics, thermal expansion of water, changes to tidal regimes and sediment supply, as well as meteorological changes (Gehrels & Long, 2008; Shennan *et al.*, 2012; Rovere *et al.*, 2016; Figure 2.1). These processes can act over millennia (e.g. ice sheet decay and resultant glacio-isostatic adjustment), or can be abrupt and instantaneous (e.g. earthquakes and resultant deformation (Garrett, 2013; Hamilton and Shennan, 2005)).

Sea level can vary due to vertical changes in the sea or land surface, or a combination of both these processes, that individually are traditionally referred to simply as eustasy and isostasy (Lowe & Walker, 2015; Gehrels & Shennan, 2015; Shennan *et al.*, 2003; 2012). However, major developments in the field of sea-level research have advanced understanding of the complex system of interrelated processes contributing to sea-level changes (Gehrels & Shennan, 2015). Vertical changes in land surface are known as isostatic change. Isostasy is the equilibrium within the Earth's crust that means a depression due to loading at a particular site, for example by ice or water, will be compensated by a rise elsewhere (Lowe & Walker, 2015; Milne & Shennan, 2007). The removal of the weight, such as ice decay, will therefore result in uplift, or rebound, at a location and is referred to as glacio-isostatic adjustment (GIA); this may also be triggered by a forebulge collapse. Based on the proximity of sites to former ice masses and loading, the globe can be characterised into six different zones (Clarke *et al.*, 1978). These reflect the trends of uplift, subsidence, or a combination of both processes (a transitional zone), and the expected relative sea-level history; the UK, for example, is located in the transitional zone (Clarke *et al.*, 1978; Horton, 2007; Figure 2.2).

Eustasy is the process of vertical changes in the world-wide sea-level surface, with respect to land surface, due to changing ocean basin and water volumes (Lowe & Walker, 2015; Murray-Wallace, 2007; Rovere *et al.*, 2016). The even distribution of water over a non-rotating and rigid planet would therefore represent eustatic sea level (Shennan, 2015; Mitrovica & Milne, 2003). However, changes to the ocean basin and water volumes are caused by numerous processes acting at differing spatial and temporal scales, such as steric changes (thermo- and halo-steric change), ice mass growth and decay (glacio-eustasy), tectonic and sedimentation processes altering ocean basin volumes (tectono- and sedimento-eustasy respectively), as well as differential mass distribution due to gravitational forces (geoidal-eustasy) (Lowe & Walker, 2015; Mörner, 1980; 1987; Rovere *et al.*, 2016; Shennan, 2015). As a result, eustatic sea level change cannot be measured directly, and it is unlikely that any location globally records only eustatic sea-level change through time, and thus the components that contribute are considered individually, such as ice-equivalent sea level (Rovere *et al.*, 2016; Shennan, 2015; Gehrels & Shennan, 2015).

Relative sea level can be considered as a change in the position of the sea relative to the land for a given location, and incorporates eustatic, isostatic, tectonic and local processes (Lowe & Walker, 2015; Milne & Shennan, 2007; Rovere *et al.*, 2016). Relative sea-level change at a given location at time t, where t is time relative to present, incorporates the components:

$$\Delta RSL(\phi, t) = \Delta EUS(t) + \Delta ISO(\phi, t) + \Delta TECT(\phi, t) + \Delta LOCAL(\phi, t) + \Delta UNSP(\phi, t)$$

where: $\Delta EUS(t)$ is the time dependent global changes in sea level from melt water; $\Delta ISO(\phi, t)$ is the total isostatic effect (glacio- and hydro-isostatic) and rotational contributions to the redistributions of ocean mass; $\Delta TECT(\phi, t)$ is the tectonic effect (though for the British Isles this is considered negligible on a Holocene timescale); $\Delta LOCAL(\phi, t)$ is the sum of the local coastal processes: tidal regime changes and elevation of the sediment (i.e. $\Delta LOCAL(\phi, t) = \Delta TIDE(\phi, t) + \Delta SED(\phi, t)$); and $\Delta UNSP(\phi, t)$ represents either unquantified or unacknowledged unspecified factors (Shennan *et al.*, 2012).

Consideration must therefore be given to all of the relative sea-level components to allow for a thorough understanding of sea-level change at any given location, past, present and future. It is important to decipher the varying signals of the global, regional, and local processes. Determining these contributions, and differentiating the processes, requires data that incorporates records from geologic proxies through to contemporary records from satellite altimetry (Kopp *et al.*, 2015).

Relative sea-level reconstructions provide vital data for the estimation of ongoing GIA, as well as for investigating the influence of tidal changes and sedimentary processes. It is also crucial from an anthropogenic perspective, as sea level affects coastal communities and their use of the coastal zone (Englehart & Horton, 2012). Successful integration of knowledge and data on the relative sea-level components, and the interpretations of both past, and crucially projecting potential future changes, is vital in terms of the management of coastal landscapes (Gehrels *et al.*, 2011; Kopp *et al.*, 2015; Long, 2003), as well as within the broader discourse on the impacts of climate change. Indeed, localised projections of sea-level rise are increasingly incorporating the network of contributing components, as are probabilistic methods of interpreting past changes; however, the effective use of projections in terms of adaption and planning for sea-level rise requires the development and adoption of new localised tools and risk assessments (Kopp *et al.*, 2015).

2.2.1. UK Sea-Level Change

The British Isles have contrasting and highly variable records of late Quaternary relative sea-level change around the coast, due to differential isostatic rebound following deglaciation after the Devensian glaciation (Bradley *et al.*, 2011; Lowe & Walker, 2015; Peltier, 1998; Shennan & Horton, 2002; Shennan *et al.*, 2000a; 2006; 2012). The differential glacio-hydro-isostasy around the British Isles is emphasised due to the former presence of ice in northern Britain, and absence in the south (Milne & Shennan, 2007). The former extent and thickness of the British and Irish Ice Sheet is shown in Figure 2.3.

Generally, in response to GIA following the decay of ice, sites closer to the centre of the ice mass have experienced relative land uplift due to the decay of ice, and those further from it relative subsidence due to collapse of the former glacial forebulge (Gehrels, 2010; Milne & Shennan, 2007; Figures 2.3; 2.4). This makes the UK a particularly interesting area to study in terms of sea-level change due to the differential responses and records that are concentrated into a relatively small area, particularly when considered on a global scale (Figure 2.5).

Predicted values of sea-level changes have been produced from various models, and numerous studies around the coast have provided reconstructed sea-level histories and index points (e.g. Edwards, 2006; Horton & Edwards, 2005; Massey *et al.*, 2008; Selby & Smith, 2007; 2015; Shennan, 1986; Shennan *et al.* 1995; 2000a; 2000b; 2005; Smith *et al.*, 2012; Wilson & Lamb, 2012; Figure 2.5). As would be expected, sea-level trends over the last 15000 years generally demonstrate the inverse of the glacio-isostatic trends, with relative sea-level fall in northern Britain, and rise in southern regions (Figures 2.5). However, in Scotland this relationship is more complex due to the proximity and loading of former ice giving varying and even contrasting trends between the western, northern, and eastern coasts (Figure 2.5).

The records in Scotland are further complicated due to the re-advancement of ice during the Loch Lomond Stadial, c. 12000 cal years BP, increasing ice-loading and slowing, or halting and potentially reversing, isostatic uplift and relative sea-level fall, though there is ambiguity over the spatial extent and mechanisms of variations in the uplift (Selby & Smith, 2007; 2015; Smith *et al.*, 2007; Shennan *et al.*, 2005). The production of relative sea-level data, in the form of sea-level index points, is crucial for constraining and validating models of vertical land movement and GIA, and for helping project future trends (Bradley *et al.*, 2011; Gehrels *et al.*, 2011). Constraining the contribution of GIA to relative sea-level records is useful as it provides constraints for other processes, such as the local ice sheet histories, as well as the global meltwater signal (Bradley *et al.*, 2011). However, there are also spatially variable regional and local factors to consider when interpreting or deriving Holocene sea-level records, such as tidal changes, and sediment compaction, all requiring consideration to provide a precise interpretation of the relative sea-level record (Brain *et al.*, 2011; Horton & Shennan, 2009; Shennan *et al.*, 2000a).

Tide gauge records provide more recent, contemporary, records of relative sea-level change, over the last c. 200 years. Based on the analysis of records from the UK and western European coasts, an acceleration of sea-level rise by 0.013±0.0035 mm a^{-1} over the last c. 150 years has occurred (Ezer *et al.*, 2016), though there is similar spatial variability to that shown in geological records (Ezer *et al.*, 2016; Woodworth *et al.*, 2009). However, within these measured tide gauge records there are also oscillations occurring on interannual and decadal timescales. These have been attributed to the influence of air pressure variations, and particularly the North Atlantic Oscillation and Atlantic Multi-decadal Oscillation (Ezer *et al.*, 2016; Woodworth & Menéndez, 2015). The published records clearly demonstrate the disparity and complexities in sea-level changes that have occurred around the UK, even between relatively close locations, and that sea-level changes should be established at local levels to enable effective shoreline management (Gehrels, 2010).

2.3. Sea-Level Reconstruction

There are numerous approaches and techniques that can be used for reconstructing relative sea-level change, including the analyses of geomorphological, lithological and microfossil evidence. Reconstructions can be based upon geomorphological features, such as raised beaches, and stratigraphic boundaries within sediment sequences, that indicate changing environments and sea level (Horton & Edwards, 2005; Tooley, 1982). However, a major limitation of such features is that they are often inappropriate for the production of a high resolution relative sea-level record due to slow response times, uneven spatial and temporal distribution, and absence of records for the Holocene and more recent (past millennia) changes (Edwards, 2001; Horton & Edwards 2005). As such, detailed study of litho- and biostratigraphy, particularly microfossils such as diatoms and foraminifera, provide a suitable additional method for relative sea-level reconstructions (Edwards, 2001; Horton & Edwards 2005).

2.3.1. Microfossils as Sea-Level Proxies

Semi-quantitative and quantitative approaches, such as the generation of sea-level index points and the development of transfer functions, rely on data from a variety of different indicators or proxies, such as sediment stratigraphy, macrofossils and microfossils, including diatoms, pollen, and foraminifera.

Microfossils have been used in a variety of coastal settings around the world to produce sea-level records of varying temporal scale, spanning the duration of the Holocene as well as more recent, centennial scale fluctuations. For example, sea-level index points and transfer functions utilising foraminifera have produced relative sea-level records for a variety of sites around the UK (e.g. Edwards & Horton, 2006; Gehrels *et al.*, 2001; Horton & Edwards, 2005; 2006; Shennan *et al.*, 2000) as well as elsewhere in the world (e.g. Gehrels, 1994; Leorri *et al.*, 2008; Wang & Chappell, 2001). Diatoms have similarly been used in both the UK (e.g. Gehrels *et al.*, 2001; Selby & Smith, 2007; 2015; Shennan *et al.*, 2000; 2005; Wilson & Lamb, 2012) and around the world (e.g. Hamilton & Shennan, 2005; Watchman *et al.*, 2013; Woodroffe & Long, 2009; 2010) to examine sea-level histories. Employing a multi-proxy approach can result in improved accuracy and precision in reconstructions, though this may be a disproportionate gain to the time and resources required for such analyses (Gehrels *et al.*, 2001).

2.3.2. Diatoms

Diatoms are unicellular algae, within the Division Bacillariophyta, that are ubiquitous within both marine and freshwater aquatic environments, forming approximately 80% of the world's primary producers (Battarbee *et al.*, 2001; Lowe & Walker, 2015; Stoermer & Smol, 1999). Diatom cell walls are siliceous and provide rigidity, aid preservation of frustules as fossils, and the patterned walls provide taxonomic identity of living and fossil diatoms (Battarbee *et al.*, 2001; Round *et al.,* 1990).

The siliceous composition of diatoms results in a high preservation potential within fossil sediments, particularly fine-grained sediments that minimise damage (Anderson *et al.,* 1997; Gehrels, 2007; Lowe & Walker, 2015; Stoermer & Smol, 1999). The taxonomy and preservation potential therefore make diatoms a useful proxy within paleoenvironmental reconstructions of long-term change, however their short lifespans and rapid regeneration ability also allows them to be used for investigating centennial scale environmental changes (LeBlanc *et al.*, 2004; Platt Bradbury, 1999). The use of diatoms for quantitative environmental reconstructions has been enhanced over recent decades through improvements in dating, sediment sampling, coring and collection methods, as well as developments in numerical techniques (Battarbee *et al.*, 2001).

The role of salinity as a forcing factor on diatom assemblages is well recognised (Denys & de Wolf, 1999; Lowe & Walker, 2015; Zong & Horton, 1999). The classification of diatoms in relation to salinity has been used to reconstruct sea-level changes in coastal and estuarine environments (e.g. Hamilton & Shennan, 2005; Long *et al.*, 1998; Woodroffe & Long 2009; 2010; Zong & Horton, 1999). The strong relationship between diatom assemblage composition and salinity along the entire salinity gradient from fresh to hypersaline, as well as their potential to indicate sediment input from fluvial and marine systems and sensitivity to other environmental factors, such as water chemistry and hydrodynamic conditions, make them particularly well suited to the reconstruction of former coastal conditions and sea-level histories (Denys & de Wolf, 1999; Gehrels, 2007; Lowe & Walker, 2015; section 2.3.1). Changes in diatom species composition within sedimentary sequences allow past sea levels to be reconstructed as diatoms respond rapidly to changes in the salinity of water (Allen, 1995; Edwards & Horton, 2000; Horton & Edwards, 2005; Horton *et al.*, 2000; Long, 1992).

As estuaries represent the meeting of marine and freshwater (section 2.1), they comprise marine, freshwater as well as transitional brackish environments, which will be reflected in the diatom species and communities for the various zones and conditions. Rivers will bring freshwater diatoms into an estuarine system, and marine diatoms can be transported into brackish areas through tidal action (Cooper, 1999). Within the currents and tides planktonic and tychoplanktonic species will be present; epiphytic species grow attached to vascular plants and algae, epipelic species shift vertically in the upper few millimetres of muddy sediments; epilithic species occur in rocky areas; epipsammic species occur attached to sand grains, and aerophile species are subaerial and can occur in the supratidal zone (Cooper, 1999; Vos & de Wolf, 1993).

Diatom species can be classified into the ‘halobian system’ based on salinity ranges and tolerances (Cooper, 1999; Snoeijs, 1999). There are five halobian classification groups: polyhalobian (marine), mesohalobian (marine-brackish), oligohalobian-halophilous (brackish), oligohalobian-indifferent (fresh-brackish) and halophobous (fresh) (Hustedt, 1953; 1957; Lowe & Walker, 2015; Ridgway *et al.*, 2000). Across marsh transects in the UK, including in estuaries, this relationship has been clearly demonstrated, with marine and brackish diatoms located in the tidal flats, mixed salinity diatoms in the low-marsh, and salt-intolerant and fresh diatom species in the high-marsh (Gehrels *et al.*, 2001; Zong & Horton, 1999). Due to the tidal nature of estuaries and coastal environments though, both autochthonous and allochthonous diatoms are present in assemblages i.e. those that originate within and represent the local in-situ environment, and those that have originated and been transported from elsewhere. This is a common problem for palaeoenvironmental interpretation (Sawai, 2001; Vos & de Wolf, 1993). There is not an accepted, universally applied method for distinguishing the autochthonous and allochthonous components of a fossil assemblage, however there are a number of proposed methods (e.g. Beyens & Denys, 1982; Vos & de Wolf, 1993). However, these too can be problematic in terms of accurately distinguishing the autochthonous component rather than other processes (such as chemical dissolution and sample treatment) that could also result in misinterpretation (Beyens & Denys, 1982; Sawai, 2001; Vos & de Wolf, 1993).

As diatom species have specific environmental tolerances, estuarine sedimentary records that preserve diatoms therefore provide an insight into the changes that have occurred in the estuary, including sea-level changes. However, given the nature of estuarine environments, sediments are at risk of re-suspension and transport, and preservation and taphonomic processes can additionally affect the assemblages and interpretation (Cooper, 1999; Sherrod *et al*., 1989). Diatoms can be exposed to both chemical and mechanical processes within estuaries that result in a biased preservation of the more heavily silicified and robust species (Cooper, 1999; Sherrod *et al*., 1989). In particular, those from fluvial inputs have on average greater silica content than marine species, and there are also differences in the silification between benthic and planktonic species (Conley *et al.*, 1989; Cooper, 1999). The fragmentation and dissolution of more delicate and weakly silicified taxa, therefore, affects the taphonomy of a diatom assemblage, potentially to the extent that the preserved assemblage does not reflect the actual palaeoenvironment (Sherrod *et al.*, 1989). The interpretation of diatom assemblages must therefore include consideration of potential preservation and taphonomic processes, as well as allochthonous components, particularly in saltmarsh and estuarine systems (Sawai, 2001; Sherrod *et al*., 1989; Vos & de Wolf, 1993).

In the context of the Humber Estuary, diatoms have been successfully used in the production of sea-level data through the Holocene (e.g. Long *et al.*, 1998; Metcalfe *et al.*, 2000). However, their preservation is sporadic both along the estuary and within sites (Metcalfe *et al.*, 2000) so the use of other indicators, such as foraminifera, may be necessary to produce a complete record.

2.3.3. Foraminifera

Foraminifera are unicellular protists found in most marine environments (Gehrels, 2007; Lowe & Walker, 2015). Foraminifera are a useful microfossil to complement diatoms as sea-level indicators, as when present in saltmarsh and intertidal environments, foraminifera generally have a high abundance, whilst the species diversity is low, assisting in the development of high resolution records (Gehrels, 2002; 2007; Kemp *et al.*, 2009).

Distinct intertidal zonation of foraminifera distribution within saltmarshes, dependent upon position within the vertical tidal regime, is well recognised (Scott, 1976; Scott & Medioli, 1978; 1980). It is this relationship between foraminifera distribution and tidal inundation extent that can be assessed within the contemporary environment and which can be compared to preserved fossil assemblages to determine former position on a palaeomarsh surface, and thus former relative sea level. As with diatoms, this relationship of foraminifera species to position within a tidal frame in intertidal environments enables them to be used as a proxy for reconstructing sea-level histories (e.g. Barnett *et al.*, 2015; Gehrels, 1994; 1999; Gehrels *et al.*, 2001; Horton & Edwards, 2005; 2006; Kemp *et al.*, 2009; 2013; Leorri *et al.*, 2008; Stephan *et al.*, 2015).

Although the distribution of foraminifera species can be influenced by environmental factors such as pH and salinity, canonical correspondence analysis has demonstrated that elevation within the tidal frame has the strongest relationship with species distribution (Horton & Edwards, 2006), and Horton *et al.* (1999) have demonstrated this relationship in the intertidal environments of the UK. The elevation within the tidal frame therefore ultimately controls the tidal inundation, in terms of duration and frequency, and thus the other environmental factors such as pH and salinity (Horton & Edwards, 2006; Kemp *et al.*, 2009). Foraminifera are, therefore, an accurate sea-level indicator, particularly in temperate coastal regions such as the UK, and provide a strong relationship to relative sea level (Horton & Edwards, 2006; Leorri *et al.*, 2008; Scott & Medioli, 1978; 1986).

2.3.4. Stratigraphy

A rising sea level would usually be predicted to lead to a landward expansion of saltmarsh and marine conditions (Dinnin & Lille, 1995). This would be reflected within the lithostratigraphy and biostratigraphy as a progression from dry land surface, to fen and reedswamp peats, with terrestrial sediments being replaced by intertidal and marine sediments (Dinnin & Lille, 1995; Tooley, 1982). Such a sequence is referred to as a transgressive overlap, with the reverse sequence, a regressive overlap, observed when there is a reduction in marine influence and shallowing of water (Shennan, 1982; Tooley 1982). When observed across an area between a series of cores, these are referred to as transgressive or regressive overlaps, and as contacts when observed within a single core (Shennan, 1982; Tooley, 1982). However, such sequences are frequently more complex due to fluctuations in sea level, groundwater table, sediment supply and accommodation space, and the prediction of such sequences assumes continuous sedimentation and therefore no hiatus in the sequence (Dinnin & Lille, 1995; Shennan, 1980; 1982; Tooley, 1982). Indeed, a transgressive or regressive overlap is a descriptive term and does not independently indicate a change in the vertical sea level, but rather a process that could be attributed to several factors (Shennan, 1980; 1982; Tooley, 1982).

The response of the coastal system to a change in sea level will have direct and indirect impact on the deposition in marshes, with the vertical accretion of marshes controlled by the complex responses of the sediment and vegetation (Reed, 1995). Sedimentation rates must therefore be considered, as the rate of sea-level change can directly influence the rate of sedimentation. For instance, the rate of peat accumulation may be greater than that of sea-level rise resulting in no evidence of the sea-level rise being recorded, to the extent that despite an accelerated rise in sea level, a shoreline advance may occur and be recorded in the stratigraphic record (Dinnin & Lille, 1995; Gerrard *et al.*, 1984). Similarly, peat and clastic sediments can undergo compaction, and can result in misinterpretation of the former altitudes of sea levels, complicating the calculation of the rates of sea-level change and sediment accumulation, and requiring corrections to be made to allow for compaction processes (Brain, 2016; Dinnin & Lille, 1995; Massey *et al.*, 2008; Shennan *et al.*, 1994; Tooley, 1978). A further complication to establishing rates of sedimentation, particularly in an estuary setting, is the changing morphology. In the Humber Estuary, the formation of Spurn Point at the mouth of the estuary will have resulted in changes to sedimentation and tidal flow (de Boer, 1964; Dinnin & Lille, 1995). Indeed, coastal stratigraphies can record both local and non-local variables, and terrestrial and fluvial processes must be considered along with sea level (Long, 2003). Intercalated and semiterrestrial peats, intertidal silts, clays and sands that accumulate in estuaries and coastal lowlands of the eastern coast provide the most comprehensive sea-level change records (Shennan, 1992), and are among the sediment sequences encountered on the Humber Estuary (e.g. Long *et al.*, 1998; Metcalfe *et al.*, 2000).

2.3.5. Sea-Level Index Points

A sea-level index point represents the position of relative sea level within space and time and is obtained through the combination of litho-, bio- and chrono-stratigraphic data (Edwards, 2006; Edwards & Horton, 2000; Horton *et al*, 2013). To produce a sea-level index point from a sediment, its age, altitude, tendency and indicative meaning (the modern counterpart height to relative sea level) are required (Barlow *et al.* 2013; Edwards & Horton, 2006; Gehrels, 2007; Horton *et al.*, 2013; Long, 1992; Shennan, 1982). The indicative meaning is important in order to account for the range in altitudes of coastal sedimentary features (Edwards & Horton, 2006). The indicative meaning represents the relationship of the environment in which a sample accumulated to a contemporaneous reference tide level, and can vary depending on the evidence used to establish it (van de Plassche, 1986; Shennan *et al.*, 2000).

The identification of small-scale changes in biostratigraphy within intertidal sediment sequences offers the potential for higher resolution reconstructions of sea level, by providing improved constraints on the indicative meaning (Horton & Edwards, 2005). Sea-level index points are obtained from the contacts between the peat and silt/clay beds that form high in the intertidal zone, and represent transgressions and regressions (Gehrels, 2007). By additionally considering the biostratigraphy, such as diatoms, to determine the indicative meaning and range, the sea-level index point can be further quantified (Gehrels, 2007).

An advantage of adopting a combined lithological and microfossil approach is that microfossils in general respond rapidly to changes in sea level, providing relatively high-resolution records of change, whereas lithological features respond less rapidly and at lower resolution (Allen, 1995; Edwards & Horton, 2000; Horton *et al.*, 2000; Long, 1992). However, a disadvantage of deriving sea-level index points from intercalated, peat-silt/clay contacts is that they may be displaced downwards due to sediment compaction, and therefore not accurately represent former sea level (Gehrels, 2007; 2010). This issue can be rectified or reduced through the derivation of sea-level points from basal peat, though this may still only provide sea-level limiting positions (Gehrels, 2007).

Potential errors must be incorporated into sea-level reconstructions, such as errors introduced through surveying to determine altitude and sediment compaction (Barlow *et al.*, 2013). Failure to quantify and acknowledge such errors, particularly sediment compaction, will result in inaccurate estimates of both the magnitude and rate of sea-level change (Barlow *et al.* 2013; van de Plassche *et al.*, 1998). Increasingly studies are incorporating methods for correcting, or ‘decompacting’, sediment compaction, with the methods varying depending on the type of sequence (Barlow *et al.*, 2013; Brain, 2016; Brain *et al.*, 2011; 2012; 2015; Edwards, 2006; Horton & Shennan, 2009; Horton *et al.*, 2013; Massey *et al.*, 2006a; Shennan & Horton, 2002). In the Humber Estuary, sea-level index points from intercalated peats often fall below those from basal units and modelled relative sea-level curve, demonstrating the role of compaction (Horton & Shennan, 2009). The compaction has been shown to have a strong relationship to the depth of overburden of sediment in the Humber Estuary (Horton & Shennan, 2009). As such, any reconstructions must consider the potential role of compaction, and apply appropriate corrections to ensure the most accurate determination of sea-level change for the Humber Estuary.

2.3.6. Transfer Functions

Transfer functions are founded on the theory of uniformitarianism, developed by Hutton (1788). Uniformitarianism assumes that the present is the key to the past, so therefore processes that are presently active on Earth can be used to explain past changes. Based on this, transfer functions can be developed from the analysis of the quantitative contemporary biostratigraphic data, such as diatoms and foraminifera, and used to reconstruct particular environmental variables based upon fossil biostratigraphic data (Imbrie & Kipp, 1971).

The transfer function approach essentially allows for the expression of an environmental variable as a function of biological data. Transfer functions achieve this through two stages: regression calculations are utilised to model the response of contemporary assemblages as a function of the environmental variable; calibration then applies this response function to predict the past environmental variable based upon the fossil assemblage (Birks, 1995). In this research, the environmental variable to be reconstructed is the former intertidal position in relation to the tidal frame, which in turn provides the sea-level altitude.

The response function produced by the regression calculations can be either a linear response or a unimodal response model (Birks, 1995; Horton & Edwards, 2006). Unimodal responses assume normalised clustering around the environmental variable, with the species optima for the environmental variable closest to the site represented by the most abundant species, which is generally the case for most species (Birks, 1995). A unimodal distribution of diatom and foraminifera abundance in coastal settings around the UK has been demonstrated (Zong & Horton (1999) and Horton & Edwards (2006) respectively). A statistical approach that produces a unimodal response is Weighted Averaging-Partial Least Squares (WA-PLS). This considers the variance along an environmental gradient, with each species assigned an ecological optimum, recording the environmental variable it lies within, as well as its preferred position and ecological tolerance (Birks, 1995). It also takes into account residual correlations among the biological data (Birks, 1995).

Transfer functions can generally be considered as an improvement on the production of sea-level index points as they increase the range of sedimentary environments for which data can be collected, and provide quantified reconstructions with defined errors to a decimetre-scale resolution, as well as objective, consistent and replicable use of data (Edwards *et al.*, 2004; Edwards & Horton, 2006; Woodroffe, 2009; Woodroffe & Long, 2009). However, there are several assumptions inherent within the use of transfer functions. Transfer functions assume that the environmental variable of reconstruction has had a consistent role in forcing species distribution, and other variables have not exerted additional force or distorted distribution (Birks, 1995; Horton & Edwards, 2006). It is also assumed that the composition of the contemporary assemblages is representative of the fossil assemblages (Birks, 1995). As such, both assumptions must be assessed to evaluate the reliability of a transfer function and any resultant reconstructions.

There are also additional factors that can influence the reliability and accuracy of the reconstructions, dependent upon the standardisation and composition of the contemporary training sets, adequate and robust statistical methods, and suitable selection of the regression model (Gehrels, 2000; Birks, 1995). Due to the assumption that the contemporary training set is representative of the fossil assemblage, the composition of the former can have consequences on the precision and accuracy of the resulting transfer function (Gehrels *et al.*, 2001; Horton & Edwards, 2006). The robustness of the transfer function is dependent upon the selection and location of contemporary training sets, and whether single site or multiple site contemporary sets are used, providing transfer functions of varying spatial scale (e.g. Horton & Edwards, 2005; Woodroffe & Long, 2010; Zong *et al*., 2003). There are also additional issues depending on the tidal range of sites and the resultant errors, which can be particularly problematic when producing reconstructions from macrotidal settings (e.g. Barlow *et al*., 2013; Mills *et al*., 2013). As well as this, there are also the errors such as compaction and surveying that need consideration when producing and interpreting the reconstructions (section 2.3.5).

Incorporating a transfer function into the methodology of creating sea-level reconstructions for the Humber Estuary will aid in assessing their utility and suitability for use in an estuarine environment, particularly due to modifications and urbanisation limiting the opportunity to develop a local scale training set (e.g. Wilson & Lamb, 2012). Indeed, a study using a diatom transfer function on the Mersey Estuary, UK, lacked modern analogues and as such the palaeo-tide estimates produced were unreliable (Wilson & Lamb, 2012), whereas they have been applied to some relative success in the macrotidal Severn Estuary, UK (Elliot, 2015; Hill *et al.*, 2007).

2.3.7. Chronology

There are a variety of techniques that can be used to establish a chronology of sea-level change. Developing a robust chronology is crucial for determining the rate of any sea-level changes, but also for comparison with other records, as well as for assessing any mechanisms that may be contributing the change (Barlow *et al.*, 2013). Radiocarbon dating is suitable for sediments of late Holocene age (though not ideally for materials younger than 500 years), and is widely used when dating various carbon-containing materials (Barlow *et al.*, 2013; Jull, 2007).

Advances in radiocarbon techniques in particular allow for the dating of small sized samples, reducing uncertainties, but also allow the production of multiple dates throughout a core (Barlow *et al.*, 2013). As such, if multiple radiocarbon dates are available from a core, an age-depth model can be produced, allowing the extrapolation of a chronological framework for an entire sequence (Barlow *et al.*, 2013). When considered carefully together with the litho- and biostratigraphical data, a dated reconstruction of the sequence, through using either specific dated levels or an age-depth model, can be established (Barlow *et al.*, 2013). However care must be taken to ensure that the reconstructed sea-level changes represent actual sea-level changes, rather than the result of extrapolation (Barlow *et al.*, 2013). The establishment and use of radiocarbon dates are discussed extensively in the methodology (sections 5.2.4; 5.2.5).

2.4. Summary

This chapter provided an overview of estuaries and sea-level change. The context, key processes and complexities of estuarine environments were examined. The processes and scale of sea level and relative sea-level change were explored, as well as the drivers and spatial variability of Holocene relative sea-level change around the UK. Methods of sea-level reconstruction were also discussed and summarised, including the use of microfossil proxies, the establishment of a chronology, and the theory and construction of sea-level index points and transfer functions.

3. Groundwater and Sea-Level Change

This chapter provides an overview of groundwater in coastal aquifers, key hydrogeological processes, and the use of groundwater as a resource. The relationship of sea level and groundwater is then examined in terms of the risk posed to groundwater resources from saline intrusions due to abstraction and changing sea level. Methods of how to model the groundwater environment and the response to changing sea levels are also outlined.

3.1. Groundwater

Groundwater is all water that is in the saturated zone below the ground surface, and is in direct contact with the ground or subsoils (European Union, 2000). This definition is important, as it is the one used within legislation dictating the management that aims to protect and improve water quality.

Groundwater is the second largest reservoir of freshwater, after snow, glaciers and ice caps, representing approximately 30% of available freshwater (Fitts, 2002). Groundwater is an integral component of the hydrological cycle, and due to the relative accessibility to humans, is also integral societally and economically, as a potable water supply and for industrial and agricultural uses (Anderson, 2014; Environment Agency, 2012; Fitts, 2002; Quevauviller, 2008). In the UK, groundwater generally requires less treatment than surface water; three-quarters of the groundwater abstracted from boreholes and springs is used for public supply, with groundwater supplying approximately one third of mains potable water within England (Environment Agency, 2012), making it a crucial resource.

Within the subsurface, there are three zones in which water can exist. In the unsaturated zone, the pore space contains a mix of air and water, and the water pressure is less than atmospheric pressure (Fitts, 2002). At the water table, pore water pressure is equal to atmospheric pressure (Fitts, 2002). Below the water table is the saturated zone, where the pore spaces are saturated with water, and the pore water pressures exceed atmospheric pressure; it is the water in the saturated zone that is considered groundwater (European Union, 2000; Fitts, 2002).

3.2. Aquifers

An aquifer is a saturated permeable subsurface layer or geological unit that has sufficient permeability and porosity that allows either the significant flow of groundwater, or the abstraction of economic quantities of groundwater (European Union, 2000; Kruseman & de Ridder, 2000). Aquifers are comprised of unconsolidated materials or consolidated rocks, and it is the aquifer parameters, dictated by the characteristics of the rock and the processes it has been subjected to, that dictates the groundwater processes, such as the flows (Quevauviller, 2008).

Central to the hydrogeology and groundwater processes is the hydraulic head. In response to an uneven distribution of energy, caused via pressure or elevation, water flows from the area with the highest mechanical energy towards the area of lower energy (Fitts, 2002). Hydraulic head is a measure of this, parameterising the energy per weight of water, with groundwater always flowing towards the region of lower hydraulic head (Fitts, 2002; Quevauviller, 2008). Groundwater flow is also dependent upon a number of factors other than the hydraulic head though, for example, the hydraulic gradient (the rate at which the hydraulic head changes with the direction of flow), the porosity (the volume of pore space) of the aquifer, as well as the hydraulic conductivity (ease that the material transmits water). The hydraulic conductivity can be measured over the thickness of the geological layer, and this is referred to as the transmissivity (Environment Agency, 2012; Fitts, 2002).

Darcy's law is a representation of the basic empirical principles of groundwater flow, incorporating the hydraulic conductivity (K_s), gradient (dh/ds) and cross sectional area (A) to produce a discharge value (Q_s) in the direction s (Anderson, 2014; Environment Agency, 2012; Fitts, 2002):

$$Q_s = - K_s \, (dh/ds) \, A,$$

Darcy's law states that the rate of flow is proportional to the loss of hydraulic head, whilst inversely proportional to the length of flow (Kruseman & de Ridder, 2000). The groundwater flows however can be complicated by obstructions or changes in rock type, as well as by the presence of cracks or fissures; this can result in variations in speed, potentially up to kilometres per day (Environment Agency, 2012).

Water that infiltrates the subsurface is classed as infiltration (Fitts, 2002). The water that then passes through the unsaturated zone and into the saturated zone is recharge (Fitts, 2002). The amount of recharge is dictated by the permeability of the materials overlying the aquifer, and as such, aquifers can be classed as unconfined or confined. In aquifers that are unconfined, the water table is exposed to infiltration and recharge due to permeable overlying material; aquifers that are confined are overlain by low permeability material (Environment Agency, 2012).

The process of water filtering through the overlying layers to reach the groundwater, along with the generally slow rate of flow and longer residence time, in comparison to surface water, can result in increased purity due to the attenuation of contaminants (Environment Agency, 2012; Quevauviller, 2008). However, once contaminants or saline waters have entered the groundwater system, the effects can be long lasting and difficult to remove (Environment Agency, 2012; Quevauviller, 2008).

3.3. Sea Level and Saline Intrusion

In coastal areas, saltwater intrusion into the aquifer and groundwater can occur. Saline water is denser than freshwater, resulting in freshwater floating on top, with a mixing interface present below (Anderson, 2014; Environment Agency, 2012). Saline intrusion, and the potential extent, is dependent upon the local groundwater flow regime, geology, as well as anthropogenic abstraction (pumping) and activities, producing a complex relationship that is challenging to predict (Anderson, 2014; Environment Agency, 2012; Ferguson & Gleeson, 2012; Ketabchi *et al.*, 2016).

The over-pumping of groundwater from aquifers in coastal areas can result in an induced flow of saline water, and a saline intrusion into the aquifer, limiting the freshwater supply (Anderson, 2014; Chadha, 1986; Hutchings & Tarbox, 2003; Liu, 2002). This is further complicated and potentially emphasised by the threat posed by climate change and rising sea levels, altering the natural extent of intrusion, as well as the ongoing demands on potable water supplies through population growth (Anderson, 2014; Beebe *et al.*, 2011; Ferguson & Gleeson, 2012; Oude Essink, 2001; Yusef *et al.*, 2016). For example, in the coastal regions of California, USA, sea-level rise has been demonstrated to pose the risk of emergence and flooding of groundwater, with saline intrusion of the groundwater continuing to be a major problem for the communities using the groundwater (Hoover *et al.*, In Press). This poses a major threat to the groundwater resource due to the difficulty in reversing the intrusion (Beebe *et al.*, 2011; Ferguson & Gleeson, 2012; Oude Essink, 2001; Quevauviller, 2008; Vafaie & Mehdizadeh, 2015).

The Ghyben-Herzberg relationship estimates the depth of fresh-saltwater interface and makes several assumptions, including that the freshwater head is equal to sea-level elevation at a shoreline, as well as there being no mixing at the fresh-saltwater interface, and no resistance to vertical flow in the waters (Anderson, 2014; Fitts, 2002). Though such assumptions are not true in all cases, this relationship can often provide good simulations of conditions (Fitts, 2002), and with regards to sea-level change the relationship of freshwater head and sea-level elevation is critical. Indeed, a rise in sea level has been demonstrated to result in more saltwater intrusion, and depending on the rate of rise, can intrude significantly further than present (e.g. Vafaie & Mehdizadeh, 2015). Based on average fresh- and saltwater densities, the Ghyben-Herzberg relationship can be simplified to:

$$z_s = 40h,$$

whereby z_s is the depth of freshwater below the sea level, and h is the height, or head, of freshwater above the sea level (Fitts, 2002).

The mixing of freshwater and saltwater from saline intrusions can result in saline to brackish groundwater within the aquifers (Moore, 1999). The general behaviour is for coastal aquifers to discharge freshwater into the coastal system (Anderson, 2014). In circumstances of abstraction or over-abstraction of groundwater, the inland hydraulic head may fall creating a cone of depression and gradient reversal, resulting in saltwater intruding inland into the aquifer and groundwater system, resulting in increased salinisation (Anderson, 2014; Burt, 1993; Chadha, 1986; Hutchings & Tarbox, 2003; Liu, 2002; Moore, 1999; Quevauviller, 2008; Smith, 1994).

Sea-level rise has also caused an increased salinisation of coastal aquifers (Anderson & Al-Thani, 2016; Moore, 1999; Vafaie & Mehdizadeh, 2015; Wassaf & Schüttrump, 2016). Within estuary environments, the interactions of groundwater and the surface waters produce temporally and spatially variable systems, due to the various processes and parameters involved (Westbrook *et al.*, 2005). The effects of groundwater use, the movement of groundwater, and the potential influence of sea level on the quality of water abstracted are, therefore, important to assess and consider to enable appropriate use and resource management.

Within estuaries, the density difference between fresh, brackish and saline waters results in mixing and convective circulation at the groundwater discharge boundary, and an intrusion of denser saltwater into adjacent coastal aquifers (Environment Agency, 2012; Westbrook *et al.*, 2005). A surficial mixing zone, or 'hyporheic zone', can also be formed due to tidal activity inducing infiltration of surface waters into the sediments (Environment Agency, 2012; Westbrook *et al.*, 2005). A conceptual model of the interaction of estuaries and groundwater is shown in Figure 3.1. In fractured Chalk aquifers such intrusions can extend rapidly inland, and are a complex and unpredictable process (Environment Agency, 2012).

3.4. Groundwater Modelling

The ability to model groundwater systems enables the simulation of the systems and environments, aiding the understanding of processes, but also allows examination of the modification of systems, such as due to the spread of contaminants or the effects of abstraction. This is particularly critical as European Legislation seeks to improve and protect the quality of water, due to increasing demands for sufficient quantities of good-quality water (European Union, 2000).

Sea-level changes can potentially affect the quality of the groundwater resource, and is particularly an issue in areas where abstraction occurs in a coastal setting. There have been multiple studies from a variety of coastal and groundwater environments considering the processes (e.g. Delsman *et al*., 2014; Hutchings & Tarbox, 2003; Langevin, 2003; Langevin *et al.*, 2005), saline intrusion (e.g. Adhikary *et al*., 2011; Beebe *et al*., 2011; Chesnaux, 2015; Lautz & Siegel, 2006; Liu, 2002; Mantoglou, 2003; Oude Essink, 2001; Prandle, 2004; Robinson *et al*., 2007), and the role of abstraction (e.g. Anderson & Al-Thani, 2016; Mantoglou, 2003; Wassef & Schüttrump, 2016). Such studies offer an insight into the suitability, scale, and also complexities, of differing modelling techniques of a groundwater system.

A model can be considered as a representation of a system, and the behaviours, characteristics and processes within that system. This can take several forms, from conceptual, to analytical and numerical models of systems. The development and advancement of computer modelling has allowed for the simulation of more complex and large systems, such as aquifers and groundwater, however, the initial conceptual stage is vital for identifying the feasibility and accuracy of complex numerical models (Brown & Hulme, 2001; Fitts, 2002; McMahon *et al*., 2001). The development and use of conceptual and numerical groundwater models are discussed extensively in the methodology (section 5.8).

3.5. Summary

This chapter provided an overview and context of groundwater and aquifers, and discussed the relationship of coastal aquifers and groundwater to sea-level change. Key hydrological processes and theories were discussed, including Darcy's Law and the Ghyben-Herzberg relationship. Saline intrusion, and the relationship to sea-level change and groundwater abstraction, was also examined, along with the potential implications of such intrusions on the environment and groundwater as a resource, particularly in the context of climate change and population growth. Methods of groundwater modelling were also introduced.

4. The Humber Estuary

The following chapter provides a detailed overview of the Humber Estuary. It provides a general background and context of the estuary, followed by a description of the geology and glacial history of the region. The existing record of Holocene relative sea level for the estuary is reviewed, as well as anthropogenic reclamation within the estuary. The aquifer and history of groundwater abstraction adjacent to the estuary is detailed, with reference to the Springhead groundwater abstraction site, the site for which the impact of sea-level change and abstraction on the groundwater is studied in this thesis.

4.1. Background

The Humber Estuary is a coastal plain estuary located on the eastern coast of England, forming part of the southern boundary between Yorkshire and Lincolnshire (Figure 1.1). It has a catchment area of 26,109 km^2, approximately 20% of the area of England, making it the largest estuarine system in England (Environment Agency, 2009a; Jarvie *et al.*, 1997; Jickells *et al.*, 2000). The intertidal estuary itself extends from Spurn Point on the coast to the confluence of the River Ouse and River Trent, approximately 60km inland (Figure 1.1); these two main contributing rivers remain sub-tidal inland, giving a total tidal length of 140km (Jickells *et al.*, 2000; Long *et al.*, 1998). The Humber Estuary is a funnel-shaped macrotidal estuary, with a tidal range of up to 7.4m at certain localities (Bird, 2008; Humber Management Scheme, 2013); it has an average width and depth of 4.3km and 6.5m respectively (Humber Management Scheme, 2013), though this increases to 6.6km and almost 20m at Spurn Point (Jickells *et al.*, 2000).

The Humber Estuary experiences an average input of freshwater of $244m^3s^{-1}$, and has a yearly discharge range of 165 to $320m^3s^{-1}$ (Pontee *et al.*, 2004). The mean flow of the estuary is $250m^3s^{-1}$ and is highly turbid, with suspended loads ranging from 200mg L^{-1} up to 20g L^{-1}, limiting primary productivity; residence times of solutes are approximately 2 months during the summer, though this declines in winter (Jickells *et al.*, 2000). Though classified as a well-mixed estuary, under specific tidal and flow conditions it can be partially mixed, and there are spatial and temporal variations in the influence of fresh and marine water (Pontee *et al.*, 2004).

Human activity has perturbed both the catchment and estuary itself. For example, the composition of the water within the estuary has a mean flow weighted nutrient concentrations of ~500μmol L^{-1} nitrate and ~50μmol L^{-1} ammonium, and over 90% of the intertidal estuary and sediment accumulation capacity has been reclaimed over the last millennia (Jickells *et al.*, 2000), resulting in a significantly altered and managed environment. Currently, the estuary is an important industrial area, with several ports, such as the ports of Hull, Immingham and Grimsby providing shipping links, and industries along the estuary include oil refineries and chemical plants, as well agriculture. As a result, over the last few decades, the Humber Estuary has become subject to a number of national and European legislations, such as the Water Framework Directive (European Union, 2000); management plans through public bodies such as the Environment Agency and the local water authorities, as well as acquiring a number of conservation statuses, including RAMSAR and Special Area of Conservation (SAC). These forms of legislation and management strategies aim to improve and maintain the quality and sustainable usage of the valuable resources that the Humber Estuary has to offer, and highlight the significance of the area in terms of the extent and diversity of environment.

In the UK, estuarine systems have been previously studied in the context of environmental and sea-level changes. Other macrotidal estuarine systems, such as the Severn Estuary, Thames Estuary, Mersey Estuary, Solway Firth and the Forth Valley, are generally comparable to the Humber Estuary in terms of scale and tidal ranges, and have been previously studied (e.g. Devoy, 1979; Elliot, 2015; Hill *et al.*, 2007; Khan *et al.*, 2015b; Lloyd *et al.*, 1999; Smith, 1965; Smith *et al.*, 2010; Wilson & Lamb, 2012). These studies have provided an insight into Holocene estuarine and relative sea-level changes, as well as highlighting some of the challenges that are encountered in the study of estuarine systems (e.g. modified and urbanised landscape, reclamation of environments, microfossil preservation) that will also be encountered in the Humber Estuary.

4.2. Geology

The bedrock geology along the Humber Estuary is varied, although it can be broadly divided into two portions. To the east, the bedrock consists of Cretaceous Chalk, covering an area north of the Humber approximately 1800km^2 (Elliot *et al.*, 1998; Figure 4.1). The Chalk escarpment, known as the Yorkshire Wolds, divides the estuary into the two portions at the Humber Gap (British Geological Survey, 2015; Elliot *et al.*, 1998; Long *et al.*, 1998; Figure 4.1). To the west of the escarpment the bedrock is comprised of north-south bands of various Jurassic and Triassic mud-, silt-, lime- and sandstones (British Geological Survey, 2015).

The Chalk north of the Humber is part of the Northern Province of the Chalk Group. The Chalk east of the escarpment is predominantly Burnham Chalk, becoming Flamborough Chalk to the east of Hull, and is part of the White Chalk Subgroup (British Geological

Survey, 2015; Hopson, 2005; Figure 4.2). There are narrow north-south bands of Hunstanton Chalk, Ferriby Chalk, and Welton Chalk that run along the dividing escarpment (British Geological Survey, 2015; Hopson, 2005; Figure 4.2).

Along the escarpment, the Chalk north-south bands consist of a narrow band of the Hunstanton Chalk formation, a rubbly to massive Chalk with marl band that progresses eastwards into the Ferriby Chalk formation, a soft grey flint-free Chalk (Burke *et al.,* 2015). To the east is a band of Welton Chalk, a white Chalk that is thickly bedded with flint nodules (Burke *et al.,* 2015). Eastwards there is a larger band of Burnham Chalk, and the Flamborough Chalk, which is a well-bedded flint-free Chalk with common marl seams, that extends from approximately east of Hull to beyond the coast (Burke *et al.,* 2015). The area studied within this thesis, with regards to groundwater, is situated within the Burnham Chalk Formation (Figure 4.2; section 4.7.1). The Burnham Chalk is a medium-hard white Chalk, thinly bedded with laminated layers of Chalk, characterised by tabular and discontinuous flint bands in the lower part, with sporadic marl seams, with an average thickness of 140m north of the Humber Estuary (Allen *et al.*, 1997; Burke *et al.*, 2015; Hopson, 2005).

Overlying the Chalk bedrock to the east, the superficial geology is largely comprised of alluvium deposits of clay, silt and sand, with local areas of sand, gravel and glacial till (boulder clay) deposits (British Geological Survey, 2015; Figure 4.3). To the west of the escarpment, the overlying superficial deposits are comprised of predominantly alluvium immediately adjacent to the estuary and contributing rivers, with lacustrine clay and sand deposits dominating further inland (British Geological Survey, 2015).

4.3. Glacial History

The Humber region has been subject to multiple Quaternary glaciations, the most recent being the Devensian, with the Last Glacial Maximum occurring approximately 21000 years BP, though the timing of the maximum varies at different locations on the margin (Clark *et al.*, 2012). Based on a limited number of dated sediments, deglaciation of the region is believed to have occurred by approximately 13000 years BP, with a minimum radiocarbon date of 15590±888 cal years BP, provided from a kettle hole at Roos (located c. 20km east of Hull) (Beckett, 1981; Catt, 2007; Evans *et al.*, 2005; Evans & Thomson, 2010).

The limits of ice and general ice flow vectors for the east Yorkshire and Humber region are shown in Figure 4.4. During the Devensian maximum, Glacial Lake Humber was formed. There is debate over the age of initiation and draining, however a general maximum age for lake initiation is regarded as 21835±1600 years BP (uncalibrated) and a minimum age of 11110±200 years BP (uncalibrated) for the lake draining (Bateman *et al.*, 2015; Evans *et al.*, 2005; Gaunt, 1974; Gaunt *et al.*, 1971). The Humber region therefore has a number of glacial sequences and tills from the various phases of ice advance and retreat.

The varying extent of ice present across the region during the last glacial period is reflected in the variability of the stratigraphy (Evans & Thomson, 2010). East of Hull, there is variation in the thicknesses and distribution of the Basement, Skipsea and Withernsea Tills, whereas north and west of Hull the presence of tills is reduced, reflecting former ice limits, and comprising Chalk, silt, sand and gravel glacial outwash (Evans & Thomson, 2010; Figures 4.3; 4.4).

Glacio-isostatic adjustment (GIA) has been a major feature around the British Isles following deglaciation (Lowe & Walker, 2015; Shennan *et al.*, 2006; 2012). GIA has produced contrasting and highly variable records of late Quaternary relative sea-level change around the coast due to differential isostatic rebound following deglaciation after the Devensian glaciation (Lowe & Walker, 2015; Peltier, 1998; Shennan & Horton, 2002; Shennan *et al.*, 2006; 2012). The spatial and temporal influence of GIA and the amount of vertical land movement it causes has been quantified, primarily through the use of GIA models (section 2.2.1).

4.4. Holocene Sea-Level History

The Yorkshire coast and Humber Estuary are situated within an area of relative land subsidence, with the coastline experiencing a rate of vertical land movement ranging from -0.78 to -0.48mm a^{-1} (Figures 2.4; 2.5; Shennan *et al.*, 2012; Woodworth *et al.*, 2009), and a sea-level rise through the Holocene (Figure 4.5). At present there is a trend of rising sea level in the region, with tide gauge data from Immingham, in the outer estuary, showing a rate of 0.64±0.38mm a^{-1} from 1960-2006 (Woodworth *et al.*, 2009), and this trend is predicted to continue, with estimates of net sea-level rise for the northeast of England increasing from 2.5mm a^{-1} for the period 1990-2025 to 7.0mm a^{-1} 2025-2055 (Gehrels & Long, 2008). Concerns over the implementation of suitable and sustainable management policies for resources along the coast and around the Humber Estuary are therefore well justified. However, to fully understand these trends, and to accurately project future trends, the late Holocene sea-level history also needs to be constrained.

Despite the plethora of studies on Holocene, recent (centennial) and future sea-level changes around the British Isles, there is relatively little specifically focussing on the

Humber Estuary. Previous studies of sea level and estuary evolution in the Humber Estuary have provided a Holocene relative sea-level record through the establishment of sea-level index points, as well as model predictions, and there is also archaeological evidence from various locations of the estuary (e.g. Gaunt & Tooley, 1974; Kirby, 1999; 2001; Long *et al.*, 1998; Metcalfe *et al.*, 2000; Millett & McGrail, 1987; Neumann, 1998; Smith, 1958; Van de Noort, 2004, Van de Noort & Ellis, 1995; 1998). However, sea-level index points for the most recent 3000 years are generally lacking, with a particular absence for the most recent millenia (Figures 4.5).

Past changes to sea level in the Humber Estuary have been reconstructed in recent years. The first major regional analysis of relative sea-level changes for the Humber region was provided by dated changes in stratigraphic sequences by Gaunt & Tooley (1974). Dinnin & Lille (1995) also examined sedimentary sequences from seven transects located near the mouth of the Humber Estuary, in the south of the Holderness coast. These transects incorporated arable land several metres above the water level to intertidal beaches. The results from the stratigraphic sequences (sediment pH, organic content, and particle size) in the area indicate that the early Holocene pre-alluvium valleys were deep, with several sites indicating the presence of meres in the valley bottoms (Dinnin & Lille, 1995). Post-glacial sea-level rise triggered expansion of the wetlands, with tidal incursions directly causing the creation of marine environments and brackish, saltmarsh environments in more marginal areas (Dinnin & Lille, 1995). Indirectly, through raising the water table, the meres became buried under clastic estuarine sediments, though these events are lacking a precise chronology (Dinnin & Lille, 1995).

Long *et al.* (1998) considerably expanded the Holocene sea-level data available for the Humber Estuary, through the examination of stratigraphic and microfossil evidence from six sites from west to east along the estuary. These sites incorporated the inner- (one site), mid- (two sites) and outer estuary (three sites). At the inner estuary site, the stratigraphy and microfossils (pollen and diatoms) indicate a period of marine conditions approximately 6400-4650 cal years BP (-3.35 to -1.82m OD), with a subsequent reduction in marine conditions and introduction of a freshwater environment indicated by a regressive contact and pollen assemblage (Long *et al.*, 2008).

In the outer estuary sites, the sites display similar stratigraphic sequences. The biostratigraphy within a thin basal peat layer indicates saltmarsh conditions initiated by sea-level fall at c. 6750 cal years BP at -7.78 m OD, followed by a positive sea-level tendency c. 6450 cal years BP at -7.68 m OD and a subsequent return to tidal flat conditions, demonstrating fluctuations of sea level within the early-mid Holocene (Long *et* *al.*, 1998). Another site with a basal peat bed, overlain by a thin silt clay deposit, indicates a positive sea-level tendency, with the formation of peat initiated c. 5200 cal years BP at -1.29 m OD followed by inundation c. 4900 cal years BP at -1.19 m OD (Long *et al.*, 1998). The third site also provided a basal silt peat unit capped by silty clays (Long *et al.*, 1998). The pollen in the peat indicates accumulation under saltmarsh conditions, with the upper transgressive contact dated at c. 2950 cal years BP at 0.98m OD, and the transition in foraminifera taxa indicating progressive inundation and a positive sea-level tendency (Long *et al.*, 1998).

Within the mid-estuary, an intertidal exposure has a basal peat unit (dated to c. 4100-3950 cal years BP at -0.58 to -0.34 m OD) that is overlain by silty-clays (Long *et al.*, 2008). The pollen and diatom records through the peat indicate an encroachment of marine conditions, with a positive sea-level tendency that initiated peat accumulation and eventual inundation at the site (Long *et al.*, 1998). On the southern bank of the mid-estuary, at Barrow Haven, the site comprises two intercalated peat units; the thicker upper peat sequence, a regressive contact, has a date of c. 2000 cal years BP at 1.79 m OD, and a transgressive contact at c. 1000 cal years BP at 2.07m OD, with pollen within the intervening section indicating freshwater and reedswamp environments (Long *et al.*, 1998). These data demonstrate a fluctuation in sea level within the past 2000 years (Long *et al.*, 1998; Figure 4.6), and the most recent sea-level index point for the estuary.

The sea-level index points established from these six sites have been compiled to produce a sea-level curve for the Humber Estuary (Figure 4.6). The sea-level index points generally indicate a rapid rise in relative sea level from around -9m OD to 0m OD between c. 7500-4000 cal years BP, an average rate of rise of 3.9mm cal a^{-1}, which slowed to c. 1mm cal a^{-1} during the last 4000 cal years (Long *et al.*, 1998).

These trends are also apparent in the additional sea-level index points from the Humber Estuary presented by Metcalfe *et al.* (2000) (Figure 4.7). This study provided an additional 37 sea-level index points, and 11 additional limiting index points, from 23 sites from the inner and outer estuary, based upon the stratigraphic and microfossil records. This widened the extent of Holocene records of change, improving both the temporal and spatial coverage of data throughout the estuary. Again, the data is consistent in showing the rapid rise in relative sea level in the early Holocene, and a slow rise through the mid-late Holocene (Metcalfe *et al.*, 2000).

The overall rise in sea level through the Holocene is reflected in the evolution of the palaeogeography and extent of tidal influence in the estuary, with the expansion of wetland areas as well as increased intertidal and subtidal reach inland (Metcalfe *et al.*, 2000; Figure 4.8). In the early Holocene, 8000 cal years BP, the intertidal and estuarine subtidal environments were restricted to the outer estuary, with the sea-level transgression continuing through the estuary over the next two millennia (Long *et al.*, 1998; Metcalfe *et al.*, 2000). Due to increasing marine influence, a sea-level rise, during the Holocene, full channel flow and marine conditions were established within the inner estuary by about 6000 years BP (Kirby, 1999; 2001; Metcalfe *et al.*, 2000).

Evidence of intertidal sedimentation occurring in the valleys that drained into the estuary is recorded at 5000 cal years BP, with significant areas of intertidal environments occurring throughout the estuary (Metcalfe *et al.*, 2000). Intertidal environments continued to expand, reaching a probable maximum at approximately 3000 cal years BP (Metcalfe *et al.*, 2000). This timing is consistent with other studies, using microfossil methods as well as organic δ13C and C/N analyses, that identified an expansion of marine conditions in the estuary from c. 3300 cal years BP, followed by a contraction of the marine conditions and return to an estuarine environment after c. 2700 cal years BP (Kirby, 1999; 2001; Lamb *et al.*, 2007; Long *et al.*, 1998).

Despite these sea-level data for the Holocene, there is a distinct absence of data points for the last 3000 years, with only one point within the last 1000 years, dated to c. 1000 cal years BP at 2.07m OD from Barrow Haven, in the mid-estuary, with a positive sea-level tendency (Long *et al.*, 1998; Figures 4.5; 4.6; 4.7). However, there are some archaeological records for the late Holocene period that can inform the record of sea-level change. Archaeological artefacts provide an insight into the use of the landscape, as well as any changes in the environment, in particular a change within the height of tides and sea level. Dated artefacts also provide an estimate for age of the sediments in which they are found, and can aid in the development of a chronology for stratigraphic sequences. Several archaeological finds (e.g. buried boats and Roman roads) around the Humber Estuary have been dated to the latter half of the Holocene (Van de Noort, 2004).

Archaeological data from sites along the estuary do provide some evidence of local changes that have occurred during the late Holocene, such as the submergence of roman roads and settlements (Metcalfe *et al.*, 2000). The estimates of sea level provided by the artefacts suggest variability in the coastal changes experienced within the estuary, particularly in the latter part of the Holocene, than the continuous rise indicated by the reconstructed sea-level history provided from sea-level index points (Long *et al.*, 1998; Metcalfe *et al.* 2000; Van de Noort, 2004).

During the last several thousand years there have been significant changes to the estuary and surrounding wetlands, largely due to anthropogenic activities (Metcalfe *et al.*, 2000; Sheppard, 1966; Section 4.5), which may be responsible for the lack of preserved sea-level data for the last c. 3000 years. Artificial drainage and land reclamation of the low-lying areas around the Humber has occurred since the Medieval period, with increased drainage activity from the seventeenth century onwards (Metcalfe *et al.*, 2000; Sheppard, 1966). Much of the area has also experienced a transition from pastoral to arable farming, resulting in further desiccation of low-lying areas (Metcalfe *et al.*, 2000). There are few remaining natural wetland areas around the estuary due to drainage, river embankments, arable farming, and urban development (Metcalfe *et al.*, 2000). Desiccation of the wetlands around the estuary reduces the preservation potential of palaeoecological and archaeological remains (Metcalfe *et al.*, 2000; Van de Noort & Davies, 1993), potentially decreasing the availability of sites suitable for late Holocene sea-level reconstructions.

Comparison of model predictions and sea-level index points for the Humber Estuary show varying fit, with the model predictions omitting some of the trends and rapid (<1000 year) changes that are indicated by the index points (Figures 4.5; 4.6; 4.7; 4.9; Long *et al.* 1998). During the late Holocene, the deceleration of eustatic sea-level rise resulted in coastal evolution being forced to a greater extent by other factors, and individual sea-level index points may have been influenced by local scale processes, such as sedimentation rates and compaction, as well as changes in tidal levels (Leorri *et al.*, 2011; Metcalfe *et al.*, 2000). Not appropriately acknowledging or correcting for such processes can result in errors in interpretation, for example, an overestimation of rate of sea-level change when a sediment sequence is compacted. If only basal sea-level index points are considered, the rate of late Holocene sea-level change within the Humber Estuary is estimated as 0.3±0.1 mm a^{-1}, compared to 0.6±0.1 mm a^{-1} when all sea-level index points are considered (Horton & Shennan, 2009), highlighting the disparity that may occur within records.

Changes in tidal ranges in particular have been demonstrated to be a significant factor in estuaries (section 2.1), and must be considered when reconstructing sea-level change, and the rate of that change (Leorri *et al.*, 2011). Models of sediment dynamics however have assisted in determining changes in tide levels through the Holocene for both the inner and outer portions of the Humber Estuary (Shennan *et al.*, 2003). Modelled tidal changes for the estuary are applied to recalculate relative sea-level changes. When the data for the inner estuary are calibrated to the height of present tide levels they lie below the data points of the outer estuary and the modelled sea-level predictions (Shennen *et al.*, 2003; Figure 4.10). When the sea-level index points are corrected for changes in tidal range during the Holocene, there is generally better agreement between the index points and modelled predictions (Figure 4.10; 4.5; Shennan *et al.*, 2003). In the context of the

Humber Estuary, taking into account changes in tidal regime can explain the apparent differences between reconstructed sea levels in the inner and outer estuary, implying there may be no significant differential glacio-isostatic land level movement between the inner and outer sections of the Humber Estuary (Shennan *et al.*, 2003).

4.5. Anthropogenic Changes

An important aspect to evaluate when considering late Holocene sea-level change on the Humber Estuary is that of historic anthropogenic activity, and modifications to the land, estuary boundary and its usage. Generally changes that have occurred since the Medieval period through to the present have some form of record either as physical remnants of evidence of the changes in the land and the usage, and/or as written records and maps.

Prior to anthropogenic records of changes in the late Holocene, changes to the landscape and environment have been inferred through the examination of sedimentary and pollen records. From along the Holderness coast, directly northeast of the Humber Estuary, pollen records provide a history of vegetation changes since the last glacial maximum to the present (Beckett, 1981). The records from Holderness indicate changes in vegetation cover consistent with climatic changes through the early and mid Holocene, as well as forest clearance and agriculture activity during the Bronze Age, c. 4000 years BP (Beckett, 1981). Indeed, deforestation and agricultural activity is also recorded in pollen records from sites within the Humberhead Levels, to the west of the Humber Estuary (Thorne and Hatfield Moors; Smith, 1958). Agricultural activity has been identified as occurring during the latter half of the Holocene, with extensive forest clearance phases proposed during the Iron Age and Roman period, c. 3000-2000 years BP, followed by agricultural decline and forest regeneration (Smith, 1958). Such phases of deforestation through the mid to late Holocene will have enabled increased sediment mobilisation into the catchment system and estuary (Beckett, 1981; Buckland & Sadler, 1985; Smith, 1958). This would have increased sediment delivery and alluviation in the Humberhead Levels and estuary during the late-Roman period and late Holocene (Buckland & Sadler, 1985).

The history of land modification along the estuary is also integral to understanding the sea-level record and producing an accurate interpretation of late Holocene sea-level change along the Estuary (section 4.4). However, most documentary evidence of modifications to the landscape refer to the maintenance of defences that had already been built; as such, the initial phases of modification and reclamation are poorly understood (Rippon, 2000).

An area of particular importance in this respect is the northern edge of the outer estuary, eastwards from Paull through to Kilnsea, as there have been extensive changes in the morphology of the area and the land use, demonstrating the scale of anthropogenic influence on the landscape (Figure 4.11). The formation of embankments from c. 1000-800 years BP encouraged the drying out of some of the higher locations, with farms becoming established on some of the reclaimed marsh areas (Sheppard, 1966). By 700 years BP, some of the reclaimed land was ploughed and the remainder used for pasture and meadow (Sheppard, 1966). However, much of reclaimed area was eroded during the period of 700-500 years BP, and the precise detail of land reclamation and position of the estuary banks is unknown, though a proposed position is shown in Figure 4.11 (Rippon, 2000; Sheppard, 1966).

References to tides of the Humber damaging banks stop after AD 1690 (260 years BP) with records instead showing an increase in the extent of sandbanks and silt accumulation (Sheppard, 1966). As a result the Sunk Island and Cherry Cobb sandbanks grew in size and saltmarsh vegetation developed (Sheppard, 1966). The embankment of Sunk Island began in AD 1695 (255 years BP) with an additional 22,000 acres incorporated by an embankment in AD 1744 (211 years BP) (Sheppard, 1966). Due to the fertile land that reclaimed marsh provides, the increasing extent of saltmarsh formation was encouraged, and Cherry Cobb sands was embanked in AD 1769 (186 years BP) (Sheppard, 1966). The final portion of saltmarsh east of Sunk Island was embanked in AD 1850 (100 years BP), completing the incorporation of Sunk Island from the estuary (Sheppard, 1966), and distinctly altering the shape and landscape of the estuary (Figure 4.12). As such, the present landscape structure reflects these reclamation processes (Berridge & Pattinson, 1994; Rippon, 2000; Sheppard, 1966).

The practice of warping, established by AD 1750 (c. 200 years BP), was also widespread in the lowland valleys bordering the contributory rivers of the inner Humber Estuary, with the technique of warping (Heathcote, 1951). Warping is the process of repeated and controlled flooding at high tide, and subsequent drainage of the flood water, of land to allow the deposition and accumulation of fine sediments (Heathcote, 1951; Kirby 1999). Generally, c. 2mm of sediment could be deposited during each flood, with accumulation rates up to c. 0.9m a^{-1} (Heathcote, 1951). These areas of warped land are generally identifiable by the distinct elevation differences either side of embankments and drains, and represented stratigraphically as a silty unit with lamination traces (Kirby, 1999).

The anthropogenic changes to the environment and landscape of the Humber Estuary and the immediate surroundings are important to consider in terms of sea-level studies. This is due to the potential modification and disturbances to the sedimentary record that would be used to provide sea-level reconstructions, particularly over the last millennia. Care must therefore be taken when selecting potential study sites, with consideration given to the potential influence of anthropogenic activity on the sedimentary sequences.

4.6. Aquifer

Chalk is the predominant bedrock and aquifer around the Humber Estuary (section 4.2). Chalk is an aquifer that is considered to have dual porosity, whereby the pores provide storage space, and fissures provide permeable pathways of flow (Environment Agency, 2012; Price *et al.*, 1993). As such, the Chalk has a high permeability (Elliot *et al.*, 1998, Environment Agency, 2012; Price *et al.*, 1993). Whilst the high permeability characteristic of Chalk allows the flow of groundwater, it makes it susceptible to potential contamination, and the low storage coefficient means the total storage is limited (Lloyd, 1993).

The Chalk has fracture sets of different scales in terms of size, spacing and orientation, and is characterised by small grain size, small pore-throat size and high effective porosity (Gale & Rutter, 2006). These properties give the Chalk the ability to transport water, including saline water and contaminants, through both the saturated and unsaturated zones (Gale & Rutter, 2006). Remnant bodies of ‘fossil’ saline groundwater within the Chalk aquifer do exist, with ages dating back through the Quaternary (Elliot *et al.*, 1998). One dated body beneath the Holderness region potentially exceeds 19000 years in age, representing the changes in sea level and hydrogeological conditions (Elliot *et al.*, 1998). Groundwater bodies, therefore, within the aquifer are a complex mix of freshwater, including ‘modern’ freshwater in the form of recharge, as well as saline waters of varying sources and ages (Elliot *et al.*, 1998).

The Chalk north of Humber is both confined and unconfined (Gale & Rutter, 2006). The Chalk west of the city of Hull is unconfined due to the absence of impermeable deposits and presence of permeable overlying material, and therefore is an area of recharge for the aquifer. The groundwater flow, as it progresses down the hydraulic gradient from the Yorkshire Wolds, emerges as springs at the base of the Chalk escarpment and baseflow to rivers and streams, or is pumped from semi-confined sections (Gale & Rutter, 2006). As the Chalk progresses east towards the coast, it becomes confined due to the overlying clay that is of low permeability, and subsequently allows for artesian flow (i.e. the pressure in the aquifer allows the water to reach the ground surface when a well is drilled). The recharge of the Chalk is controlled by a number of factors, including the effective rainfall, thickness and permeability of Quaternary deposits, thickness of the unsaturated zone and the potential for rapid bypass flow (Gale & Rutter, 2006), creating a complex framework of processes contributing to the head and flows of groundwater within the Chalk aquifer.

4.7. Groundwater Abstraction

Groundwater from the Chalk aquifer in East Yorkshire, north of the Humber Estuary, is a key resource. The groundwater has contributed to urban, industrial and agricultural development in East Yorkshire, with many industries relying on groundwater supplies during the early 20^{th} Century (Gale & Rutter, 2006). At present, the annual average abstraction from the Chalk aquifer is approximately 100 Ml d^{-1}, of which approximately 25% is abstracted from sources around the city of Hull (Gale & Rutter, 2006). The development of abstraction from the Hull area has resulted in a reduction in the artesian head, and thus an end of natural spring flows (Elliot *et al.*, 1998; Gale & Rutter, 2006). Groundwater is therefore currently abstracted through the pumping of boreholes and adit networks (Elliot *et al.*, 1998; Gale & Rutter, 2006).

The over-abstraction of groundwater around the Hull area has previously resulted in saline intrusion. Prior to AD 1976, pumping of the groundwater in the Hull area reduced the natural discharge from the aquifer (Chadha, 1986; Gale & Rutter, 2006). The total abstraction exceeded the estimated annual recharge for a period of at least 70 years, leading to saline water intruding into the aquifer, and the abstracted water being brackish (Chadha, 1986; Gale & Rutter, 2006). Abstraction was therefore reduced to allow sufficient recharge and groundwater to flow to the Humber Estuary and to maintain a static saline and freshwater interface (Gale & Rutter, 2006). Monitoring between AD 1976 and AD 1980 indicated that the saline front was almost static despite a slight increase in the zone of mixing (Gale & Rutter, 2006). If local groundwater abstraction exceeds the recharge and freshwater flow rates, then saline intrusion may occur again (Elliot *et al.*, 1998), demonstrating the intricate and sensitive interaction of dynamic environmental processes and anthropogenic influence.

Presently, for abstraction of potable water from the Chalk aquifer, a level of protection is given to groundwater quality through the use of Source Protection Zones (SPZs) (Environment Agency, 2012). SPZs are applied to areas close to potable water sources where the associated risk of groundwater contamination is greatest. SPZs have three subdivisions incorporating the source catchment protection zone, outer protection zone, and the inner protection zone with a 50 day travel time to abstraction source (Environment Agency, 2012). These are applied by the Environment Agency with the aim of preventing the deterioration of groundwater quality, though they can only provide protection against anthropogenic influences (Environment Agency, 2012). As such, saline intrusion that is occurring due to sea-level processes or changes cannot be prevented by SPZs, but may be managed through abstraction practices, as previously demonstrated in the Hull area. It is therefore important to consider the role of groundwater abstraction and the interaction with sea level, and the implications the relationship may have for the management and protection of abstraction sources along the Humber, particularly around the urban area of Hull. Indeed, due to climate change, it is anticipated that there will be an increase in saline intrusion due to sea-level rise in the Hull area (Environment Agency, 2009a; 2009b).

4.7.1. Groundwater Abstraction- Springhead Source

The groundwater abstraction site of interest in this research is the Springhead source, operated by Yorkshire Water. Springhead is located to the north of the Humber Estuary, approximately 3.5km inland, the closest Yorkshire Water groundwater abstraction site to the Humber Estuary, and is within an area of confined Burnham Chalk (Figure 4.2). It is situated to the west of Hull, north of the village of Anlaby and east of the village Kirk Ella, at an elevation of approximately 5m OD. The source was constructed in AD 1862, comprising a main pumping shaft connected to a network of adits excavated in the underlying Chalk, and is currently pumped continuously to provide water, but also to prevent flooding due to high groundwater levels (ARUP, 2007). It is currently one of a network of four groundwater sources located near Hull that contribute to water supplies (ARUP, 2007), and as such can be considered as an integral resource for supplying and meeting water demands of the region.

4.8. Summary

This chapter provided an overview of the Humber Estuary, setting the context for the research study area. A general background of the estuary, as well as glacial history and geology was provided. A detailed history of Holocene relative sea-level change was provided based upon existing records and reconstructions, as well as late Holocene and historic anthropogenic changes to the estuary and wider catchment and landscape. The aquifer and groundwater system, and the history of abstraction and saline intrusion in the region, was introduced, as well as the Springhead source, the groundwater abstraction site studied within this thesis.

5. Methodology

This chapter describes the methods and techniques used in this research to reconstruct sea-level changes and to model changes in the groundwater. This section includes fieldwork, laboratory techniques and microfossil analyses, as well as the development and use of groundwater conceptual and numerical models.

5.1. Fieldwork

Several techniques were employed in the field in order to understand the site location, stratigraphy and geomorphological setting.

5.1.1. Site Selection

Sites suitable for study were selected through a number of methods. A review of the literature of the Humber Estuary, particularly of sea level and Holocene environmental change, was undertaken to identify previously studied sites and highlight potential areas of investigation (e.g. sites with stratigraphy or microfossil records consistent with saltmarsh environments). Published borehole records from the literature and also the British Geological Survey (British Geological Survey, 2015), were also examined to identify sites that had the potential to preserve sea level and saltmarsh environments. The use of Ordnance Survey (OS) maps, both present and historic, and Google Earth, assisted in highlighting areas of potential study, as they provided an overview of the topography and altitude of sites, the proximity to the estuary, any recent (c. last 200 year) changes to the estuary channel and land reclamation, as well as the land use of sites. These are important factors as they help to identify what may have been former lowlands or marsh areas, as well as helping to identify pristine and undisturbed records. Identified sites were visited, and initial borehole and core spot samples were taken to evaluate their suitability to produce a Holocene sea-level reconstruction based upon the stratigraphy and preliminary assessment of the microfossil record.

Ten potential sites throughout the estuary were visited and cored to assess the suitability for reconstructing the history of late Holocene sea level. Two sites were subsequently determined as suitable for the reconstruction of sea level: East Halton and Brough. Three marsh sites were selected for surface sample selection: Spurn, Welwick, and East Halton marsh.

5.1.2. Surveying

Surveying of sites was undertaken to record the precise location and changes in elevation at the field site, and to provide the surface altitude of any samples and cores taken, fundamental for producing sea-level reconstructions. All sites were described in detail, with any distinct features (e.g. embankments, abrupt slopes) marked on maps and photographed, to provide a geomorphological context for the study sites. Surveying was undertaken along the transects of sediment cores and samples, providing individual locations and altitude.

Initially surveying was done with a hand-held GPS, with the precise surveying undertaken using a differential GPS base station and rover unit (Trimble R6). The use of the differential GPS provides improved accuracy compared to a handheld GPS or manual surveying from the nearest OS benchmark, as it uses a network of fixed ground-based reference stations as well as satellite measurements to provide an accurate determination of location and altitude (with an error of c. 0.01m). All samples were surveyed to the UK National Grid system, with altitudes provided in m OD (Ordnance Datum).

5.1.3. Coring and Stratigraphy

Transects are straight lines across a field site along which cores are collected to reveal the stratigraphy across a wide area of the site (Lowe & Walker, 2015). Transects cover the range of variables at a field site, such as the elevation and vegetation changes across a saltmarsh, to provide a thorough overview of the stratigraphy. Locations from which to take representative cores of the sites can then be identified and collected for laboratory analyses.

The stratigraphy of all cores were described and recorded in detail in the field following the Troels-Smith (1955) sediment classification scheme, which is a widely used method for describing stratigraphic sequences. The depths of units were carefully measured, with the description including various aspects, such as the components of the sediment (i.e. clay, silt, sand), colour, any detritus and stratification, as well as the type and size of transition/boundary between units. This was repeated in detail in the laboratory for the cores collected for laboratory analysis.

Coring was undertaken using narrow (3cm diameter) and large (6cm diameter) gouge augers, both 1m in length, to establish the stratigraphy of the sites. A Russian auger (7.5cm diameter, 0.5m length) was used to collect sample material for laboratory analyses. A Russian corer is only suitable however for coring unconsolidated sediments such as peat. When stiff minerogenic sediments dominate the stratigraphy, a large gouge corer was used, although ideally this would be undertaken with a power corer (e.g. percussion corer). The large gouge provides abundant material for laboratory analysis, and careful sampling from the centre of the core to reduce the risk of contamination from smearing was practised.

The sediment augers were manually pushed into the ground, turned, and pulled out to bring up a sediment core; additional metre long rods were attached to reach deeper depths. Adjacent parallel boreholes were used when sampling the boreholes with an overlap of 10cm to prevent the contamination and compression of the ends of cores and any sediment loss (due to slumping). Sediment cores were transferred into plastic guttering, and securely wrapped in cling film and foil, and placed into cold ($<5^{\circ C}$) storage in the laboratory until required; freezing was avoided to prevent damage to foraminifera microfossils.

5.1.4. Surface Sample Collection

Modern marsh sediment samples were collected along transects, with samples taken to cover the different sub-environments encountered, from high marsh to tidal flat (Barlow *et al.*, 2013; Horton & Edwards, 2006; Leorri *et al.*, 2008). The upper c. 1cm of surface sediment was collected, with enough sample volume to enable diatom, foraminifera, and environmental analyses (loss on ignition and particle size analysis) to be undertaken (c. $20cm^3$) (Barlow *et al.*, 2013; Horton & Edwards, 2006; Horton *et al.*, 2006). The modern surface diatom film was cleaned away, to remove the influence of seasonal blooms of diatoms (Hamilton & Shennan, 2005; Watcham *et al.*, 2013). Care was taken to avoid compression of the sediments during sampling. Once sampled, the sediments were sealed in bags, and refrigerated ($<5^{\circ C}$) upon return to the laboratory within 24 hours of sampling.

5.2. Laboratory Analyses

The following section provides an overview of the methods and techniques used in the laboratory analyses, including sediment sampling, loss on ignition, particle size analysis, and radiocarbon dating.

5.2.1. Sediment Sampling

The sediment cores were subsampled for laboratory analysis using a sterilised scalpel. The subsamples consisted of narrow bands of sediment approximately 0.5cm wide taken horizontally across the core. Initially the samples were taken at a low resolution, normally every 16cm, and incorporated all stratigraphic units. Higher resolution sampling occurred based upon the results of analyses of samples taken at 16cm. At the highest resolution, cores were sampled every 2cm. Sufficient material was taken at each horizon for loss on ignition, particle size, diatom and foraminifera analyses. The subsamples were sealed in individual bags, labelled, and placed in cold (<5$^{\circ C}$) storage until required for analyses.

5.2.2. Organic and Carbonate Content

The loss on ignition (LOI) method was used for determining the organic and carbonate content of the sediment samples. Though a simple method, the approach does provide a quick and inexpensive measure of the weight percentage organic matter and carbonate content of sediments (Heiri *et al.*, 2001; Lowe & Walker, 2015), and is useful for assisting in establishing the environment in which the sediments were deposited. The method adopted follows that outlined by Heiri *et al.* (2001). Approximately 1g of sediment was dried at 105°C for c. 18 hours and weighed to provide the dry weight of the sediment. The sediment was then heated at 550°C for 4 hours and weighed to determine organic content. The sediment was finally heated at 950°C for 2 hours and weighed to establish the carbonate content.

5.2.3. Particle Size Analysis

Particle size analysis was undertaken to determine the grain size composition of the sediment samples in order to assist with the accurate description of the sediments and provide information on the depositional environment (Lowe & Walker, 2015). Grain size, along with the organic content of sediments, is also useful when assessing the microfossil distribution and preservation (in both core samples and contemporary environments) (e.g. Horton & Edwards, 2006; 2005; Zong & Horton, 1999).

Organic material was removed prior to particle size analysis (Allen & Thornley, 2004). Approximately 1g of wet sediment was placed in a glass beaker and covered with 30% hydrogen peroxide (H_2O_2), stirred with a glass rod and heated on a hotplate; ethanol was added to control any effervescence. H_2O_2 was continually added to the sediments until the reaction stopped, at which point all the organic materials had been oxidised. To deflocculate any clays, 30ml of 0.4% sodium pyrophosphate solution, a dispergent, was added and the samples stirred (Allen & Thornley, 2004).

Particle size analysis was undertaken using a Malvern Mastersizer 2000 laser granulometer. The use of laser diffraction and granulometers is widespread, and provides an efficient, precise and reliable method for determining the particle size of mixed sand, silt and clay sediments (Blott and Pye, 2006). Prior to the analyses of the samples, the apparatus was washed with a solution of water and a surfactent (e.g. washing up liquid) for at least 12 hours to alleviate the risk of contamination, and subsequently washed with deionised water before running the samples. The analyser was calibrated using a sand 0.152-0.422mm standard to increase the reliability and consistency of the results. Samples were sonicated for 5 seconds and then analysed. Each sample was run in triplicate, with the apparatus being thoroughly washed with deionised water between samples to prevent contamination. The results of the particle size analysis were grouped into three categories: clay, silt, and sand, following the Wentworth scale (1922), for interpretation (Table 5.1).

5.2.4. Radiocarbon Dating

Developing a robust chronology is crucial for determining the history and rates of sea-level change. Radiocarbon dating is a suitable method for sediments of late Holocene age, and is widely used in sea-level studies (section 2.3.7). The radiocarbon method of dating is based upon the rate of decay of the unstable carbon 14 isotope (^{14}C), and enables the dating of any material composed of carbon. The measurement of ^{14}C content can be achieved through either radiometric dating or Accelerator Mass Spectrometry (AMS) (Lowe & Walker, 2015). The AMS method is advantageous due to the small sample size required (tens of milligrams) compared to radiometric method (tens of grams), ultimately allowing for precise dating of sediment sequences (Lowe & Walker, 2015).

Samples were selected for radiocarbon analysis based upon the litho- and biostratigraphical changes identified within the core. These changes may represent changes in sea level, and obtaining dates from these horizons allows the production of a sea-level index point. The dates also provide a chronology that can be extrapolated to provide an age-depth model for the sedimentary sequence.

Sediments for radiocarbon dating were meticulously dissected to extract any dateable macrofossils, using sterile equipment to avoid contamination. If available, horizontal plant macrofossils were used, as they are considered to be more precise than bulk sediment. When an insufficient volume of plant macrofossils were present (<10mg), bulk sediment samples were submitted. These may be considered less precise as they consist of a mixture of sediment from the horizon within a core.

Radiocarbon ages were determined by accelerator mass spectrometry (AMS) ^{14}C analyses at the ^{14}Chrono Centre, Queen's University Belfast, and by the Natural Environment Research Council (NERC) Radiocarbon Laboratory (allocation grant number 1932.1015). The radiocarbon ages were calibrated using OxCal v4.2.4 (Bronk Ramsey, 2013; 2009) with the IntCal13 atmospheric curve (Reimer *et al.*, 2013). All dates were calibrated to cal years BP. All dates in this thesis are quoted in this style, unless stated otherwise.

Chronologies and age-depth models were established based upon the dated horizons in sediment cores using the software package Bacon v2.2 in R (Blaauw & Christen, 2011). Bacon is a form of Bayesian age-depth modelling that uses Bayesian statistical methods to reconstruct the accumulation history of a sediment core and thus age estimates (Blaauw & Christen, 2011). Bayesian age-depth modelling is considered a more sophisticated approach than other methods, such as linear or polynomial regression and weighted splines, provided by software such as Clam (Blaauw, 2010). The age-depth models are established between the dated horizons, and not applied between the uppermost date and the core surface due to the unknown deposition rates, which are likely to be complicated by anthropogenic activities such as drainage and land reclamation (Kirby, 1999; sections 4.4; 4.5).

5.2.5. Radiocarbon Dating Errors

There are multiple sources of error that must be considered when utilising radiocarbon dates. Primary to this is the assumption that the amount of ^{14}C has not changed over time (Lowe & Walker, 2015). However changes do exist, and hence the requirement to calibrate the radiocarbon ages that are obtained (Lowe & Walker, 2015; section 5.2.4). The contribution of reservoir effects can also influence the measured ages, (e.g. hard-water regions, contribution of glacial melt waters, marine reservoir effect) with older radiocarbon dates being obtained (Lowe & Walker, 2015). The marine reservoir effect results from the delay in the exchange between marine and atmospheric carbon, as well as the dilution effect of surface and deep water mixing (Mangerud, 1972), which results in ages c. 400 years older than they should be (Lowe & Walker, 2015; Stuiver & Braziunas, 1993). Conversely, younger carbon can be also be introduced, producing younger ages. This could be caused by, though is not limited to, contamination from local groundwater, the penetration of roots into the sample, as well as the vertical sample thickness and contamination whilst sampling (Lowe & Walker, 2015). To limit the potential of this, care was taken whilst sampling, and AMS allows the use of small sample sizes (section 5.2.4).

5.3. Diatom Analysis

The following sections outline the techniques used for diatom analysis, including sample preparation, counting and identification.

5.3.1. Preparation

Diatom preparation followed standard techniques and procedures (e.g. Palmer & Abbott, 1986). A small amount of wet sediment (c. $0.5cm^3$) was taken from the core subsamples. For the contemporary samples, c. $0.5cm^3$ of sediment was taken from the upper 0.5cm of the surface samples. Hydrogen peroxide (30%) was added to the sediment samples, and gently heated until all material was oxidised. Once cooled, samples were centrifuged at 1200rpm for 4 minutes, to remove the supernatant. This was repeated a minimum of three times. Permanent slides were produced by air-drying the prepared diatom solution on cover slips, and mounted using Naphrax.

5.3.2. Counting and Identification

Diatoms were counted from each sample using a systematic approach (i.e. traverses every 2mm) using a microscope with x1000 magnification and phase contrast under immersion oil. 250 valves were counted from each sample and identified according to the taxonomy of Hartley *et al.* (1996), Hendey (1964) and Krammer and Lange-Bertalot (2010). A count of 250 diatoms only represents a proportion of the assemblage present within a sample, but is an optimum amount given the time constraints, and is consistent with other studies (e.g. Long *et al.*, 1998; Ridgeway *et al.*, 2000; Watcham *et al.*, 2013).

5.4. Foraminifera Analysis

The following sections outline the techniques used for foraminiferal analysis, including sample preparation, counting and identification.

5.4.1. Preparation

Foraminifera sample preparation followed standard techniques (e.g. Gehrels *et al.* 2001; Horton & Edwards, 2006; Scott & Medioli, 1980). $2cm^3$ of wet fossil sample was measured using water displacement and wet sieved through 500μm and 63μm sieves. The 63μm fraction was retained for foraminiferal analyses. Floating organic material was removed by allowing the sample to settle for c. 1 minute, and the excess surface water decanted. If the abundance of foraminifera in a sample hindered accurate counting and identification, a wet splitter was used to divide the sample into eight parts.

Contemporary samples were prepared within several days of fieldwork sampling to limit any post sampling changes in the living/dead assemblage. $2cm^3$ of sediment was taken from the upper 1cm of the surface samples, and prepared in the same way as the fossil samples. Once sieved and prepared, the samples were submerged in a solution of 30%

ethanol and Rose Bengal to stain the living foraminifera. Unstained, dead foraminifera were identified and counted, as they remain relatively unaffected by seasonal fluctuations that may otherwise skew the assemblages (Gehrels, 1994; Horton & Edwards, 2005; 2006).

5.4.2. Counting and Identification

Foraminifera were systematically counted wet on a spiral tray using a microscope with adjustable magnification (magnifications 32x-120x used). The foraminifera were picked and placed on a pre-glued slide to assist in identification, following standard methods (e.g. Gehrels, 1994; Scott & Medioli, 1980). An optimum number of c. 200 specimens per sample were counted, as generally saltmarsh diversity is relatively low (section 2.3.3), and this is consistent with other studies (e.g. Gehrels *et al.*, 2001). Foraminifera were identified according to the taxonomy of Murray (1971; 2000) and Horton and Edwards (2006).

5.5. Diatom and Forminifera Analysis

Diatom and foraminifera diagrams were created using C2 (Juggins, 2003) and Tilia (Grimm, 2004). Throughout the analysis of contemporary diatom and foraminifera training sets, species that did not exceed 3% abundance in at least one sample were excluded. Excluding species with low abundance (<3%) restricts the influence that potentially insignificant species may otherwise have on the statistical analyses (Horton & Edwards, 2006; Shi, 1993; Szkornik *et al.*, 2006; Zong & Horton, 1999). For contemporary samples, all samples with <100 foraminifera individuals counted were excluded (Fatela & Taborda, 2002; Horton & Edwards 2006); all diatom samples provided the minimum 250 valves. Species with abundance >5% in two or more samples were included in diagrams.

The zonation of the diatom and foraminifera assemblages was calculated using Constrained Incremental Sum of Squares (CONISS) cluster analysis, and was performed using TIlia v.2.0.2 and TG View v.2.0.2 (Grimm, 2004). CONISS divides the proxy data into assemblage zones statistically based on the major taxa, and reduces the subjectivity introduced when attempting to do so by visual interpretation (Bennett, 1999). CONISS was undertaken using the Euclidian distance method (no data transformation). CONISS was undertaken constrained by sample depth on the fossil proxy data, dividing the fossil assemblages into zones through the sediment cores, and by elevation (represented by standardised water level index, SWLI; section 5.7) for the contemporary training sets.

Detrended Correspondence Analysis (DCA) was used to establish the most appropriate ordination and transfer function regression methods to use for the training sets. The axes produced by DCA were ranked in order so that the first axis explained the principal sources of variation in sample assemblages, with the progressively higher axes explaining less (Holland, 2003). The DCA axis 1 scores therefore were taken as a measure of the species response to the principal forcing environmental, and represent the shape of the species assemblage response to the environment i.e. linear or unimodal (Best, 2013; Holland, 2003; ter Braak & Prentice, 1988).

If the DCA axis 1 length is greater than 2 standard deviations (SD), then a unimodal response is indicated and unimodal methods should be used; those less than 2 SD require linear methods (Barlow *et al.*, 2013; Birks, 1995; ter Braak & Prentice, 1988). The use of DCA axis 1 scores is widely used as a technique to reconstruct former environmental change (e.g. Best, 2013; Shennan *et al.,* 1995; Kurek *et al.,* 2009), and frequently used to determine the most appropriate ordination and regression methods (e.g. Elliott, 2015; Horton & Edwards, 2006; Horton *et al.*, 1999; 2006).

To establish the relationship between the contemporary diatom and foraminifera assemblages to the environment, ordination methods were utilised. Canonical Correspondence Analysis (CCA), a unimodal method of constrained ordination, was used. In an ecological context, constrained ordination expresses the relationship between the species composition of samples to measured environmental variables (Austin, 1976; Horton & Edwards, 2006). The axes produced in CCA are a linear combination of the environmental variables, with the species composition and environmental variations directly related (Horton & Edwards, 2006). As such, the axes can be used interpret the important environmental gradients by extracting the variation in the species assemblage that is explainable by the measured environmental variables (Best, 2013; Lepš & Šmilauer, 2003; ter Braak & Prentice, 1988).

Both CCA and partial CCA was carried out. CCA was conducted to establish the percentage of variation within the species assemblages in the training sets that was explained by the environmental variables (SWLI (section 5.7), clay, silt, sand, LOI) (Horton & Edwards, 2006; Zong & Horton, 1999). Partial CCA was conducted to establish the percentage variation that was explained by each individual measured environmental variable (Horton & Edwards, 2006). The remainder from the sum of individual environmental percentages to the total explained variation was taken to represent the intercorrelation of the environmental variables (Zong & Horton, 1999).

5.6. Sea-Level Index Points

Sea-level index points represent the position of relative sea level within space and time, and quantify litho- and biostratigraphical data in relation to the sedimentary environment and the water level (Edwards, 2006; Edwards & Horton, 2000; Horton *et al*, 2013; Ridgeway *et al.*, 2000; Shennan, 1982; 1986). To calculate a sea-level index point from a sediment, its age, altitude, tendency and indicative meaning (the modern counterpart height to relative sea level) are required (Barlow *et al.*, 2013; Edwards & Horton, 2006; Gehrels, 2007; Horton *et al.*, 2013; Long, 1992; Shennan, 1982). The use of sea-level index points was detailed in section 2.3.5, and is a widely used methodology for sea-level reconstruction (e.g. Edwards, 2006; Englehart & Horton, 2012; Gehrels, 1999; Gehrels *et al.*, 2011; Horton *et al.*, 2000; 2013; Massey *et al.*, 2008; Ridgeway *et al.*, 2000; Shennan *et al.*, 2000).

The determination of sea-level index point uses the basic equation:

$$RSL = H - RWL,$$

whereby RSL is the relative sea level, H is the altitude of the sample (determined when core surface altitude is known, as a measure of depth down the core), and RWL is the altitude of the determined reference water level (mid-point of the indicative meaning) (Englehart & Horton, 2012; Horton *et al.*, 2013; Shennan *et al.*, 2000).

The indicative meaning represents the relationship of the environment in which a sample accumulated to a contemporaneous reference tide level (Horton *et al.*, 2013; section 2.3.5). This is determined based on the litho- and biostratigraphical data. For example, a transition from peat to clastic sediments is indicative of the depositional regime that occurs around mean high water spring tide (Ridgeway *et al.*, 2000). The use of microfossils refines this, as distinct species or assemblages occur at different positions across a saltmarsh, representing the vertical relationship to the position in the tidal frame. With diatoms and foraminifera, assemblages are used to determine the indicative meaning, with the species distribution reflecting the position in the tidal frame (e.g. Gehrels *et al.*, 2001; Horton & Edwards, 2006; Horton *et al.*, 2006; 2013; Massey *et al.*, 2008; Metcalfe *et al.*, 2000; Vos & de Wolf, 1993; Zong, 1998; Zong & Horton, 1999; section 2.3.1)

Based upon the microfossil assemblages, the indicative meaning can be quantified using the relationship of the species to the position in the tidal frame i.e. deposited in the high marsh (above mean high water spring tide), the low marsh (between mean high water spring tide and mean tide level), or the tidal flat (below mean tide level) (Horton *et al.*, 2013; Vos and de Wolf, 1993). Within the Humber Estuary, key diatom species associations with the palaeoenvironment have been previously identified (Metcalfe *et al.*, 2000). The indicative meaning is comprised of the reference water level, which is the mid-point within the range in which the sample may occur, with the associated vertical range providing the indicative range (Horton *et al.*, 2013; Metcalfe *et al.*, 2000). The indicative meaning can also be quantified by the use of a transfer function (section 5.7).

There are several vertical errors that must also be quantified, along with the indicative range, and incorporated into each individual sea-level index point. These errors included surveying errors, affecting the altitude of samples, as well as the angle of coring, compaction during coring, sample thickness, sediment compaction and changes to the tidal range (Barlow *et al.*, 2013; Englehart & Horton, 2012; Horton *et al.*, 2013). The total error is then calculated using the equation:

$$E = \sqrt{(e_1^2 + e_2^2 + e_3^2 + e_n^2)},$$

whereby E is the error for a sample, and e_1-e_n are each individual source of error for each sample (Barlow *et al.*, 2013; Englehart & Horton, 2012; Shennan & Horton, 2002).

The error introduced to the altitude of samples through the use of high precision survey equipment is ±0.01m; the error from the angle of coring is ±1% of the sediment overburden (Englehart & Horton, 2012; Törnqvist *et al.*, 2008); compaction during coring is ±0.01m, and the error from sample thickness is ± half the sample thickness (Englehart & Horton, 2012; Shennan, 1986). Suitable tidal corrections for samples, based on their age and position in the estuary (inner or outer estuary), were calculated using the corrections identified by Shennan *et al.* (2003) for the Humber Estuary; all data younger than 4000 cal years BP use a linear correction, with sites older than this in the inner estuary using a polynomial correction due to larger changes in the tidal range (Shennan *et al.*, 2003; Shennan, personal communication 27th October 2015). Tidal corrections are applied to each individual sea-level index point.

Sediment compaction was calculated for each individual intercalated sea-level index point, and applied to the sea-level index point and the associated error range. Modelled relative sea-level predictions are plotted to fit with basal index points (due to the reduced effect of compaction on basal index points) (Shennan *et al.*, 2003). The residual difference between intercalated points and the predictions is attributed to compaction (Edwards, 2006; Horton & Shennan, 2009; Horton *et al.*, 2013; Shennan *et al.*, 2002). The residual difference is then compared to different stratigraphic parameters (i.e. overburden, depth and thickness) to assess statistical significance, and the linear regression between the significant parameter and the residual value is used to correct for any compaction (Edwards, 2006; Horton *et al.*, 2013). Within the Humber Estuary, sediment compaction has been demonstrated to have a strong relationship with the depth of the overburden (Horton & Shennan, 2009) and this has also been demonstrated in other studies at other locations (e.g. Edwards, 2006; Horton *et al.*, 2013).

5.7. Transfer Functions

Transfer functions can be developed from the analysis of the quantitative contemporary biological data to reconstruct particular environmental variables for the microfossil data (Barlow *et al.*, 2013; Imbrie & Kipp, 1971). This process essentially allows for the expression of an environmental variable as a function of the biological data. Transfer functions achieve this by utilising regression calculations to model the response of the contemporary biological assemblages as a function of the environmental variable (Birks, 1995). Calibration then applies the response function to predict the past environmental variable based upon the microfossil assemblage (Birks, 1995).

Transfer functions were developed and applied using C2 (Juggins, 2003). Training sets of both diatoms and foraminifera from within the Humber Estuary were produced, and also combined to provide a multi-proxy training set. These were combined with existing national (UK) datasets (Horton & Edwards, 2006; Zong & Horton, 1999), and the suitability of this method to reconstruct sea level within an estuarine environment examined.

The environmental variable of elevation used within the transfer functions is technically a proxy of the frequency of flooding, i.e. the tidal range (Horton and Edwards, 2006). As the development of a transfer function for the estuary requires the combining of multiple sites with differing tidal ranges, it is necessary to standardise the elevation for each sample to take into account variations in the vertical range (Barlow *et al.*, 2013; Hamilton & Shennan, 2005; Horton and Edwards, 2006; Watcham *et al.*, 2013). Ideally, to accurately determine this variation between sites, tidal gauges would be available for each site (van der Molen, 1997). However, as this does not occur, the nearest tidal gauge data is used. The standardisation of each site is achieved by converting each elevation to a standardised water level index (SWLI) using the equation:

$$X_{ab} = [((A_{ab} - MTL_b) / (MHWST_b - MTL_b) \times 100) + 200],$$

whereby X_{ab} is the SWLI of sample *a* at site *b*; A_{ab} is the altitude of sample *a* at site *b* (m OD); $MHWST_b$ is the mean high water spring tide at site *b* (m OD), and MTL_b is the mean tide level at site *b* (m OD) (Zong & Horton, 2009). Using this equation, if the altitude of a sample is equal to MTL or MHWST, the SWLI value will be 200 and 300 respectively. This SWLI equation was used to allow the data to be combined with the existing diatom dataset (from Zong & Horton, 2009), and also allow comparison to other studies using the same dataset (e.g. Wilson & Lamb, 2012). Tidal levels were taken from the nearest tide gauge (Admiralty Tide Tables, 2006), and for sites within the Humber Estuary, interpolated from the network of tide gauges within the estuary.

A unimodal response model, Weighted Averaging-Partial Least Squares (WA-PLS), was used to determine the relationship of the unimodal response to environmental variables that the species have demonstrated (Birks, 1995; Zong & Horton, 1999; section 6.3.2). WA-PLS produces a series of components. The first of these components maximises the covariance between the vector of the weighted averages and the biological data (Birks, 1995; Hamilton & Shennan, 2005). The further components maximise the same criteria but are uncorrelated to the previous components (Hamilton & Shennan, 2005; ter Braak *et al.*, 1993), and are therefore more removed from what is occurring in the environment. Due to this, only the first three components are generally considered for use for reconstruction, as components beyond this can be thought to be too far from reality (Barlow *et al.*, 2013).

Selection of the most suitable component is based upon the Root Mean Square Error of Prediction (RMSEP) and Coefficient of Determination (r^2). RMSEP gives the error of the predicted values (in SWLI units), an assessment of the overall predictive ability and therefore precision, and r^2 represents the strength of the relationship between the contemporary and inferred values (Birks, 1995; Leorri *et al.*, 2008). Bootstrapping provides cross validation. The bootstrapped r^2 value is considered as it is based upon pseudo-replicate datasets (1000 cycles), therefore improving the confidence. The components that are used for reconstruction are selected based upon a minimisation of RMSEP and maximisation of r^2 (Birks, 1995; Juggins, 2003).

Whilst the use of RMSEP and r^2 provide a measure of the performance, they only really reflect the internal consistency of the transfer function and fail to offer a measure of the overall reliability of the estimates that the transfer functions produce (Horton and Edwards, 2006). It is important to consider whether the modern training set offers a fair representation of the fossil samples (Birks, 1995; Horton and Edwards, 2006). The greater the extent of dissimilarity between the fossil and training set data the more the transfer function is forced to extrapolate, producing a greater potential for error in the resultant estimates (Birks, 1995; Horton and Edwards, 2005; 2006).

To identify fossil samples that lack good modern analogues, Modern Analogue Technique (MAT) can be applied (Birks, 1995; Horton and Edwards, 2005; 2006). The dissimilarity is calculated between the fossil samples and the ten most similar contemporary samples. This was done in C2, using the squared chord distance dissimilarity coefficient (Juggins, 2003; Overpeck *et al.*, 1985). Those with coefficients below the tenth percentile can be considered as having good modern analogues, those below the twentieth percentile as having close modern analogues, and those above the twentieth percentile as having poor modern analogues (Birks, 1995; Horton and Edwards, 2005; 2006; Wilson & Lamb 2012).

5.8. Groundwater Methods

The following section provides an overview of the methods used for the development of the conceptual model and use of a numerical model for the analysis of groundwater, and the impacts of sea-level change and abstraction.

5.8.1. Conceptual Model

A conceptual model is an initial representation of a system, and is useful to identify the components of a system, and aid understanding of the various elements of a system and potential complexities. Developing a conceptual model helps to ensure that a subsequent analytical or numerical model is useful, valid and feasible (Robinson, 2008). The purpose of a conceptual model is to consider and identify all aspects of the system, and to collate the relevant information and values (Brown & Hulme, 2001; McMahon *et al*., 2001). In the context of this study, a conceptual model of the groundwater between the Humber Estuary and Springhead abstraction site is considered (section 4.7.1; 53° 45' 3.6722"N; 0° 25' 18.3213"W). Conceptual models necessitate the simplification of natural systems, leading to assumptions regarding parameter values and the structure of the system (McMahon *et al.*, 2001; Robinson, 2007). As such, any assumptions made within the conceptual model must be clearly stated and justified. Conceptual models also aid the assessment and validation of the outputs from numerical models of the same systems.

The development of the conceptual model involved the collation of various field data and literature reviews, with the systematic synthesis of all relevant literature, borehole records, reports and monitoring/field data (provided by organisations such as the Environment Agency, British Geological Survey and Yorkshire Water). The geology of the area was obtained from geological maps, and borehole records were used to establish the superficial geology at a high resolution. The geology was extrapolated between adjacent boreholes, introducing some assumptions into the interpretation and analysis. Parameter values (e.g. hydraulic conductivity of the geological units) were taken from the conceptual model established and used within the East Yorkshire Chalk numerical model (section 5.8.2).

5.8.2. Numerical Model

Numerical models are used to simulate a conceptual model, and the development and advancement of computer modelling allows for the simulation of more complex systems (Fitts, 2002), such as the groundwater in the Chalk aquifer adjacent to the Humber Estuary. An existing model of the East Yorkshire Chalk aquifer that is used by the Environment Agency, and subsequently Yorkshire Water, to inform decisions regarding the quality and use of groundwater resources, was used in this study.

The East Yorkshire Chalk (EYC) model of the aquifer was commissioned, and is currently used and operated, by the Environment Agency, and was developed by Environmental Simulations International (ESI)(ESI 2013a; 2013b; 2015). Initially, a groundwater model of the East Yorkshire Chalk, 'YORKMOD', was developed and refined over a twenty-year period from the 1980's (ESI, 2013a), and the development of the newer EYC model represents the evolution and enhancement of understanding and modelling techniques. The EYC model was created over two phases. The first phase comprised a conceptualisation of the East Yorkshire Chalk, and supported the development of the EYC numerical model (ESI, 2013a). The second phase comprised the construction and calibration of the EYC numerical model, and involved two components: a recharge runoff model to calculate the recharge input and runoff for the model, and the subsequent numerical groundwater model (ESI, 2013b). All reports, and access to, and assistance in using the EYC numerical model, was provided by the Environment Agency, at the Environment Agency offices in York.

The EYC conceptual model provided a collation of the geological, hydrogeological, hydrological and meteorological data for the EYC region (section 9.1; ESI, 2013a). The conceptual model addressed the physical and human setting (i.e. landscape, surface waters, groundwater exploitation, Water Framework Directive), the geology (i.e. bedrock, superficial, soils), the aquifer properties, groundwater levels, groundwater-surface water interactions, groundwater recharge, groundwater chemistry, and groundwater balances, as well as highlighting the important information and uncertainties associated with the variables and parameters (ESI, 2013a). The EYC conceptual model (ESI, 2013a) provided the basis for the development of numerical EYC model (ESI, 2013b), and provided a collation and analysis of current understanding of the hydrogeology of the EYC aquifer.

The EYC numerical model is a numerical finite difference groundwater model constructed using MODFLOW-VKD code (ESI, 2013b), based upon the conceptualised model (ESI, 2013a), and is visualised and used within the National Groundwater Monitoring System (NGMS) programme by the Environment Agency (Whiteman *et al.*, 2012). The recharge and runoff for the numerical model was estimated separately using a recharge-runoff model, Routing of Rainfall, Runoff and Recharge (4R) developed by Entec, and input into the groundwater model (ESI, 2013b). The numerical model encompasses the terrestrial area of Chalk in East Yorkshire, c. 2040km^2, and is defined by a rectangular grid of 200m by 200m cells, and comprised of three layers, representing the superficial deposits, active Chalk aquifer, and the underlying strata (ESI, 2013b). Full information of the model construction and parameters are provided in substantial detail in the multiple model reports (ESI, 2013a; 2013b; 2015).

The EYC conceptual and numerical model were updated and recalibrated following a review of the information and data available (ESI, 2015), providing confidence that it is a reliable representation of the groundwater system (based on current understanding). It has been concluded that the model is fit for purpose and credible in terms of use for informing management decisions, including, though not limited to, abstraction licensing, groundwater flooding, climate change (e.g. recharge), and diffuse pollution (ESI, 2015). It has also been concluded that the model can aid the strategic water resource decision making and planning by Yorkshire Water (ESI, 2015). Indeed, it has been demonstrated that the EYC model is well calibrated for the Hull area, and as a result can be used to examine and assess the potential for saline intrusion from the Humber Estuary (ESI, 2013b), making it a suitable tool for this research, due to both the capabilities of the model, but also because it is used to inform current decision making processes.

Though not designed with the intention of exploring the impacts of sea-level change, the EYC model provides an opportunity to investigate the impacts such changes will have. Along with the ability to alter abstraction regimes, the EYC model provides a unique opportunity to examine the impact that changes to both sea level and anthropogenic abstraction has on the groundwater system. This was explored through a series of scenarios.

5.8.3. Numerical Model Scenarios

A total of nine scenarios, incorporating sea-level change and groundwater abstraction, have been studied: three past, three present, and three future scenarios. All were designed to examine the relationship between the groundwater and changing sea level, as well as the role of anthropogenic abstraction of groundwater, between the Humber

Estuary and the Springhead source, by quantifying the changes in head and flows of the groundwater.

Within the EYC numerical model, there are three predefined model scenarios. These comprise a naturalised scenario, whereby there is no groundwater abstraction; a recent actual scenario with all groundwater abstractions in the region operating at an average calculated from 2003-2007 data, and a fully licensed scenario, with all groundwater abstractions operating at fully licensed rates. For the Springhead source, the recent actual and fully licensed abstraction rates are 21.7 Ml d^{-1} and 24.5 Ml d^{-1} respectively (ESI, 2015). These default scenarios are used alongside the changes to sea level to examine the impacts of groundwater abstraction for the present and future scenarios. The three default scenarios are used to represent the present day environment. The model boundary conditions, located on the northern edge of the estuary, are adjusted to represent changing sea level for the palaeo and future scenarios.

The northern edge of the Humber Estuary provides the southern boundary for the EYC model, and is represented by MODFLOW river boundary cells (ESI, 2013b; 2015). The fixed head boundary is defined as +0.2m OD, with a bottom elevation of -15.8m OD, and a conductance of 1500m^2 d^{-1} (ESI, 2015). MODFLOW drain cells, with an increased conductance of 5000m^2 d^{-1}, are present at locations where discharge into the estuary is known to have occurred, to better simulate the differing boundary conditions along the estuary (ESI, 2013b). It is the head for the boundary cells along the estuary that are altered to represent changes to sea level for the various scenarios.

The palaeo sea-level estimates are determined based upon the existing suite of sea-level index points for the Humber Estuary, along with those that were produced in this study. The sea-level estimate for the future, AD 2100 scenarios, are based upon “business as usual” carbon emission scenarios, whereby there is assumed to be no significant abatement of global carbon emissions. The value of 0.73m is the mean of median value calculated using process-based methods (Church *et al.*, 2013), and is in-line with other assessments and studies of future sea level (e.g. Horton *et al.*, 2014; Kopp *et al.*, 2014; 2016), and is comparable to the rate of sea-level rise projected for the North Sea AD 2025-2055 (Gehrels & Long, 2008).

To provide consistency across the scenarios in terms of recharge, all results were taken from the same point within the simulation (21/03/2005). This provides a result that represents an ‘average’ year in terms of rainfall, rather than ‘drought’ or ‘wet’ years.

Using the results of changes to the head at the Springhead source, the simplified Ghyben-Herzberg relationship (section 3.3) is used to produce a crude estimate of the change to the saline front within the groundwater (Fitts, 2002). Using this relationship, the estimates provide an initial quantification of the contribution sea-level change has on saline intrusion within the aquifer, as well as a quantification of the contribution of abstraction. Crucially, based upon the future scenarios, it provides an insight of the risk that saline intrusion may pose for the use of the Springhead source.

5.8.4. Numerical Model Limitations

It is important to recognise the limitations of the EYC model. Along with the standard issues with numerical models, such as the model being inherently limited by the extent of knowledge and data for the region, there are several others. As well as the limitations discussed within the model reports (ESI 2013a; 2013b; 2015), and particularly the scale of cells (200m by 200m) resulting in a potential loss of any finer characteristics of the parameters that could alter the simulations, there are several key limitations regarding the use of the model and the resultant scenario simulations that must be considered and acknowledged.

A key limitation is the position of the boundary of the model, on the northern edge of the Humber Estuary. As the Chalk aquifer extends south below the estuary and into Lincolnshire, the model does not necessarily incorporate or represent the groundwater flows that may be occurring below or within the estuary. As such, possible outflows, and therefore potential inflows, from the aquifer that may be present within the estuary are not represented. As well as this, the parameter of the flows at the boundary, the conductance, is assumed to be an accurate representation based upon the calibrations (ESI, 2013b), and for the purposes of this study assumed not to change. It is not therefore altered for the different scenarios. The outflows, and potential inflows, from the simulations are dependent on that parameterisation, and in the context of this study, are crucial in assessing the impact of sea-level change, and must be acknowledged as a limitation.

For the palaeo scenarios, the position of the model boundary is not changed. However, reconstructions of the estuary suggest an expansion of marine conditions c. 3000 cal years BP followed by a subsequent contraction (Kirby, 1999; Lamb *et al.*, 2007; Long *et al.*, 1998; section 4.4). Indeed, the Hull area is proposed to have had a sub- and inter-tidal environment 3000 cal years BP (Metclafe *et al.*, 2000; section 4.4), which is not represented by the model. As well as this, additional parameters, such as the bottom elevation of the estuary, are assumed constant and not altered. As such, the simulations of the palaeo scenarios may not accurately reflect the palaeo groundwater environment. However, the simulations do provide a useful insight into how the naturalised groundwater environment has changed when compared to the present and future scenarios.

Other variables key to the groundwater system, such as recharge, could also change based upon the time periods that were considered for the scenarios. In previous work considering the palaeohydrogeology of the North Lincolnshire Chalk (Hiscock and Lloyd, 1992), south of the Humber Estuary, the recharge from 5000 years BP to present was assumed constant, at 200mm a^{-1}, as the late Holocene period coincides with wetter conditions and forest clearance (Hiscock and Lloyd, 1992). This value is in line with other values used for present conditions, of 227mm a^{-1} (Parker, 2009), and that calculated in the conceptual stage of the EYC model of 261mm a^{-1} based upon average annual recharge from 1969/70-2006/07 (ESI, 2013a). Due to this, and the use of the separate model to determine the recharge in the EYC numerical model (section 5.8.2), the recharge was not adjusted for the palaeo scenarios in this study, or for the future scenarios. However, it is acknowledged that recharge is likely to change in the future due to climate change and anthropogenic activity (e.g. urbanisation, agriculture).

5.9. Summary

This chapter introduced and summarised the methods used throughout this thesis. Site selection, field and laboratory methods were detailed, including microfossil analyses. The reconstruction of sea-level change using sea-level index points and transfer functions was explained. The methods to address the groundwater component of the thesis were also detailed, including the use of conceptual and numerical groundwater models, including the use and limitations of the East Yorkshire Chalk numerical model, and the scenarios to examine the relationships between groundwater, abstraction and sea level.

6. Contemporary Environment and Sea-Level Transfer Functions

This chapter presents the results of analyses of three contemporary intertidal saltmarshes within the Humber Estuary, the relationship of the microfauna assemblages to sea level, and the development of transfer functions to reconstruct palaeo sea level for sites within the Humber Estuary.

6.1. Contemporary Humber Marshes

Modern intertidal marshes within the Humber Estuary are spatially limited. Widespread reclamation of land and the presence of embankments throughout the estuary have limited the marshes in both spatial extent and distribution in the estuary (section 4.5). This has resulted in a squeeze on the upper saltmarsh environments within the estuary to the extent that most have been lost (Allen *et al.*, 2003). As such, the estuary lacks 'traditional' saltmarsh environments, encompassing the full transition from terrestrial, through high, middle and low saltmarsh, to marine environments.

The following sections present the results of the analyses of contemporary samples collected from three remaining areas of marsh within the estuary: Welwick, Spurn, and East Halton marshes. A total of 40 samples were collected from the three locations, with 92 species of diatoms and 19 species of foraminifera identified.

6.1.1. Welwick

Welwick is the largest area of saltmarsh remaining within the estuary, and has been used in previous studies of the estuary (e.g. Horton, 1997; Horton & Edwards, 2006; Lamb *et al*. 2007). It is located on the northern banks of the estuary, east of Sunk Island, in the outer portion of the estuary (53° 39' 0.1116" N; 0° 1' 23.5812" E; Figure 6.1). It is a relatively young marsh (~100 years old) that formed following the reclamation of Sunk Island throughout the 1700s and 1800s, which provided a sheltered bay for deposition (Sheppard, 1966; section 4.5). Welwick covers an area of c. 0.4km^2, incorporating tidal flats through to a mid-marsh environment. A high marsh is absent due to the presence of an embankment on the landward edges.

The transect sampled across Welwick marsh covered 625m, from the rear of the marsh, backed by an embankment, down to unvegetated tidal flats. The marsh is characterised by a generally flat profile, with an elevation of c. 3.12m OD over the first c. 350m, and a decrease in elevation over the remaining c. 275m to a low of 1.93m OD on the tidal flats

(Figures 6.1; 6.2). A total of 22 contemporary surface samples were collected across the marsh.

The rear marsh is waterlogged and is populated by *Spartina anglica* (Common Cord Grass), with some *Festuca rubra* (Red Fescue) and occasional *Aster tripolium* (Sea Aster). As the marsh becomes less waterlogged, the vegetation shifts to *Ammophilia arenaria* (Marram Grass) with some *A tripolium*. As the elevation decreases across the middle marsh, the vegetation consists of *Halimione porulacoides* (Sea Purslane) and *A. tripolium*, with the gradual introduction of *S. anglica*, *F. rubra*, and *Limonium vulgare* (Common Sea Lavender). Towards the lower marsh, the vegetation transitions into *S. anglica* and *F. rubra*, with some *L. vugare* and *Salicornia europea* (Glasswort). This transitions into patches of *S. anglica* and some *S. europea*, before becoming unvegetated tidal flats. The organic content decreases continually across the marsh, with carbonate content generally <5%, and the sediment composition remains relatively stable, with occasional minor fluctuations (Figure 6.2).

6.1.2. Welwick: Microfauna distribution

A total of 78 diatom species and 16 foraminifera species were identified from the 22 samples (Figure 6.3). The diatom assemblages across the marsh are dominated by brackish and marine species, with marine species generally increasing in presence across the marsh towards the tidal flats. Freshwater species are present across the mid portion of the marsh, ~100-550m along the transect, where elevations exceeded 2.5m OD. The rear of the marsh has a lower (<1%) freshwater species than the mid portion of the marsh; this is attributed to the presence of standing water at the rear of the marsh forming a brackish environment. The foraminifera species identified demonstrate a shift from predominantly agglutinated species, particularly *Jadammina macrescens*, in the upper and mid portions of the marsh, to a dominance of calcareous species, particularly *Haynesina germanica*, across the lower portion and tidal flat.

6.1.3. Spurn

Positioned inwards to the estuary, on the western side of Spurn, located at the mouth of the estuary, there is a narrow strip of saltmarsh that extends along sections of the spit (53° 36' 37.8792" N; 0° 8' 39.8076" E; Figure 6.1). The extent of the marsh can be variable due to storm events breaching and overtopping the spit. The environment encompasses tidal flats through to mid-marsh. High marsh is absent due to the presence of an embankment and road, and further inland a narrow dune system.

The transect at Spurn covered 100m, from the rear of the saltmarsh system, down to the unvegetated tidal flats. The marsh at Spurn is characterised by a westward sloping topography, towards the estuary. The rear of the marsh has an elevation of 5.34m OD; this rises slightly to 5.37m OD ~20m along the marsh, before continuing to fall over the rest of the transect to a low of 3.92m OD on the tidal flat (Figures 6.1; 6.2). A total of 12 contemporary surface samples were collected across the marsh.

The rear of the marsh is predominantly populated by *A. arenaria*; this shifts into *H. porulacoides*, with the progressive inclusion of *A. tripolium*, and *S. anglica*, as well as *F. rubra* and *L. vulgare*. Around the creeks in the lower marsh, the vegetation consists of *A. tripolium*, *S. europea*, *F. rubra* and *S. anglica*. The vegetation gradually becomes patchy, with a decrease in diversity, and some *S. anglica* occurring prior to the unvegetated tidal flats. The decrease in elevation and vegetation across the marsh is reflected by a fall in the organic content of samples, and a rise in the silt content. An exception to a trend of low sand content was a sample midway along the transect, which had an unusually high sand content of 39%. This sample however occurred at the base of an abrupt drop in elevation of c. 0.15m, where coarse sediments may have accumulated (Figure 6.2).

6.1.4. Spurn: Microfauna distribution

A total of 53 diatom species and 13 foraminifera species were identified from the 12 samples (Figure 6.4). The sample from the rear of the marsh had a diatom assemblage comprised of 28% freshwater species; this decreased to ~1% across the rest of the marsh, with brackish and marine species dominating the assemblages. The foraminifera assemblages for the samples located towards the rear of the marsh were dominated by agglutinated species, and the presence of *Miliammina fusca* through the mid portion of the marsh. The assemblages became increasingly dominated by the calcareous species *H. germanica* and *Ammonia batava* through the lower portions of the marsh and tidal flat.

6.1.5. East Halton

East Halton marsh site is located on the southern banks of the estuary, located in the inner portion of the outer estuary (53° 41' 39.4980" N; 0° 15' 57.8412" W; Figure 6.1). The area is small (c. 0.1km^2), and encompasses a tidal flat, with an erosional cliff (c. 1m in height) fronting a raised marsh containing ponds and reeds, backed by an embankment on the landward edge. Though not a ‘classic’ saltmarsh environment, the site was included as it provided an additional site that had saltmarsh vegetation on the estuary edge, and was in close proximity to the East Halton palaeo study site (Chapter 7).

The transect across the marsh at East Halton covered 42m, from the raised rear marsh, down to unvegetated tidal flats. The rear marsh is relatively flat, at an elevation of c. 3.72m OD; there is then a sudden drop, with an eroding cliff, at 2.74m OD, and then a continuous fall in elevation down to 1.83m OD on the tidal flat (Figures 6.1; 6.2). A total of 6 contemporary surface samples were collected across the marsh.

On the raised rear marsh the vegetation is dominated by *A. arenaria*, becoming less dense prior to the eroding cliff. At the base of the eroding cliff there is no vegetation, but on the tidal flats there are occasional patches of *L. vulgare*, *A. tripolium* and *S. anglica*, prior to becoming completely unvegetated. The drop in elevation, from the rear marsh down to the tidal flat, is marked by a decrease in the organic content and an increase in the carbonate content, and also corresponds to an increase in the silt and clay content of samples.

6.1.6. East Halton: Microfauna distribution

A total of 54 diatom species and 14 foraminifera species were identified from the 6 samples (Figure 6.5). The rear marsh samples are largely comprised of brackish and freshwater diatom species. On the tidal flats, the freshwater and brackish species decrease, and the marine species dominate, comprising >60% of the assemblages. This shift is also reflected in the foraminifera assemblages, with the agglutinated species decreasing in abundance and calcareous species increasing down the marsh profile.

6.2. Training Sets: Scales and Proxies

Two proxy datasets, diatom and foraminifera, have been produced from the three sites within the Humber Estuary, comprising 40 samples in total. These have also been combined to produce a multi-proxy training set for the Humber Estuary. Existing UK datasets of foraminifera (11 locations; Horton & Edwards, 2006) and diatoms (6 locations; Zong & Horton, 1999) have also been utilised to expand the training sets into ones of a UK-wide and UK-estuary scale to explore the implications of both the proxies and spatial scale used to develop transfer functions. Each training set is outlined in detail in Table 6.1, however as they are referred to in the following sections, to summarise they are as follows:

D= Diatom, *F*= Foraminifera, *M*= Multi-proxy

D-1 Humber diatoms; 3 sites (this study)
D-2 UK diatoms; 6 sites (Zong & Horton, 1999)
D-3 UK-Humber diatoms; 9 sites (this study; Zong & Horton, 1999)
D-4 UK estuary diatoms; 3 sites (Zong & Horton, 1999)
D-5 UK estuary-Humber diatoms; 6 sites (this study; Zong & Horton, 1999)
F-1 Humber foraminifera; 3 sites (this study)

F-2 UK foraminifera; 12 sites (Horton & Edwards, 2006)

F-3 UK-Humber foraminifera; 15 sites (this study; Horton & Edwards, 2006)

F-4 UK estuary foraminifera; 4 sites (Horton & Edwards, 2006)

F-5 UK estuary-Humber foraminifera; 7 sites (this study; Horton & Edwards, 2006)

M-1 Humber multi-proxy; 3 sites (this study)

M-2 UK multi-proxy; 18 sites (Horton & Edwards, 2006; Zong & Horton, 1999)

M-3 UK-Humber multi-proxy; 21 sites (this study; Horton & Edwards, 2006; Zong & Horton, 1999)

M-4 UK estuary multi-proxy; 7 sites (Horton & Edwards, 2006; Zong & Horton, 1999)

M-5 UK estuary-Humber multi-proxy; 10 sites (this study; Horton & Edwards, 2006; Zong & Horton, 1999)

D-1, F-1, and *M-1* can be considered as local training sets, representing sites from within the Humber Estuary; *D-2-3, F-2-3* and *M-2-3* as regional, UK scale training sets, and *D-4-5, F-4-5* and *M-4-5* as UK estuarine environment training sets. For the Humber Estuary multi-proxy datasets, the diatom and foraminifera datasets are combined following the recommendations of Elliott (2015). The foraminifera samples considered to have low counts (<100 tests; section 5.4.2) have had all foraminifera species values converted to zero, but still retain the sample's diatom assemblage. This is considered best practice rather than excluding the entire sample, reducing the volume of samples and environment represented, or to include the low counts which may introduce additional uncertainty (Elliot, 2015). When using the additional datasets, all SWLI values were calculated as stated in the methodology (section 5.7). Ideally, foraminifera and diatom data should be from the same sites and samples, as with the Humber dataset, however such a dataset was not available. Taxonomic harmonising of the additional datasets was also undertaken to ensure the correct names of species was applied throughout all the datasets.

6.3. Diatoms and Foraminifera: Relationship to Elevation

The use of diatoms and foraminifera within the project is as a proxy to reconstruct former elevation on a marsh, which in turn can be used to determine former sea level. Visual inspection of the diatom and foraminifera assemblages indicate there to be a relationship to elevation, as there is a shift in the assemblages present as elevation decreases across the marshes. However, this could also represent shifts in other environmental variables, or some inter-correlation between environmental variables. As such, the diatom and foraminifera training sets produced within this study (*D-1, F-1 and M-1*) have undergone Constrained Incremental Sum of Squares (CONISS), Detrended Correspondence

Analysis (DCA), Canonical Correspondence Analysis (CCA) and partial CCA to establish the relationship to the environment, and the most suitable transfer function approach (sections 5.5; 5.7).

6.3.1. Cluster Analysis

The results of cluster analysis on the separate diatom and foraminifera training sets are displayed in Figures 6.6 and 6.7. CONISS revealed there to be 5 distinct zones within the diatom assemblages from the three sites studied in the Humber Estuary (Figure 6.6). Zone 1 represents the tidal-lower marsh zone, comprised predominantly of marine and marine brackish species, from SWLI 248-261. Zone 2 extends from SWLI 261-280, representing the lower saltmarsh environment, with a diverse combination of marine, marine brackish and brackish species. Zone 3, from SWLI 280-307, represents the upper saltmarsh environment, around MHWST (SWLI 300), and is dominated by brackish diatom species. There is however a lack of coverage in this zone, from SWLI 294-304, with no samples representing that range.

There are no samples covering the range 307-332 SWLI between Zones 3 and 4. Zones 4 and 5 revealed by CONISS of the diatom training set are problematic, as they only contain the 12 samples collected from Spurn, and cover a high SWLI range from 330-385. However, the samples show similar species assemblages and shifts present in Zones 1 and 2, suggesting perhaps a unique environment at Spurn exceeding MHWST, or perhaps some errors in the measurement of elevation or determination of the tidal values for the site. Due to the flora identified at Spurn, and the presence of tidal limits indicated by litter visible on the marsh, an error within the elevation may be the most likely cause for the potentially erroneous elevation and SWLI values. As such, Zones 3 and 4 are also considered to represent lower and upper saltmarsh environments respectively.

CONISS analysis of the foraminifera revealed 4 separate zones (Figure 6.7). Zone 1 covers SWLI 248-277, and is dominated by calcareous foraminifera species, consistent with a lower marsh environment. Zone 2 covers SWLI 283-307, with a break in the coverage from SWLI 294-304, and represents the upper saltmarsh environment, around MHWST (SWLI 300), and is dominated by agglutinated foraminifera species. As with the diatom training set, Zones 3 and 4 reflect Zones 1 and 2 and only contain the samples from Spurn.

The key species identified from both the diatom and foraminifera zones are shown in Figure 6.8. Important to note however is an absence in coverage for certain portions of the tidal range of the training sets, represented by SWLI, meaning these training sets are not representative of the full intertidal environment.

6.3.2. Linear or Unimodal Methods?

DCA was carried out on the training sets developed in this study (D-1, F-1, and M-1) to establish whether the species response in the training sets was linear or unimodal to the forcing environmental variable (section 5.7). The length of DCA axis 1 was 2.87, 2.32 and 2.42 SD units for the diatom, foraminifera and combined training sets respectively (Table 6.2), indicating that unimodal ordination (CCA) and unimodal regression (WA-PLS) are the most appropriate methods for the training sets. The UK diatom training set (Zong & Horton, 1999) and UK foraminifera training set (Horton & Edwards, 2006) both also have a unimodal response.

6.3.3. Canonical Correspondence Analysis

CCA and partial CCA was undertaken to establish the relationship between the contemporary diatom and foraminifera assemblages to the five measured environmental variables (SWLI, clay, silt, sand and LOI), and the proportion of the variation in the species assemblage they explain. These variables are in keeping with environmental variables examined in Zong & Horton (1999) and Horton & Edwards (2006).

Within the diatom training set, the environmental variables explained 27.68% of the variance. Of this, partial CCA revealed that SWLI, the proxy for elevation, explained 9.97%, clay 13.37%, silt 13.11%, sand 13.11%, and LOI 32.98%; the remaining 17.45% is attributed to intercorrelation of the environmental variables (Figure 6.9).

For the foraminifera training set, the environmental variables explained a larger proportion of the variation, with 47.83% being explained. Of this, the partial CCA revealed that SWLI explained 6.0%, clay 6.90%, silt 5.67%, sand 6.03%, and LOI 44.95%, with the remaining 30.42% attributed to intercorrelation of the environmental variables (Figure 6.9).

In the combined diatom-foraminifera training set, the environmental variables explained 30.4% of the variance. Of this, partial CCA revealed that SWLI explained 8.65%, clay 14.38%, silt 12.60%, sand 13.0% and LOI 32.96%, with the remaining 18.42% attributed to the intercorrelation of the environmental variables (Figure 6.9)

6.3.4. Canonical Correspondence Analysis: Interpretation

None of the datasets produced explained more than 50% of the variation in the assemblages (Figure 6.9). Though the overall explained variation values appear low, they are in line with many other studies (e.g. Horton, 1997; Horton & Edwards, 2006; Zong & Horton, 1999). The foraminifera training set had the greatest amount explained at 47.83%; however, within the environmental variables, it had the highest amount of intercorrelation, at 30.42%. The diatom training set had the lowest amount of explained variation, at 27.68%, but also the lowest amount of intercorrelation at 17.45%. LOI explained the largest amount of variation in all the training sets (30.42-32.98%), followed by the grain sizes, with SWLI explaining the least (6-9.97%).

However, the large proportion (17.45-30.42%) attributed to intercorrelation is significant to consider, as it demonstrates the interdependent nature of the variables. Indeed, it has been demonstrated that LOI values have a strong positive relationship with SWLI, and that LOI and grain size are related to the SWLI (Horton, 1997; Zong & Horton, 1999). As such, SWLI can be considered as being representative of all environmental variables, and the distribution of the micro-fauna can be considered to be directly influenced by the elevation (Horton, 1997; Scott & Medioli 1980; 1986; Zong & Horton 1999).

6.4. Transfer Functions

Transfer functions were developed based on the proxy as well as spatial scale i.e. diatom, foraminifera or multi-proxy, and local (Humber), regional, or regional estuarine scales. This resulted in the development of 15 transfer functions using the training sets outlined in section 6.2 (Table 6.1). These training sets were established to explore the difference that the proxy used, as well as the spatial scale and environment from which they are from, may have on the resultant reconstructions of the palaeo sea level in the Humber Estuary. This is particularly important, given the dynamic nature of an estuarine environment, particularly a macrotidal and highly modified estuary such as the Humber Estuary (Chapter 4). Analyses of the training sets revealed them to have a unimodal response (section 6.3.2), so WA-PLS was used to produce the transfer functions, as outlined in section 5.7.

The construction of each training set, the resultant transfer functions and performance, is outlined in the following sections; Table 6.3 summarises each of the transfer functions.

6.4.1. Diatom Transfer Functions

Five transfer functions, *D-1-5,* were based upon the five corresponding diatom training sets (section 6.2). *D-1* uses the diatom training set produced from the Humber Estuary, comprised of 40 samples from 3 sites (this study; sections 6.1; 6.2). These sites are taken to represent the 'local' environment for the Humber Estuary. The first component was assessed, as the improvement in RMSEP to the next component was less than 5% (section 5.7). *D-1* produced a RMSEP value of 41.90, and a low bootstrapped r^2 value of 0.10, and covers a small part of the environmental gradient (Table 6.3; Figure 6.10). Due to these poor values, this transfer function alone cannot be considered as accurate, and would produce considerable errors for any reconstructions.

Transfer function *D-2* uses an existing diatom training set comprised of 88 samples from 6 sites around the UK (Zong & Horton, 1999). This is taken to be a 'regional' scale training set. The second component is assessed, as it provided an improvement in RMSEP of 6.15% from the first component; this provided an improved performance from *D-1*, with a RMSEP of 22.70 and a higher bootstrapped r^2 of 0.65, therefore providing increased accuracy and covering a larger environmental gradient (Figure 6.10). *D-3* uses both the UK dataset and the Humber dataset, combining the local and regional datasets to produce a training set of 128 samples from 9 sites. The first component was assessed, and revealed a reduction in the accuracy achieved with *D-2*, with a RMSEP of 31.00 and bootstrapped r^2 of 0.43 (Table 6.3; Figure 6.10).

Transfer functions *D-4* and *D-5* were produced to assess the role that estuarine environments may have on the performance, and ultimately the reconstructions, of the diatom based transfer functions. *D-4* is based upon the sites from estuaries within the existing UK dataset used in *D-2*, reducing it to 51 samples from 3 sites. The third component was assessed, as there was an improvement greater than 5% between each of the former components, with the third component having an improvement in RMSEP of 16.46% from the second component. *D-4* provided the lowest RMSEP of 16.46, and highest bootstrapped r^2 value of 0.80. In contrast, *D-5*, which combines *D-4* with the Humber dataset, uses the first component and produced a RMSEP of 32.88 and low bootstrapped r^2 of 0.31. The variation in the accuracy of these diatom based transfer functions and the environmental gradient they represent can be seen by the spread of the data when the observed SWLI is plotted against the estimated SWLI, with those that provided an improved performance (i.e. lower RMSEP and higher bootstrapped r^2 values) producing a reduced spread in the data, with the estimated SWLI values being closer to the observed values (Figure 6.10).

Overall, the assessment of these diatom-based transfer functions of varying size and spatial scale indicate that the local, Humber based training set does not provide an accurate transfer function to reconstruct palaeo data (*D-1*). This may be a result of the limited scale of the dataset (i.e. 40 samples from 3 sites), but also due to the limited range of the tidal frame they represent (section 6.3.1), and a direct result of the lack of remaining areas of saltmarsh in the Humber Estuary. In contrast, the UK scale transfer functions perform better (*D-2-5*), particularly when the poorer preforming local scale Humber are excluded (*D-2* and *D-4*), indicating that an increased spatial scale, along with an increased volume of samples, improves performance of the diatom based-transfer functions. However, the UK estuaries dataset, *D-4*, comprised of 51 samples from 3 sites, provided the best performance overall, and out-performed the UK wide dataset, *D-2*, which is based on 88 samples from 6 sites, suggesting that estuarine environments are actually useful for producing diatom-based transfer functions when taken from a larger 'regional' spatial scale.

However, despite the performance of the diatom-based transfer functions, crucial to the reliability of the reconstructions that they produce is whether the training sets provide analogues for the fossil dataset (section 5.7). This is assessed for each fossil record in subsequent chapters (Chapters 7 and 8), and used in conjunction with the performance to select the most appropriate transfer function for the palaeo reconstructions.

6.4.2. Foraminifera Transfer Functions

Five transfer functions, *F-1-5,* were based upon the five corresponding foraminifera training sets (section 6.2). The variation in the accuracy of these foraminifera based transfer functions and the environmental gradient represented can be seen in Figure 6.11, where the estimated SWLI values are plotted against the observed SWLI values.

F-1 uses the foraminifera training set produced from the Humber Estuary, comprised of 34 samples from 3 sites (this study; sections 6.1;6.2). The first component of *F-1* was assessed, and produced a RMSEP value of 44.58, and a very low and negligible bootstrapped r^2 value of 0.00 (Table 6.3; Figure 6.11). Due to these poor values, this transfer function can not be considered as viable, and produces considerable errors for any reconstructions. Notably, the performance is worse than that provided by the Humber diatom-based transfer function *D-1,* though the values of RMSEP and bootstrapped r^2 are similar (Table 6.3).

Transfer function *F-2* uses an existing foraminifera training set comprised of 162 samples from 12 sites around the UK (Horton & Edwards, 2006). The first component is assessed; this provided an improved performance from *F-1*, with a RMSEP of 25.78 and bootstrapped r^2 of 0.28; however, this is still an unacceptably low r^2 value. *F-3* uses both the UK dataset and the Humber dataset, providing a training set of 196 samples from 15 sites. The first component was assessed; as with the diatom equivalent transfer function, it saw a reduction in the accuracy achieved with *F-2*, with a RMSEP of 29.44 and bootstrapped r^2 of 0.26 (Table 6.3; Figure 6.11).

As with the diatom transfer functions, transfer functions *F-4* and *F-5* are based upon samples from estuarine environments. *F-4* is based upon the sites from estuaries within the existing UK dataset used in *F-2*, reducing it to 64 samples from 4 sites. The first component of *F-4* was assessed; it provided the lowest RMSEP of 14.48, however it had a reduction in the bootstrapped r^2 value to 0.09 and represented a limited environmental gradient (Table 6.3; Figure 6.11). *F-5*, which combines *F-4* with the Humber dataset, also uses the first component and produced an increased RMSEP of 28.33 and reduction in bootstrapped r^2 to 0.03.

Overall, the assessment of these foraminifera-based transfer functions of varying size and spatial scale indicate that the local, Humber based training set does not provide an accurate transfer function to reconstruct palaeo data (*F-1*), consistent with the findings with the diatom-based transfer functions (section 6.4.1). The UK scale transfer functions perform better (*F-2-5*), particularly when the local scale Humber are excluded (*F-2* and *F-4*), though the reduction in the accuracy through their inclusion is not as large as that seen in the diatom transfer functions (*D-2-3)*. The UK estuaries transfer functions (*F-4* and *F-5*) do not perform well; despite offering RMSEP values consistent with the UK wide transfer functions, and the lowest RMSEP in the case of *F-4*, the bootstrapped r^2 are extremely low (<0.1). Based therefore upon the minimisation of RMSEP and maximisation of bootstrapped r^2, the UK scale transfer function, *F-2*, is the best performing foraminifera-based transfer function, despite the poor prediction error and low r^2 value of <0.5. This contrasts to the results of the diatom-based transfer functions (section 6.4.1), suggesting the different proxies have varying utility over the different spatial scales. However, the utility of the transfer functions is also individually assessed for each fossil record in terms of the presence or absence of modern analogues (Chapters 7 and 8).

6.4.3. Multi-Proxy Transfer Functions

Five transfer functions, *M-1-5,* are based upon the five corresponding multi-proxy training sets (section 6.2). The variation in the accuracy of these multi-proxy based transfer functions and the environmental gradient represented can be seen in Figure 6.12, where the estimated SWLI values are plotted against the observed SWLI values.

M-1 uses the multi-proxy (diatom and foraminifera) training set produced from the Humber Estuary, comprised of 40 samples from 3 sites (this study; sections 6.1; 6.2). The second component of *M-1* was assessed (5.37% improvement from component 1), and produced a RMSEP value of 42.79, and a low bootstrapped r^2 value of 0.14 (Table 6.3; Figure 6.12). As would be expected based on the poor performance of the individual diatom and foraminifera components of this dataset (*D-1* and *F*-1), this transfer function is also inaccurate, though it does offer a slight improvement on the single proxy counterparts.

Transfer function *M-2* combines the existing UK diatom and foraminifera training sets, providing a dataset comprised of 250 samples from 18 sites around the UK (though some of the locations are the same between sites, the samples are not) (Horton & Edwards, 2006; Zong & Horton, 1999). The second component is assessed (5.15% improvement from component 1); this provided a much improved performance from *M-1*, with a RMSEP of 24.78 and bootstrapped r^2 of 0.48, and covers a large environmental gradient (Table 6.3; Figure 6.12). *M-3* uses both the multi-proxy UK dataset and Humber dataset, providing the largest training set of 290 samples from 21 sites. The first component was assessed and provided a reduced accuracy from *M-2*, with a RMSEP of 28.47 and lower bootstrapped r^2 of 0.36 (Table 6.3; Figure 6.12).

As with the diatom and foraminifera transfer functions, transfer functions *M-4* and *M-5* are based upon samples from estuarine environments. *M-4* is based upon the sites from estuaries in the existing UK datasets used in *M-2*, reducing it to 115 samples from 7 sites. The third component of *M-4* was assessed (10.31% and 7.51% improvement from the first and second components respectively). *M-4* provided the lowest RMSEP of 15.71, and the highest bootstrapped r^2 value of 0.66, and covers an environmental gradient comparable to that in *M-2* (Table 6.3; Figure 6.12). In contrast, *M-5,* which combines *M-4* with the *M-1* Humber dataset, uses the first component and produced a higher RMSEP of 29.97 and a lower bootstrapped r^2 of 0.30 (Table 6.3; Figure 6.12).

The multi-proxy transfer functions of all scales generally provide improved transfer functions than those based on single proxies (sections 6.4.1; 6.4.2). As with the single proxies, the assessment of these multi-proxy-based transfer functions demonstrate that the local Humber based training set alone does not provide an accurate transfer function to reconstruct palaeo data (*M-1*). The UK scale transfer functions perform better (*M-2-5*), particularly when the local scale Humber are excluded (*M-2* and *M-4*), as with the individual diatom and foraminifera training sets.

The UK estuaries transfer functions (*M-4* and *M-5*) generally perform well, and *M-4* is the best performing multi-proxy-based transfer function based on RMSEP and bootstrapped r^2 values. This is consistent with the results of the diatom-based transfer functions, though contrasts with the foraminifera that performed best on a UK scale (section 6.4.2), and indicates significant variability across proxies based upon the scale of training sets and type of environments included. As with the other transfer functions, the utility of the transfer functions is dependent on the presence of modern analogues (Chapters 7 and 8).

6.5. Summary

Training sets of diatoms and foraminifera have been established for the Humber Estuary. Visual and cluster analysis of the diatom and foraminifera assemblages indicate there to be a relationship in the distribution of species to elevation, and DCA revealed the proxies to have a unimodal response. CCA indicated a more complex relationship, with the distribution being dependent on a number of environmental variables, particularly LOI. However, there is also a high proportion of intercorrelation between the environmental variables, and elevation can be taken to be representative of the other contributing variables.

Three training sets from the Humber Estuary have been established; a diatom, foraminifera, and a combined foraminifera and diatom multi-proxy training set. Additional UK wide and estuarine environment training sets of diatoms and foraminifera were also taken from previous studies (Horton & Edwards, 2006; Zong & Horton, 1999), to explore the implications of training set spatial scale, size, and proxy on the performance of resultant transfer functions.

A total of 15 training sets and the associated WA-PLS transfer functions were constructed. As would be anticipated, overall the use of multiple proxies provide a better performance for the transfer functions at all scales, rather than individual proxies, with those from estuarine environments offering the best performance. In terms of the individual proxies, the diatoms offer an improved performance when taken on a ‘regional’ scale, and particularly from estuarine environments. The ‘regional’ scale transfer functions performed best for foraminifera, and in contrast to the diatom and multi-proxy results, those from just estuarine environments did not perform well. However, the suitability of the transfer functions must be individually considered in the context of each palaeo record, based on the microfossils preserved in the palaeo record, as well as the provision of modern analogues in the training sets.

7. Palaeoenvironment and Relative Sea-Level Reconstruction: East Halton

East Halton is the first of two sites for which Holocene relative sea-level reconstructions have been produced. This chapter presents the results of the palaeoenvironmental study of the site including the site context, stratigraphy and core descriptions, microfossil analyses and the resultant relative sea-level reconstructions.

7.1. Location

East Halton is a village located in North Lincolnshire, on the southern side of the outer portion of the Humber Estuary, approximately 25km west of the mouth of the estuary. This area surrounding the estuary has a low relief, with the land heavily used for agricultural crops. The study site is located approximately 2km north of the village, east of the Skitter Beck inlet, within a field presently used for agriculture (53° 41' 14.2044" N; 0° 16' 29.4060" W; Figure 7.1). The site is c. 8km east of Barrow Haven, where the current youngest sea-level index points for the estuary were obtained; two indicating negative sea-level tendencies at 2107-1882 cal years BP and 2466-2153 cal years BP at +1.79 to +1.77m OD and 1.48 to +1.43m OD respectively, and the youngest index point is dated to 1063-927 cal yrs BP at 2.09 to 2.07m OD and has a positive sea-level tendency (Long *et al.*, 1998).

The field in which the study site is located has previously undergone a palaeoenvironmental assessment (Kirby, 2000). This comprised a lithostratigraphic auger survey over three transects; one in the northwest corner of the field, and two longer transects running east-west towards the estuary. Within the transect in the northwest of the field, a basal peat unit was identified overlying a consolidated diamict (Kirby, 2000). The microfossils within the peat unit indicated that it accumulated adjacent to reedswamp and saltmarsh vegetation, and the diatom taxa identified in the overlying alluvium unit indicated it to have been estuarine in origin; these proxies indicated a transgressive sea-level contact (Kirby, 2000). The northwest transect was explored further in this thesis.

The area studied in this thesis is at the far north-western corner of a field referred to locally as ‘Courthill’, approximately 0.75km west of the estuary, and directly south of Skitter Beck. This north-western corner is at the base of gradual north-south and east-west slopes, lying at an elevation of c. +2.6 to 3m OD.

7.2. Site Stratigraphy

A detailed stratigraphy of the site was established through a series of transects of cores. A total of 10 additional cores were taken (Figure 7.2), to expand the existing stratigraphic overview provided by the previous environmental assessment (Kirby, 2000).

The surface elevation of the cores taken varied from +2.58 to +3.05m OD. The maximum depth reached was 2.7m (-0.05m OD). All cores terminated on an impenetrable base. The stratigraphy is generally characterised by a decrease in sand content up the cores, and in certain cores gravel was present at the base, with some Chalk fragments and pebbles (up to 3cm x 2cm in size) identified. A distinct feature of the stratigraphy of the site was the presence of dense brown and brown-blue silty-clay. This was present in all cores taken, with the extent varying c. 0.5-1.5m, from c. +1 to +2.75m OD.

In the north-south transect, the most northerly core, EH05, terminated after c. 0.5m of dense silty-clay; this is attributed to the presence of rubble resulting from the construction of a drainage ditch and road. To the south, core EH09, reached a depth of 2.7m (-0.05m OD). This core terminated on a sandy gravel unit, and was overlain with alternating c. 0.2m layers of a silty-clayey-sand unit and an organic peaty silty-clayey-sandy unit. This was then overlain by 1.5m of the brown-blue silty-clay unit. Core EH02 reached a depth of 2.15m (+0.47m OD), within the same peaty silty-clayey-sandy unit identified in EH09. This was overlain by 0.5m of a silty-clayey-peat unit that gradually transitioned into 1.25m of the dense brown-blue silty-clay unit. The southern core of the transect, EH07, terminated on a sandy gravel base containing Chalk fragments and stones (up to 1cm in diameter) at 1.60m depth (+1.24m OD). This was overlain by sandy and gravelly units with varying silt-clay content for 0.7m, and topped with 1m of the dense brown-blue silty-clay unit.

The east-west transect (Figures 7.2; 7.3) began with core EH04, comprising 1.5m of the brown-blue silty-clay unit, which terminated at 1.70m depth (+0.95m OD). The next core, EH08, terminated on a sandy gravel base containing Chalk fragments and pebbles (up to 3cm x 2cm) at 2.00m depth (+0.60m OD). Overlying this was a 0.2m of a coarse sandy-silty-clay unit, that progressively increased in organic content forming 0.3m of a peaty sandy-silty-clay unit, overlain with 1.2m of the dense brown-blue silty-clay unit. The next core was EH02, as described in the north-south transect, followed by EH03, which was very similar to EH02. EH03 terminated at 1.90m (+0.687m OD), and comprised 0.1m silty-clayey-sandy-peat, overlain with 0.3m silty-clayey-peat, followed by a 0.05m transition into 1.3m of the brown-blue silty-clay unit. The next core, EH10, terminated at 1.70m (+0.97m OD), and consisted of 0.35m of sandy-silty-clayey, with the sand varying between very coarse to fine throughout the unit. This was overlain with an organic sandy-silty-clayey unit of 0.15m in thickness, and topped by 1.2m of the brown-blue silty-clay unit. The most westerly core in the transect, EH06, terminated at 0.74m (+2.3m OD), and comprised 0.2m silty-clayey-sand that became less sandy up core, and was overlain by 0.4m of the brown-blue silty-clay unit.

The southwest-northeast transect began with core EH01, which terminated at 1.21m depth (+1.55m OD). It comprised of 0.3m of a sandy-silty-clay, topped by 0.7m of the brown-blue silty-clay. The next cores in the transect were EH07 and EH03/EH10, described previously in the north-south and east-west transects respectively.

Overall, the site was characterised by the presence of a silt-clay unit that occurred across all cores. The silt-clay often contained varying sand content, ranging from fine to coarse, with coarse sand common further down cores. All cores terminated on an impenetrable base. In some cases coarse sand, gravel and Chalk fragments were recovered at the base. Several cores contained silty-clay units that also had some organic content. However two cores, EH02 and EH03, had higher organic content with distinct silty-clay-peat units present. Both were collected for laboratory analysis (Figures 7.2; 7.3), with the EH03 core suitable for establishing a chronology. The results of analysis of core EH03 are discussed in detail in the following sections.

7.3. Sediment Core Analysis

7.3.1. Stratigraphy

Core EH03 terminated on a solid diamict base, at a depth of 1.9m, at +0.69m OD; the surface elevation was 2.59m OD. The sediment descriptions of the core can be seen in Table 7.1. At the base were small stones, up to 7mm x 5mm in size. The lowest unit, 1.9-1.85m, was comprised of a medium coarse sandy dark brown silty-clayey peat. The sand became finer above this, with a dark brown silty-clayey peat containing visible rootlets, plant fragments and fine sand flecks from 1.85-1.54m. There was then a 0.05m gradational transition from the dark brown silty-clayey peat unit into a dense brown-blue silty-clay unit. This silty-clay unit was homogeneous and continued from 1.5m to 0.2m, becoming less blue in colour from approximately 0.5m upwards. From approximately 1m upwards there were also indications of possible disturbance, with reworking, plant roots and stones. The upper c. 0.3m of the core was comprised of stony, crumbly topsoil.

7.3.2. Sediment Composition

The results of particle size analysis are shown in Figure 7.4. The amount of clay present up core EH03 remains fairly constant, at around 15%, though in the lower section of the core, from 1.9-1.8m (+0.69 to +0.79m OD), this value was consistently higher, at 18-20%.

Silt comprised the majority of the sequence, with values from 65-80%. Generally the values for silt were higher, and remained above 70%, from 1.58m onwards, prior to the stratigraphic transition from the organic unit into the silty-clay unit at 1.54-1.495m (+1.05 to +1.09m OD). From 1.34m (+1.25m OD) onwards, the silt content remained relatively stable at about 80%.

There are some fluctuations throughout in the silt content that are largely inversely reflected in the sand content; for example, at 1.6m (+0.99m OD), 1.48-1.44m (+1.11-+1.15m OD) and at 1.4m (+1.19m OD). The sand content varied from 3-22% through the core. In the lower sections, the content was generally higher, fluctuating from 7-22% between 1.9-1.52m (+0.69 to +1.07m OD). There was a fall to 4% at 1.5m (+1.09m OD), before a rise to around 15% 1.48-1.44m (+1.11 to +1.15m OD), following the stratigraphic transition. There were then some minor fluctuations between 7-15%, with values then remaining low from 3-5% from 1.34m to the top (+1.25m OD).

7.3.3. Organic and Carbonate Content

The organic and carbonate content are shown in Figure 7.4. Organic content varied between 11-25% in the lower section of the core, from 1.9-1.52m (+0.69 to +1.07m OD), consistent with the stratigraphic description of an organic, silty-peat unit, and coinciding with the stratigraphic transition. From +1.087m OD to the top of the core, the organic content fell and remained below 10%.

Carbonate content was relatively low through the core, and varies from 1.5-3.5%. The values from 1.9m-1.6m (+0.69 to +0.99m OD) vary from 1.8-2.7%, with a spike to 3.0-3.4% from 1.58-1.54m (+1.01 to +1.05m OD), immediately prior to the stratigraphic transition, falling to 2.7-2.9% 1.52-1.5m (+1.07 to +1.09m OD) towards the transition. There was then a fall to generally steady values of around 1.6% at 1.48-1.24m (+1.11 to +1.35m OD).

7.4. Microfossil Analyses

The following sections present the results and interpretation of diatom and foraminifera analyses.

7.4.1. Diatom

A count of 250 diatom valves per sample was targeted. However, preservation of diatoms between samples varied, and thus the 250 total was not reached for some samples, despite the counting of multiple slides. The counts and assemblages of some samples should therefore be treated with caution, particularly those with counts below 100 valves. From 1.36m (+1.23m OD) onwards, no diatoms were found preserved in samples.

A total of 27 diatom species were identified within the sediment core. Generally, the core was dominated by brackish and brackish-marine species (Figures 7.4; 7.5). The species identified are consistent with saltmarsh and intertidal environments. Mesohalobous species such as *Diploneis didyma, Diploneis interrupta, Navicula digitoradiata* and *Navicula peregrina* are common within saltmarsh and reedswamp environments, *Actinoptychus senarius* is often found in subtidal channels, and *Caloneis westii* and *Nitzschia navicularis* are associated with mudflats and the littoral zone (Hartley, 1996; Hendey, 1964; Metcalfe *et al.*, 2000; Vos & de Wolf, 1993).

The increase in *N. navicularis* and *C. westii* at 1.54m (1.05m OD) upwards suggests an increase in marine influence at the site, as these generally occur lower in the tidal frame; this also coincides with the stratigraphic transition, as well as a fall in *D. interrupta*, which previously dominated the assemblages, and is associated with the environment around mean high water spring tide (Figure 7.5; Metcalfe *et al.*, 2000; Vos & de Wolf, 1993; Zong, 1997). However, the dominance of *D. interrupta* should be treated with some caution due to its highly siliceous composition, making it more robust to dissolution compared to diatoms that are weakly siliceous (e.g. Cooper, 1999; Flower, 1993; section 2.3.2). The presence of other species and variability in the *D. interrupta* abundance though suggest that the assemblages reflect a changing environment.

7.4.2. Foraminifera

Despite multiple samples, no foraminifera were identified within the sediment core.

7.5. Chronology

A chronology for the core was provided through accelerator mass spectrometry (AMS) radiocarbon dating of two bulk sediment samples, conducted by the ^{14}CHRONO Centre at Queens University Belfast. Bulk material from the core underwent acid pretreatment prior to AMS radiocarbon dating, as outlined by the ^{14}CHRONO Centre protocols. A measured age was produced for the base of the core, at 1.9m depth (+0.69m OD), and at 1.55m (+1.04m OD), just prior to the transition from silty-clayey-peat into silty-clay. The

^{14}C ages produced are 3169±41 and 3029±26 respectively (Table 7.2). These ages were calibrated using OxCal v4.2.4 (Bronk Ramsey, 2013; 2009) with the IntCal13 atmospheric curve (Reimer *et al.*, 2013) to 3395 (3257-3476) cal years BP and 3227 (3158-3342) cal years BP respectively. A chronology for the short (0.35m) sediment sequence between the two radiocarbon dates was established using Bacon (Blaauw & Christen, 2011; Figure 7.6).

7.6. Relative Sea-Level Reconstruction

The following sections outline the relative sea-level reconstructions determined through transfer functions, and the production of sea-level index points for the East Halton site.

7.6.1. Transfer Function Selection

Only the diatom based transfer functions are available for use with the East Halton core due to the absence of fossil foraminifera preserved within the core. This provided 5 different transfer functions (Table 7.3). The UK Estuary, *D-4,* transfer function provided the best predictive power out of all the diatom transfer functions, with the lowest RMSEP value and highest bootstrapped r^2 value at 16.37 and 0.81 respectively. However, MAT analysis revealed that it fails to provide any close or good modern analogues for the fossil assemblage in core EH03, and is therefore not comparable to the fossil assemblage, making the reconstructions unreliable. The predictive power of the transfer function must therefore be compromised to improve the reliability of the reconstructions.

The next best performing transfer function is that from the complete UK data set, *D-2*, (RMSEP 22.57, bootstrapped r^2 0.65; Table 7.3), with close analogues provided for 16 out of 27 samples, followed by the UK-Humber, *D-3*, transfer function (RMSEP 30.4, bootstrapped r^2 0.42; Table 7.3), which provides close analogues for 10 samples and good analogues for a further 10 samples. The reconstructions from these two transfer functions are shown in Figure 7.7 (reconstructions based on fossil assemblages <50 valves excluded). Both demonstrate similar overall trends through the cores. However there are differences of c. 1m in the reconstructions, though this difference generally decreases up the core, with several sample reconstruction errors overlapping. Based on the agreement in the overall trends, and due to the increased number of good modern analogues provided, the UK-Humber, *D-3*, transfer function is selected for further discussion of the East Halton core.

7.6.2. Indicative Meaning

The indicative meaning can be assigned based upon the interpretation of the stratigraphy of sediment core and microfossil profile, or quantitatively estimated using a transfer function.

Based upon the litho- and biostratigraphy of the dated horizons, indicative meanings associated with a high saltmarsh environment were assigned for both dated horizons at +0.69m OD (basal date) and +1.04m OD. This is due to the stratigraphy consisting of organic silty-peat, consistent with a high marsh setting. The high abundance of *D. interrupta* is consistent with an environment around or above MHWST (Vos & de Wolf, 1993). In the context of the Humber Estuary specifically, *D. interrupta* and *N. navicularis* are associated with high saltmarsh environments, and *N. peregrina* and *N. digitoradiata* are associated with coastal reedswamp environments (Metcalfe *et al.*, 2000). The reference water level is therefore considered to be the mid point between MHWST and HAT, with the indicative range covering MHWST to HAT (Horton *et al.*, 2013). Based upon the contemporary tidal ranges within the estuary, this provides a reference water level of 3.905m OD, with a range of ±0.395m.

The assigned reference water level falls between that of the two transfer functions that provided modern analogues, of 4.35m and 3.25m for the basal date, and 4.19m and 3.25m for the date at +1.04m OD, for the *D-2* and *D-3* transfer functions respectively. This offers some confidence in the reconstructions provided by the transfer functions, however also increases the complexity of selecting and justifying the most appropriate transfer function. As such, the assigned indicative meaning is used for the production of the sea-level index points. Despite having larger errors than the transfer function estimates of the reference water level, the additional error of 0.05m is significantly less than the variation of 1m that may be introduced based upon the different transfer function that may be selected.

7.6.3. Sea-Level Index Points

To produce a sea-level index point, an altitude of the sample, indicative range and age are required, as well as corrections for various errors (section 5.6). Two sea-level index points have been produced for this site. The details of the sea-level index points are shown in Table 7.4. The basal index-point at 1.9m depth (+0.69m OD) in the core produces a sea-level index point of -3.04m OD, and the intercalated index point at 1.55m depth (+1.04m OD) a sea-level index point of -2.41m OD.

The errors associated with each point were calculated following the methods outlined in section 5.6. As the ages of the sea-level index points are younger than 4000 cal years

BP, a tidal range correction based on a linear correction was calculated and applied (Table 7.4; section 5.6). In terms of compaction, the sea-level index points were compared to the existing suite of Humber Estuary sea-level index points, and the residuals between the sea-level index points and modelled sea-level demonstrate a strong relationship to depth of overburden (r^2 0.64), a greater relationship than that shown by total thickness and depth to base (r^2 0.61 and 0.00 respectively), findings consistent with Horton & Shennan (2009). An error for compaction was therefore calculated using this relationship (section 5.6). A compaction error was calculated for the 1.55m (+1.04m OD) point, but not for the 1.9m (+0.69m OD) point as it is basal and therefore not subjected to compaction (Table 7.4). The value is a crude estimate of compaction, and is likely to be an exaggerated estimate as the sequence is relatively short, and the point is at the top of the basal unit, in close proximity (0.35m) to the underlying diamict. Sea-level index points within 1m of the basal substrate at other UK locations have been calculated using geotechnical corrections to have been displaced by <0.2m (Gehrels *et al.*, 2011; Massey *et al.*, 2006a), and a value similar to this is a more realistic estimate for the compaction this index point will have undergone.

7.7. Palaeoenvironment and Relative Sea-Level History

The Holocene environment and relative sea-level history of the site is interpreted based upon the core stratigraphy, microfossil record and the sea-level reconstructions. The relative sea-level history is then considered in the broader context of the Humber Estuary.

7.7.1. Stratigraphic Interpretation

The sequence of sediment units- a basal silt-organic peat unit, topped by clastic silt-clays- is consistent with many other Humber and UK coastal sediment sequences (e.g. Horton & Edwards, 2005; 2006; Long *et al.*, 1998; Metcalfe *et al.*, 2000). It is consistent with a relative sea-level rise through the mid to late Holocene, with the basal silt-peat formation being initiated due to waterlogging around MHWST, and the eventual expansion of estuarine conditions depositing the blue-brown silt-clays. The silty-peat unit at the base of the core, from 1.9-1.54m depth (+0.687 to +1.047m OD), was deposited over a c. 200 year period, from c. 3400-3200 cal years BP, at a rate of approximately 2.08mm a^{1}; this increased to 3.78mm a^{-1} once the correction for compaction was applied. However, as the dates are in close proximity and overlap in range (section 7.5), this rate should be treated with caution. The homogeneity of the unit suggests that the accumulation was keeping pace with the changes in relative sea level. The stratigraphic transition, from 1.54-1.495m depth (+1.047 to +1.092m OD), covering a c. 20 year period from c. 3218-3199 cal BP (assuming a linear continuation of the chronology over the 5cm sequence from 1.55-1.5m depth), from the silt-peat unit into the clastic brown-blue silt-clay unit suggests an expansion in the marine influence and estuarine environment at the site.

7.7.2. Microfossil Interpretation

The presence of brackish and marine diatom species though the basal silty-peat unit indicated it was a saltmarsh peat that formed adjacent to the marine environment and intertidal zone, near to the MHWST. The stratigraphic transition from a silty-peat unit into a brown-blue silty-clay suggests an expansion of the estuarine conditions at the site, and the slight shift in diatom species, with a 10% increase in presence of marine species, through this stratigraphic transition is consistent with an increase in marine influence at the site.

7.7.3. Deposition and Relative Sea-Level History

The sequence used to establish the palaeoenvironment and relative sea-level history at East Halton is from the base of surrounding slopes (sections 7.1; 7.2; Figures 7.2; 7.3), with the silt-peat unit, interpreted as a saltmarsh unit, forming and accumulating within the basin (sections 7.7.1; 7.7.2; Figures 7.2; 7.3). The rise in relative sea-level within the estuary through the early and mid Holocene will have resulted in waterlogging and the initiation of silt-peat formation overlying the solid diamict base within the basin, from c. 3395 cal years BP onwards (sections 7.3.1; 7.5; 7.7.2). The increased levels of sand within the basal silt-peat unit are indicative of the surrounding slopes remaining exposed during this period, with sand and coarse material being washed down and deposited onto the silt-peat unit as it accumulated in the basin (section 7.3). The gradual transition from the organic silt-peat unit into the overlying silt clay unit, a transgressive contact, at c. 3227 cal years BP, suggests an expansion of estuarine conditions at the site, supported and reflected by a c. 13% reduction in organic content and c. 10% increase in the presence of marine diatom species (sections 7.3.3; 7.7.1; 7.7.2).

Based upon the dated horizons at the base of the silt-peat unit and immediately prior to the stratigraphic transition, the sequence was deposited at a rate of 3.78mm a^{-1}. The two sea-level index points produced from the sequence indicate an overall relative sea-level rise at the site, with a rise of 0.62m occurring c. 3395-3227 cal years BP (when the tidal and compaction corrections are incoporated). Due to the homogeneity of the silt-peat unit, and the gradational transition into the overlying silt-clay unit, the rise in relative sea level is likely to have kept pace with the rate of accumulation of the basal saltmarsh unit, with saltmarsh deposition subsequently unable to maintain this rate, resulting in the deposition of the overlying intertidal silt-clay unit (section 7.7.1). However, this rate of sedimentation must be treated with caution as the dated horizons are in close proximity with overlapping age ranges (section 7.7.1).

The stratigraphic interpretation and sea-level index points produced demonstrate a relative sea-level rise at the site. Due to the resolution of the data available, no further interpretations can be made. Although the transfer function estimates produced based upon the diatom assemblages throughout the core could be used to interpret possible fluctuations in relative sea-level change, the poor performance and large errors, and thus low resolution of the data, makes such inferences inappropriate (sections 7.6.1; 7.6.2).

7.7.4. Humber Estuary Sea Level

The two new sea-level index points from East Halton are consistent with the overall trend in relative sea level throughout the Humber Estuary, and fit within the trends for other sites from both the inner and outer portions of the estuary for the same period (Figure 7.8). When compared exclusively to the existing data for the outer estuary, the East Halton sea-level index points fill a c. 2000 year void data period.

Within the existing data for the outer estuary, between 4474-2761 cal years BP, there are no sea-level index points. The production of the two new sea-level index points from East Halton help to fill this period, by representing relative sea level at c. 3400-3200 cal years BP. The new index points are consistent with a relative sea-level rise during the latter half of the Holocene, and are consistent with the overall slower rate of sea-level rise identified during the last 4000 years compared to that in the early Holocene (Long *et al.*, 1998; Metcalfe *et al.*, 2000).

The relative sea-level rise identified coincides and is consistent with an expansion in marine conditions identified by previous studies as occurring from c. 3300 cal years BP, that was then followed by a contraction and return to estuarine conditions at c. 2700 cal years BP (Kirby, 1999; Long *et al.*, 1998; Metcalfe *et al.*, 2000; section 4.4). The new sea-level index points provide a constraint during this phase of expansion not previously provided by other sea-level index points from the outer estuary.

7.8. Summary

The site at East Halton provides a record of expanding marine conditions and relative sea-level rise during the late Holocene. This is indicated by the stratigraphy and properties of the sediment sequence, as well as the preserved biostratigraphy. The diatom transfer functions that offer good performance failed to provide good modern analogues; as such, the quality of the performance was compromised through using a transfer function that provided some good modern analogues but weaker performance. Due to the questionable reliability of the transfer function reconstructions, an assigned indicative meaning was used to produce two sea-level index points, one basal and one intercalated.

The two new sea-level index points are consistent with the overall Holocene relative sea-level rise within the Humber Estuary. The new sea-level index points fill a crucial gap in the existing dataset for the outer portion of the estuary, providing constraints of relative sea level during a 2000 year period for which there was previously no data. The new sea-level index points are consistent with an expansion of marine conditions from c. 3300 cal years BP onwards.

8. Palaeoenvironment and Relative Sea-Level Reconstruction: Brough

Brough is the second of two sites for which Holocene relative sea-level reconstructions have been produced. This chapter presents the results of the palaeoenvironmental study of the site including the site context, stratigraphy and core descriptions, microfossil analysis and the resultant relative sea-level reconstructions.

8.1. Location

Brough is located on the northern banks of the inner Humber Estuary. The site is approximately 50km from the mouth of estuary, and approximately 10km from the confluence of the River Ouse and River Trent. The study site is located to the south east of the town of Brough, and is positioned immediately north of the estuary and the estuary embankment, on an area of low relief (53° 42' 56.8224" N; 0° 33' 53.0784" W; Figure 8.1). To the north of the town the relief increases dramatically as it lies on the southern edge of the Yorkshire Wolds.

The study site is situated within the southeastern corner of an airfield that is historically, and currently, operated by a military contractor; as such, the site has restricted access and is undisturbed by local urban development. The area is grassed and encompassed by an artificial embankment, and has a central pond covering c. 0.7km^2 with dense reed vegetation.

8.2. Site Stratigraphy

A series of 38 borehole records were taken from the area in 1953, and provide a larger stratigraphic overview of the site with detailed stratigraphic descriptions (British Geological Survey, 2015). Three transects consisting of 11 boreholes were cored in this study: one parallel to the estuary and two perpendicular to the estuary (Figures 8.1; 8.2). The boreholes taken and logged show good agreement with the stratigraphic descriptions that are described in the published record (British Geological Survey, 2015). Using the boreholes taken during fieldwork, a detailed stratigraphy of the site was established (Figure 8.3).

The surface elevation of the cores taken varied from +2.27 to +3.37m OD. The maximum depth reached was 6.45m, an elevation of -3.71m OD. All cores terminated on an impenetrable base. Generally, the site stratigraphy consists of the Jurassic sedimentary limestone and clay formations bedrock (British Geological Survey, 2015), overlain by silty medium-coarse sand units. Overlying this base unit is a highly organic peat layer, up to 1.8m thick, the lower portion of which contains degraded wood fragments, identified as Alder. These organic peats become increasingly minerogenic, becoming silt-clay units with occasional organic patches, as well as intercalated minerogenic peat units. The upper c. 1m of the boreholes consists of minerogenic sediments, with the upper c. 0.3m comprising organic material with rootlets.

In the west-east transect, borehole B01 was the most westerly core taken, and reached a depth of 3.55m (-0.85m OD). It comprised 0.2m of silty-sand overlying a solid base, before transitioning into a silty-peat and into c. 1.7m of highly organic, and occasionally wooded, peat. This transitioned into 0.5m of organic silts, and then 0.85m of brown-grey silty-clay, and topped with 0.2m of clayey topsoil. Core B02 reached a depth of 4.6m (-2.14m OD). It was comprised of 0.5m of sand and silty-sand, including some Chalk fragments; this transitioned into a narrow (0.1m) band of silty-peat, before becoming a highly organic peat unit. The peat unit covered c. 2m; the lower 1.75m of the peat unit contained many wood fragments, before becoming more silty, and transitioning into an organic silty unit for c. 0.8m, with occasional peaty layers. The sequence was topped with 0.9m of brown-grey silty-clay and 0.2m of dense clayey topsoil.

B03 reached a shallower depth of 4m (-1.37m OD). It was comprised of 0.28m of coarse silty-sand with fine gravel, topped by 1.02m of wooded peat, which transitioned into 0.7m of silty-peat with decreasing organics up the core. This was topped by 0.4m of blue silty-clay, with increasing organic content over the following 0.07m, and a narrow 0.09m band of peat, transitioning into a 0.19m silty-peat unit. This was topped by 1.05m of a brown-grey silty-clay, with occasional mottling and sand visible, and then 0.18m clayey topsoil. Core B04 reached a depth of 5.85m (-2.87m OD), and followed the same stratigraphic sequence as B03, with a larger (c. 0.24m) peat unit intercalated between the silty-clay units. Core B05 was the most easterly core, and reached a depth of 5.62m (-2.47m OD). This comprised 0.14m of sandy-silty gravel, topped with 1.08m of wooded peat, followed by 2.2m of an organic silty-clay unit, followed by a c. 0.05m grey-blue silty-clay unit, and then a return to c. 0.1m of silty-organics. This was followed by 1.4m of brown-blue-grey silty-clay unit with occasional organic patches and sand, and topped by 0.2m clayey topsoil.

A westerly north-south transect was taken, comprising cores B06, B01 and B08. Core B06 was taken north of core B01, within the ponded reed area. It reached a depth of 3.6m (-1.33m OD). The core terminated on an impenetrable base; the lowest 0.42m of the core was lost during coring, however it is assumed to be similar to other sequences at the site i.e. a sandy-silt unit transitioning into a peat unit. This was followed by 1.6m of fibrous peat with occasional wood fragments, which transitioned into 0.32m of organic silty-clay, covered by 1.22m of brown-blue-grey silty-clay, topped with c. 0.1m of clayey topsoil. South of this was core B01, followed by core B08. Core B08 reached a depth of 4.01m (-0.80m OD). It was comprised of 0.16m of coarse silty-sand, followed by 0.15m of silty-peat, followed by 0.82m of wooded peat, becoming increasingly silty with no wood in the upper c. 0.3m. This was followed by c. 2.9m of brown-blue-grey silty-clay, with occasional organic patches, including a narrow c. 0.1m band of silty-peat, and topped by 0.2m of clayey topsoil.

An easterly north-south transect comprised cores B07, B04 and B09. Core B07 was collected north of B04, within the reeds and edge of the pond. B07 reached a depth of 4.35m (-1.95m OD). It was comprised of c. 0.05m coarse sandy gravel, followed by 0.08m organic silty-sand, and 0.27m sandy-silty fine gravel. This was covered by 1.83m of peat, with wood present in the lower 1.33m, then 0.49m of organic silty-peat, and then 1.46m of brown-grey-blue silty-clay, with c. 0.2m of clayey topsoil. South of this was core B04, followed by core B09. B09 reached a depth of 6.45m (-3.08m OD) and is the deepest core from the site. B09 was comprised of 0.25m coarse silty-sand, with decreasing sand content up the core; this transitioned into 0.05m of organic silts, followed by a 0.1m band of wooded peat, and then 0.1m of organic silty-clays, before returning to a wooded peat unit of 1.15m. This was followed by c. 0.15m of silty-peat, and then 4.44m of brown-blue-grey silty-clay, with occasional organic patches and two distinct organic silty-peat units (c. 0.1m and 0.2m in size), topped by 0.28m of clayey topsoil.

Two additional cores were taken, B10 and B11. B10 was the most northerly core, taken north of B04. However, the ground was impenetrable, reaching just 0.1m due to the presence of stones, gravel, and rubble; this is attributed to the proximity of the core to the embankment and airfield runway. Core B11 was taken to the north of core B05, and reached a depth of 3.45m (-0.99m OD). It was comprised of 0.1m silty coarse sand, followed by 1.12m of wooded peat, covered by 0.71m of organic silty-clay, topped by c. 1.3m of brown-grey silty-clay, and c. 0.2m clayey topsoil.

Overall, the site is characterised by the presence of a highly organic woody peat, becoming increasingly inorganic and minerogenic up the core, with a presence of silty-clay units with varying organic content, and occasional intercalated peat units (Figure 8.3). Two representative cores immediately adjacent to B01 and B04 (BC01 and BC02 respectively) were collected for detailed laboratory analysis.

8.3. Sediment Core Analysis: BC01

8.3.1. Stratigraphy

Core BC01 terminated on a solid diamict base, at a depth of 3.49m, at -0.79m OD; the surface elevation is +2.70m OD. The sediment descriptions of the core can be seen in Table 8.1. At the base of the core was a coarse silty-sand covering 0.14m, which became progressively finer up the core, followed by a narrow 0.03m band of silty-peat containing fine sand. Above this was 1.14m of a highly fibrous woody peat unit; the wood has been identified as Alder. A highly fibrous peat unit follows with significant organic material for 0.18m, followed by a silty-peat unit for 0.29m; this becomes increasingly minerogenic over 0.23m, and becomes a 0.29m silty-clay unit with occasional organic patches. This is overlain by a narrow 0.7m silty-peat unit, followed by a 0.19m silty-clay unit that became increasingly inorganic; this is topped by 0.63m of brown-grey-blue silty-clay, and 0.3m of dense rooty and clayey topsoil.

8.3.2. Sediment Composition

The results of particle size analysis are shown in Figure 8.4. The amount of clay throughout the core remains fairly constant, from 10-20%, though this decreases to <10% in particularly sandy units. Silt comprises the majority of the core, ranging from c. 70-80% throughout, with the exception being the basal silt-sand units, where silt content is 40-50%. Sand content generally displays an inverse relationship to the silt and clay content, comprising 40-50% in the basal silty-sand unit, decreasing to low values of c. 1-10%, with occasional fluctuations up to c. 20%, throughout the remainder of the core, and increasing to 10-20% in the uppermost silt-clay unit.

8.3.3. Organic and Carbonate Content

The organic and carbonate content are shown in Figure 8.4. The organic content reflects the stratigraphic descriptions. The organic content is low (<5%) in the basal silty-sand units, increasing to c. 70-85% through the peat unit, decreasing to c. 10-20% through the overlying silty-clay unit with organic patches. The organic content increases to 36-40% in the upper silty-peat unit, 1.19-1.12m depth (+1.51 to +1.58m OD), before decreasing to values <10% in the overlying silty-clay unit. The carbonate content is low throughout the core, ranging from 0-2.9%, and is particularly low, from 0-1.7% in the lower peat unit; the upper most part of the silt-clay unit at the top of the core has the highest value at 4.4%.

8.4. Sediment Core Analysis: BC02

8.4.1. Stratigraphy

Core BC02 terminated on a solid diamict base, at a depth of 4.55m, at -2.146m OD; the surface elevation is +2.40m OD. The sediment descriptions of the core can be seen in Table 8.2. At the base of the core was a coarse silty-sand unit covering 0.21m, overlain by a black silty unit of 0.13m, containing snail shell fragments in the lower 0.11m, identified as *Zenobiella subrufescens,* characteristic of established woodlands and river valleys (McMillan, 1968). Overlying this was 1.35m of highly organic woody peat identified as Alder, and was overlain by 0.21m of highly fibrous peat. This was followed by 0.16m of an organic silty-clay unit, overlain by a 0.3m peat unit, followed by a transitional unit of 0.13m of organic silty-clay, becoming increasingly inorganic; this is topped by 0.9m of the brown-grey-blue silty-clay unit, and 0.37m of dense rooty-clayey topsoil.

8.4.2. Sediment Composition

The results of particle size analysis are shown in Figure 8.4. Clay content in the basal silt-sand units is low (c. 5%), increasing to c. 20% in the overlying peat and silty-peat units, and c. 15% in the upper silty-clay unit. Silt comprises the majority of the core, ranging from c. 70-80% throughout, with the exception being the basal silty-sand unit, where silt content is c. 50%. Sand content generally has an inverse relationship to the silt and clay content, comprising c. 45% in the basal silty-sand unit, decreasing to c. 1-10% with occasional fluctuations up to c. 20%, throughout the remainder of the core, and increasing to c. 10% in the uppermost silt-clay unit.

8.4.3. Organic and Carbonate Content

The organic and carbonate content are shown in Figure 8.4. The organic content is low (<2%) in the basal silty-sand units, increasing to c. 70-82% through the wooded peat unit. It decreases gradually through the peat to c. 20-40% and throughout the overlying organic silt and silty-peat units, with a peak of 52-58% in the uppermost intercalated peat unit. The organic content decreases to <20% through the uppermost silty-clay unit. The carbonate content is high, c. 40% in the basal sand units, decreasing to 25-36% in the silt unit with shells; following this the carbonate content drops to generally 1-3% in all the overlying sediments, increasing to c. 6% in the uppermost silty-clay unit.

8.5. Microfossil Analyses

The following sections present the results and interpretation of the diatom and foraminifera analyses.

8.5.1. Diatom: BC01

Diatom preservation throughout core BC01 was sporadic. A total of 250 diatom valves were targeted per sample, however this was not achieved for all samples, with large sections not having any preserved. The lower section of the core, from 3.49-1.53m (-0.78 to +1.17m OD) had no diatoms, with the exception of one sample at 2.96m (-0.26m OD), which provided a low (44 valves) count, comprised of brackish and marine species. Diatoms were present sporadically over the following 0.54m (+1.18m OD to +1.72m OD) through the silty-peat and organic silt units (Figures 8.4; 8.5). Samples in the remaining overlying silt-clay unit contained no diatoms.

A total of 36 species were identified through the core. The diatom assemblages are characterised by the presence of predominantly brackish species, particularly *Diploneis interrupta*, with a varying presence of marine and freshwater species throughout (Figures 8.4; 8.5). The species identified are consistent with saltmarsh and intertidal environments. Mesohalobous species such as *D. interrupta, Diploneis smithii* and *Navicula peregrina* are common within saltmarsh and reedswamp environments, whilst *Nitzschia navicularis* is associated with the general littoral zone from high marsh to mudflat (Hartley, 1996; Hendey, 1964; Metcalfe *et al.*, 2000; Vos & de Wolf, 1993). The assemblages do not appear to show any distinct trends up the core, however, the decrease in *N. peregrina* evident from 1.38m to 1.3m (+1.32 to +1.40m OD) suggest a possible increase in marine influence. As with the East Halton diatom assemblages, the dominance of *D. interrupta* should be treated with some caution due to potential preferential preservation (sections 7.4.1; 10.1.3).

8.5.2. Foraminifera: BC01

Foraminifera were present within the sediment core. None were identified within the highly organic and wooded peat unit that makes up the lower portion of the core, from 3.32-2.00m depth (-0.62 to +0.70m OD). From 2.00m depth (+0.70m OD) onwards, foraminifera were identified, and the occurrence coincides with the transition into the overlying silty-peat layers (Figures 8.4; 8.5). The presence of foraminifera continues through the organic silt-clay unit, and the abundance generally decreases up the core, with no foraminifera present from 0.98m onwards (+1.72m OD), through the brown-grey-blue silt-clay. The foraminifera assemblages are dominated by agglutinated species, particularly *Jadammina macrescens*, a common species found across saltmarsh environments, though generally associated with high to middle marsh environments.

8.5.3. Diatom: BC02

Diatom preservation throughout core BC02 is sporadic. A count of 250 valves was not achieved for all samples, however there was a more substantial assemblage profile than in core BC01. Diatoms were present from 2.7m to 1.2m (-0.30 to +1.12m OD), with occasional barren samples and decreases in abundance of diatoms. There is then a hiatus in the presence of diatoms, with diatoms occurring again from 1.04m to 0.94m (+1.36 to +1.46m OD), and not occurring through the upper silt-clay unit. Generally, the presence of diatoms through the core coincides with the silty-peat and organic silt units (Figures 8.4; 8.6).

A total of 34 diatom species were identified through the core. As with core BC01, the diatom assemblages are characterised by the presence of predominantly brackish species, particularly *D. interrupta*, with a varying presence of marine and freshwater species throughout. Mesohalobous species such as *D. interrupta, D. smithii* and *N. peregrina* are common within saltmarsh and reedswamp environments, whilst *N. navicularis* is associated with the general littoral zone from high marsh to mudflat (Hartley, 1996; Hendey, 1964; Metcalfe *et al.*, 2000; Vos & de Wolf, 1993). Due to the consistent presence of predominantly brackish species, the assemblages present no clear trend, though as with core BC01, the declines in species such as *N. peregrina*, *D. interrupta* and *D. smithii* are indicative of a change in the marine influence. As with the East Halton and core BC01 diatom assemblages, the dominance of *D. interrupta* should be treated with some caution due to potential preferential preservation (sections 7.4.1; 8.5.1; 10.1.3).

8.5.4. Foraminifera: BC02

Foraminifera were not present through the majority of the highly organic peat unit that makes up the lower section of the core, from 4.16m onwards (-1.76m OD). Foraminfera were consistently present from 2.66m (-0.26m OD), coinciding with the transition to the organic silt unit, through to 1m depth (+1.40m OD), with some sporadic abundance between 1.84 to 1.6m depth (+0.56 to +0.80m OD) (Figures 8.4; 8.6). The assemblages are comprised of agglutinated foraminifera species, particularly *J. macrescens*, as well as *Miliammina fusca* from 2.66m to 1.92m depth (-0.26 to +0.48m OD). The presence of only agglutinated species of foraminifera is consistent with high and middle saltmarsh environments.

8.6. Chronology

A chronology for both cores BC01 and BC02 was provided by eight accelerator mass spectrometry (AMS) radiocarbon dates awarded by NERC, and undertaken at the NERC Radiocarbon Facility in East Kilbride (allocation number 1932.1015; Table 8.3). Sample materials underwent acid pre-treatment and were washed, dried and homogenised; carbon was then recovered in the form of carbon dioxide and converted to graphite prior to AMS dating. Three dates were produced for core BC01, and five for core BC02 (Table 8.3).

For core BC01, dates at 2.02m, 1.19m and 1.05m depth (+0.68, +1.51 and +1.65m OD respectively) were produced. The ^{14}C ages produced for the samples were 2606±37, 2448±37 and 3624±35 respectively, calibrated to 2745 (2540-2791), 2522 (2359-2705) and 3935 (3841-4078) cal years BP. The date at 2.02m depth was produced from plant macrofossils, and was selected as it marked the transition from the peat unit into overlying organic silt-peat. The samples at 1.19m and 1.05m depth were from bulk sediment samples, and were selected based upon changes in the litho- and biostratigraphy. Due to the age reversal for the uppermost sample at 1.05m depth, an age-depth model could not be established for the core, however a chronology was produced for the sediment sequence between the two lower radiocarbon dates using Bacon (Blaauw & Christen, 2011) (Figure 8.7).

For core BC02, dates at 2.59m, 1.75m, 1.59m, 1.30m and 0.93m depth (-0.19, +0.65, +0.81, +1.10 and +1.47m OD respectively) were produced. The ^{14}C ages produced for the samples were 3682±38, 2343±37, 1639±37, 1583±36, 7556±39 respectively, calibrated to 4022 (3902-4145), 2356 (2209-2489), 1540 (1414-1616), 1470 (1396-1550) and 8376 (8315-8425) cal years BP (Table 8.3). The dates at 1.59m and 1.30m depth established from plant macrofossils, and 2.59m, 1.75m and 0.93m depth from bulk sediment samples. The horizons were selected based upon changes in the litho- and biostratigraphy. As with core BC01, the uppermost date at 0.93m depth produced a much older date than anticipated, creating an age reversal. However, an age-depth model using the four radiocarbon dates from 2.59m to 1.3m was produced using Bacon (Blaauw & Christen, 2011) (Figure 8.7).

Both cores demonstrate age reversals, with the uppermost samples of each core (+1.65 and +1.47m OD in cores BC01 and BC02 respectively) producing substantially older ages than anticipated, and that are inconsistent with the other radiocarbon dates from the cores (Table 8.3). The inaccurate production and interpretation of radiocarbon ages from upper organic and peat units of late Holocene age in coastal areas is not a unique problem (Waller *et al.*, 2006). A potential cause of this is the natural composition of sediments deposited within the system, as well as anthropogenic activity in the wider region. The Humber Estuary catchment covers a large proportion of England (c. 20%; section 4.1), within which coal and pre-Quaternary particles are prevalent. These particles will have been transported into the estuarine system and deposited, resulting in erroneous radiocarbon ages. The introduction of such particles was potentially exacerbated by anthropogenic activity and deforestation during the late Holocene, which resulted in increased sediment mobilisation and thus increased sediment loads and deposition within the estuary system (section 4.5).

The sample at 1.3m depth, +1.10m OD, in core BC02 provided an age of 1470 cal years BP; the uppermost dates from cores BC01 and BC02 were at +1.65 and +1.47m OD respectively, and should therefore be assumed to be younger than c. 1400 cal years BP. The sample at 1.19m depth, +1.51m OD, from BC01 also produced a questionable age, as it is older than anticipated, and suggests an accumulation of 0.83m over a period 223 year from the sample at 2.02m depth. As the age at 1.19m depth however is in chronological sequence, the date is accepted to produce a sea-level index point, however it is acknowledged that the age is likely to be erroneous, and based on its altitude may also be younger than c. 1400 years BP.

8.7. Relative Sea-Level Reconstruction

The following sections outline the relative sea-level reconstructions determined through transfer functions, and the production of sea-level index points for the Brough site.

8.7.1. Transfer Function Selection

Due to the presence of both diatoms and foraminifera in the cores at Brough, all of the 15 transfer functions developed (diatom-based, foraminifera-based, and multi-proxy) are available for use (Table 8.4). Although the UK estuary diatom transfer function, *D-4*, offers the best performance overall, it provides no modern analogues for either core BC01 and BC02, and therefore the reconstructions it provides cannot be considered as reliable. In contrast, the UK estuary foraminifera transfer function, *F-4*, provides good modern analogues for all foraminifera samples from both cores, however the performance is not as good as those provided by the diatom and multi-proxy based transfer functions, and the foraminifera fossil record is not as complete as the diatom record.

Due to the demonstrated improved performance (section 6.4), and the availability of both proxies, multi-proxy transfer functions were used. The best performing multi-proxy functions for the cores is the UK estuary scale, *M-4*, with a RMSEP value of 15.8 and bootstrapped r^2 of 0.66; however, it does not provide good modern analogues for the fossil record throughout both cores. The predictive power of the transfer function is therefore compromised in a bid to provide more modern analogues and improve the reliability of the reconstructions. As such, the UK-Humber scale transfer function, *M-3*, is selected, with a RMSEP of 28.47 and reduced bootstrapped r^2 of 0.36; this provides the closest modern analogues for both records (Table 8.4). Despite the decreased predictive power of this transfer function, the reconstructions it provides are in generally good agreement and within the errors of those that have an improved performance, but lack analogues. This therefore offers confidence in the accuracy of the reconstruction estimates produced by transfer function *M-3* for cores BC01 and BC02, and it is used for further discussion of the Brough cores.

8.7.2. Indicative Meaning

The indicative meaning can be assigned based upon the interpretation of the stratigraphy of sediment core and microfossil profile, or quantitatively estimated using a transfer function. Based upon the litho- and biostratigraphy of the dated layers, indicative meanings associated with a high saltmarsh environment were assigned. This is due to the stratigraphy consisting of organic and silty-peat, consistent with a high marsh setting. The high abundance of *Diploneis interrupta* is consistent with an environment around or above MHWST (Vos & de Wolf, 1993). In the context of the Humber Estuary specifically, *D. interrupta* and *Nitzschia navicularis* are associated with high saltmarsh environments, and *Navicula peregrina* and with coastal reedswamp environments (Metcalfe *et al.*, 2000). The reference water level is therefore considered to be the mid point between MHWST and HAT, with the indicative range covering MHWST to HAT (Horton *et al.*, 2013). Based upon the present tidal ranges within the estuary, this provides a reference water level of 4.345m OD, with a range of ±0.395m.

The assigned reference water level is similar to the estimates of the reference water level produced by the preferred transfer function, *M-3*, of c. 4m OD for each of the palaeo samples. Due to the confidence in the selected transfer function, the similarity in the estimates produced by the various transfer functions, and its similarity to the assigned reference water level, the quantitatively estimated reference water level is used for the production of sea-level index points for the cores. The quantitative estimates of the reference water levels provides smaller errors, and due to the quantitative methodology, could be taken as more accurate than the use of assigned values.

8.7.3. Sea-Level Index Points

To produce a sea-level index point, the altitude of the sample, indicative range and age are required, as well as corrections for various errors (section 5.6). Six sea-level index points have been produced for this site: two from core BC01, and four from core BC02. The details of the sea-level index points are shown in Table 8.5. All the index points are intercalated, and produced changes in relative sea level ranging from -1.9 to -0.46m. The sea-level index point BC01-119 must be treated with caution, as the age of 2522 cal years BP is potentially erroneous, and is believed to be younger than 1400 years BP (section 8.6).

The errors associated with each point were calculated following the methods outlined in section 5.6. In terms of compaction, the sea-level index points were compared to the existing suite of Humber Estuary sea-level index points, and the residuals between the sea-level index points and modelled sea-level demonstrate a strong relationship to depth of overburden (r^2 0.59), a greater relationship than that shown by total thickness and depth to base (r^2 0.58 and 0.02 respectively). This is consistent with the East Halton site (section 7.6.3) and other Humber Estuary sites (Horton & Shennan, 2009). The errors for compaction were therefore calculated using this relationship (section 5.6; Table 8.5). The values are a crude estimate of the compaction of these intercalated sea-level index points, however they are vital to incorporate otherwise the index-points produced will be knowingly underestimating the position of relative sea level.

Tidal corrections were also applied to each of the sea-level index points. For those younger than 4000 cal years BP, a linear correction was applied, and for the date older than 4000 cal years BP, a polynomial correction was applied, following Shennan *et al.* (2003) (section 5.6; Table 8.5). Due to the large nature of the tidal corrections, ranging from 1.1 to 2.8m in size, the values have not been incorporated in the calculated change in relative sea-level errors for clarity (Table 8.5).

8.8. Palaeoenvironment and Relative Sea-Level History

The Holocene environment and relative sea-level history of the site is interpreted based upon the core stratigraphy, microfossil record and the relative sea-level reconstructions. The relative sea-level history is then considered in the broader context of the Humber Estuary.

8.8.1. Stratigraphic Interpretation

The cores show evidence of a changing environment at the site. The lower peat unit, with the high organic content, presence of wood fragments and lack of saltmarsh microfossil proxies, is interpreted as freshwater in origin, consistent with the presence of eutrophic wetland and freshwater aquatic environments around the inner estuary identified during the early to mid Holocene (Metcalfe *et al.*, 2000; Figure 4.8). The overlying sequence of sediment units- silty-organic peat units topped by clastic silty-clays- is consistent with the East Halton site, as well as with many other Humber and UK coastal sediment sequences (e.g. Horton & Edwards, 2005; 2006; Long *et al.*, 1998; Metcalfe *et al.*, 2000), and consistent with the relative sea-level rise through the mid to late Holocene. The overall rate of accumulation between the maximum dated horizons, 4022-1470 cal years BP, is 0.51mm a^{-1}. However, there are variations in the rate of accumulation; between 4022-1540 cal years BP, the rate of accumulation is low, at 0.42mm a^{-1}, increasing to 3.21mm a^{-1} between 1540-1470 cal years BP (though these dates are in close proximity).

The transition from the freshwater peat into brackish and saltmarsh organic silt-peats, c. 4000 years BP, is identified by a decrease in the organic content and an increase in the presence of silt and clay. An eventual expansion of the estuarine conditions deposited the overlying brown and brown-grey-blue silt-clay units, and is marked by a significant decrease in the presence of organics, with the bands of organic silts and silty-peat intercalated in the silty-clay units representing fluctuations is the extent of the estuarine conditions. Overall, the site stratigraphy indicates an expansion in the marine influence and estuarine environment through the mid to late Holocene.

8.8.2. Microfossil Interpretation

The presence of brackish and marine diatom species though the silty-peat units indicate them to be a saltmarsh peat that formed adjacent to marine conditions, near to the MHWST. The stratigraphic transition from a silty-peat unit into a brown and brown-blue silty-clay suggests an expansion of the estuarine conditions at the site, and the slight increases in the presence of marine diatom species that coincides with these units are consistent with an increase in marine influence at the site. This is also reflected in the presence of predominantly agglutinated species of foraminifera that are consistent with high and middle marsh saltmarsh environments.

8.8.3. Deposition and Relative Sea-Level History

The sequences used to establish the palaeoenvironment and relative sea-level history at Brough show an interesting sequence of environmental change during the Holocene. The sequences are from a low-lying area within the inner estuary, in an area previously identified as being a freshwater aquatic and eutrophic wetland during the early to mid Holocene (Metcalfe *et al.*, 2000; section 8.8.1; Figure 4.8). The presence of the highly organic peat unit, and presence of wood fragments within the peat, overlying the basal diamict is consistent with this (sections 8.2; 8.3; 8.4). The rise in relative sea level within the estuary through the early to mid Holocene will have increased the local water table, initiating peat formation and the establishment of wetland environments adjacent to the expanding estuary. The basal peat units transition into significantly less organic silty-peats, saltmarsh units, at c. 4000 cal years BP, and subsequently into silt-clay units, indicative of an expansion of the estuarine conditions at the site, and relative sea-level rise (section 8.8.1). Overall, the rate of sediment accumulation for the site, between the maximum dated horizons, 4022-1470 cal years BP, in one of the cores is 0.51mm a^{-1}. However, there is some variation in the stratigraphy and rates of deposition, for example the accumulation rate increases to 3.21mm a^{-1} 1540-1470 cal years BP (section 8.8.1), suggesting changes in the conditions and processes at the site.

When considered together, the six sea-level index points produced from the two Brough cores indicate potentially stable relative sea-level conditions at the site, with overlap in their vertical position and errors, as well as minor variation in the biostratigraphic assemblages (sections 8.7.3; 8.8.2). Indeed, the sea-level index points produced are within the late Holocene period for which relative sea-level rise had slowed to just c. 1mm a^{-1} (section 4.4). This is despite the presence of some significant variation in the stratigraphy within the cores and implied tendencies that may otherwise suggest fluctuating relative sea levels rather than a 'smooth' relative sea level, and this is the result of multiple coastal mechanisms and processes (e.g. Baeteman, 2008; Baeteman *et al.*, 2011).

The presence of intercalated units within the silt-clay units is a response to varying sediment loads and accommodation space at the site, rather than specific vertical fluctuations in the relative sea level (e.g. Long *et al.*, 2000). Through the mid to late Holocene, there was ongoing relative sea-level rise and increase in the tidal range within the estuary, as well as increased sediment loads and a reduction in the rate of relative sea-level rise in the late Holocene (sections 4.4; 4.5; Shennan *et al.*, 2003; Beckett, 1981; Buckland & Sadler, 1985; Smith, 1958). As estuarine conditions expanded and encroached onto the wetlands, freshwater peat collapse and compaction occurred, creating accommodation space for saltmarsh and estuarine material, and hence a dominance of such materials in late Holocene stratigraphic sequences (Baeteman, 2008; Baetman *et al.*, 2011; Long *et al.*, 2000). Indeed, it is likely that the increased sediment loads, coupled with the reduced rate of relative sea-level rise and thus a slow rise in the water table, prevented the accumulation and preservation of high marsh environments

(Long *et al.*, 2000). Combined with the compaction of underling units and creation of accommodation space, the deposition of the series of varying organic and intercalated units resulted, with the changing stratigraphy representing the interplay of sedimentary processes and mechanisms (Baeteman, 2008; Baeteman *et al.*, 2011; Long *et al.*, 2000; 2006).

The stratigraphy from Brough therefore provides a record of the sedimentary and deposition processes within the inner estuary during the late Holocene, as well as enabling the reconstruction of the relative sea-level history. The sea-level index points indicate potentially stable relative sea-level conditions through the late Holocene, with the transfer function estimates, based upon the biostratigraphy of the cores, indicative of stable or slightly rising relative sea-level (Figures 8.8; 8.9). However, due to the resolution of the data produced, more detailed interpretations regarding the changes or rates of relative sea-level change are not possible.

8.8.4. Humber Estuary Sea Level

The six new sea-level index points produced from Brough are consistent with the overall trend in relative sea level throughout the Humber Estuary. The Brough sea-level index points fit within the trends for sites from both the inner and outer portions of the estuary for the same period, and provide constraints for periods previously devoid of data (Figure 8.10). The oldest sea-level index point from Brough, at 4022 cal years BP, fits the trend of other index points from the inner estuary during the period, and is consistent with expanding marine conditions. The sea-level index point from the same core at 2356 cal years BP corresponds to a transition from a silt-clay unit into an intercalated saltmarsh unit, consistent in timing with a contraction of the marine conditions within the estuary identified c. 2700 cal years BP (Kirby, 1999; Lamb *et al.*, 2007; Long *et al*. 1998; section 4.4) and changes to estuary sedimentation (sections 8.8.3; 4.5).

Three of the sea-level index points produced constrain relative sea-level during an otherwise c. 1000 year void data period 2766-1774 cal years BP, and two sea-level index points provide the two youngest sea-level index points for the inner estuary. These two youngest sea-level index points constrain relative sea level in the previously data void period between 1774 cal years BP and the youngest sea-level index point for the entire estuary, produced from the outer estuary with an age at 992 cal years BP.

All of the sea-level index points from Brough are intercalated in nature, and therefore subject to post-depositional compaction. Ideally, sites with basal sediments that record sea level would be utilised to avoid the issue of compaction (section 2.3.4; 2.3.5; 5.6), however such sites are unknown for the inner portion of the Humber Estuary that represent the late Holocene. However, despite the index-points produced being intercalated in nature, they generally show good agreement with the existing data (Figure 8.10). In particular, the oldest data point produced, at 4022 cal years BP, fits well with the basal index points from around the same period, both prior to, and following, the application of compaction and tidal corrections, indicating that the use of intercalated sea-level index points produced are reliable for constraining the relative sea-level history of the estuary.

8.9. Summary

The field site at Brough provides a complex record of expanding and contracting estuarine conditions in response to multiple sedimentary processes and relative sea-level change, as indicated by the stratigraphy and properties of the sediment sequences, as well as the preserved biostratigraphy. The site provides an insight into the various mechanisms driving coastal evolution during the late Holocene within the inner estuary, including changes to the sediment supply, wetland collapse and the creation of accommodation space, as well as relative sea-level change. Both diatoms and foraminifera were preserved at the site, enabling the use of a multi-proxy transfer function. A transfer function was selected that compromised the predictive power but provided the closest modern analogues, and was used to provide the indicative meanings to produce six intercalated sea-level index points. All were corrected for compaction and tidal changes.

The six sea-level index points are consistent with the trends of late Holocene relative sea-level change within the Humber Estuary. Overall the index-points indicate a stable or slight rise in relative sea level, consistent with the slow rate of late Holocene relative sea-level rise previously identified. The new sea-level index points produced fill several crucial gaps in the existing dataset for both the inner portion and whole estuary, and two of the new sea-level index points are now the youngest constraints for relative sea level for the inner estuary.

9. Sea Level, Groundwater and Abstraction: Past, Present, and Future

This chapter presents the results of the modelled groundwater abstraction and sea-level change scenarios in the context of the Springhead abstraction site. The development of a conceptual model of the system is detailed, as well as the results of the various sea level and abstraction scenarios conducted using the Environment Agency numerical East Yorkshire Chalk (EYC) model. The implications that sea-level changes and abstraction will have on the groundwater system are examined.

9.1. Conceptual Model

Key to acquiring an understanding of the relationship between sea level, groundwater and abstraction, is establishing a conceptual model that represents the system, incorporating the processes and parameters, and acknowledging any assumptions and unknowns (section 5.8.1). The conceptual model highlights the various processes and parameters integral to the relationship between sea level and groundwater, as well as any potential for saline intrusion. The model was focussed on the Springhead source utilised by Yorkshire Water, adjacent to the Humber Estuary (section 4.7.1). A background of the existing understanding of the system is detailed, along with the geology and potential pathways of saline intrusion. The groundwater conditions at the Springhead source are outlined, and a conceptual model of the groundwater system between the Humber Estuary and the Springhead abstraction site developed.

9.1.1. Background

The Chalk aquifer of East Yorkshire is a complex hydrogeological system, and a vital water resource for the region (section 4.6; 4.7; 4.7.1). Due to the coast and Humber Estuary bounding to the east and south of the regional aquifer, the ingress of saline water into the aquifer is of particular interest (sections 3.3; 4.6). The local water company that covers the area north of the Humber Estuary, Yorkshire Water, are concerned by the potential of historic, current, and future, saline intrusions impacting upon groundwater abstractions, in particular the Springhead source, due to the proximity of the Humber Estuary (sections 4.7; 4.7.1).

Groundwater has been actively abstracted from the Chalk aquifer around Hull since the late 19th Century, and has been integral to urban and industrial development during the 20th Century (section 4.7.1). Prior to industrial abstraction, there were numerous springs and artesian flows in the region between Beverley and Hull, as well as springs adjacent to the estuary, such as at Hessle Whelps, and these will have provided water supplies for populations over the last millennia. However, increased and sustained abstraction from around the turn of the 20th Century resulted in the cessation of groundwater discharge into the estuary, as well as the substantial lowering of the groundwater level at abstraction sites, resulting in some former artesian flows requiring pumping (Smedley *et al.*, 2004). The lowering of the groundwater head resulted in a reversing of the hydraulic gradient, and identification of saline intrusions through the 20th Century (Elliot *et al.*, 1998; 2001; Gale & Rutter, 2006; section 4.7). Indeed, the presence of a saline zone around Hull was established by 1951, with minimal change to the extent occurring through to 1973 (Chadha, 1986; Gale & Rutter, 2006). Monitoring indicated that the saline front remained in a stable position, and may have actually retreated towards the shore following 1973, with an increase in the zone of mixing (Chadha, 1986; Gale & Rutter, 2006). However, such conclusions are based upon the sampling of Chalk from various localities and boreholes, and are therefore subject to differing sampling strategies (ARUP, 2016). As such, there is little knowledge or detailed constraints on the extent of existing saline waters within the aquifer around Hull, and particularly little regarding the contemporary conditions.

Three potential sources and types of saline waters have been identified within the Chalk aquifer. The oldest of the 'fossil' saline waters are considered to originate from the Ipswichian interglacial, c. 120000 years BP, and is characterised by sulphate and potassium enrichment (Chadha, 1986). The second identified ancient saline water is from sometime in the Holocene, and is characterised by a lack of enrichment of sulphate and potassium evident in the Ipswichian waters (Chadha, 1986). This saline water is not considered to be contemporary in origin due to enrichment of strontium, iodide, tritium and ^{14}C (Chadha, 1986). The intrusion of the Holocene water is considered to have occurred during the mid to late Holocene, a period which is consistent in timing with the expansion of estuarine and marine conditions identified in this thesis and other studies (sections 4.4; 10.2.3), although this is erroneously referred to as a period of 'higher sea-levels' c. 5000-2000 years BP within groundwater literature (Chadha, 1986).

The third body of saline water identified is that of recent water from the Humber Estuary, characterised by tritium and no enrichment of sulphate, potassium or strontium (Chadha, 1986). This saline water intruded as a result of intermittent hydraulic connection between the aquifer and the estuary, as well as the reversing of the hydraulic gradient due to abstraction through the 20th century (Chadha, 1986). However, the intrusion is complicated to assess due to the macrotidal character of the estuary, and maybe influenced by the positioning of Hull, and groundwater abstraction sites around Hull, on the estuary meander, as the impact of high tides and erosional patterns on the superficial geology (predominantly clays with varying sand content; sections 4.2; 9.1.3) may complicate the hydraulic connection (ARUP, 2016; Rowlands, 2000). Determining the spatial extent and sources of the saline waters is further complicated due to mixing of the waters within the aquifer; ancient saline waters have altered the groundwater chemistry, and ancient and younger saline waters have mixed and been diluted by fresh groundwater (Rowlands, 2000).

The geology of the area, hydraulic connections and interactions between the aquifer and the estuary are complex and not fully understood or known (ARUP, 2016; Rowlands, 2000), and as such the accurate determination or quantification of the saline intrusion is not possible. Indeed, boreholes adjacent to the estuary have high groundwater chloride concentrations, indicating that intrusion may still be occurring, or that there is little flow into the area since previous intrusions (ARUP, 2016). The absence of continuous monitoring and dating of the groundwater, and a lack of consensus on the extent and sources of saline waters, means that a thorough assessment or quantification of saline intrusion has not been possible (ARUP, 2016). The position of the saline front and depth of salinity within the chalk aquifer is not currently known for the Hull area (ARUP, 2016), but is now assessed in this thesis for the Springhead source.

9.1.2. Springhead Conditions

The Springhead source is operated by Yorkshire Water, and is located 3.5km north of the Humber Estuary, on the western edge of the city of Hull (section 4.7.1). The source was constructed in 1862, and has been used continuously through the 20th Century and into the 21st Century; it is currently one of a network of four groundwater abstraction sources that supply Hull and the wider region, along with various river and surface water sources (ARUP, 2007; section 4.7). Based on data spanning AD 1989-2015, despite relatively constant groundwater head and outflow levels, there is a distinct increasing trend in chloride concentration at the source, rising c. 15mg l^{-1} over the period (ARUP, 2016; Figure 9.1). When compared to additional chloride data from 1953-1973 (Foster *et al.*, 1976), this increasing chloride trend is indicated to have occurred since c. 1960-1970 (ARUP, 2016), and represents an increasing salinity at the site. As discussed in section 9.1.1, this increase in salinity maybe the result of an intrusion into the Chalk aquifer from the estuary, and a shift in the saline front through a combination of the contemporary and fossil saline waters.

9.1.3. Geology and Pathways

The bedrock geology of the area is relatively well understood and mapped. The various Chalk types and distribution are described in detail in sections 4.2 and 4.6. Springhead is located within the area of Burnham Chalk, with a Chalk base depth of c. -100 to -150m OD (Gale & Rutter, 2006; section 4.7.1). The Burnham Chalk extends c. 2.5km directly south towards the estuary, with Welton Chalk comprising the remaining c. 1km to the Humber Estuary. The eastward extent of Welton Chalk ceases to the east of Hessle, with Ferriby and Hunstanton Chalk extending to the escarpment (section 4.2). The superficial geology, however, is not thoroughly understood or constrained to a high resolution. Overview maps of the superficial geology identify Springhead as being located within Devensian glacial till (boulder clay), however to the immediate east and c. 2km south towards the estuary, the superficial geology is characterised as Holocene clay and silt alluvium deposits (British Geological Survey, 2016; section 4.2). Additional studies have identified the presence of glaciofluvial and glaciolacustrine deposits to the south and north of Springhead, as well as a band of glaciofluvial sand and gravels to the east of Springhead which extends northwards from the estuary towards Cottingham (British Geological Survey, 2016; ESI, 2013a), highlighting the complexity within the superficial geology of the area, and the possibility of permeable pathways of flow between the estuary and the Chalk aquifer.

Published borehole records of the superficial geology (British Geological Survey, 2016) have been used in order to establish the superficial geology between the estuary and the Springhead source, and to determine the potential of pathways and hydraulic connections to exist between the estuary and the Chalk aquifer. Some descriptions of the sediments in the records are vague, with little consistency between the stratigraphic descriptions, resulting in the generalisation and extrapolation of the units; however, the interpretations of these records provide an improved and area specific constraint of the superficial geology.

Over the south transect, Section 1, running from Springhead to the Humber Estuary, the stratigraphy consists predominantly of clay overlying the Chalk (Figure 9.2). However there are variations in the descriptions of the clay units, with some descriptions indicating sand content, and some identifying specific sandy-clay units (Figure 9.2). At the Springhead source, there is c. 6m of sandy-gravel-Chalk overlying the Burnham Chalk, topped by c. 2m of clay; the clay layer increases in depth over the next c. 1km south towards the estuary, and directly overlays the Burnham Chalk. Within the clay unit however, one of the boreholes identifies two narrow (c. 0.5m) intercalated sand layers, indicating the presence of sand lenses within the clay unit. The depth of the clay layer and Chalk varies towards the estuary, and from c. 2km south towards the estuary, a sandy-clay unit is identified overlying the Chalk, topped by the clay unit. This sequence extends c. 1km to the estuary, under which there is then an additional sandy-gravel unit extending into the estuary overlying the chalk. Boreholes adjacent to the estuary also identify peat layers and additional sand lenses (Figure 9.2).

The transect running south-south-east, Section 2, from Springhead to the estuary follows a similar stratigraphic sequence as the southern transect (Figure 9.2). Sandy-gravel layers and sand layers are present overlying the Chalk, as well as sand lenses within the clay identified in specific boreholes. At the estuary, the clay layer is substantially thinner, with the sandy-clay unit extending further vertically and horizontally (Figures 9.2). The southeast transect, Section 3, traverses the Springhead source and the estuary, and again demonstrates the variability in the clay thickness, as well as the presence of sandy-clay and sand layers. In particular, it demonstrates the presence of sand and sandy-clay layers adjacent to the estuary (Figure 9.2).

Based upon the published stratigraphic records, it is clear a complex and highly variable superficial geology exists between the Humber Estuary and the Springhead source. Of particular interest is the presence of sand, particularly the sand and sandy-clay units described across multiple boreholes overlying the Chalk aquifer. Sand is a highly permeable unit, and therefore potentially enables a pathway of flow into, and out of, the aquifer. The proximity of these units to the estuary, the presence of sand lenses at multiple borehole locations, as well as the varying descriptions of sand content within the clay unit, suggest that despite the presence of impermeable clay-silt units that technically confine the aquifer, there are potential pathways of flow enabled by the varying sand content and sand units. Indeed, erosional events along the estuary may expose the sand and sandy-clay units, creating intermittent hydraulic connections and pathways of flow. There may also be exposures of Chalk within the estuary, providing direct hydraulic connections. As such, there may be permanent and temporally variable pathways for saline waters from the estuary to intrude into the Chalk aquifer, and ultimately the Springhead source. The presence of pathways is consistent with the historical records of springs outflowing into the Humber Estuary at Hessle Whelps, as well as intrusions attributed to the reversal of the hydraulic gradient due to abstraction activities (ARUP, 2016; section 4.7; 9.1.1). However, without a thorough investigation and detailed mapping of the superficial geology, the detailed stratigraphy and the current pathways of flow for saline intrusion between the Springhead source, Humber Estuary and the Chalk aquifer are unknown.

9.1.4. Conceptual Model Overview

There are significant gaps in knowledge regarding the groundwater around Hull, and specifically around the Springhead source. Hydraulic connections and pathways of groundwater flow out of the aquifer and into the estuary have previously existed, and the reversal of the hydraulic gradient is believed to have led to an inflow of saline waters. Such pathways potentially remain, and the presence of sand within the superficial geology indicates that pathways for saline water to enter the aquifer may currently exist, and in the context of this study are assumed to. However, without substantial surveying of the area to establish the stratigraphy to a high resolution, such pathways cannot be specifically identified. As well as this, the absence of a defined position of existing saline waters, and the chronology of the waters, creates additional unknowns within the groundwater system.

Ideally, a model of the saline intrusion would be beneficial to determine the threats of sea-level change and abstraction on the groundwater system, particularly as current evidence suggests an intrusion is presently occurring (section 9.1.2). Due to the limited knowledge of the superficial geology, groundwater system and existing saline waters within it, at present it is not appropriate to pursue such a model. However, the use of the existing EYC groundwater model will help to contextualise how the groundwater has changed and will change under sea level and abstraction scenarios, and the results can be used to infer potential changes in saline intrusion. In terms of the parameters associated with the groundwater system, these are outlined thoroughly in the EYC groundwater model reports (ESI 2013a; 2013b; 2015), and several of the key parameters (i.e. boundary conditions, conductivity), as well as some of the key assumptions and limitations associated with it are discussed in the methodology (sections 5.8.1; 5.8.4).

9.2. Numerical Model Results

The Environment Agency's East Yorkshire Chalk (EYC) model was used to simulate nine sea level and abstraction scenarios (sections 5.8.3; 9.2.1). All simulations were conducted in March 2016, at the Environment Agency offices in York. The following sections outline the scenarios and the results of the simulations of the scenarios.

9.2.1. Scenarios

A total of nine scenarios have been studied: three past, three present, and three future scenarios. All were designed to examine the relationship between the groundwater and changing sea levels, as well as the role of anthropogenic abstraction of groundwater. The details of each scenario are outlined in Table 9.1. Within each scenario, either the sea level in the estuary (represented by the estuary boundary head; section 5.8.3) was adjusted, or the volume of groundwater abstraction was adjusted (section 5.8.3). Such adjustments were conducted separately to distinguish how each variable affected the modelled environmental conditions.

Three scenarios were established to represent the conditions through the late Holocene, representing conditions at 3000, 2000 and 1000 years BP. The sea level for the scenarios were calculated based upon the suite of sea-level index points for the Humber Estuary (from this and previous studies; section 5.8.3). Sea level at 3000, 2000 and 1000 years BP were 1.2m, 0.4m and 0.2m lower than present respectively. These scenarios were conducted with naturalised conditions, with no abstraction of groundwater, to represent conditions prior to anthropogenic abstraction of groundwater from the Chalk aquifer.

Three scenarios represent the present, AD 2016, environment. These have the present, default sea level of the EYC model, 0.2m OD (section 5.8.3). The three scenarios have differing levels of groundwater abstraction: no abstraction naturalised conditions, recent actual average levels of abstraction, and fully licensed maximum abstraction volumes (section 5.8.3). These scenarios allow a comparison of the role of abstraction on the groundwater compared to the effect of sea-level change alone.

Three scenarios represent possible future, AD 2100, environment. These use the same three groundwater abstraction scenarios (naturalised, recent actual and fully licensed), but with a higher sea level. The sea level selected for the 2100 scenarios was based upon "business as usual" carbon emission scenarios, and produces a median sea level that is 0.73m higher than present (Church *et al.*, 2013; section 5.8.3). All scenarios were simulated individually using the EYC model, following the methodology outlined in section 5.8.3.

9.2.2. Model Simulation Results

For each of the nine scenarios simulated, both the groundwater head and the groundwater flow values were considered, and were taken to best represent the effect on the groundwater at both the Springhead abstraction site (EYC cell: 258, 131), and at the estuary boundary immediately 3.5km south of Springhead (EYC cell: 276, 131). Raw value estimates were collected, as well as diagrams of the groundwater head and flow vector outputs.

The results of all the simulations are shown in Table 9.2. With naturalised conditions, there is a relatively small increase in the level of head at the Springhead source, of 0.27m (from 5.31 to 5.58m OD) between 3000 years BP and present (2016), during a period in which sea-level rose 1.2m. Between 2016 and 2100, the sea-level rise of 0.73m resulted in an increase in head of 0.14m (from 5.58 to 5.72m OD). In total, as a result of sea-level rise of 1.93m and no abstraction, the groundwater head at Springhead increased by 0.41m (from 5.31 to 5.72m OD) between 3000 years BP and AD 2100 (Table 9.2; Figures

9.3; 9.4). This result is anticipated, due to the decreased hydraulic gradient as a result of the increased sea level, and is also apparent, and amplified, at the estuary boundary. The level of the groundwater head at the estuary increased by 0.66m (from -0.22 to 0.45m OD) between 3000 years BP and 2016, and increased an additional 0.31m between 2016 and 2100 (from 0.45 to 0.76m OD). This is a total rise in the groundwater head at the estuary edge of 0.97m (from -0.22 to 0.76m OD) between 3000 years BP and AD 2100 (Table 9.2; Figures 9.3; 9.4). As would be anticipated due to a reduction in the hydraulic gradient under naturalised conditions, the groundwater flow declines at both the Springhead source and the estuary boundary. At Springhead the flow is reduced by just 32m^3 d^{-1} between 3000 years BP and 2100, whereas at the estuary boundary, it is reduced by 76.15m^3 d^{-1} (Table 9.2; Figure 9.4).

Under recent actual abstraction conditions, the groundwater head level in the Chalk at Springhead in AD 2016 is -0.11m OD, which is 5.69m lower than the naturalised simulation for AD 2016 (Table 9.2; Figures 9.4; 9.5). As abstraction is the only parameter to have changed within the model between these simulations, the decrease in head is attributed to anthropogenic abstraction. As industrial abstraction began in the region c. late 19th-20th Century, this reduction in head level will have occurred in a c. 100 year period. However, the projected rise in sea level through to year AD 2100 resulted in a rise in the head at Springhead to 0.13m OD, a rise of 0.24m from the present conditions (from -0.11 to 0.13m OD). However, this is 5.58m lower than the naturalised simulation for AD 2100 (Table 9.2; Figures 9.4; 9.5). At the estuary boundary, a decline, then rise in the head is also experienced from AD 2016 to AD 2100. With recent actual abstraction, the head is at 0.21m OD, 0.23m lower than in naturalised conditions (0.45m OD); the head increases to 0.54m OD at AD 2100, 0.22m lower than naturalised conditions (0.76m OD) (Table 9.2; Figures 9.4; 9.5).

Abstraction has a significant effect on the groundwater flows in the simulations (Table 9.2; Figures 9.4; 9.6). Under recent actual conditions, at Springhead the flow is almost doubled from that under naturalised conditions, with a flow of 1312m^3 d^{-1}, due to the lowering of the head at the site and pumping inducing an increase in the flows. In contrast, the result is a lowering in the flow at the estuary boundary, with a flow of just 74.64m^3 d^{-1} in AD 2016, and a small increase to 79.02m^3 d^{-1} in AD 2100. These values are 135.96m^3 d^{-1} and 128.15m^3 d^{-1} lower than the respective naturalised conditions (Table 9.2; Figures 9.4; 9.6).

The fully licensed simulations represent the maximum volume of groundwater abstraction that is allowed by current groundwater abstraction licenses (section 5.8.3). These simulations resulted in the same trends produced by the recent actual abstractions. At

Springhead, the head levels were -2.84m OD in 2016 and -2.49m OD in AD 2100, 8.41m and 8.21m lower than the respective naturalised levels (5.58 and 5.72m OD respectively; Table 9.2; Figures 9.4; 9.5). At the estuary boundary, the groundwater head was at 0.09m OD in 2016 and 0.42m OD in AD 2100, 0.36m and 0.34m lower than the respective naturalised levels (1.22 and 14.74m OD respectively; Table 9.2; Figures 9.4; 9.5). In terms of groundwater flow, at Springhead in AD 2016 the flow increased to 1778m^3 d^{-1}, and in AD 2100 was 1786 m^3 d^{-1}; these levels are 1066m^3 d^{-1} and 1085m^3 d^{-1} greater than the respective naturalised values (712 and 701m^3 d^{-1} respectively; Tables 9.2; Figures 9.4; 9.6). At the estuary boundary, the flows are reduced to just 1.22m^3 d^{-1} in 2016 and 14.74m^3 d^{-1} in AD 2100, 209.39m^3 d^{-1} and 192.43m^3 d^{-1} lower than the respective naturalised values (210.61 and 207.16m^3 d^{-1} respectively; Table 9.2; Figures 9.4; 9.6).

9.2.3. Model Simulation Results: Interpretation

Changes in sea level have an influence on the groundwater in the area examined (Table 9.2; Figures 9.3 to 9.6), with the overall rise in sea level resulting in an increased head and decreased flow through the aquifer at both the Springhead abstraction site and the estuary boundary when there is no abstraction. At Springhead, the changes in the groundwater do not fully reflect the magnitude of change in the sea level, whereas the influence is more pronounced at the estuary boundary, with the changes in head and flow following the shifts in sea level more closely (Figure 9.4). This indicates that generally the groundwater will reflect the rise in sea level to a varying extent, with the changes in head altering the hydraulic gradients and flows. Abstraction, however, results in significant alterations to the groundwater, at both the Springhead site and the estuary boundary.

The abstraction of groundwater, under both recent actual and fully licensed volumes has a significant effect on the groundwater, exceeding the amplitude of change that fluctuations in the sea level have on the groundwater (Figures 9.4; 9.5; Table 9.2). At Springhead, abstraction results in a lowering in the head of c. 5.6m and c. 8.3m under the recent actual and fully licensed for the AD 2016 and AD 2100 simulations from the naturalised conditions. The rise in sea level from AD 2016 and AD 2100 results in a rise in the head at Springhead, indicating that the groundwater levels will rise at Springhead, though at a slower pace than sea level. In terms of groundwater flows, abstraction results in a significant increase in the flow at Springhead (Table 9.2; Figures 9.4; 9.6), a result of the lowered head inducing flow to the area. In terms of rising sea level, the flow at Springhead is reduced minimally (Table 9.2; Figure 9.4). Overall, this suggests that abstraction at Springhead will not be impacted by rising sea levels in terms of changes to groundwater head and flow. However, this assumes there is no change in the quality of water, and the risk of change to the saline intrusion in the aquifer must be considered to fully assess whether sea-level rise will affect the abstraction of groundwater from Springhead.

In terms of groundwater flows, abstraction has a significant effect. At Springhead, the impact of abstraction is an increase in the volume of flow by c. 600m^3 d^{-1} and 1000m^3 d^{-1} from the naturalised conditions under recent actual and fully licensed abstraction respectively (Table 9.2; Figure 9.4). This dramatic increase in groundwater flow is a direct result of the pumping of groundwater lowering the head at the site and inducing increased flows, and significantly altering the direction of flows towards the abstraction site (Figure 9.6). The implications of these shifts in the volume and directions of groundwater flow to the abstraction location is a reduction in the volume of flow out to the estuary boundary (Table 9.2; Figures 9.4; 9.6).

The reduction in the flows, and almost complete cessation of flow under fully licensed conditions at the estuary boundary, is significant to consider, as it may result in a reversal and potential inflow of saline waters from the estuary into the groundwater, assuming the hydraulic connection and pathways of flow remain available, altering the salinity of the groundwater and posing implications for future abstraction. As with Springhead though, the groundwater does respond to the rise in sea level in the future under the abstraction scenarios. At the estuary boundary, both the head and flow increase over the phase of sea-level rise from AD 2016 to AD 2100, whereas under the naturalised scenarios the head and flow at the estuary boundary decrease in response to the sea-level rise (Table 9.2). This demonstrates that the groundwater has a constant, dynamic response to the sea level and abstraction conditions, and highlights the complexity that abstraction of groundwater creates within the groundwater system.

9.2.4. Changing Sea Level and Saline Intrusion

Key to the management and sustainable use of the groundwater is whether sea-level rise will result in a change in the saline waters and extent within the groundwater system, and a salinisation of the groundwater abstracted. Using the groundwater head values produced from the EYC model simulations of the nine scenarios, the change in position of the saline front can be crudely estimated using the simplified Ghyben-Herzberg relationship (sections 3.3; 5.8.3). Crucial to note however is that the Ghyben-Herzberg relationship assumes an unconfined coastal aquifer, whereas in this situation the aquifer is confined, though it is considered semi-confined, or ‘leaky’, with historic and potentially current hydraulic connections and pathways of flow identified. As such, all estimates are assumed to be over-estimates of the position of the saline front, though such depth estimates are also complicated due to the known presence of ‘fossil’ saline waters within the aquifer and mixing of groundwater, as well as the depth of the Chalk (sections 4.2; 4.6; 9.1.1; 9.1.2). The Chalk between Springhead and the estuary is c. -100 to -150m OD; as such, any estimates of saline water below this depth are not feasible, and it is therefore assumed that the saline waters are lying across the base of the Chalk along with potential 'fossil' saline waters. This thesis however offers a first attempt to establish the position and potential depth of saline waters with regards to the Springhead source.

The results of using the Ghyben-Herzberg relationship for each of the model scenarios are shown in Table 9.3. The relationship, $z_s = 40h$, whereby z_s is the depth of freshwater below the sea level, and h is the height of freshwater above the sea level (Fitts, 2002; section 3.3), assumes that for every unit of freshwater above sea level, there is 40 times that unit of freshwater below. Due to the significant lowering of the groundwater head under abstraction scenarios, the groundwater head falls below the respective sea levels, and the relationship is no longer fully applicable. However, the results do demonstrate the changes of position in saline water that are the consequence of sea level and abstraction, and offer an initial insight into the depth of the saline waters, and the changes induced by abstraction at Springhead.

Under naturalised conditions, at Springhead there was a vertical increase in the position of the saline water head in response to the rise in sea level (Table 9.3; Figure 9.7). Over the 3066 year period (3000 years BP to AD 2016), sea level increased by 1.2m (from -1 to 0.2m OD). At Springhead, this resulted in a rise of in the position of the saline water in the aquifer of 37.2m (from -253.28 to -214.88m OD), or 38.4m in relation to the respective relative sea levels. Over the 3150 year period (3000 years BP to AD 2100), sea level increased by 1.93m (from -1 to 0.93m OD). This resulted in an increase in height of the saline water at Springhead of 60.88m (from -253.28 to -190.47m OD), or 62.81m in relation to the AD 2100 relative sea level, a rise of 31.54m for each 1m of sea-level rise. This is a dramatic increase in the position of the saline water head within the aquifer due to a proportionally small increase in the sea level within the estuary. In particular, there is a large change between the present, AD 2016, and future, AD 2100, scenario, and demonstrates that the predicted accelerated rise in sea level will have a significant impact on the position of the saline waters over a relatively short, century time scale.

In contrast, under the abstraction conditions, the position of the groundwater head falls lower than that of the sea level (Table 9.3; section 9.2.2), and as such the Ghyben-Herzberg is no longer applicable at the Springhead source. However, based on the changes in the groundwater head contours around the Springhead source (Figure 9.5), the position of the saline water is, and will be, raised as a result of the abstraction, and drawn up towards the abstraction location, and the effect is further exaggerated under fully licensed scenarios (Figure 9.8). This rise in the saline head at Springhead is consistent with increasing chloride concentrations, and therefore salinity, identified at the Springhead source (section 9.1.2). Under the future sea-level rise, the conditions are similar to those at present at Springhead, suggesting that the alteration to the head caused by the sea-level changes will have no significant impact in terms of the abstraction conditions at Springhead. However, this does not take into account the change in conditions at the estuary boundary.

At the estuary boundary, under the Ghyben-Herzberg relationship, the saline water is relatively shallow in comparison to the Springhead source, and in response to the rise in sea level, the saline head increased (Table 9.3). Over the 3066 year period (3000 years BP to AD 2016), sea level increased by 1.2m (from -1 to 0.2m OD); under naturalised conditions, this resulted in a rise in the saline head of 21.44m (from -32.21 to -9.68m OD), or 22.64m in relation to the AD 2016 relative sea level (Figure 9.8). Within the abstraction and future scenarios, the position of the groundwater head falls below the position of sea level, and as such the Ghyben-Herzberg is no longer applicable. However, under the assumption of hydraulic connections and pathways existing between the estuary and aquifer through the overlying superficial geology, saline water may be entering into the groundwater system above the groundwater head (Figure 9.8). This is particularly likely if there is a cessation of flow out of the aquifer, as suggested under fully licensed conditions (Table 9.2), and a reversing of the hydraulic gradient inducing intrusion, as occurred historically (sections 4.7; 9.1.1).

The position of the saline front within the aquifer, between the estuary and the Springhead source, does change in response to sea-level rise. Ultimately, the rise in sea level results in a vertical increase in the position of the saline waters at both the estuary and the Springhead source. Under abstraction scenarios, and with all future scenarios at the estuary boundary, the groundwater level drops below the sea level, which may lead to a reversing of the hydraulic gradient and induce intrusion. The results are consistent with an encroachment of saline waters at the Springhead source that are indicated by the increasing chloride levels (section 9.1.2). Sea-level rise is responsible for a proportion of this; however, abstraction practises are altering the groundwater system significantly, including the position and flow of saline waters into the Chalk aquifer.

9.3. Summary

The Chalk aquifer of East Yorkshire is a highly complex system. The aquifer around Hull has multiple bodies of saline water present, including contemporary saline waters attributed to the reversing of the hydraulic gradient due to abstraction practices in the 20th Century. At the Springhead source, increases in chloride content through the late 20th and early 21st Century indicate increasing salinity, despite consistent and regulated abstraction practices. Despite the implications of saline intrusion on the use of groundwater as a crucial water resource, there are significant gaps in the knowledge and understanding of the system and current conditions. Potential hydraulic connections and pathways exist between the estuary and the Chalk aquifer, however these may be intermittent.

Under various sea level and abstraction scenarios, the groundwater changed significantly. However, sea-level rise had a minimal effect on the groundwater head and flows at Springhead, whereas abstraction resulted in a significant lowering of the head and increased flows, as well as a lowering of head and reduction of flow at the estuary. In terms of estimating the position of saline waters in the aquifer, sea-level rise resulted in an increase in the saline head at both the estuary and Springhead. At Springhead, a sea-level rise of 1.93m resulted in the position of the saline waters rising 60.88m in the aquifer. At the estuary, under the abstraction and future scenarios, the sea level was higher than the groundwater head, suggesting a reversal of the hydraulic gradient and potential intrusion of saline waters. However, these are crude saline water estimates based on the Ghyben-Herzberg relationship, and are potentially substantial overestimates. Significant research on the geology, groundwater flows, and existing saline waters within the aquifer is required to provide improved constraints on the saline waters, and to accurately model and quantify the changes induced by both sea-level change and abstraction practices. This is crucial to ensure the sustainable use of the groundwater resource at Springhead into the future.

10. Discussion

This chapter discusses the results with respect to the original research aims set out at the beginning of this thesis, section 1.2. For reference, the original research aims were:

1. *To assess the validity of palaeo sea-level techniques in a modern estuarine environment.*
2. *To reconstruct and elucidate the late Holocene relaitve sea-level history of the Humber Estuary.*
3. *To examine the interactions of groundwater and sea level between the Humber Estuary and an adjacent groundwater abstraction site.*

10.1. Validity of Palaeo Sea-Level Techniques

To reconstruct palaeoenvironmental and relative sea-level changes, there are a number of methods and techniques, such as microfossil analysis, transfer functions, and sea-level index points, that are ubiquitous in their use across the discipline (section 2.3). This research on the Humber Estuary addresses whether such approaches are suitable within a modern estuarine environment, and discusses specific challenges, making recommendations for future studies.

10.1.1. Palaeo Sea-Level Study Sites

Fundamental to applying palaeo sea-level reconstruction methods is the identification of sites and sediment sequences that provide a well-preserved record of changes. A significant challenge to establishing the late Holocene relative sea level within the Humber Estuary, and to enable additional reconstructions in the future, is the identification of suitable sites that preserve a pristine, undisturbed record.

The use of sea-level index points to reconstruct sea level requires sediment sequences with contacts, between organic and inorganic units, that formed high in the intertidal zone (Gehrels, 2007; section 2.3.5). Transfer functions can also be used to provide palaeo sea-level estimates, however this is dependent upon the presence of microfossil proxies within the sediments (section 2.3.6). An additional issue with these methods is compaction of the sediment sequence (e.g. Barlow *et al.*, 2013; Brain, 2016; Brain *et al.*, 2011; 2012; 2015; Edwards, 2006; section 2.3.4). Ideally, basal units would be used to provide compaction free palaeo sea-level estimates (Gehrels, 2007; Kemp *et al.*, 2015; section 2.3.4). However within a highly turbid estuarine environment, such as the Humber Estuary, the presence of such units that represent the late Holocene period is limited.

The Humber Estuary is one of the most turbid estuarine systems within the UK (Jickells *et al.*, 2000; Rees, 2006; section 4.1). There was an overall trend of sedimentary infilling of the estuary through the Holocene, with increasing storage and dominance of marine sediments (Rees *et al.*, 2000; Shennan *et al.,* 2003; Townend *et al.*, 2007). The projected resultant decrease in storage capacity, assuming continuation of the sediment supply through the Holocene, resulted in an increased frequency of estuarine channel migration and erosion (Rees *et al.*, 2000). Anthropogenic deforestation and soil erosion over the latter half of the Holocene has also resulted in an influx of additional clastic sediments to the estuary (Buckland & Sadler 1985; Dinnin, 1997; Long *et al.*, 1998; Metcalfe *et al.*, 2000). The dominance of clastic and marine sediments is consistent with the stratigraphic units encountered in this research, with all sequences comprising thick, >1m, marine and/or tidal flat silt-clay units in the upper portion of cores, and the turbidity resulting from the sediment flux explains the lack of late Holocene basal units (sections 7.3; 8.3; 8.4).

The migration of the estuary channel, and associated erosion, may have resulted in the loss of potential sequences relating to the late Holocene period. Despite palaeogeological maps of the Humber Estuary representing changes 8000-3000 cal years BP (section 4.4; Figure 4.8), the general lack of knowledge of the morphology of the estuary over century-millennial temporal scales limits understanding of sediment transport dynamics (Rees, 2006), as well as confidence in identifying suitable palaeo sea-level study sites. This is further complicated by the spatial and temporal variability of the sediment properties within the estuary, such as at the Skeffling mudflats in the outer estuary, with variable re-suspension and erosion resulting in mixed sediment units (Lee & Cundy, 2001; Paterson *et al.*, 2000), unsuitable for the production of a palaeo sea-level record using current methods.

Anthropogenic activities within the estuary, particularly during the last millennia, have also influenced the availability of suitable study sites throughout the estuary (sections 4.5; 6.1). The construction of embankment flood defences, estuary dredging, and widespread reclamation of Holocene sediments (Morris *et al.*, 2004; Sheppard, 1966; Townend *et al.*, 2007) has significantly altered the morphology, sediment fluxes, and extent of the intertidal zone within the estuary, and hence the availability of undisturbed late Holocene sequences. On-going developments within and around the estuary, such as urbanisation and managed realignment schemes, may further limit access to, or disturb, potential remaining late Holocene sequences. As such, there should be a focus on studying the late Holocene sea level within the Humber Estuary in the immediate future to maximise any remaining suitable sediment sequences.

Despite the issues with identifying sites, there is confidence in those used within this study. Multiple sites were considered through the course of this research (section 5.1.1), however only two, Brough and East Halton, were suitable for the reconstruction of late Holocene sea level and provided sea-level index points (sections 7.6.3; 8.7.3). Numerous other sites were eliminated due to one or more of the reasons outlined above, and those that were utilised were relatively short (<5m) in depth, and comprised of basal or intercalated saltmarsh units (sections 7.2; 8.2). However, the constraints produced, by both transfer functions and sea-level index points, were limited in number as a result of the availability of study sites, as well as by the quality of the preserved biostratigraphic record. This demonstrates that the capacity for reconstructing late Holocene sea level in the Humber Estuary is restricted, and to provide further constraints for the period will require extensive stratigraphic surveys to identify additional sites, and potentially the revisiting of previously studied sites to update records using more recent techniques (section 10.1.6).

10.1.2. Contemporary Environment and Transfer Functions

The Humber Estuary has an uncharacteristically low extent of saltmarsh for a macrotidal estuary (Morris *et al.*, 2007), attributed to the widespread reclamation and construction of embankments limiting the intertidal zone, with the particular loss of upper saltmarsh environments (Allen *et al.*, 2003; Morris *et al.*, 2007; Sheppard, 1966; Townend *et al.*, 2007; sections 4.5; 6.1). This limited the availability of suitable sites for constructing a contemporary training set of proxies that represent the present and complete altitudinal range of the intertidal environment (sections 6.1; 6.3.1).

Within this research, a training set of modern diatom and foraminifera distribution was established from a series of 40 samples collected from three remaining areas of marsh in the outer portion of the estuary (section 6.1). This is fewer than would be recommended for a 'local' training set, a direct consequence of the history of land reclamation and anthropogenic activity, and does not represent the full spatial range of environments (i.e. inner and outer estuary) within the Humber Estuary. These issues have also been encountered in other macrotidal estuaries with large populations and industrial activity e.g. Mersey Estuary (Mills *et al.*, 2013; Wilson & Lamb, 2012) and the Severn Estuary (Hill *et al.*, 2007; Elliot, 2015), and make the construction of a local scale training set unrealistic and restricted (Wilson & Lamb, 2012). The inclusion of local environments within a training set, such as in this thesis, can however enhance and improve the accuracy and reliability of the transfer function (Watcham *et al.*, 2013; Woodroffe & Long, 2010).

The training sets constructed for the Humber Estuary fail to represent the complete vertical tidal range, and the range they cover is not continuous (sections 6.3.1). This is a common problem encountered within macrotidal environments, where the vertical range sampled is generally low compared to the actual tidal range, and can result in the reduction in the statistical significance of elevation explaining the proxy assemblages (Mills *et al.*, 2013). Within the Humber Estuary contemporary training sets, the measured environmental variables explained 27.68% of the diatom assemblage, 47.68% of the foraminifera, and 30.42% of the multi-proxy dataset. Of this, elevation explained 9.97%, 6.0% and 8.65% respectively, and these values are comparable to other sea level and estuarine studies (e.g. Elliot, 2015; Horton, 1997; Horton & Edwards, 2006; Mills *et al.*, 2013; Zong & Horton, 1999; sections 6.3.3; 6.3.4).

However, the levels of intercorrelation between the environmental variables (17.45%, 30.42% and 18.42% respectively) demonstrate the dynamic and interdependent relationships present within saltmarshes, and follow the conclusions of other studies (e.g. Horton, 1997; Scott & Medioli 1980; 1986; Zong & Horton 1999) whereby the elevation ultimately dictates the other variables and therefore the distribution of the micro-fauna and flora. It has been suggested that when the elevation range of the sampled marsh is low (<10%) in comparison to the tidal range, then the significance of the intercorrelations of the environmental variables in explaining foraminiferal distribution is greater than elevation, and is challenging to overcome when in a macrotidal environment (Mills *et al.*, 2013). To limit the influence of this, c. 20% of the range is represented at the respective contemporary sites in the Humber Estuary that were sampled (East Halton: 25.63%, Spurn: 22.26%, Welwick: 18.16%), and demonstrates that sampling of a range greater >10% of the contemporary saltmarsh surface is possible within the macrotidal setting, although this disproportionally represents the middle-low intertidal environment due to the lack of upper marsh environments.

The problem of representing the full tidal range and environments within a macrotidal setting has been previously overcome by the sampling of two sites within the Severn Estuary (Hill *et al.*, 2007). However, the extent of reclamation within the Humber Estuary prevented this being achieved, despite sampling at three separate locations. The sampling of marshes demonstrates that the ability to produce a training set that represents the full tidal range in the Humber Estuary is not possible, and the resultant transfer functions have a poor predictive ability (section 6.4), although the inclusion of the training set does prove beneficial in improving the reliability of regional scale transfer functions. The use of a localised training set from within a macrotidal estuary by itself therefore has not been demonstrated, in this case, to be a valid method for producing a transfer function to reconstruct palaeo relative sea-level changes.

The rationale of a local training set is that contemporary marshes in close proximity to the fossil core location will have the most representative environmental conditions found in the fossil core (Gehrels, 1994; Horton & Edwards, 2005; 2006). However, as the environments change through time, the contemporary local environment may no longer reflect the fossil environment and therefore fail to provide modern analogues for the fossil assemblage, and thus the sampling of a range of contemporary sites (e.g. micro-, meso-, macrotidal locations) from a larger, regional, spatial scale is necessary (Horton & Edwards, 2005; 2006; Watcham *et al.*, 2013). This approach will provide a training set that represents the spatial, geomorphological and ecological range of a region, and can negate the need for local samples (Kemp *et al.*, 2015; Zong & Horton, 1999). The use of a regional training set for the Humber Estuary was necessary to provide an improved representative range of contemporary environments, and is consistent with research findings in other UK macrotidal estuaries e.g. Mersey Estuary (Wilson & Lamb, 2007), Tees Estuary (Plater *et al.*, 2000), and other coastal locations worldwide (e.g. Horton & Edwards, 2005; Kemp *et al.*, 2013; 2015; Watcham *et al.*, 2013).

The incorporation of the regional, UK scale, diatom, foraminifera, and multi-proxy data do provide improved transfer functions for use in the Humber Estuary (section 6.4; Horton & Edwards, 2006; Zong & Horton, 1999). The UK datasets were considered on the full regional scale, an estuary sites only scale, and an enhanced full regional scale incorporating the local Humber Estuary dataset (section 6.2; Table 6.1). In terms of diatoms, the full regional and estuary only training sets, excluding the local Humber data, provided the best performance, with the estuary scale transfer function outperforming the full regional data set (section 6.4.1). This contradicts the suggestions that modern estuaries are not suitable for developing a training set (e.g. Wilson & Lamb, 2012). However, it demonstrates and reaffirms the rationale that sampling from a larger spatial and environmental range improves the ability of the transfer functions, and suggests that estuarine environments, when considered on a regional scale are valid locations for developing diatom-based transfer functions.

In contrast, the foraminifera estuary scale transfer function was outperformed by the full UK dataset (local data excluded; section 6.4.2), indicating a dichotomy in the utility of the different proxies depending on the environment sampled. Previously, the potential of foraminifera from macrotidal estuaries to reconstruct palaeo conditions has been demonstrated (Mills, *et al.*, 2013), however the results of this research suggest that foraminifera from estuaries do not provide the most valid dataset, and that it is necessary to incorporate a range of coastal environments to produce a more valid foraminifera transfer function (section 6.4.2). Overall, the multi-proxy training sets outperformed the individual proxy training sets (section 6.4.3), consistent with the rationale of multiple proxies providing improved constraints in other studies (e.g. Elliot, 2015; Kemp *et al.*, 2009). However, the reliability of the transfer functions is not only dependent on the relationship of the proxies to the environment, but also crucially on the suitable availability of modern analogues for the fossil record being reconstructed.

The availability of modern analogues is significant in assessing the reliability of a transfer function. Indeed, a lack of analogues within the contemporary training set for the fossil assemblages can result in the reconstructions produced being unreliable and unsuitable, despite good statistical predictability of the transfer function (Wilson & Lamb, 2012). The presence, or lack thereof, of modern analogues can also influence the selection of transfer functions used for reconstructions and the size of associated errors (Horton and Edwards, 2005; Massey *et al.*, 2006b). The presence of modern analogues can result in the selection of a poorer performing transfer function, and thus larger errors, in a bid to provide more reliable reconstructions, compared to the use of a better performing transfer function that lacks modern analogues (e.g. Horton & Edwards, 2005). This was a key issue and consideration in selecting the most appropriate transfer functions for the palaeo sites within the Humber Estuary (sections 5.7; 7.6.1; 8.7.1).

The variable availability of modern analogues is a direct result of whether the range of environments incorporated in the training set reflects the fossil assemblage, and is thus also directly dependent upon the fossil record. However, this can alter depending on the proxy used. Diatoms have been found in previous studies to provide poor analogues in comparison to foraminifera, because of their high species diversity and site-specific distributions of contemporary diatom assemblages (Kemp *et al.*, 2009); this higher level of diversity was also encountered in the Humber Estuary (section 6.1). The availability of analogues can also influence the range of environments that are reliably reconstructed, with reconstructions of the upper intertidal zone generally being poorer due to the higher diversity in diatom species encountered (Wilson & Lamb, 2012), or lack of representative environments included, as previously discussed. The presence of modern analogues can therefore limit the success of using diatom-based transfer functions in estuarine environments, as noted in this study and in others (e.g. Hill *et al.*, 2007, Wilson & Lamb, 2012). These factors have resulted in the recommendation of the use of foraminifera-based and multi-proxy transfer functions in estuarine settings (Elliot, 2015; Mills *et al.*, 2013; Wilson & Lamb, 2012), the latter of which was demonstrated to offer the best performing transfer functions for the Humber Estuary (section 6.4.3). However, the proxies present within the palaeo records ultimately dictate what transfer function was applied, and whether the reconstructions produced were reliable and appropriate.

10.1.3. Microfossil Preservation

There were significant issues regarding the preservation of fossil foraminifera and diatoms in the sediment cores from sites in the Humber Estuary, a consistent problem encountered in other studies from the Humber Estuary region (e.g. Kirby, 1999; Long *et al.*, 1998; Metcalfe *et al.*, 2000), other estuarine locations (e.g. Elliot, 2015), as well as other palaeoenvironmental settings, such as lakes (e.g. Best, 2013; Ryves *et al.*, 2006). There was differential preservation between the proxies studied, diatoms and foraminifera, both within and between the cores from the palaeo study sites. Foraminifera were not preserved at the East Halton palaeo site, whilst diatom preservation varied within the core with evidence of fragmentation and dissolution (section 7.4). Both proxies were present at the Brough site, however with sporadic and varied preservation within and between the sampled cores (sections 8.5). At both sites, the absence or fragmented preservation of diatoms within the overlying silt-clay units is not a unique problem (e.g. Kirby, 1999). As a consequence of this some of the microfossil records from the Humber Estuary are considered biased due to the differential preservation and are therefore interpreted with the support of other proxies (litho- and biostratigraphical) (e.g. Long *et al.*, 1998; Metcalfe *et al.*, 2000). Overall, the biological proxies, when considered individually or together, failed to provide continuous records, highlighting the importance of a thorough lithostratigraphic analyses to complete and complement the interpretation of the palaeo sea-level record.

The sporadic and variable preservation of diatoms within a sedimentary record is not an uncommon problem when reconstructing palaeoenvironments. Despite the significance of differential preservation in determining an environmental signal, the issue is generally overlooked, particularly with regards to diatom dissolution (Ryves *et al.*, 2009), and can result in unpredictable errors within reconstructions (Barker *et al.*, 1994; Ryves *et al.*, 2006). Diatom preservation can be influenced by taphonomic and pedogenic processes within the sediments and environmental changes (e.g. pH, silica concentrations and recycling), resulting in the dissolution or fragmentation of the diatom valves (Flower & Ryves, 2009; Mayer *et al.*, 1991; Plater *et al.*, 1999; Ryves *et al.*, 2001; 2006; 2009; Spencer *et al.*, 1998; Vos & de Wolf, 1997). For example, within peat bogs there can be a deficiency in silica due to the uptake of formerly available silica (by diatoms or macrophytes, for example), but also acidity from anaerobic decomposition can reduce dissolved silica concentrations, ultimately resulting in the dissolution of diatom frustules (Flower, 1993; Vos & de Wolf, 1994). Within lakes, salinity, temperature, pH, and bacteria have all been demonstrated to influence diatom dissolution, with differential effects dependent on species (Flower & Ryves, 2009; Ryves *et al.*, 2001; 2006; 2009), with possible linkages to seasonal growth patterns and sedimentation conditions (Ryves *et al.*, 2009). Differential preservation results in the more robust species being preserved, and results in a small proportion of the total original assemblage present in the palaeoenvironmental record (Denys, 1989; 1994; Vos & de Wolf, 1994; section 2.3.2).

Foraminifera are also subject to similar preservation issues and taphonomic processes. Generally however, the most prominent issue considered with foraminifera is the dissolution of calcareous species within acidic, low pH, organic saltmarsh sediments, again resulting in a potentially biased assemblage record (Edwards & Horton, 2000; Gehrels *et al.*, 2001). It has been hypothesised that under a rising sea level in a macrotidal estuary, calcareous species are deposited higher, on the organic saltmarsh surface, and thus not preserved in the fossil assemblage (Elliot, 2015). As the samples analysed are generally saltmarsh in origin, and are interpreted as demonstrating an overall sea-level rise, the general absence of calcareous foraminifera in all but a few of the fossil samples analysed is consistent with these previous findings. Due to the complexity of the factors involved in preferential preservation of the proxies, it makes the overall effect on fossil assemblages difficult to constrain or quantify, and requires extensive further research to fully understand the impact within estuarine and coastal settings.

10.1.4. Vertical Uncertainty: Correcting for Compaction and Tidal Changes

There are a number of vertical errors that must be acknowledged and incorporated into the production of the sea-level index points, including those associated with both field and laboratory methods (section 5.6). Two significant sources of vertical uncertainty however are frequently not fully addressed or quantified: those associated with changes in the tidal regime at a palaeo site, and the post-depositional compaction of the sediment sequence. These have however been addressed and quantified within this thesis, to provide an improved constraint of the late Holocene relative sea-level history.

Changes in the tidal regime within estuaries can result in significant vertical uncertainties, with potential over- or under-estimates of palaeo sea-level change (Horton & Shennan, 2009; Kirby, 1999; 2001; Leorri *et al.*, 2011; Shennan *et al.*, 2003). Within the Humber Estuary, Holocene tidal range changes have been determined and applied to the reconstructions in this thesis (sections 5.6; 7.6.3; 8.7.3; Shennan *et al.*, 2003). This has been significant in reducing the vertical range of sea-level index points that otherwise occurs depending on the location of the palaeo site within the estuary (i.e. inner or outer portion) (Kirby, 1999; 2001; Shennan *et al.*, 2003; sections 4.4; 5.6; 7.6.3; 8.7.3). Within the macrotidal setting of the Humber Estuary, the tidal corrections for the late Holocene period in this research vary from a decimetre scale (0.17-0.18m) for the outer estuary site (sections 7.6.3), to a more significant metre scale (1.03-2.84m) for the inner estuary location, altering the interpretation of the sea-level history (sections 8.7.3; 8.8.3). However, the use of such corrections for dates younger than c. 1000 years BP is potentially problematic for the Humber Estuary, as the tidal influences are likely to have been adjusted by the extensive land reclamation, as hypothesised for the macrotidal Severn Estuary (Elliott, 2015), adding additional uncertainty as the impact and extent are not known or quantified. As all the dates in this thesis are older than c. 1500 years BP, the tidal corrections applied are assumed to be accurate, with no impact from the land reclamation.

The corrections applied demonstrate the significance that tidal changes can have on the interpretation of a sea-level record, and the importance of quantifying these changes to accurately constrain the rate of sea-level changes. However, the current absence of a consistent, robust method to model tidal changes limits the ability for this to be achieved for all palaeo sea-level records, and requires further research to address this uncertainty fully.

Similarly, correcting for the compaction of intertidal sequences lacks an established or rigorous method suitable for the differing sediment sequences that may be encountered (Barlow *et al.*, 2013; section 5.6). The consequence of not correcting for the compaction of sediment is a potential underestimate of former relative sea level, and an overestimate of the rate of change (Barlow *et al*. 2013; Brain, 2016; Edwards, 2006; van de Plassche *et al.*, 1998; section 2.3.4; 2.3.5; 5.6). Compaction should therefore be addressed, and should not be dismissed as just a limitation of reconstructing from intertidal, saltmarsh environments (Brain *et al.*, 2015). Sediment compaction has been demonstrated to have a significant relationship with the depth of sediment overburden (sections 7.6.3; 8.7.3), consistent with other studies in the Humber Estuary (Horton & Shennan, 2009), and other macrotidal estuarine environments (e.g. Edwards, 2006). This relationship was used to determine an estimate of compaction to 'decompact' and correct the sea-level estimate (Edwards, 2006; Horton *et al.*, 2013; section 5.6). This calculation provided relatively small (0.01-0.28m; sections 7.6.3; 8.7.3) corrections compared to the tidal corrections, though they are still important to include.

The method applied to correct for compaction is a relatively crude estimate based on one variable of the sediment core (section 5.6). An improved approach would be to provide an empirically calculated geotechnical correction for compaction based upon the properties of the sediment sequence (e.g. Brain *et al.*, 2011; 2012; 2015; Massey *et al.*, 2006a). However, this approach is research intensive, though continuing research on the topic may ultimately enable the routine use of geotechnical corrections of compaction in the future (Brain *et al.*, 2015).

10.1.5. Sea-Level Index Points: Quantifying the Indicative Meaning

Traditionally, sea-level index points are produced with an indicative meaning assigned based upon the stratigraphy and environmental preferences of the microfossil proxy utilised (e.g. Gehrels, 1994; Horton *et al.*, 2013; Lloyd *et al.*, 1999; Long *et. al*, 1998; Shennan, 1982; 1986; Shennan *et al.,* 2000a; 2000b; Zong, 1998). Increasingly, transfer functions are being used to quantitatively estimate the indicative meaning to improve the accuracy of sea-level index points (e.g. Edwards, 2006; Gehrels, 1999; Massey *et al.*, 2008). Transfer functions are also being used to produce continuous quantified records of the sea-level change from sediment cores (e.g. Edwards & Horton, 2006; Hill *et al.*, 2007; Horton & Edwards, 2005; Kemp *et al.*, 2009; 2013; Zong & Horton, 1999). Throughout this thesis, these three approaches have been tested and assessed in terms of their application to constrain late Holocene sea level within the macrotidal setting of the Humber Estuary.

The stratigraphic record and sediment properties, as well as the presence of microfossils, allowed the assignment of an indicative meaning and associated range to the sea-level index points produced (sections 7.6; 8.7), however microfossil preservation (as discussed in section 10.1.3) often limited the horizons for which a biostratigraphical constraint of indicative meaning could be made. The microfossil preservation within the palaeo sequences had significant repercussions on the use of transfer functions (sections 7.6; 8.7), as well as there being separate issues in the construction, performance and accuracy of the transfer functions (section 6.4). The availability of microfossils was a key issue in the quest to produce the most refined estimates of palaeo sea level, and the defining of the indicative meaning.

In the context of the East Halton palaeo site, only a diatom record was preserved (section 7.3). This restricted the use of transfer functions to diatom-based only, for which the best performing transfer functions provided a combination of poor, close and good modern analogues, with significant issues regarding accuracy and reliability for the individual reconstructions, and therefore selection of the most appropriate transfer function (section 7.6.1). As a result, the continuous record that was produced by the transfer function is not considered wholly accurate. In terms of determining the indicative meaning, an assigned value was used to construct the two sea-level index points. The discrepancy between the transfer function estimates was deemed too great to confidently quantify the indicative meaning, and the additional 0.05m vertical error introduced by an assigned indicative meaning was considered an acceptable compromise.

In contrast, the Brough palaeo site yielded both foraminifera and diatom records, which enabled the use of a multi-proxy transfer function. However, the sporadic and variable preservation and availability of modern analogues for the microfossils restricted the ability to produce a continuous record for the entire sedimentary sequence (sections 8.5; 8.7.1). Again, the accuracy of the transfer function had to be significantly reduced to provide improved modern analogues and reliability of the reconstructions produced. There was some consistency between the reconstructions produced by the transfer functions. The reconstructions produced from the most reliable transfer function, in terms of number of good analogues, were used, although it was acknowledged that they were not the most accurate in terms of predictability. The reconstruction estimates were in relatively close agreement (c. 0.4m) to the assigned indicative meaning value, and produced smaller errors. The indicative meanings calculated from the transfer functions were therefore used to produce the sea-level index points for the Brough site.

The two methods for determining and quantifying the indicative meaning of sea-level index points have been applied successfully. The sites studied have demonstrated that the most suitable method is sample and site specific, even from within the same estuarine system. The application of either method is dependent upon the preservation of the microfossil record, and the quality of the modern analogues. The method of determining the indicative meaning cannot be predetermined prior to collection of a fossil sequence, and is reliant upon the preserved microfossil record. The ultimate utility of the transfer functions is questionable based upon their statistical performance. Significant compromising of the accuracy of the transfer functions to improve the reliability, through the provision of modern analogues, increased the errors of the resulting estimates. As such, it is recommended that best practice in cases of an incomplete or potentially biased fossil record is to use both methods, and to then assess the most accurate and reliable estimate for use in the sea-level index point. However, the additional time and fieldwork required in the development of a transfer function means it could be considered an inefficient method due to the relatively small reduction in error that was achieved, and particularly in the absence of complete and continuous biostratigraphic records, that was demonstrated in this thesis.

Despite the overall improved accuracy that transfer functions potentially offer, this is not always guaranteed and cannot be universally adopted for all sites. The traditional approach of quantifying the indicative meaning is still a relevant and valid method of reconstructing former relative sea level, and particularly so in a modified and macrotidal estuarine environment. Indeed, the application of transfer functions in other estuaries has also proved problematic (e.g. Hill *et al.*, 2007; Wilson & Lamb, 2012). There is therefore a need to develop existing and new methods to improve constraints and quantification of indicative meanings and sea-level change to provide consistently reliable, accurate and high-resolution records.

10.1.6. Suitability of Palaeo Methods in Estuarine Environments

Several widely used palaeo methods have been applied to produce a record of late Holocene relative sea-level change within the Humber Estuary. The use of transfer functions and the production of sea-level index points have been applied with some success at two sites within the estuary. However, the overall suitability of the methods varied significantly within and between sites.

Eight sea-level index points have been produced, demonstrating that the palaeo sea-level methods ustilised are suitable within macrotidal estuarine environments. However, the limited availability of appropriate palaeo sites and preservation of microfossils, problematic chronology, as well as the constraints of the indicative meaning, limited the accuracy and the number of sea-level index points produced (Chapters 7 and 8). Indeed, the issues regarding the use of transfer functions meant that some indicative meanings could not be quantified using this approach, and as such had larger errors. The use of assigning an indicative meaning based upon the litho- and biostratigraphy is a valid method, and provided estimates similar to those produced by transfer functions.

The chronology for the sedimentary sequences and sea-level index points was established using AMS radiocarbon dating of bulk sediments and plant macrofossils. A total of ten dates were produced (sections 7.5; 8.6). Of these, eight were used to successfully constrain sea-level index points and the records produced using transfer functions. Two dates however produced age reversals, and were significantly older than anticipated. Both of these were the uppermost dates of two separate cores, and produced from bulk sediment samples (Table 8.3). The reversals were attributed to the influence of human activity and the introduction of older carbon from industry and fossil fuel use, as other bulk dates from lower in the core produced sequentially sensible ages (section 8.6; Table 8.3).

Problems obtaining dates from sediment within estuarine settings is not uncommon, particularly due to the rapid accumulation and reworking of sediment that can occur in Holocene sequences, as well as the multiple sources of sediments and therefore carbon (Colman *et al.*, 2002). Alternative dating methods (e.g. radionuclide dating of ^{210}Pb and ^{137}Cs) are therefore worth considering for estuarine settings, particularly for the latter Holocene period (i.e. last millennia), during which anthropogenic influence and sources of carbon affect the reliability of radiocarbon dating. The dating of plant macrofossils, as done for several dates in this thesis (section 8.6), or microfossils (foraminifera) are alternative options, however the issue of microfossil preservation and presence of low marsh-tidal flat deposits within the upper portions of the cores limited or prevented this.

Local mixing, re-suspension and erosional processes of Humber Estuary mudflat sequences results in the complex vertical distribution of heavy metals used for examining pollution trends (Lee & Cundy, 2001) that could otherwise offer a chronology for more recent sequences from the last c. 100 years. To therefore date the latter Holocene period i.e. last millennia, within macrotidal estuarine environments there needs to be further research and development of methods to overcome the issues of incorporation of older carbon, lack of datable material, and reworking of more recent mudflat sequences. As it stands, this period within the Humber Estuary is currently constrained by a single sea-level index point, and represents a significant period for which there is little understanding.

Alternative methods of reconstructing palaeo sea level in estuarine environments to overcome some of the issues outlined have been developed. The use of geochemistry, such as bulk sediment stable isotopes ($\delta^{13}C$), total organic carbon (TOC) and organic carbon to total nitrogen (C/N) is one such method. The utility of $\delta^{13}C$ and C/N as an indicator of sea level and environmental change has been previously explored at Welwick Marsh, within the Humber Estuary (Lamb *et al*., 2007). $\delta^{13}C$ and C/N are considered as proxies of change resulting from differing sources of organic matter, which are driven by changes in the relative sea level, and river catchment disturbance and discharge (Lamb *et al*., 2007). The proxies produced a continuous and detailed record of Holocene environmental change from Welwick Marsh that was in good agreement with a microfossil proxy (Lamb *et al*., 2007). However, the issue of poor modern analogues within the Humber Estuary was noted, as the artificial introduction of C_4 plants limited and complicated the use of C/N; as such, the use of $\delta^{13}C$ and C/N was considered as a complementary technique to the use of microfossils (Lamb *et al*., 2007).

More recently, the use of $\delta^{13}C$, C/N and TOC of sediment organic matter has been assessed in the absence of a microfossil record within the macrotidal Thames Estuary (Khan *et al.*, 2015b). This study identified good agreement between the modern analogues and Holocene estimates, and was further supported by microfossil interpretations, enabling the production of several new sea-level index points (Khan *et al.*, 2015b). The lack of modern environments to provide analogues within the Thames estuary was overcome with the inclusion of modern sites from Norfolk, outside of the estuary, as well as a compilation of data from other UK sites (Khan *et al.*, 2015b). It was demonstrated and concluded that the geochemistry can provide additional confidence in the interpretation of a sedimentary record, and is an effective method when microfossils are absent or not preserved (Khan *et al.*, 2015b).

The successful application of $\delta^{13}C$, C/N and TOC to reconstruct the environment of a similar estuarine setting suggests that it is an approach that should be considered and developed for use in future studies of the Humber Estuary. In particular, the development of a UK database of modern analogues may overcome the problems encountered in the previous study by Lamb *et al.* (2007). As well as this, the incorporation of $\delta^{13}C$ in a multi-proxy bayesian transfer function with foraminifera resulted in a reduction of the vertical uncertainty by 28-70% (Cahill *et al.*, 2016), demonstrating the significant advantage that geochemical analysis can provide in combination with the litho- and biostratigraphy. As these geochemical and statistical methods are developed, in future studies they may be successfully utilised to provide additional and improved constraints of relative sea-level change in the Humber Estuary.

10.1.7. Summary and Recommendations

Palaeo sea-level techniques are valid within modern estuarine environments such as the Humber Estuary. Sea-level index points have been successfully produced from multiple cores and sites, and transfer functions have been developed and applied with some success to provide a partial record for the late Holocene. However, there have been significant challenges in the application of these methods. The most significant of these challenges was identifying suitable sedimentary records that preserved an undisturbed record of the late Holocene, and contained preserved microfossils to enable quantified estimates of palaeo sea-level change. Future work within the Humber Estuary, as well as for other large, modified estuaries, will therefore require extensive stratigraphic surveys to identify late Holocene sequences to allow use of these methods, as well as the use of multiple microfossil proxies to achieve as complete and well constrained record as possible. Continuing efforts within the palaeo sea level community to address vertical uncertainties, such as tidal changes and sediment compaction, are improving constraints, and as demonstrated can have a significant effect on the sea-level estimates within an estuarine environment. The development of additional geochemistry techniques is a positive progression, and should be considered and applied in future studies in the Humber Estuary to complement and enhance biostratigraphic records.

10.2. Late Holocene Relative Sea-Level History of the Humber Estuary

This research has successfully reconstructed and elucidated the late Holocene relative sea-level history of the Humber Estuary. The relative sea-level history was constrained from locations within the inner and the outer portions of the estuary, allowing the comparison of the records from the two localities in the estuary, and consideration of the estuary as a whole. The results and reconstructions of the palaeo relative sea level from the individual sites are presented and discussed extensively in Chapters 7 and 8.

10.2.1. Outer Estuary

Litho- and biostratigraphical interpretations from East Halton have provided a new record of deposition and relative sea-level change for the outer portion of the Humber Estuary (Chapter 7). This site has provided two new sea-level index points that constrain sea level for the outer estuary in a previously data void c. 2000 year period. Crucially, one of the sea-level index points produced is now the youngest basal sea-level index point for the whole estuary, and provides an estimate with reduced vertical uncertainty since it has not undergone compaction.

The two new sea-level index points for the outer estuary constrain relative sea level change between c. 3400-3200 cal years BP. The sea-level index points and litho- and biostratigraphy are consistent with the existing data, with an expansion of estuarine conditions and relative sea-level rise in the outer estuary. The dated basal unit was deposited at a rate of 3.78mm a^{-1}, and the sea-level index points indicate a relative rise of 0.62m occurring c. 3395-3227 cal years BP, followed by the subsequent deposition of estuarine silt-clays. These two new sea-level index points and stratigraphic transition coincide with a phase of expanding marine conditions previously identified throughout the estuary, occurring from c. 3300 cal years BP (Kirby, 1999; Lamb *et al.*, 2007; Long *et al.*, 1998; section 4.4), and provide additional evidence and constraints for this period not previously provided by sea-level index points for the outer estuary.

10.2.2. Inner Estuary

The litho- and biostratigraphical interpretations from Brough have provided a new relative sea-level record for the inner portion of the Humber Estuary (Chapter 8). This site has provided a suite of six new sea-level index points that constrain relative sea level between c. 4022-1470 cal years BP. The data points provide estimates for a previously c. 1000 year data void period for the inner estuary, 2766-1774 cal years BP, and crucially provide the two youngest sea-level index points for the inner estuary, that are also now the second and third youngest for the whole estuary (Figure 8.10).

The stratigraphy of the site indicates an initial freshwater environment, with the overlying sediment units and microfossil assemblages indicating a response to both relative sea-level rise, as well as significant changes in the sedimentary and deposition processes through the mid and late Holocene. The litho- and biostratigraphy, sea-level index points and transfer function estimates indicate the complex interplay of late Holocene relative sea-level change, sedimentary processes and coastal evolution at the site, although the sea-level index points produced are consistent with the existing data (Figure 8.10). Indeed, this site offers an insight into the processes and mechanisms of coastal wetlands, and their response to changes to sediment loads and deposition, as well as relative sea-level rise and the significance of compaction and accommodation space (section 10.2.3).

The index points produced are again consistent with the expansion and contraction of estuarine conditions identified by other studies in the latter part of the Holocene (Kirby, 1999; Lamb *et al.*, 2007; Long *et al.*, 1998; section 4.4). The sea-level index point at 2745 cal years BP has a positive tendency, indicating expanding estuarine conditions up to the time of contraction previously identified from c. 2700 cal years BP. Similarly, the positive relative sea-level tendency indicated by the youngest sea-level index point produced, at 1470 cal years BP, is generally consistent in timing with archaeological evidence of abandoned and buried Roman settlements and infrastructure around the estuary (Metcalfe *et al.*, 2000; Neumann, 1998; Stitch, 1990).

All of the sea-level index points from the Brough cores are intercalated, and as such are likely to have undergone post-depositional compaction (sections 2.3.4; 2.3.5), potentially reducing the accuracy of the index points. However, quantified corrections were calculated and applied to each individual point to improve the accuracy of the constraints, and as such are considered to be as accurate as possible given the methodology used. The application of geotechnical corrections, as the method is developed, will improve such constraints in the future (section 10.1.4). However, despite the intercalated nature of these sea-level index points, there is confidence in their vertical accuracy as they demonstrate consistency with the trends of existing intercalated and limiting sea-level index points from the inner estuary. Crucially however, the oldest sea-level index point produced is in good agreement with existing basal sea-level index points which will not have been subjected to compaction (Figure 8.10; section 8.8.3), demonstrating that intercalated sea-level index points are a valid and acceptable method for the Humber Estuary, particularly in the absence of suitable basal sites.

10.2.3. Humber Estuary

The eight new sea-level index points produced provide a significant contribution to the Holocene relative sea-level history of the Humber Estuary (Figure 10.1). The sea-level index points offer additional constraints from c. 4000-1500 cal years BP. Crucially, the new index-points provide constraints for previously data void periods, providing more comprehensive records for both the inner and outer portions of the estuary during the late Holocene.

Intertidal environments expanded during the latter half of the Holocene, from c. 5000-3000 cal years BP (section 4.4; Figures 4.6; 4.9; Metcalfe *et al.*, 2000), and the index points produced are consistent with this expansion. In particular, the sea-level index points produced from the outer estuary are consistent with an expansion of marine conditions c. 3300 cal years BP that has been identified in other studies in the estuary (sections 7.7.4; 10.2.1; Lamb *et al.*, 2007; Long *et al.*, 1998). The stratigraphy and changing environmental conditions from the study site in the inner estuary are also consistent with expanding marine conditions in the latter Holocene. The sea-level index points produced from the inner estuary indicate a contraction in the marine influence occurring c. 2700 cal years BP, as previously identified in other studies (Kirby, 1999; Lamb *et al.*, 2007; Long *et al.*, 1998).

The new sea-level index points are consistent with the trends indicated by the existing suite of sea-level index points (basal, intercalated and limiting), and the overall rising relative sea-level trend in the Humber Estuary during the Holocene. As such, the sea-level index points are generally consistent with a rate of rise of c. 1mm a^{-1} during the last 4000 cal years (Horton & Shennan, 2009; Long *et al.*, 1998). Indeed, due to the lack of additional sea-level index points during the last 1000 cal years BP, this rate cannot be constrained further.

Both sites studied within the estuary show stratigraphic sequences common within areas experiencing Holocene relative sea-level rise, though such stratigraphic sequences can be complicated to interpret during the latter Holocene stages due to the interplay of dominant driving mechanisms, as exemplified particularly by the Brough site (e.g. Baeteman, 2008; Baeteman *et al.*, 2011; Long *et al.*, 1998; 2000; 2006; Metcalfe *et al.* 2000; section 10.2.2; Chapter 8). Indeed, for macrotidal estuaries in the southern UK coast, and in other North Sea coastal regions, the process of wetland collapse and resultant sediment compaction have been suggested as the mechanisms of coastal inundation and change rather than significant vertical changes in the relative sea level (Baeteman, 2008; Baeteman *et al.*, 2011; Long *et al.*, 2000; 2006). As relative sea-level rise within the Humber Estuary had slowed to c. 1mm a^{-1} from c. 4000 years BP, then these mechanisms will have been significant in driving the deposition and evolution of the estuary landscape that is recorded. The beginning of lower rates of relative sea-level rise was also subsequently followed by a proposed increase in sediment loads and deposition within the estuary during the late Holocene (sections 4.5 10.1.1).

As coastal wetlands surrounding the estuary became inundated by the relative sea-level rise in the mid to late Holocene, the deposition of sediments and collapse and compaction of underlying peats or sediment units would result in the creation of accommodation space for estuarine sediments, without there necessarily being significant changes in relative sea level (Baeteman, 2008; Baeteman *et al.*, 2011; Long *et al.*, 2000; 2006). With continued high levels of sediment supply, such as those experienced during the late Holocene, the accommodation space created could be rapidly filled, and accretion could have occurred to high water level resulting in the development of saltmarsh environments, and thus intercalated organic units such as those found at Brough, without there necessarily being a fall or change in the rate of sea-level change (Baeteman *et al.*, 2008; 2011; Long *et al.*, 2000). However, the low rate of sea-level rise would limit the rise in the water table, and thus hinder the accumulation of organic environments (Long *et al.*, 2000), and the ongoing process of compaction, accommodation space and sediment supply would allow the deposition of minerogenic estuarine sediments again. These processes are represented in the stratigraphic variation seen at Brough, and are likely responsible for the deposition of thick estuarine silt-clay units encountered at both the sites studied and throughout the estuary during the late Holocene, a period when the rate of relative sea-level rise was minimal. Indeed, such processes are key mechanisms for coastal changes during the late Holocene, having significant impacts on coastal environments and estuaries (e.g. Baeteman, 2008; Baetman *et al.*, 2011; Long *et al.*, 2000; 2006), including the Humber Estuary. Relative sea-level change in the Humber Estuary was relatively stable during the late Holocene period, with a slow rate of rise, however significant changes to the landscape occurred and are recorded within the stratigraphy, and these ultimately represent the interplay of both sedimentary processes and relative sea level.

10.2.4. Summary

The late Holocene relative sea-level history of the Humber Estuary has been reconstructed between c. 4000-1500 cal years BP through the production of eight new sea-level index points. These reconstructions have been produced from multiple cores at two sites, representing both the inner and outer portions of the Humber Estuary. The litho- and biostratigraphical interpretations, particularly from the site within the inner estuary, provide an insight into the relationship between late Holocene relative sea level and mechanisms of coastal change, including the significant influence of sedimentary process and compaction. The reconstructions and interpretations indicate, and are consistent with, an overall stable relative sea level and slow rate of rise through the latter half of the Holocene, consistent with previous studies and existing data. The new sea-level index points produced provide vital constraints for both the inner and outer estuary, and particularly for periods for which there was previously no record. However, no data was produced for the most recent millennia, and this is still a very poorly constrained period for the Humber Estuary, and will require further work in the future.

10.3. Groundwater and Sea-Level Change

The interactions between sea-level change, groundwater and anthropogenic abstraction of groundwater adjacent to the Humber Estuary have been explored and quantified in relation to a groundwater abstraction site, Springhead. The existing literature on groundwater was reviewed and any shortcomings in the research identified. An existing model of the East Yorkshire Chalk (EYC) aquifer was used in an attempt to evaluate how both sea-level change and abstraction of the groundwater alter the groundwater system, in terms of groundwater head and flow through the aquifer, and the potential of saline intrusion and the future use of the groundwater as a potable water resource.

10.3.1. Humber Estuary, Groundwater and Saline Intrusion: Current Understanding

The development of a conceptual model within this thesis, and the existing models developed in the production EYC numerical model (ESI 2013a; 2013b; 2015), revealed the significant absence of understanding of the region within the hydrogeology and academic community, as well as an absence of data for the many components of the groundwater system, including the detailed geology and pathways of flow into the aquifer, sources and ages of the groundwater, and the extent and presence of previous saline waters and intrusions (section 9.1). There is therefore a need for significant and multi-disciplinary research in the immediate future to improve knowledge and understanding of the groundwater system in the East Yorkshire and Humber region. The lack of understanding prevented the accurate determination of the implications of sea-level change and abstraction on the groundwater system, and the potential for saline intrusion. As a result, many assumptions have been made in assessing the impacts of abstraction, sea-level change and saline intrusion, and this limited the ability to model the system. Two of the key gaps demonstrated in the current understanding of the system are the extent and sources of existing bodies of saline water within the Chalk aquifer, as well as the hydraulic connection and pathways for saline water from the estuary to enter the aquifer.

The bedrock and superficial geology, as well as the hydraulic connection and pathways of flow between the Chalk aquifer and the estuary, are not fully understood or constrained (section 9.1.3). To overcome the challenge of accurately understanding the pathways into the aquifer, extensive stratigraphical surveys and mapping are required. Improvements in high-resolution maps of geology are becoming increasingly accessible (e.g. British Geological Survey 3D models). As constraints and mapping of the geology improve in the future, the hydraulic connection and pathways of flow, and thus saline intrusions into the aquifer, may be more accurately determined. Currently however, the historic presence of springs surrounding the estuary, such as Hessle Whelps (section 9.1.1), and the trend of increasing salinity at Springhead (section 9.1.2), are assumed to indicate relatively recent, and ongoing, hydraulic connections and pathways of flow between the estuary and aquifer.

In terms of previous pathways and saline intrusions, there is evidence of multiple saline intrusions during the Quaternary period, with potentially three different bodies of saline water identified within the aquifer (section 9.1.1). However, there is a lack of consensus over these saline waters within the aquifer, including a lack of clarity and constraint over the extent (spatially and vertically within the aquifer), age, and sources of the saline waters; this is exacerbated by the absence of continuous monitoring of the groundwater, preventing an accurate determination of saline intrusions past and present (ARUP, 2016; section 9.1.1). To, therefore, improve the understanding and actively constrain saline waters that may enter, or that are already present within the aquifer, substantial research is required. The research required includes the isotopic dating of the groundwater to accurately determine the sources and extent of existing saline water and previous saline intrusions, as well as the establishment of a monitoring network to consistently and continually assess the salinity of groundwater and the extent of saline waters, particularly around the Hull area. Such information would improve constraints of the current groundwater conditions with respect to existing saline water extent, as well as trends of salinity within the groundwater. This information would enable improved modelling and estimates regarding the changes to groundwater, and potential saline intrusions, caused by both sea-level change and groundwater abstraction.

However, the synthesis and quantified assessment of changes to the groundwater head and flows through the Chalk aquifer, and the potential extent of saline intrusion into the aquifer, established through the use of the existing EYC numerical model, has been beneficial. It has provided a useful initial insight into the relationship between, and impacts of, both sea-level change and abstraction on the groundwater system, and demonstrated the potential of future saline intrusions. Crucially however, it demonstrated that there is a need for extensive multi-disciplinary research in the future, to further improve these constraints, and to provide a sound scientific basis to inform management plans and policies that will ensure the sustainable supply of potable water from the Chalk aquifer.

10.3.2. Groundwater and Sea-Level Change through Time

Changes to the groundwater in the study area, between the northern bank of the Humber Estuary and Springhead abstraction site, have been assessed with respect to changing sea level and abstraction regimes. This has been done for five different time periods, with a total of nine scenarios assessed (sections 5.8.3; 9.2.1). The assessments were made based on the results of the scenarios undertaken on the EYC numerical model (section 5.8.2).

In the palaeo scenarios (3000, 2000, and 1000 years BP), the extent and marine influence of the estuary will have been geographically and spatially different to the present conditions (sections 4.4; 5.8.4). As the model is parameterised using present conditions, the boundary parameters and position of the estuary, and thus the model boundary, for these palaeo scenarios are not wholly accurate. This is an issue that has been encountered in other studies of coastal aquifers and groundwater that also used the contemporary boundary conditions, but highlighted the importance of trying to use the palaeo boundary conditions to better represent the system (Delsman *et al.*, 2014). However, the importance of having constraints of palaeo conditions to better define the numerical model emphasises the issues relating to the current absence of data and gaps in understanding of the groundwater system, discussed in section 10.3.1. As well as this, the position of the EYC model boundary, on the northern banks of the estuary, excludes any potential pathways and hydraulic connections between the aquifer and the estuary within the main body of the estuary for all the scenarios (section 5.8.4). Despite this however, the scenarios do provide an insight into how sea-level change over the last 3000 years has influenced the groundwater head and flows in the aquifer, and demonstrates how rising sea level and anthropogenic groundwater abstraction may impact the groundwater in the immediate future.

In all the naturalised scenarios, with no anthropogenic abstraction of the groundwater, the rises in sea level resulted in an increase in the groundwater head through the Chalk aquifer (section 9.2.2). This has also been demonstrated in studies of other coastal aquifers (e.g. New Zealand (Tutulić *et al.*, 2016), USA (Hoover *et al.*, In Press)). The increase in groundwater head however is not of the same magnitude as the increase in the sea level, although the increase of groundwater head at the estuary boundary is larger than that experienced further inland at the Springhead source (0.97m and 0.41m respectively over the 1.93m sea-level rise from 3000 years BP to AD 2100; section 9.2.2). The rise in sea level also resulted in a reduction in the groundwater flows through the aquifer to the estuary (section 9.2.2). These trends are as expected, as the rise in the sea level at the estuary boundary would result in a reduction in the hydraulic gradient through the aquifer, and thus a reduction in the groundwater flow (sections 9.2.3). As a result of the increase in the groundwater head due to sea-level rise, the volume and height of saline water within the aquifer increases, confirming the assumption of sea-level rise causing an increase of saline intrusion in coastal aquifers (Wassef & Schüttrump, 2016;

section 3.3). Indeed, in a conceptual study of sea-level rise and saline intrusion, it has been demonstrated that the faster the rate of the rise, the greater the extent of saline intrusion (Vafaie & Mehdizadeh, 2015).

In terms of applying these findings to address the issues relating to existing bodies of saline water identified in the Chalk aquifer, mid Holocene marine waters have been identified from isotopic analysis in other coastal aquifers, such as those in Australia (Lee *et al.*, 2016). As the palaeo reconstructions of sea level in the Humber Estuary are consistent with a period of expanding marine influence c. 3000 years BP (sections 4.4; 10.2.3), this expansion may be the source of the saline waters of Holocene age previously identified in the Chalk aquifer (section 9.1.1). Consideration and development of a palaeo model of the saline intrusion, such as that done for coastal regions in the Netherlands for the Holocene period (Delsman *et al.*, 2014), should therefore be pursued, along with dating of the groundwater and contemporary monitoring (section 10.3.1), to enable a thorough understanding and constraints of the previous and contemporary saline intrusions within the aquifer.

Anthropogenic abstraction of groundwater has had, and will continue to have, a significant impact on the groundwater, and is likely to result in increased saline intrusion and the salinisation of abstracted groundwater at Springhead (sections 4.7; 9.1.1; 9.2). This is not dissimilar to the situation in other coastal aquifers that are exploited by groundwater abstraction e.g. Egypt (Wassef & Schüttrump, 2016), Libya (Gejam *et al.*, 2016), Italy (Maschiopinto & Liso, 2016), Cyprus (Egrill, 2000; Koussis *et al.*, 2010; Ragab *et al.*, 2010; Rapti-Caputo, 2010), Greece (Kallioas *et al.*, 2006) and USA (Anderson & Al-Thani, 2016). The volume of changes to the groundwater based on abstraction alone were of greater amplitude than those induced by changing sea level (section 9.2.2), and were demonstrated to have potentially resulted in an increased saline intrusion and salinisation of the Springhead source when compared to no abstraction, with the effects further exacerbated by future sea-level rise (sections 9.2.3; 9.2.4). Indeed, the trend of increasing salinity measured at the Springhead source suggests this is already occurring (section 9.1.2 Figure 9.1). This salinisation is consistent with studies of other coastal aquifers (e.g. USA and Egypt), which identified sea-level change and groundwater abstraction as significant factors in altering the salinity of groundwater, though the significance of abstraction in altering salinity is greater (Anderson & Al-Thani, 2016; Wassef & Schüttrump, 2016). The importance of both variables however cannot be overlooked, and highlight the importance and need for resource management with respect to maintaining the quality and sustainable use of the groundwater resource in the face of changing climate and sea level, as well as population demands in the future.

10.3.3. The Groundwater Resource: A Sustainable Future?

Abstraction has significantly altered the groundwater head and flows in the study area, more so than rising sea level, and poses significant challenges to maintaining the quality of the groundwater in terms of salinity, and thus the sustainable use of the resource (sections 4.7; 9.1.1; 9.1.2; 9.2). Indeed, crucial to Yorkshire Water's Water Management Plan (Yorkshire Water, 2014), that considers the demand forecast of water over the next 25 years (to AD 2040) for the region, is the need to balance supply and demand. The Yorkshire Water Management Plan forecasts that there will be a reduction in supply availability of 136.03Ml d^{-1} for the Yorkshire region as a result of climate changes by AD 2040, as well as additional losses due to the Water Framework Directive Compliance (Yorkshire Water, 2014). With regards to the projected impact of sea-level rise and abstraction from the aquifer adjacent to the Humber Estuary, at Springhead, this supply availability by AD 2100 is likely to be further reduced due to the impacts of saline intrusion and salinisation of the groundwater (sections 9.2.4; 10.3.2).

The impact of continued sea-level rise and groundwater abstraction from the Springhead site will exacerbate the potential saline intrusion, and degrade the quality of the groundwater by contributing to an ongoing salinisation of the resource evident from the increasing chloride levels measured at the Springhead source (section 9.1.2; Figure 9.1). This may also result in an increased salinisation of the other groundwater abstraction sites around the Hull area that are located further inland from the Humber Estuary. Indeed, under the Water Framework Directive (2000-2015), the East Yorkshire Chalk aquifer groundwater chemistry was classed as poor status (Environment Agency, 2009c; ESI, 2013a), and increasing salinity would result in a further deterioration of this status.

Based on the measured trends from the 1950's of increasing chloride at the Springhead source (section 9.1.2; Figure 9.1), and assuming a continuation of the apparent linear trend, the salinity of the groundwater at Springhead will not exceed the chloride limit of potable water (250mg L^{-1}; Yorkshire Water, 2015) by AD 2100, however it may potentially double to c. 100mg L^{-1}. Should the chloride increase exponentially however, due to the projected saline intrusion, the chloride content may increase to c. 160mg L^{-1} by AD 2100. With the projected acceleration of sea-level rise into the future, and the impacts this may have in terms of increasing saline intrusion (Vafaie & Mehdizadeh, 2015), the increase in the chloride levels at Springhead may be higher than this.

Although the chloride levels at Springhead are not projected to breach the drinking water standard of 250mg L^{-1} by AD 2100, it may result in a decrease in the quality perceived by the customer, as well as affect the treatment processes of the water within the wider water supply network, and thus require reassessment or modification as a result of increased chloride content. A study of a coastal aquifer in Egypt demonstrated that both abstraction and sea-level rise will cause an increase in the salinity of the groundwater, as well as an increase in the spatial extent of salinity within the aquifer (Wassef & Schüttrump, 2016). The study in Egypt indicated the need for the reconsideration of management and agricultural practices to prevent the projected deterioration of the aquifer (Wassef & Schüttrump, 2016). As such, the management, and abstraction yields within the aquifer around the city of Hull and the Humber Estuary, may need readjusting in an attempt to reduce the rate of, and restrict, the further salinisation of the groundwater resource.

The issue of sea-level change and abstraction affecting the head, flow, and quality (in terms of salinity and potable standard) of the groundwater, however, are not just unique to the Humber Estuary and East Yorkshire Chalk aquifer. They are a global challenge that is likely to increase in the face of climate change and growing population pressures (Beebe *et al.*, 2011; Ferguson & Gleeson, 2012; Oude Essink, 2001; Yusef *et al.*, 2016; section 3.3). Though different in context to the area studied in this thesis, in terms of setting and scale of groundwater salinisation, Cyprus provides a case study and significant insight of how salinisation of an aquifer can develop and the potential repercussions of this (Egrill, 2000; Koussis *et al.*, 2010; Ragab *et al.*, 2010; Rapti-Caputo, 2010). As has been attributed to previous saline intrusions in the aquifer in Hull (section 4.7; 9.1.1), the salinisation experienced in the aquifers of Cyprus are attributed to both excessive abstraction and the close proximity of abstraction to shorelines (Egrill, 2000; Rapti-Caputo, 2010).

As result of the deterioration in the Cypriot aquifers, the remaining freshwater supplies of the aquifer will be depleted by AD 2090 (Egrill, 2000), with an increasing demand over supply resulting in a decrease of both surface and groundwater supplies of 17-35%, depending on the catchment, by AD 2050 (Ragab *et al.*, 2010). In terms of determining the most suitable and efficient management schemes of the groundwater resource in the coastal aquifers of Cyprus (e.g. technological de-salination schemes versus holistic artificial recharging (Koussis *et al.*, 2010)), it requires continuous monitoring of the salinisation processes (Rapti-Caputo, 2010), as recognised with the East Yorkshire Chalk aquifer (section 10.3.1). Indeed, the intrusion of saline waters into a coastal aquifer in northern Greece has been attributed to a lack of scientifically informed groundwater resource management (Kallioras *et al.*, 2006), reinforcing the necessity of conducting investigations and immediate monitoring to inform the long term management of the groundwater resource (section 10.3.1).

In the Gulf Coast of the USA, increased population demands and sea-level rise will result in the degradation of the quality, and an increase in the salinity, of the groundwater (Anderson & Al-Thani, 2016). It was concluded there was therefore a need to limit the use of the groundwater and the potential impact of abstraction induced salinisation (Anderson & Al-Thani, 2016). The study of the Gulf Coast also advised that further research is necessary to assess the vulnerabilities of coastal communities, in terms of the potential socioeconomic (i.e. de-salination costs) and the agricultural impacts, as a result of groundwater salinisation (Anderson & Al-Thani, 2016). Hull, the city located on the northern banks of the Humber Estuary, directly east of the Springhead source (section 4.7.1), has the third largest proportion of deprived neighbourhoods in England (Department for Communities and Local Government, 2015). Increased salinisation of the groundwater in the future may potentially exacerbate the existing socioeconomic problems due to the impacts on industry (i.e. de-salination costs), and the availability and quality (i.e. potable) of the groundwater resource in the region, demonstrating the potential broader impacts of sea-level change and the salinisation of the groundwater resource.

10.3.4. Summary

There is a significant lack of understanding regarding the current groundwater system and the processes and pathways between the Humber Estuary and the East Yorkshire Chalk aquifer. Particularly problematic is the lack of data and consensus over the spatial extent of existing saline water within the aquifer, and significant investigations in the future are required to allow for a thorough and detailed understanding of the groundwater system around Hull, and specifically at the Springhead source. Without an improved understanding of the groundwater system, an accurately quantified assessment of the changes to the groundwater caused by abstraction and sea-level change cannot be made. However, the use of a numerical model of the aquifer provides an initial insight into the relationships: both sea-level rise and abstraction result in changes to the groundwater head and flow within the aquifer, as well as altering the extent of saline intrusion, at both the estuary and Springhead source. However, consistent with other coastal aquifers, groundwater abstraction results in significantly larger changes to the groundwater than sea-level rise. Rising sea level increases the extent of saline intrusion and the deterioration of the groundwater quality, and continued abstraction will exacerbate this, though potentially not beyond suitable standards for potable water by AD 2100.

10.4. Late Holocene Relative Sea-Level Change and the Groundwater Resource: Summary

This thesis has used Holocene relative sea-level reconstructions produced from the Humber Estuary to examine the relationships between sea-level change and the groundwater environment in the past, and also considered the impacts that abstraction of groundwater and sea-level change have had, and will have, in the future. The project has encompassed multiple disciplines, linking a traditional Quaternary sea-level reconstruction project to hydrogeology, and incorporating broader issues of present and future groundwater resource use and management.

The reconstructions of relative sea-level change during the late Holocene indicate an overall rise within the Humber Estuary during the last c. 3000 years, however there are some differential tendencies and rates of change within the inner and outer portions of the estuary. The overall rise throughout the Holocene is projected to continue to rise into the future. The rise in sea level during the late Holocene resulted in changes to the groundwater within the Chalk aquifer around the estuary, resulting in an increase in the groundwater head and a reduction in flow through the aquifer at both the estuary edge and at an adjacent groundwater abstraction site, Springhead, as well as causing a vertical increase in the saline waters within the aquifer. However, the amplitude of the changes induced by sea-level rise are not as large as those caused by the relatively recent, 20th-21st Century, abstraction of groundwater from the aquifer.

Abstraction from the Springhead source has resulted in a decrease in the groundwater head at Springhead, as well as altering the flows of the groundwater through the aquifer, inducing increased flow to Springhead, and a resultant decrease in flow to the estuary. This has potentially caused additional intrusion of saline water into the aquifer, and is increasing the salinity of the groundwater. These processes are projected to continue into the future as a result of ongoing abstraction and sea-level rise, with the problem potentially becoming more acute, raising issues as to the sustainable use and management of the Springhead and groundwater resource. However, to enable a complete and accurate assessment, as well as to improve understanding of the groundwater system and current conditions, significant further research is required.

11. Conclusion and Future Research

This research was undertaken to increase our understanding of late Holocene relative sea-level change for the Humber Estuary, and to explore the impacts of sea-level change on the groundwater resource in the Humber region. To address these, three research aims were identified in Chapter 1. The conclusions for each of these are now summarised.

1. *To assess the validity of palaeo sea-level techniques in a modern estuarine environment.*

Critical to addressing this objective was to identify suitable sites that retained an undisturbed late Holocene record, allowing palaeo sea-level techniques and methods of reconstruction to be applied. Despite suitable palaeo sites being identified, they were few in number and as a result limited the volume of sea-level constraints that could be produced. Additionally, due to the anthropogenic modifications of the estuary environment, there are few remaining areas of saltmarsh within the estuary, significantly limiting the development of a contemporary training set from the estuary to produce transfer functions. The use of transfer functions overall was problematic, and generally did not provide improved or higher resolution estimates due to compromises regarding the accuracy and reliability of the transfer functions. These issues were largely due to the problem of availability of modern analogues for the fossil data sets, as well as the preservation of microfossils within sediment cores.

Overall, palaeo sea-level techniques have been applied with variable success in the modern and macrotidal estuarine environment of the Humber Estuary, with variability in the suitability of methods between different sites. To produce additional constraints from new sites in the future, significant research would be required to identify those that retain records of the late Holocene. In terms of the methods used to reconstruct the sea-level changes, this research has demonstrated that the most suitable methods and proxies that can be used are site specific, and cannot be pre-determined. Also demonstrated was the importance of applying tidal and compaction corrections to the reconstructions. As the development and use of geochemistry-based methods are becoming more widespread (e.g. Cahill *et al.*, 2015; Khan *et al.*, 2015; Lamb *et al.*, 2007), future research in the Humber Estuary should consider and incorporate these methods to overcome the challenges of microfossil preservation, and to provide additional and improved constraints of late Holocene sea-level change in the Humber Estuary.

2. *To reconstruct and elucidate the late Holocene relative sea-level history of the Humber Estuary.*

A suite of 8 new sea-level index points has been produced for the Humber Estuary; two from a site in the outer portion of the estuary, and six from the inner portion. These have provided new and significant constraints of relative sea-level change between c. 4000-1500 cal years BP. The new data are consistent with the existing suite of data and the trend of overall relative sea level during the latter half of the Holocene, however they also demonstrate some differential environmental changes in the inner and outer portions of the estuary. The reconstructions are consistent with a phase of marine expansion previously identified from c. 3300 cal years BP, and the inner estuary reconstructions are consistent with a contraction occurring from c. 2700 cal years BP onwards (Kirby, 1999; Lamb *et al.*, 2007; Long *et al.*, 1998). From c. 1500 cal years BP, there is a positive tendency within the inner estuary, consistent with archaeological evidence (Metcalfe *et al.*, 2000; Neumann, 1998; Stitch 1990). The sea-level index points are generally consistent with a rate of sea-level rise of c. 1mm a^{-1} during the last 4000 cal years (Horton & Shennan, 2009; Long *et al.*, 1998).

3. *To examine the interactions of groundwater and sea level between the Humber Estuary and an adjacent groundwater abstraction site.*

To achieve this, current understanding and data regarding the groundwater system was assessed. An existing numerical model of the Chalk aquifer was used in an attempt to quantify the impacts of both sea-level change and abstraction on the groundwater, and the potential implications of future sea-level rise on the salinisation and use of the groundwater resource. Clearly evident was the lack of knowledge and understanding regarding the current groundwater system and pathways between the Humber Estuary and the Chalk aquifer, and the need for significant, multi-disciplinary research to improve the understanding, and thus constraints of the impacts of both abstraction and sea-level change on the groundwater.

Using an existing numerical model of the aquifer however demonstrated that both sea-level rise and abstraction have altered the groundwater head and flows through the aquifer, although it is abstraction that results in significantly larger changes. Sea-level rise potentially results in an increase in the saline waters within the aquifer, and the salinisation of the Springhead abstraction site. However, abstraction is potentially causing additional intrusion, and projected future sea-level rise will likely exacerbate this process should abstraction continue at current rates (though the potable water standards at Springhead should not be breached by AD 2100). There is therefore a need to consider the management of the groundwater resource and abstraction practices to ensure the sustainable use in the future, and to limit further deterioration of the aquifer and groundwater. However, without further research and monitoring of the current groundwater, and particularly the presence of existing saline water within the aquifer, the exact sources and causes of the salinisation past, present and future cannot be accurately determined or quantified.

11.1. Summary

The Humber Estuary and the surrounding area is an interesting and complex environment. It is an area for which future research is necessary to understand the physical evolution of the estuary and groundwater system in the past, and the development and management of the region under future climate change and sea-level rise. This research has successfully reconstructed relative sea-level changes in the estuary during the late Holocene period, and demonstrated some of the challenges of reconstructing palaeo records from a macrotidal and modified estuary environment. It has provided recommendations for areas of future work. This research has also explored the relationship between sea-level change, groundwater, groundwater abstraction, and the potential of saline intrusion, with specific reference to an abstraction site currently used, presenting considerations in the context of future sea-level rise, as well as highlighting the need for significant further research to safeguard the groundwater resource in the future.

12. Abbreviations

AD	Anno Domini
AMS	Accelerator Mass Spectrometry
BP	Before Present
c.	Circa
cal years BP	Calibrated Years Before Present
CCA	Canonical Correspondence Analysis
CONISS	Constrained Incremental Sum of Squares
DCA	Detrended Correspondence Analysis
EYC	East Yorkshire Chalk
GIA	Glacio-Isostatic-Adjustment
GPS	Global Positioning System
HAT	Highest Astronomical Tide
LOI	Loss On Ignition
MAT	Modern Analogue Technique
MHWST	Mean High Water Spring Tide
Ml	Mega Litres
MTL	Mean Tidal Level
NERC	Natural Environment Research Council
OD	Ordnance Datum
OS	Ordnance Survey
r^2	Coefficient of Determination
RMSEP	Root Mean Square Error of Prediction
RSL	Relative Sea Level
RWL	Reference Water Level
SWLI	Standardised Water Level Index
WA-PLS	Weighted Averaging-Partial Least Squares

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