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Investigation into the spatial distribution of salt loads into the Upper Thurne SAC and likely timescales for response to management controls

School of Applied Sciences

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This thesis is submitted in partial weighting fulfilment of the requirements of the Degree of MSc in Water Management

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Investigation into the spatial distribution of salt loads into the Upper Thurne SAC and likely timescales for response to management controls

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ABSTRACT

The Upper Thurne Broads (shallow lakes) in the Norfolk Broads are sites of international conservation importance. The protected aquatic species of these lakes are currently threatened by poor water quality, largely due to discharges of saline water from the Brograve land drainage pump, which maintains groundwater levels on adjacent marshlands below sea level. The lowering of water table levels by drainage has caused seawater to intrude into the coastal aquifer and salinise the groundwater and drain network.

Through surveying salt concentrations and flow regimes in the drains of the coastal marshes and analysis of telemetry data from the land drainage pumps, this thesis investigates

1) the spatial distribution of the salt loading into the drain system in order to identify where management changes should be targeted and

2) assesses whether changes to the water level management in a nearby drainage area have had any impact on the salt load that is discharged from the pump.

Research has shown an uneven distribution of salt loading across the coastal marshes. These differences appear to be driven by the nature of the drain-aquifer interaction in the individual marshes and the relative gradient differential produced between the marsh drainage ditches and the main drain at times of pump activity.

The research indicates that restoration of the Upper Thurne water quality will necessitate scaling down water table level management to individual marshlands in order to ensure efficacy of measures. It also makes recommendations for further research to be carried out in the study area. There is insufficient data at the time of

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writing to suggest that raising water levels in an adjacent marshland has conclusively reduced saline discharges from the pumps since management controls were implemented. However, some lowering of salt concentrations was observed which appear to be distinct from climatic influences.

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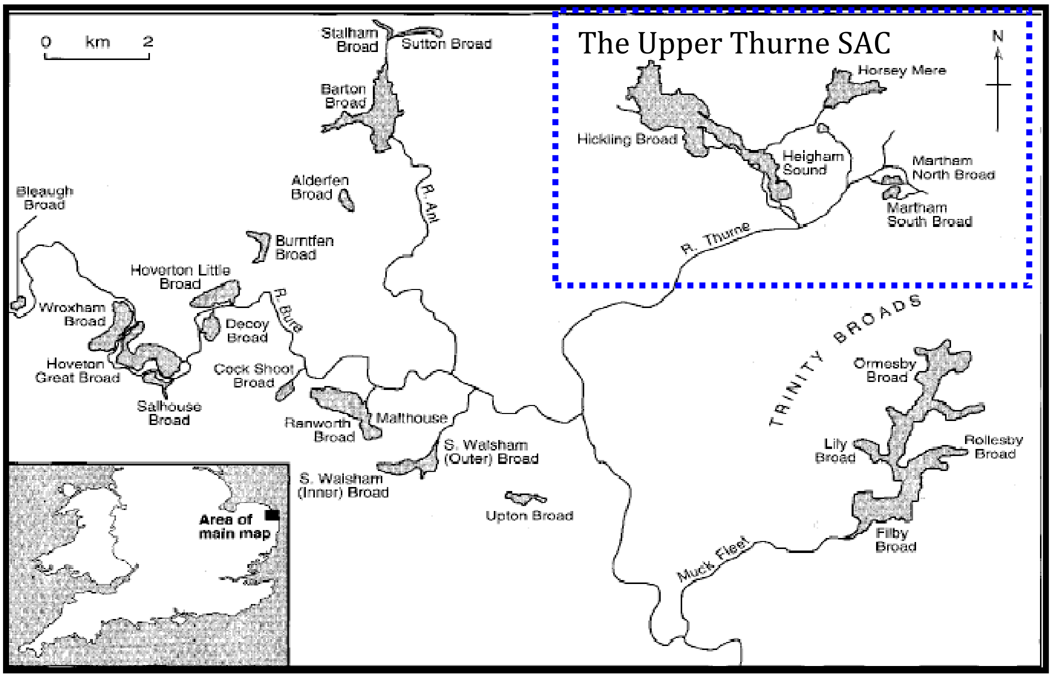
1 INTRODUCTION

The Broads National Park situated in North-East Norfolk on the East coast of England, consists of a series of wetland areas with large shallow lakes (Broads), formed from flooded peat pits dug in the 14th century (Fig.1) (Moss, 1984). Over time the lakes and wetlands have come to support complex ecosystems and habitats and as a result host a wide variety of rare and endangered plants and animals (Driscoll, 1984). They come under a number of designations (such as Site of Special Scientific Interest (SSSI)and RAMSAR) thus making them priority sites for conservation under the Habitats Directive (92/43/EEC) and Water Framework Directive (2000/60/EC) (Broads Authority, 2008; ELP, 2004)

The Broads of the Upper Thurne SAC (Special Area of Conservation) within the park are home to a number of these rare species in particular the *Chara intermedia* and *Nitellopsis obtusa* both found almost exclusively within the Norfolk Broads (Stewart, 2004)

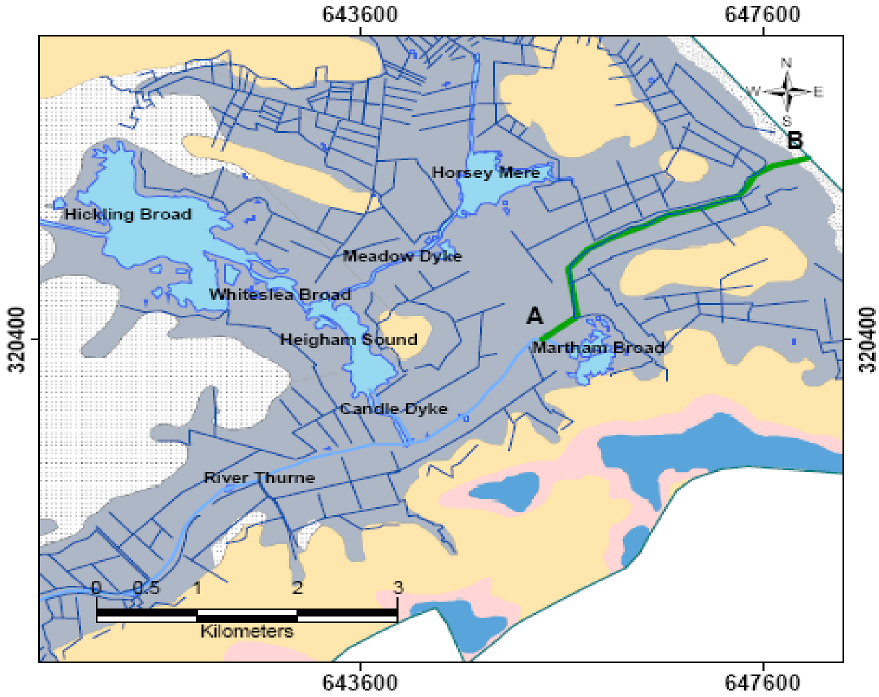
Figure 1: The Norfolk Broads (Serwan, 1999)



The system of lakes and coastal marshes that characterizes the Upper Thurne is a heavily modified one. One of the most important modifications has been the drainage of the marshlands for agricultural purposes. Drainage has lowered water table levels, caused peat degradation and land subsidence and the embankment of the surface water bodies -

hydrologically isolating them from the catchment and making them dependant on discharges from electrical drainage pumps to sustain their water levels.

Figure 2: The major surface water bodies of the Upper Thurne Catchment (Simpson, 2007)



The low water table levels established by the catchments' drainage schemes, have reversed the seaward hydraulic gradient of the groundwater and caused saline water to intrude into the coastal aquifer (ELP, 2004; Holman, 1994; Simpson, 2007). This saline water is transported via the drainage channels, where it mixes with freshwater inputs from the upper reaches of the catchment, and is discharged via pump systems into the Broads of the Upper Thurne and eventually the River Thurne.

These rapid and radical changes to the landscape, hydrology and water quality of the catchment are threatening rare freshwater aquatic species, particularly in two major surface water bodies – the Horsey Mere and the Hickling Broad which are fed by water from the Brograve drainage catchment in the North of the SAC (Broads Authority, 2008).

Saline discharges from the pumps have not only increased the chlorinity of these surface water bodies (Holman, 1994; Simpson, 2007) but has also resulted in a significant increase in the production of ochre from the acid sulphate soils (ELP, 2004). Ochre is an iron based compound which precipitates out of the peaty soil when it comes into contact with seawater (see figure 3).

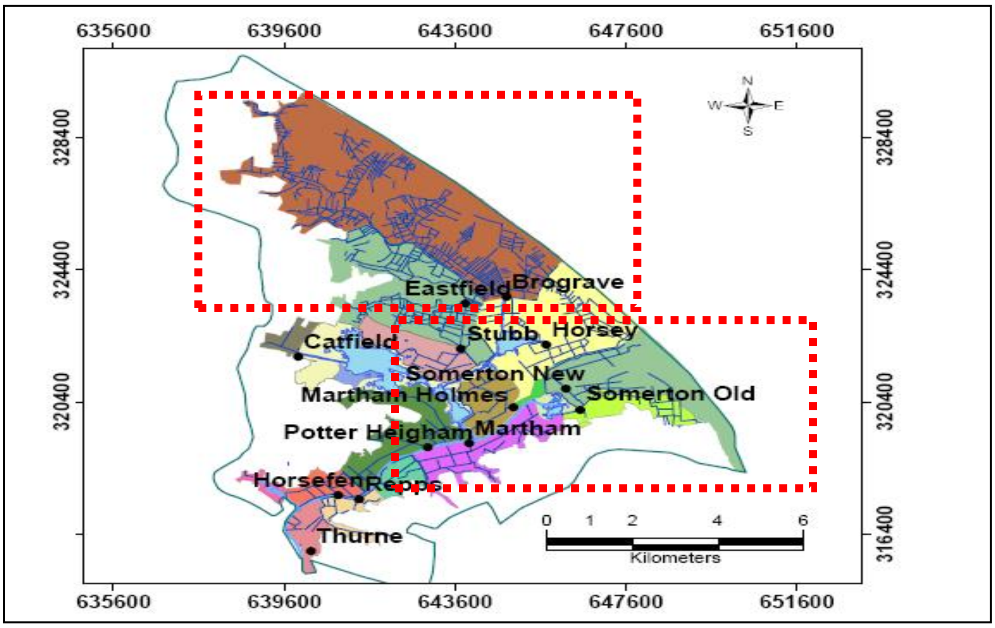
Figure 3: The red colour of the ditch water is caused by ochre deposits in the water (photo taken during field survey, July 2008)

High ochre levels suffocate benthic flora and fauna and high chlorinity levels place osmotic stress on sensitive freshwater or brackish aquatic plant communities resulting in their collapse (Driscoll, 1984; ELP, 2004).

The Environment Agency together with the Broads Authority monitor the condition of the habitats in the broads and are responsible for implementing management strategies to conserve or restore their ecological functions. The Habitats Directive (92/43/EEC) and the more recently introduced Water Framework Directive (2000/60/EC) and its daughter directive – the Groundwater Directive, are the key legislative drivers behind the current programme for restoration of the Upper Thurne. The UK Biodiversity Action Plan also includes plans to reintroduce some of the rare stonewort species that have been lost to the area (UK BAP, 2008).

The Upper Thurne Catchment (UTC) is divided into a number of drainage catchments (figure 4) distinguished by their drainage systems and discharge points. The Brograve and Somerton drainage catchments in particular have been targeted for chlorinity management as water from the Brograve Level is pumped into Horsey Mere and impacts on the water quality within the Hickling Broad and water from the Somerton Level drains in to the Martham Broad. All these water bodies have seen significant declines in water quality due to high salt and ochre levels. Hickling Broad is the largest broad in the catchment and is covered by a number of designations. It falls under the Upper Thurne Broads and marshes SSSI and has also been designated as National Nature Reserve.

Figure 4: The drainage catchments of the Upper Thurne SAC showing the Brograve and Somerton catchments



Previous research into management options for the restoration of the Upper Thurne Catchment have already included site characterisation studies (Holman, 1994); chlorinity surveys (Driscoll, 1984; Holman, 1994), an investigation the coastal aquifer properties (Holman, 1994) and research on the characteristics of groundwater flow in the catchment (Simpson, 2007). Water level management plans for the Brograve and Somerton catchments were published by the Internal Drainage Board for the area (IDB, 2001) and feasibility studies into the various management options for combating chlorinity in the Brograve catchment have been commissioned by the IDB (ELP, 2004). Details of how this research has contributed to the management of the Upper Thurne are detailed in the literature review in the following chapter.

Management options that have been looked at include:

- Raising of the water table in the Brograve catchment through ditch water level management in order to prevent saline intrusion occurring in the first place (ELP, 2004).
- Construction of an interceptor pipe to divert the saline water away from the Broads in the catchment (Simpson, 2007)

These options have been found to have differing outcomes with respect to environmental and economic impacts (Broads Authority, 2006; ELP, 2004; Simpson, 2007). For example, raising water levels in the coastal marshes may reduce the saline influx from the sea but will also result in a loss of viable arable land with economic impacts for farmers and could increase flood risk to settlements near the area - the catchment already suffers from some localised flooding (ELP, 2004). There is also an increased risk of saline intrusion in adjacent catchments and installation of additional water control infrastructure across the catchment could prove expensive (Broads Authority, 2006).

The general consensus appears to be that the raising of water levels within the drained marshes will have to form part of any solution to chlorinity issues in the area (ELP, 2004; Simpson, 2007). Therefore, the externalities associated with changes to water level management will need to be mitigated against and implementation of measures planned carefully. Mitigation against negative impacts of interventions favours a targeted approach with careful impact analysis as opposed to a blanket water level raising scheme.

Effective control of chlorinity in the drains and receiving waters requires detailed knowledge of the **magnitude, extent and distribution** of chlorinity in representative drains within the catchment; knowledge of the **changes and trends in chlorinity** over time and the ability to determine the impact of management changes

1.1 AIM AND OBJECTIVES

So far previous studies have only looked at the distribution of chlorinity concentrations within the drain system and not how this salt is transported through the catchment that is the salt load (Driscoll, 1984; Holman, 1994). The salt load from the drainage system is defined as **the mass of seawater salt transported by the drainage water**.

There is evidence to suggest that the salt load contribution from drainage sub-catchments in the Upper Thurne may not be uniform (Simpson, 2007). Salt transportation within a drainage ditch occurs as a function of the chlorinity of the water and the discharge in the ditch - this is likely to vary within the different hydrological units of the catchment.

The aim of this research project is therefore to investigate the spatial variability of chlorinity loads within the Brograve drainage catchment in order to identify where water level management changes should be targeted. Additionally this research will also look at how changes to water table management have affected salt load discharges from an adjacent drainage pump (on the Somerton drainage catchment) in order to predict the likely timescale of response to any restorative measures.

The specific objectives for this research are as follows:

1. Assess the spatial distribution of the chlorinity loads within the Brograve sub-catchment.
2. Assess the effects of raising ditch water levels in the Somerton catchment on chlorinity concentrations in drainage ditches and saline loads to the pump and the timing of any responses observed
3. Make recommendations on where management changes should be targeted in the Brograve sub-catchment

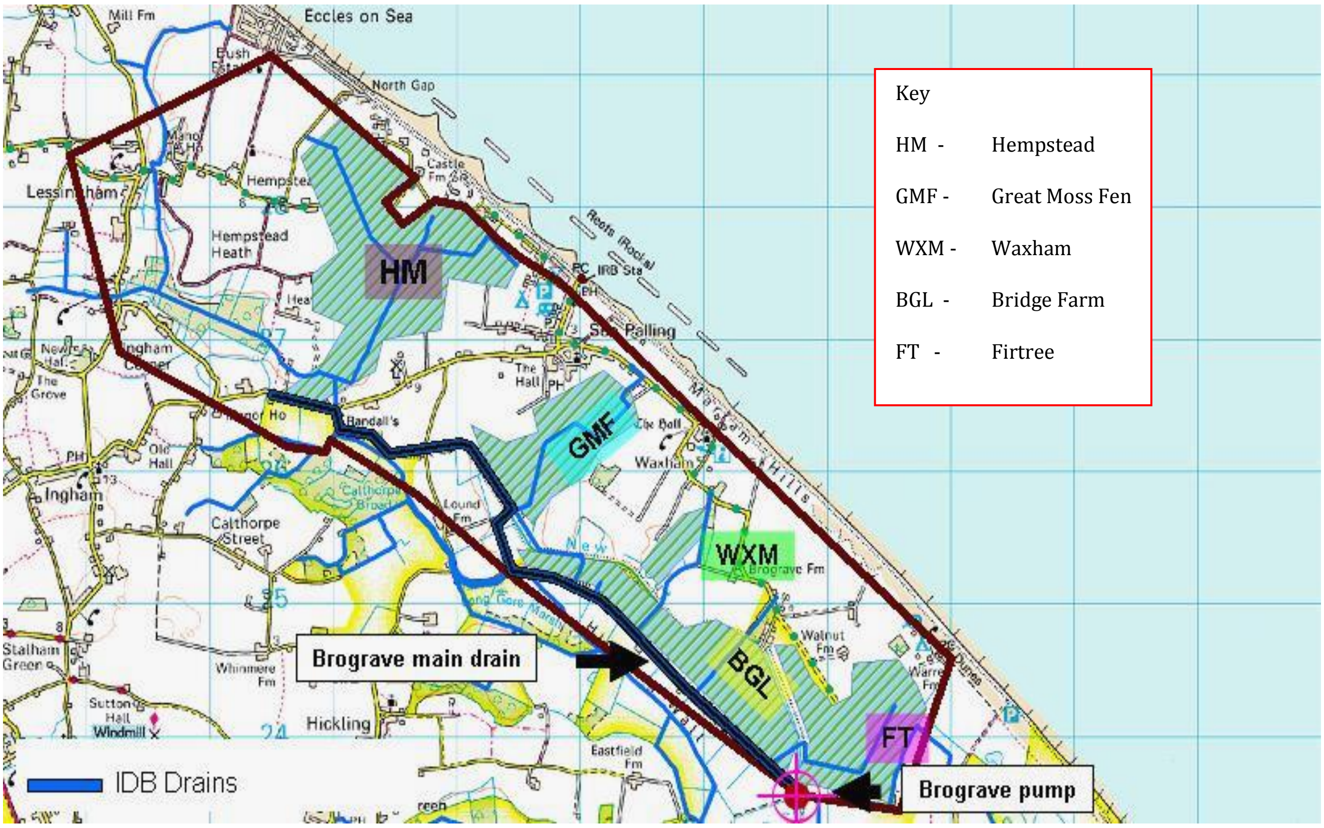
1.2 THE STUDY AREA

1.2.1 THE BROGRAVE DRAINAGE CATCHMENT

Tillage and drainage of the peat has been carried out in the Brograve catchment area for about 40 years and has caused significant environmental impacts including land subsidence and erosion (ELP, 2004). The impacts on water quality as a result of drainage of this area were first described in 2002 in a report on the 'Ochre problem' (ELP, 2004).

There are five coastal marshland units within the Brograve catchment which are considered to be the source of saline inflows (Driscoll, 1984; ELP, 2004; Holman, 1994; Simpson, 2007); these will be the focus of the salt load investigation.

Figure 5: Coastal Marshes of the Brograve drainage catchment (ELP, 2004)

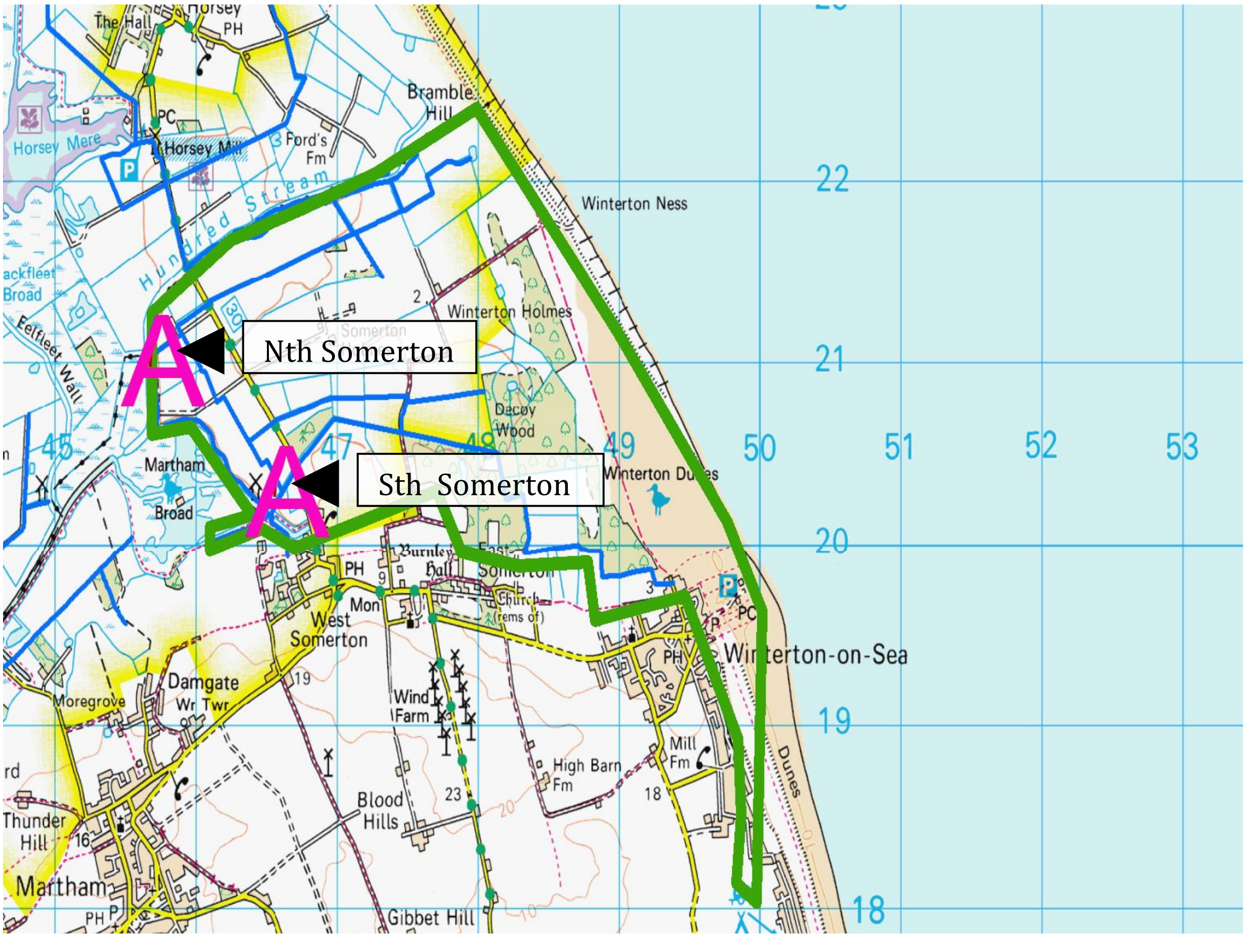


1.2.2 *SOMERTON DRAINAGE CATCHMENT*

There are two water management systems in the District; the New Somerton Pump referred to as Somerton North in this thesis and the Old Somerton Pump referred to as Somerton South. The Somerton North pump drains the northern and central part of the District and the Somerton South pump drains the Southern sections.

Drainage of the Somerton area back in the 1970s caused similar problems to those observed within the Brograve catchment, with land subsidence and saline intrusion of the coastal aquifer. Recently, the land within this area has been put under an Environmental Stewardship Scheme (ESA) which means water table levels are maintained at much higher levels than in the Brograve catchment (Broads Authority, 2006). Due to its close proximity to the Brograve catchment, similar relief and climate, the Somerton drainage catchment will be used as a proxy in this study in order to determine the likely timescale for effects of water level changes to be seen.

Figure 6: Diagram of the Somerton Drainage Catchment showing the location of the North and South Pumps



1.3 THESIS OUTLINE

The author has carried out a detailed literature review which involved compiling and synthesising existing information about the hydrological processes taking place in the study area and investigating what, if any, data gaps exist. Following the literature review, chlorinity and discharge surveys were carried out to assess the chlorinity load contributions within the coastal marshlands of the Brograve sub-catchment. Chapters 3 and 4 detail the methodology used during these surveys and the results achieved respectively. Chapter 5 and 6 includes a detailed analysis of the results and the conclusions that can be drawn from the results. The thesis ends with a set of recommendations based on the previous chapters' findings.

2 LITERATURE REVIEW

This literature review has been carried out in order to collate research carried out on the origins of chlorinity within the Upper Thurne catchment and establish a theoretical framework for the investigation into spatial distribution of chlorinity loads within the Upper Thurne Catchment.

The first section will deal with current theory behind saline intrusion and provide some background into investigations of saline intrusion in the study area. It presents the evidence of a problem with chlorinity in the surface waters of the study area, describes the impacts it has had on the ecology, the extent of saline effects in the study area and how these have changed over time.

This is followed by a section on the catchment characteristics of the study area such as topography, hydrogeology etc. and how these might influence the flow characteristics in the catchment. A short section on the approach to management of chlorinity in Upper Thurne follows, containing the current status on feasibility of management options, data gaps that need to be filled to aid chlorinity management and how this research feeds into the overall conservation aims.

2.1 THEORETICAL BACKGROUND TO RESEARCH: SALINE INTRUSION

Seawater intrusion is defined as the permanent inflow of saline groundwater into an aquifer containing freshwater (Essink, 2001). Investigations into the origin of saltwater intrusion in various areas have identified the main causes to be either (i) excessive abstraction of groundwater resources or (ii) drainage of coastal wetlands (Monety et Al, 2008).

Where aquifers occur along a coastline, a natural hydraulic gradient exists between the groundwater within the aquifer towards the sea. This results in the discharge of freshwater into the sea. When this natural hydraulic gradient is locally or regionally reversed due to abstraction or drainage of fresh groundwater, sea water intrusion can occur (Essink, 2001).

Salinisation of coastal aquifers as a result of seawater intrusion is one of the most common causes of groundwater degradation in coastal areas (Moreaux & Reynaud, 2001). Figures 7 and 8 below show the extent of seawater intrusion in Europe and the UK respectively.

Figure 7: Saltwater intrusion across Europe. Source: http://www.eea.europa.eu/themes/water/water-resources/impacts-due-to-over-abstraction

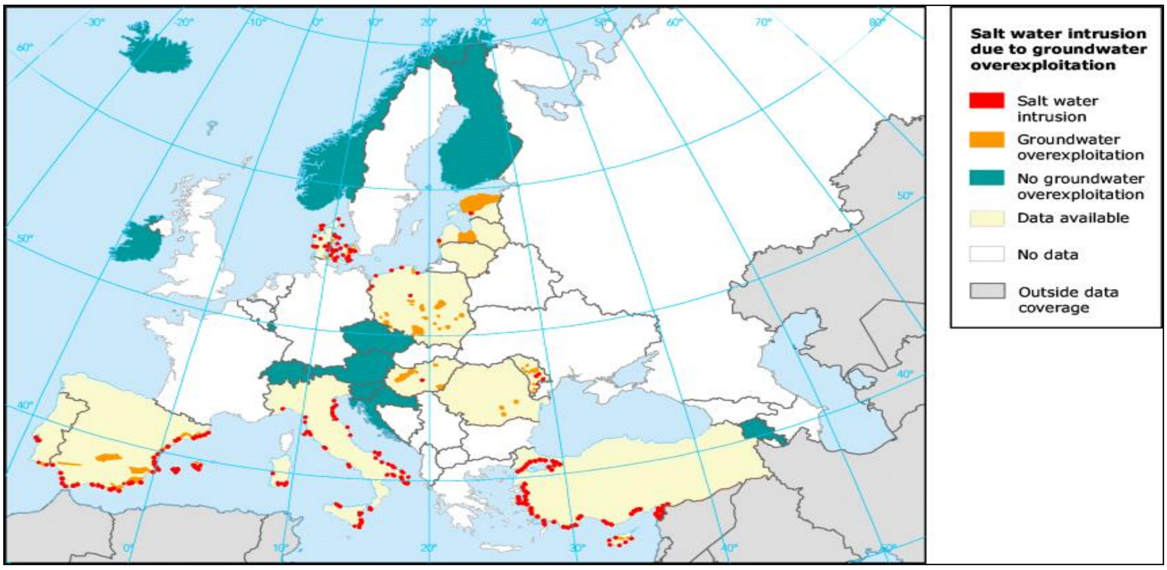
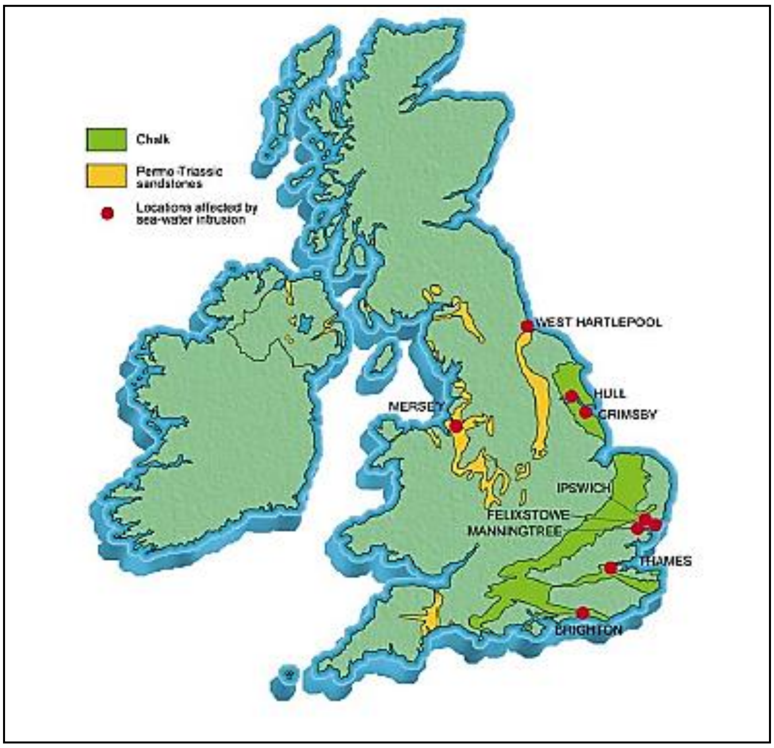


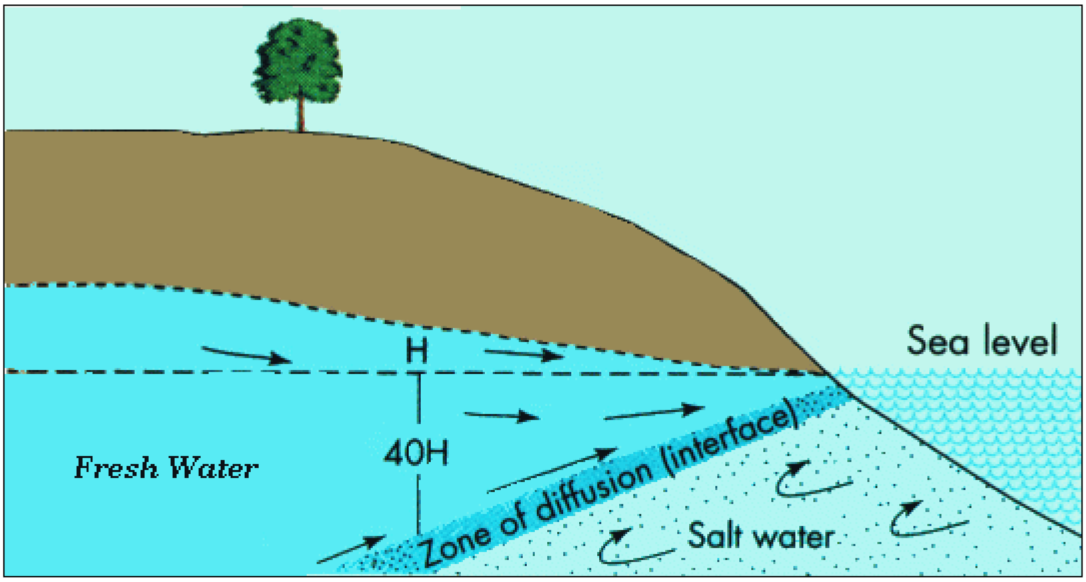
Figure 8: Locations of seawater intrusion within the UK (British Geological Survey, 2004)



Many areas along the coastlines of European countries have developed intensive agricultural schemes which have resulted in alterations to the water balance and saline intrusion into coastal aquifers (Andrew, 1984). This is particularly a problem along the Mediterranean coastlines of Italy, Spain and Turkey (EC 2008) which suffer from low rainfall levels and therefore abstract high levels of groundwater from the coastal aquifers. Saline intrusion for similar reasons also occurs in a number of locations within the UK (British Geological Survey, 2004).

Because seawater is denser than fresh it forms what is known as a 'saline wedge' below the freshwater of a coastal aquifer. The position of this saline wedge is estimated according to the Ghyber-Herzberg relationship (Fig. 9) which relates the depth of freshwater below sea level to its 'head'.

Figure 9: The Freshwater / Saltwater Interface at the discharge point of a coastal aquifer as predicted by the Ghyber-Herzberg relationship. Source: www.lenntech.com/groundwater/origin.htm



According to this relationship, salt water occurs at a depth approximately 40 times the height of freshwater above sea level. This equation does not however, take into account the nature of the aquifer concerned, but provides a useful estimation of the location of the sea water belt found under the freshwater (Cameo & All, 2006)

The interface between the freshwater and saltwater is known as the zone of diffusion and is in a state of dynamic equilibrium. The position of the zone of diffusion varies according to seasonal changes in the water table level and tidal fluctuations (Kim-Young & Al, 2006). The width of the zone of diffusion is also dependant on factors such as the horizontal permeability of the aquifer and its hydraulic conductivity (Cameo & All, 2006). All these parameters combined influence the amount of salt that enters the aquifer.

Saline water from a coastal aquifer flows upwards along the zone of diffusion until it reaches its discharge point. This creates the convection cell through which sea water enters the aquifer at depth and exits near the aquifer surface. As more freshwater is displaced by drainage or abstraction the interface between fresh and saline waters moves further landward and upward (Cameo & All, 2006; Moreaux & Reynaud, 2001).

The movement of saline water into the freshwater aquifer within the Upper Thurne SAC can be dated back to at least the beginning of the twentieth century when unusually high salt levels in the Thurne River system were observed. The source of the chlorinity at this time was thought to be due to “salt springs" within Hickling Broad and Horsey Mere (Holman, 1994). In 1911, Marietta Pallis published a paper on the origin of saline water on the Broads in which she correctly hypothesised that the source of the chlorinity was in fact an underground connection between the waters of the Upper Thurne and the North Sea (Holman, 1994).

Under natural conditions these waterbodies would be only slightly brackish with a low amount of saline influence arising from tidal ebbing of estuary waters in the lower section of the catchment. The ‘higher than expected’ brackish conditions observed in the higher reaches of the catchment indicated that some amount of saline intrusion had occurred as early as the 1900s.

At this time the catchment was mainly grazing marshes for cattle and sheep. Chlorinity levels in the main water bodies were low and water quality was generally quite high (Driscoll 1984). However, drainage of the land following the Enclosure Acts of 1800 had already caused sinkage and embankment of drained lands (Moss 1983) and it is likely that seawater had already begun to intrude into the aquifer.

In the 1960s, drainage improvement schemes were carried out across the catchment in order to convert the land from grazing marshes to arable agriculture. For arable production, extensive drainage of the marshlands was necessary due to the nature of the soils found there and their tendency to become water-logged. Drainage ditches were re-profiled to convey larger amounts of water from the catchment and pumping capacities were enhanced through the installation of electrical drainage pumps to maintain low ditch water levels.

In the Brograve Level drainage catchment this occurred in the 1950s. In Somerton this was carried out between 1979 and 1981 (Driscoll, 1984; IDB, 2001).The effects of this land drainage in the Upper Thurne included peat shrinkage and land subsidence resulting in ditches below sea level. Drainage of peatlands reduces the buoyancy of soil water causing a compression of peat and increase in bulk density. This leads to aerobic conditions, decomposition of organic matter, reduction of water storage and decreases infiltration and the drainage capability of the soil (Holden 2004).

The deepening of the profiles of the ditches to enhance drainage in the catchments placed them in direct contact with the salinised aquifer, introducing saline groundwater into the drainage system (Holman 1994).

Table 1: There has been a significant increase in chlorinity levels in the Broads of the Upper Thurne since the end of the 19th century (ELP, 2004).

Name of Upper Thurne Broad	Chloride levels from 1900 (mg/L)	Current Chloride levels (mg/L)
Hickling	~600	~1800 – 2000
Horsey	~1000	~2900
Martham	~1000	~1500

2.2 IMPACTS OF ELEVATED CHLORINITY LEVELS ON THE UPPER THURNE BROADS ECOSYSTEM

In 1965, following drainage improvement in the Brograve drainage catchment, a study on biodiversity in the lakes was commissioned by ‘Nature Conservancy’, a non-profit conservation organisation. This study highlighted a severe decline in the water plants and fish in the lakes, increase in algal communities and the erosion of the river and lake margins although initially the finger was pointed at nutrient runoff from agricultural land and subsequent eutrophication of the lakes (Madgwick, 1999). A survey carried out in 1975 on the land use, drainage and aquatic flora and fauna within the Upper Thurne, concluded that chlorinity was in fact the main determinant of diversity and species composition in the area and elevated chlorinity levels had caused the observed decline in water plants (Driscoll, 1984).

Driscoll’s report on chlorinity distribution was one of the first studies to connect the improved drainage of the coastal marshlands to increased chlorinity in surface waters within the catchment and additionally implicate this elevated chlorinity in the decline of aquatic floral communities in the Broads. He showed that elevated levels of chlorinity were directly correlated to the implementation of more efficient drainage schemes in the area (Driscoll, 1984).

Aquatic species are extremely sensitive to even minor fluctuations in chlorinity levels (Vasquez, 2006). Since the increase in chlorinity, aquatic floral communities have been in an unstable state within the catchment; fluctuating between an ecologically diverse state dominated by aquatic plants to an unstable state characterised by the dominance of algal species (Driscoll, 1984).

Driscoll's work has been further backed up by recent research carried out by the Internal Drainage board in 2001 in order to establish water level management plans for the two drainage catchments. They concur that drainage improvement has significantly impacted on water quality in the area (IDB, 2001).

Table 2: Table to show how elevated chlorinity levels have followed drainage improvements and resulted in ecological impacts. Adapted from (Barker & Al, 2008; Driscoll, 1984; Madgwick, 1999; Moss, 1978; Moss, 2001)

Date	Agricultural practice and drainage System	Research on Water quality	Aquatic Plant Communities
19th – 20th Century	Most of land under grazing marshes. Drainage provided by shallow ditches	High water quality in Hickling Broad – chlorinity around 600mg/L	Hickling Broad was dominated by rare charophytes species
1900s – 1950s	Intensification of Agriculture. Drainage still characterised by shallow ditch systems	Increase in nutrient loading mainly from Agricultural sources;	Phytoplankton and algal communities increased in abundance.
1960s - 1970s	Onset of drainage improvement schemes in 1960s for arablisation. Drainage ditches re-profiled and dug deeper. Capacity of drainage pumps enhanced.	Poor water quality, elevated nutrient status particularly phosphates from breeding gull population, high chlorinity levels	Collapse of freshwater aquatic plant communities. Complete dominance of phytoplankton Freshwater plant grazers such as Daphnia (intolerant to high salt levels) severely declined and remain rare up to this day.

1980s – 1990s	Deep drainage and high capacity pumps	Some recovery of water quality due to lowered nutrient levels	Rare Chara intermedia thrived in conditions
Present day	Some conversion of land back to grazing marsh however catchment dominated by heavily drained arable land	Chlorinity levels almost four times those observed at beginning of 19th century. Salinities in Hickling broad have since increased to 1800 - 2000mg/L	There have been significant losses of rare stonewort species from the Horsey mere and Hickling Broad. Cladocera sp. which play a key part in stabilising plant communities through grazing phytoplankton are still absent in many of the Broads.

2.3 CURRENT LAND USE AND DRAINAGE

Approximately 74% of the land in the Brograve Level was under arable cultivation in the early 1990s (Holman, 1994) although this has since declined. The marshlands in this area are extensively drained and seawater intrusion can be observed from elevated chlorinity of ditch water in all marshes with the exception of the Lessingham drainage ditches found in the North of the catchment.

Drainage in the Upper Thurne Catchment consists of the three main components

1) **Field Drain system**: system composed of ditches for draining groundwater with a deep draining base.
2) **Main Drain System** – System of Large drains used to convey water to a central main outlet.
3) **Outlet** - discharge point for the drained water and situated at the drainage pumps.

In general drainage profiles are set below sea level and the pump systems maintain low water levels in the catchment. The salt load contributions from individual marshes depend on the salt concentration within the drainage channels and the discharge which conveys this saline water through the network.

Figure 10: Picture showing how ditches from marshlands connect with Brograve Main Drain in catchment (Field Survey, July 2008)

2.4 DISTRIBUTION OF CHLORINITY IN THE DRAIN SYSTEMS

Salt concentrations in ditches in the Somerton and Brograve catchment are on average quite similar however; far more salty water is discharged via the Brograve pump than at the Somerton pump, most likely due to its larger catchment area.

Various studies carried out over the last twenty years have suggested that the Hempstead Marsh contributes the highest salt load to the catchment area (Driscoll, 1984; Holman, 1994; Simpson, 2007). This is because chlorinity surveys have shown Hempstead to have the highest chlorine concentrations in its ditch water.

While this does not prove conclusively that the highest loads come from this marsh, it does however indicate that the ditches in this area have direct contact with saline groundwater. Without the measurement of flow in these ditches it is impossible to ascertain whether this salty water is being transported down to the Brograve pump. Concentrations alone are not able to tell us much about the salt load contribution from this particular marsh.

The table below show some of the factors identified as influencing both salt concentration and discharge in drainage network.

Table 3: Chlorinity and discharge in drainage ditches is determined by an interaction of climatic and geological factors

1. **Amount of seawater entering into the drainage channels**: This is determined by the proximity of the drains to coast and the amount of deep cut drains in the area (Holman, 1994).
2. **Quantity of freshwater available to dilute the saline water within the ditches**: This will depend on the level of precipitation in the study area. The Brograve catchment has very low rainfall (between 600-700mm per annum) which limits the freshwater recharge of the aquifer and dilution of salt water in the ditches.
3. **Water levels in the drained marshes:** Seawater will intrude as far inland as the dyke with the lowest water level (minimum equipotential line), the Brograve, Somerton and Hickling catchments effectively acting as flow interceptors for saline intrusion (Holman 1994).
4. **Transmissivity of the aquifer in these sections:** The transmissivity of the aquifer will in turn be impacted by the presence of any clay layers, perched aquifers and the thickness of these impermeable layers within the rock.

The temporal variability and spatial distribution of chlorinity in the Brograve Level and Somerton Level ditches is a direct consequence of their profiles, proximity to the coast, as well as the underlying geology and hydrology. The next section will highlight the catchment characteristics found in the study area that impact on seawater intrusion.

2.5 CATCHMENT CHARACTERISTICS INFLUENCING THE HYDROLOGICAL RESPONSE AND SALT LOAD DISTRIBUTION

2.5.1 TOPOGRAPHY

The groundwater catchment area of the Upper Thurne area is approximately 110km^2 and is composed of 4 distinct topographical areas: the Loam uplands, Holmes, Flegg Hundreds and the Marshes (Holman, 1994). The Marshes (found from Happisburgh to South of Winterton) form part of a lowland valley area with a mainly flat landscape ranging between 0 – 2m ODN. The Somerton Level to the south of these marshlands has a similarly subdued relief again ranging between 0 – 2m ODN. The marshes are protected from flooding from the sea by a belt of sand dunes.

Figure 11: Figure showing bird's eye view of Upper Thurne Catchment area. The flat relief of the land is apparent from this photograph.

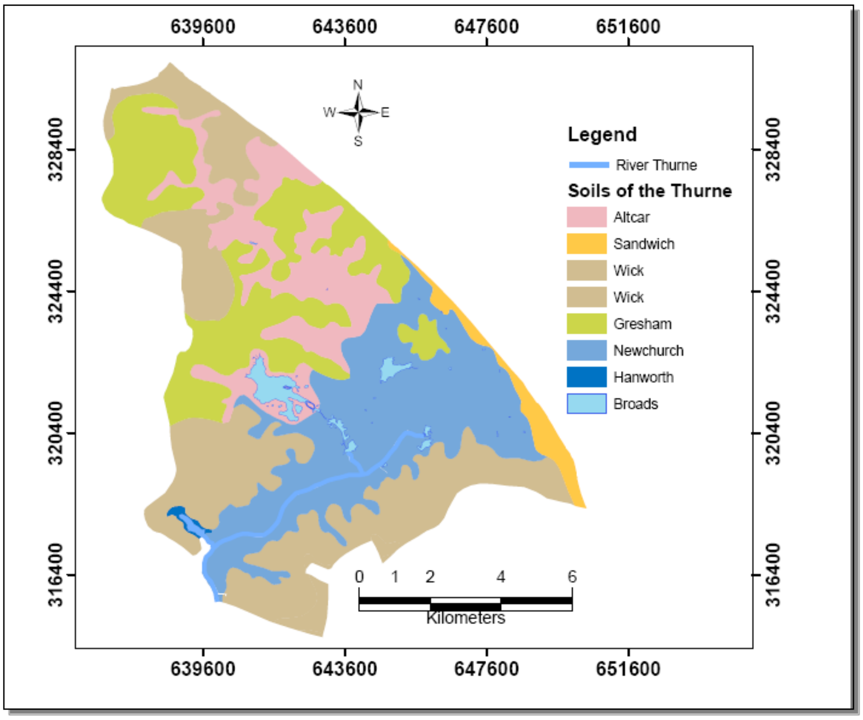
(Source: www.2bconsultancy.co.uk/images/05_vis/photom/norfolk/Norfolk2.jpg)

2.5.2 GEOLOGY AND SOILS

The study area has a complex geology which has been studied by various authors, research which was synthesised in PhD research conducted by Trevor Simpson in 2007 (Simpson, 2007). The following description of the areas geology is adapted from this synthesis.

The Upper Thurne Catchment area contains a large Pleistocene Crag Aquifer made up of a sand-gravel mixture which varies between -30 ODN and -65 ODN. It is shallowest on the Western side. Different textures can also be found within the body of the Crag including a clay layer at approximately -25 ODN. Underlying the aquifer is an impermeable layer of London Clay, overlying it a soil layer containing Norwich Brick Earth, Peat and Estuarine Alluvium Clay of varying thicknesses and hydraulic conductivity. Finally at the surface there are superficial coastal deposits which form the beaches and sand dunes that embank the coast.

Figure 12: Soils found within the Upper Thurne Catchment (Simpson, 2007)



Soil types within the Marshes are geographically divided by north and south and the two types of underlying alluvium found within the catchment – peaty and clayey. The peaty alluvium soils occur in Hickling and the Northern marshes (from Hempstead village to the Brograve pump). The peat's thickness varies and is deepest beneath the main drain running from Lessingham village to the Brograve pump. The clayey estuarine alluvium occurs in southern marshlands from Brograve pump to the mouth of the river Thurne in the South-West and Winterton in the South-East (Simpson, 2007).

Both the peat and clay within the area is heavily drained which results in little or no vertical flow from percolation through soils into the aquifer (Holman, 1994).

2.5.3 GROUNDWATER AND AQUIFER PROPERTIES

Information for this section comes largely from Holman's investigation into chlorinity controls in the Upper Thurne (Holman 1994). Despite the fact that the surface distribution and variability in chlorinity had been mapped out, particularly by Driscoll (1984), the connection between this and the underlying geology within the catchment was poorly understood up until Holman's research.

Holman used a range of techniques from electrical resistivity studies, electromagnetic surveys and direct hydrogeological measurements to better understand the properties of the aquifer that were influencing the distribution of chlorinity within the Upper Thurne catchment. He concluded that the crag aquifer was highly variable in composition, effectively acting as two aquifers split by a layer of clay which inhibited vertical flow.

Groundwater flow from the underlying aquifer into the drainage ditches was restricted by the low permeability alluvium and peat deposits in the marshes. This explained why the drainage improvement schemes, which involved the re-profiling of ditches to make them deeper, made the problem of saline intrusion significantly worse. Only drains which are dug deep down are in direct hydraulic contact with the aquifer.

The aquifer itself is semi confined, acting as an unconfined aquifer in some parts and a confined aquifer in others. In the Eastfield and Hempstead marshes, relatively impermeable alluvium means that when there is precipitation in the Marshland the response in groundwater head changes are that of a confined aquifer (Holman 1997).

Regions of the permeable Norwich Brickearth found extensively throughout the catchment, are main areas for groundwater recharge to the crag aquifer as well as some areas of exposed crag (Holman, 1994). There is evidence that the shallow lakes of the Broadland are in hydraulic conductivity with the aquifer and could therefore be an additional source of recharge or act as discharge points. Alluvial deposits within the marshlands have low hydraulic conductivities and as such restrict the rate of vertical recharge of the aquifer within this area; this prevents freshwater dilution of the saline groundwater (Simpson, 2007).

As the crag aquifer is non-homogenous, hydraulic conductivity ($\boldsymbol{K}$) within it varies. Table 3 below shows the distribution of $\boldsymbol{K}$ and thickness of alluvial deposits in catchment. Hydraulic conductivity will have some influence on the distribution of chlorinity within the catchment. In Simpson's thesis on groundwater flows the northern marshes are approximated to have higher K than the southern marshes and as a result the upper marshes are assumed to be contributing more to saline inflows than those found in the lower reaches (Simpson, 2007), however, research has shown chlorinity distribution to be more sensitive to the drainage configuration and influence of recharge than hydraulic conductivity (Narayan et al, 2007).

Table 4: Hydraulic conductivity values estimates for Marshlands (Simpson, 2007)

Geology	**Saturated hydraulic conductivity**	**Location**	**Typical thickness**
Overlying strata			
clay (Newchurch Association)	Kv=0.0008 m/day* (Approximated)	Southern Marshes	1-5m Fieldwork
peat (Altcar 2 association)	Kv=0.0016 m/day (Approximated)	Northern Marshes	1-5m (Burton et al., 1987)
Norwich Crag (Sands and Gravels)	Kh = 20 m/day Erskine (1991)	Catchment wide	25-65m (Holman et al. 1999)
'Clayish' layer within Crag (consolidated material)	Kv = 0.1 m/day (Approximated)	Catchment wide	3 m (Holman et al. 1999)

2.5.4 DRAIN-AQUIFER INTERACTIONS:

Chlorinity in the Upper Thurne Catchment (UTC) is dependent on the quantity of seawater that enters into the coastal aquifer system and the nature of the underlying geology within the coastal marshes. The velocity of flow within an aquifer is governed primarily by the porosity and hydraulic conductivity of the material through which the water flows (Balance & Bartram, 1996).

Within the aquifer itself, preferential flow conduits such as areas where there is highly permeable material will alter the spatial and temporal distribution of salt water (Arfib & Al, 2007) . Other factors likely to affect the transport and distribution of chlorinity within the aquifer include the presence of perched aquifers and the varying thickness of aquifer material.

Upward vertical flows of saline groundwater will be affected by the thickness of alluvial deposits in the ditches. As the deposits at the bottom of the main Brograve drain are relatively thick, drain-aquifer interaction along the main drain is believed to be limited (Simpson, 2007). This indicates that most if not all of the saline groundwater is from water drained from the marshes.

2.6 MANAGEMENT AND REMEDIATION

The Lessingham and Hempstead marshes dominate composition of water at Brograve. It is estimated that Hempstead marsh for instance, contributes up to 50% of salt load and inflows along lower reaches have little to no effect on surface water chlorinity (Simpson 2007).

The Consortium of authorities responsible for the Broads, including the Environment Agency and Broads Authority, has set ambitious targets for the restoration of water quality in the Horsey Mere. They would like to see salt levels lowered from their current levels of 2900mg/L to 1000mg/L and the chlorinity of water passing through the Brograve pump lowered to 1600mg/L (ELP 2004). The methods proposed include raising water levels in marshes to restore the natural hydraulic gradient. As the Hempstead Marshes (HM) are believed to be the main conduit for salt water transport in the catchment, recommendations have been for water level rises to be targeted to the Hempstead Marshes (Holman 1994, IDB 2001 and Simpson 2007).

Following on from Harding and Smith's report in 2002 and Harding et al's 2005 report, Simpson addressed the question of raising water levels in the Hempstead and Lessingham areas. A proposal was put forward for water table depth to be maintained at -0.4m ODN at targeted drainage locations such as Hempstead, in this way the groundwater discharge into the dykes would be reduced.

Also proposed was a combination of lowered water levels within the Lessingham Marsh and raised water table levels in the Hempstead. An advantage of this would be that the hydrology of surrounding areas including those of large water bodies would be maintained. However, changes to Lessingham and Hempstead drains might result in a reduction in input into River Thurne which in turn might result in more saline incursion upstream.

Further research is therefore needed to identify and mitigate against any externalities resulting from interventions. Data gaps exist which are relevant to any management controls in terms of identifying these risks. These include data such as:

1. Volumetric flows of drains
2. Identification of any specific drains which may be disproportionately contributing to saline water discharge of Brograve pumps

3. Contribution of individual marshes to salt load discharged from Brograve and confirmation of dominance of Hempstead marsh.
4. Effect of raising water table levels in the Somerton Level on chlorinity measured at the Somerton pumps

The information from this literature review provides a conceptual model of the chlorinity controls within the Brograve and Somerton Level drainage catchment. It outlines how the drainage of the coastal marshes has driven the salinisation of the groundwater in the catchment. It notes how management interventions could have important implications for adjacent catchments. It has outlined what is currently known about chlorinity controls within the catchment, their spatial extent and temporal variability and how different aspects of the catchment characteristics and water level management regimes impact on this. This information has been used to design chlorinity and flow surveys for the Marshlands of the Brograve drainage catchment and to assist the analysis and interpretation of data from the Somerton drainage catchment. The methodology for the collection of data for these two drainage catchments follows in the next section.

3 METHODOLOGY

The second stage of research for this thesis involved the collection of data through field surveys of the Brograve drainage catchment and collection of the Water Management Alliance's (formerly the King's Lynn Consortium of Internal Drainage Boards) data on discharges from the Brograve and Somerton pumps. The objectives of the surveys and data collection are to provide input for salt load analysis of drain waters and discharges from both the Brograve Level and Somerton Level drainage catchments.

As touched upon in the literature review: where soils are highly permeable, and there is connectivity between the drain and the aquifer, large amounts of salty water are likely to be transmitted from the marsh to the pump which conveys water to the Brograve drainage pump and subsequently the Horsey Mere.

Measuring the concentrations of salt in the ditches will give an indication of where this drain-aquifer interaction is occurring. The measure of flow in the identified ditches will give an indication of the volumes of seawater that are being transmitted through the aquifer sections. This information will give an idea of the spatial distribution of chlorinity flow within the sub-catchment and indicate where raising water levels is likely to be the most effective. Here chlorinity is used as a proxy for salinity levels.

This section will outline the data collection methods and conclude with a list of the data available for the results and analysis section that follows in the next chapter. The key variables include**:**

1. Salt concentration in ditches
2. Discharge of ditches
3. Depth of ditch
4. Underlying Geology
5. Volume of water transferred from pump
6. Salt concentration in water transmitted by pumps.

Telemetry data from Brograve and Somerton pumps provides information on volume of water (discharge) and electrical conductivity which is a proxy for chlorinity concentrations; the results of chlorinity survey carried out in 1984 and 1994 by Driscoll and Holman respectively which covers research areas of the Brograve Level and Somerton level is also used to derive salinity levels

3.1 CHLORINITY AND FLOW SURVEY IN BROGRAVE DRAINAGE CATCHMENT

The first part of the field data collection was to obtain extensive information on chlorinity levels and flow in the Brograve drainage catchment. An intensive programme of grab sampling of water samples and subsurface particle velocity measurement in main drains from respective marshes leading to Brograve main drain was thus designed. Sites were sampled on the basis that they represented the water quality and flow conditions found in the entirety of the coastal marsh they drained.

Table 5: Data collected during survey

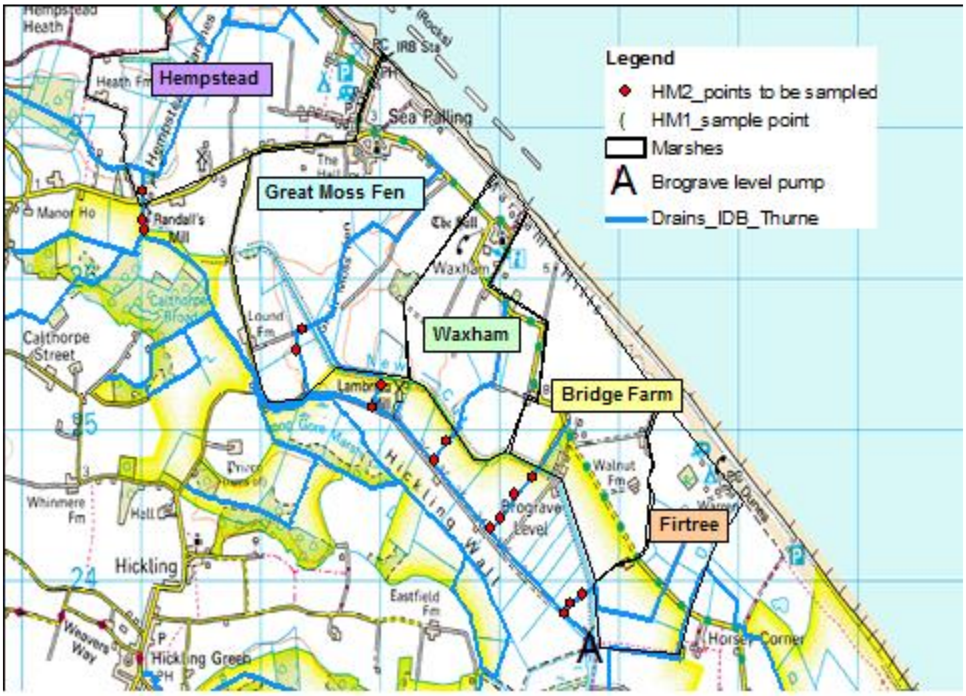
TYPE OF DATA	INSTRUMENT USED	UNITS	HOW TO BE USED
1. Average velocity	Pooh sticks and stopwatch	Metres per second	Calculating discharge
2. Instantaneous value of Electrical conductivity	EC meter	Micro or millisiemens per cm (mS/cm or µS/cm)	Calculating salt concentration
3. Depth of water in ditches	Stick and measuring tape	Metres	Calculating cross sectional area of channel
4. Width of channels	Stick and measuring tape	Metres	Calculating cross sectional area of channel
5. Grid reference	GPS meter	British National Grid	To create survey outcome maps on GIS
6. Aerial Photograph	Camera		In report

Water samples were collected in a plastic bottle which was submerged top down and then turned upside down to allow water entry at approximately 60% of the depth down.

It was not possible to have water samples taken at consistent depths across the catchment due to the variety of water depths encountered, however as far as possible water samples were taken below surface to avoid surface particles such as floating pieces of ochre or soil entering the bottle and contaminating the sample. The water bottle was rinsed with water from the ditch to be sampled prior to a water sample being taken and measured for chlorinity.

Water samples were collected at the end of July 2008, figure 13 below shows the locations within the Brograve catchment.

Figure 13: sample points within Brograve catchment



3.1.1 MEASUREMENT OF CHLORINITY

The ability of water samples to conduct electricity (conductivity) depends on the concentration of ions in solution. In this instance we assume that the majority of the ions present in the water are derived from seawater salt (NaCl).

In order to measure the conductivity an electrical conductivity meter was inserted into the plastic bottle containing the water sample. The EC meter gave a reading in either µS/cm or mS/cm depending on the salt concentration. This figure was automatically corrected to 25°C, therefore there was no requirement to carry out temperature adjustments when data was being analysed. All data was instantly recorded in a field notebook with the date and time noted.

3.1.2 DISCHARGE MEASUREMENT

Discharge of the drainage ditches was measured using a velocity-area method.

Initially an acoustic flow meter was to be used to gauge flow at the sample sites however due to the water velocity being extremely low the speed of submerged ochre particles was judged to be the most appropriate methodology for estimating velocity.

A length of 2m was measured along the back and the time taken of submerged particles to travel this 2m distance was recorded. The particles were selected at various points along the width of the channel to get an average velocity. The particles were selected to be of similar size – approximately 2-3cm across.

The channel is assumed to have a rectangular profile; the width was calculated to be the section of the channel clear of the reed fringe that was found in all the ditches. In reality the dredging machinery used by the IDB gives the ditches a trapezoidal profile; however the murkiness of the water, congested with sediment and ochre, made it difficult to measure or estimate the slope and it was assumed that the slight difference in area calculated would have minimal impact on the velocity and flow parameters.

Depth measurements were taken at various points along the width of the channel and an average depth calculated. Finally a GPS meter was also used to record the location at which the sample was taken and a photo of the ditch conditions taken.

3.1.3 DATA ANALYSIS

Data from the field survey was used to calculate the discharge and salt load as shown below.

i. Discharge (m^3/s): $\mathbf{Q = v \times A}$

Where Q = discharge (m^3/s), v = average velocity (m/s) and A = cross-sectional area ($m^{2)}$.

The velocity measured was adjusted by multiplying it by a correction factor of 0.84 – given as the factor used to correct for rough bed channels.The reason this factor was used was that the deposits of ochre along the drainage channel bed are assumed to be uneven and haphazard resulting in an uneven surface.

This value was then converted to m^3/day by multiplying by 86,400.

ii. Salt concentration (Cl^{-1}mg / *l*): **= (302.84mS) - 248.81)**

The chlorinity of the water was calculated using the EC to chloride conversion derived from Holman's lab data in 1994 (Holman, 1994). A simple regression line was drawn from the values of chloride obtained and their corresponding EC.

The Chloride concentration in mg/l was then converted to kg/m^3 by dividing the value by thousand.

iii. Salt Load (kg/day) : **mF = c x Q**

Where mF = mass flux, c= chloride concentration (Cl-/kg/m^3) and Q = discharge (m^3/day)

3.2 TELEMETRY DATA FROM BROGRAVE LEVEL AND SOMERTON LEVEL DRAINAGE CATCHMENTS

3.2.1 BROGRAVE:

Data on pump discharges and chlorinity levels from the 1980s to current day was obtained from the IDB and Environment Agency measurements were converted as described below.

Table 6: Table of data obtained from IDB and EA and conversion method

Data type	Given As	Conversion	Initial Units	Final Units
Chlorinity	Electrical Conductivity in µS/cm	(Cl^{-1}mg /L) = (302.84mS) - 248.81)	Cl^{-1}mg / *L*	CL-1/kg/m^3
Discharge Data	Length of time pumps were switched on in seconds	Data converted using pump discharge which gave litres pumped per seconds of pump activity (IDB 2008)	Litres per second	M^3/second

Load was then calculated as kg/second and then scaled up to daily amounts.

3.2.2 SOMERTON:

Water levels were raised in the Somerton catchment in 2004 in order to restore water quality (IDB 2001). Analysis was done in two parts, the first part was the analysis of the volume of water pumped, chlorinity and thus the load from the Somerton North and South pumps prior to the raising of water levels (1991/1992). Data for the 1991/1992 period was taken from Ian Holman's PhD research (Holman 1997) on Somerton South (Old) and Somerton North (New) pumps and covers a time period of 24 months from April 1991 to March 1993. An analysis was carried out on the volumes of water pumped from the two pumps using IDB data, the chlorinity of the water and from these figures the load was calculated and analysed.

The data on chloride concentrations in the water pumped was given as mg/L this was then converted to the standard unit used, kg/m^3, by dividing by one thousand.

The second part of the analysis was similarly on discharge, chlorinity and load from the Somerton pumps. Due to incomplete data the North and South pumps were analysed in different years. The Somerton South pump data was analysed for the year 2004/2005 and the Somerton North for the years 2007/2008. Data for this section was taken from the Internal Drainage Board (now Water Management Alliance) automatic data from their pumps.

The analysis of the pumps post restoration implementation is thus done on the basis of comparing the Somerton South (Old) pump data from 1991-1993 with pump data from 2004 to 2005

For the South Somerton pump the data for water volume pumped was derived from the pump hour meter. The number of pump hours was converted into seconds. The IDB provided the conversion for pump running time to litres pumped. This was given as 280 litres of water pumped per second of pump running time. They also advised that since the pumps are fairly old the efficiency of pumping would be reduced to around 80%.

Table 7 shows more clearly how the pump hour's data was used.

Table 7: Sample of raw pump data obtained for South Somerton Pump and how this was converted to standard units used in analysis.

pump 1 dates	pump 1 hours	pump 2 dates	pump2 hours	total hours	conversion to secs = *3600	volume 280L / sec	80% efficiency	litres converted to m^3
01-Jun-04	0	01-Jun-04	0	0	0	0	0	-
02-Jun-04	0	02-Jun-04	0	0	0	0	0	-
03-Jun-04	0	03-Jun-04	7.83	7.83	28188	7892640	6314112	6,314.11
04-Jun-04	0	04-Jun-04	0.61	0.61	2196	614880	491904	491.90
05-Jun-04	0	05-Jun-04	0.61	0.61	2196	614880	491904	491.90
06-Jun-04	0	06-Jun-04	0.64	0.64	2304	645120	516096	516.10
07-Jun-04	0	07-Jun-04	0.65	0.65	2340	655200	524160	524.16

The Somerton South pump data provided by the IDB is much more complete than that of the North Pump. It seems there were numerous mechanical failures with the North's pump hours metre and the salinity gauge used during the time period and there is a lack of consistent data for any month during the years provided.

Data for the years 2007 / 2008 appeared to have the most consistent data. This data was thus "cleaned" and used for analysis.

Pump data was selected from the raw data according to the following criteria

1. Data was within the normal range i.e. pump hours between 1 and 10 hours of operation
2. Data from the meter was consistently within this range for at least 2 days

Table 8 demonstrates how this data was then transformed.

Table 8: Sample of data obtained for North Somerton pump meter to show conversion to pump hours

DATE READING TAKEN	PUMP METER READING	PUMP ON TIME (HRS) - CALCULATED BY SUBTRACTING PREVIOUS METER READING FROM CURRENT
06/09/2007	34.78	0.80
07/09/2007	35.03	0.25
08/09/2007	36.58	1.55
09/09/2007	37.72	1.14
10/09/2007	38.13	0.41
11/09/2007	38.85	0.72

Chlorinity data was then taken from the EA monthly sampling. This data was supplied in mg/L which were then converted to kg/m^3 by dividing the value by thousand. Table 9 below shows how the raw data was transformed to give Load values. Data was obtained for 11 months, February through to December.

Table 9: Table showing conversion of pump hours and calculation of Load from Somerton North pump 2007/08

Month	average pump hours (hours per day)	Total per month (average daily on time x no. of days in month)	Total per month in seconds (Hours x 3600)	Volume of water (litres) - pump capacity = 400 l/sec therefore litres = total secs x 400 x %80 efficiency	Volume of water (m^3) - litres to m^3 = L /1000	Average Chlorinity = Conc Cl- (mg/l)	Average Chlorinity (kg/m^3) = mg/l/1000	Load (kg/m^3/month) = chlorinity (kg/m^3) x vol. of water (m^3/month)
Feb-07	3.00	84.00	302,400.00	96,768,000.00	96,768.00	1,860	1.86	179,988
Mar-08	1.66	51.42	185,121.72	59,238,951.50	59,238.95	1,400	1.40	82,935
Apr-08	1.78	53.38	192,185.26	61,499,282.05	61,499.28	2,120	2.12	130,378
May-08	0.99	30.58	110,090.12	35,228,839.84	35,228.84	2,840	2.84	100,05

The results were then compared with Somerton North pump data from 1992. Comparison was made between the volume of water pumped, the chlorinity range and finally the load values.

3.3 ASSUMPTIONS AND LIMITATIONS

Certain assumptions were made during the course of this field work with regards to the nature and shape of the channels being investigated, there were in many limitations in terms of accessibility to the water or measuring the channel dimensions. Key assumptions made included:

- Channels have a regular rectangular shape and the beds of the channels are regular and stable
- The influence of aquatic growth on the width measured is negligible
- Data collected from the main drain connecting the marshes to the Brograve main drain is assumed to capture the majority of flow from the marshlands.
- The data provides a snapshot of flow conditions during the summer and when the pumps are inactive – it cannot be directly extrapolated to the winter months or flow conditions when the pumps are active.
- The measurements were taken during a prolonged dry period in the catchment with little or no rainfall falling during the sampling period and therefore are not necessarily representative of the full range of conditions during the year.
- The sampling methodology used is very limited as velocity of water in a channel varies according to depth. The pooh stick method only provides a very rough measure of flow conditions.

4 RESULTS

One of the main aims of this research project was to investigate how chlorinity varied within the Brograve drainage catchment and the relative contribution of the different marsh areas to the total salt load pumped from the Brograve pumps into its adjacent broads. The results from this analysis could then be used to identify where water level management changes could be targeted, that is, where marshes were demonstrated to contribute the largest loads, water levels could be raised in these specific areas.

This targeted approach would mitigate against disruption to agricultural activities in the area, prevent possible knock-on effects of raising the water table in other areas and hopefully serve to sufficiently restore the quality of water pumped into the broads. In order for this targeted approach to be efficient, the results of chlorine and load surveys would have to indicate that a) the quantity of seawater contributed from a marsh was significant and that b) raising water levels in this area would not adversely affect seawater contribution from other marshes. The field study carried out as part of this thesis investigates this first point and provides a basis for further investigation.

4.1 BROGRAVE DRAINAGE CATCHMENT FIELD STUDY

Out of the seven sampling points selected, five marshes were found to have ditches that were accessible and from which water discharge and chlorine concentration could be determined. These were the

1. Waxham
2. Hempstead
3. Lessingham
4. Great Moss Fen (location 2)
5. Bridge Farm.

The results from the field survey were analysed according to the following criteria:

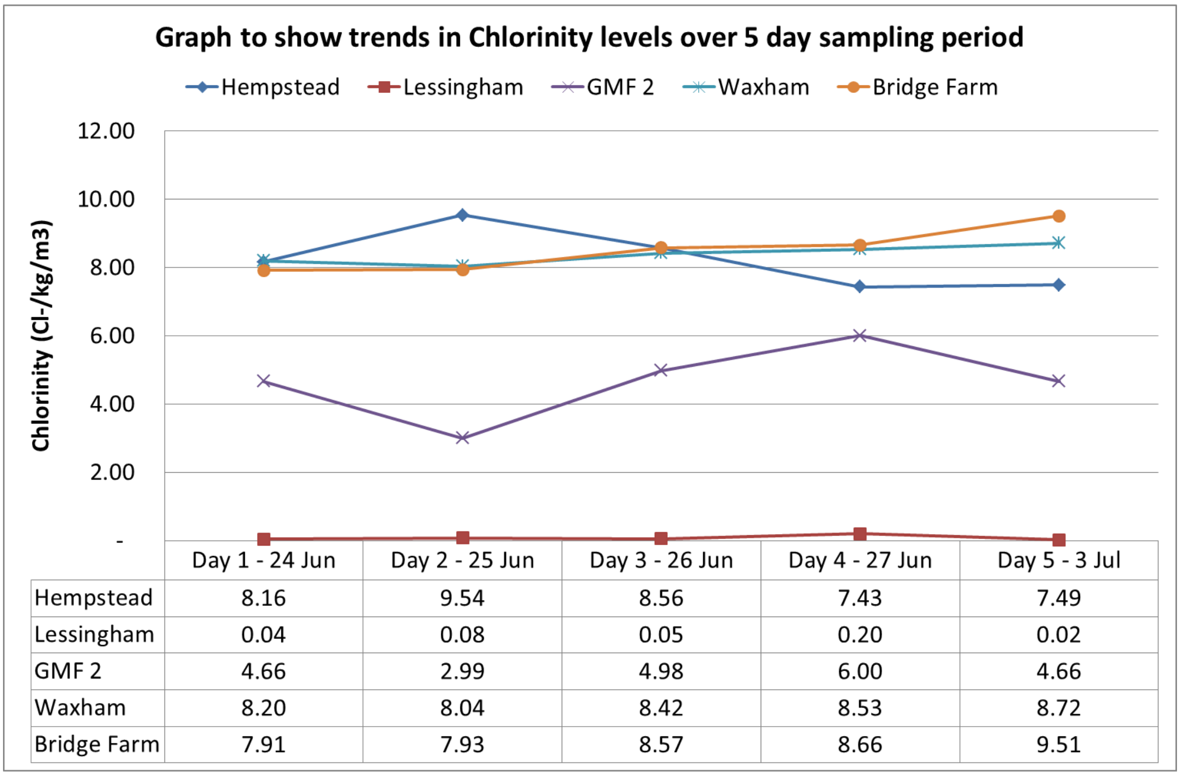
1. Chlorinity Levels in the ditches – to determine the relative quantity of seawater entering into the ditches in this area

2. Discharge – the volume of water from this area of the catchment transferred towards the pump system. This amount is influenced not only by the size of ditches but also by slope of the land.
3. Load – calculated as the chlorine concentration multiplied by the discharges, these results indicate the quantities of seawater contributed by each marsh.
4. Further analysis were carried out on the results to assess correlation of other factors such as:
    - Correlation between ditch size and load contribution to determine ratio that can be used in determining ditches that potentially contribute disproportionate amounts

4.1.1 CHLORINITY LEVELS IN THE DITCHES

Figure 14 shows chloride ion concentrations from the 5 sampling areas measured on 5 different days. Of the samples taken, those from Hempstead, Waxham and Bridge Farm marshes were consistently higher than the rest.

Figure 14: Chloride concentrations measured during 5 days of sampling and chlorinity ranges



	Day 1 - 24 Jun	Day 2 - 25 Jun	Day 3 - 26 Jun	Day 4 - 27 Jun	Day 5 - 3 Jul
Hempstead	8.16	9.54	8.56	7.43	7.49
Lessingham	0.04	0.08	0.05	0.20	0.02
GMF 2	4.66	2.99	4.98	6.00	4.66
Waxham	8.20	8.04	8.42	8.53	8.72
Bridge Farm	7.91	7.93	8.57	8.66	9.51

Great Moss Fen (2) shows the highest variance with Lessingham and Waxham showing the lowest. Hempstead Marsh had the highest average chlorinity and Lessingham the lowest as shown in the table below. Lessingham chlorine levels are extremely low and out of range with the rest of the marsh results

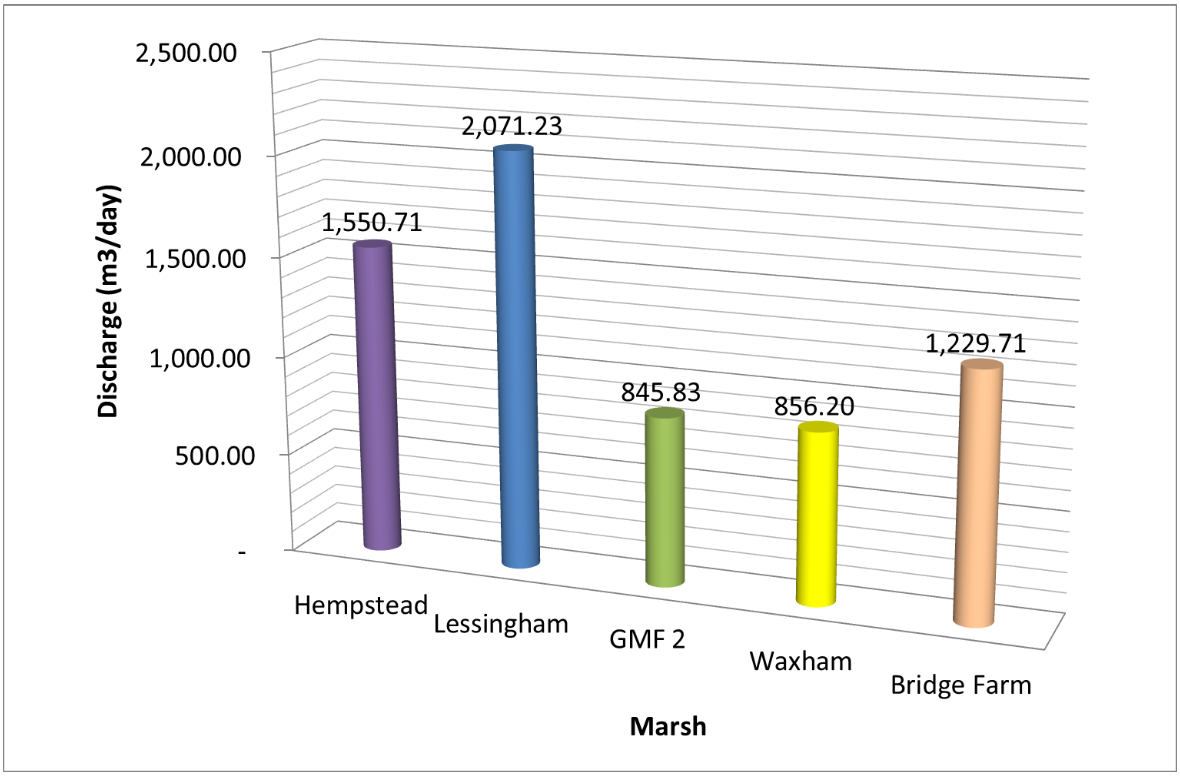
Table 10: Statistical Analysis of Chlorinity results from field survey on Brograve Level

MARSH	MEAN (Cl^- /kg/m^3)	STANDARD DEVIATION (Cl^-/kg/m^3)
Hempstead	8.24	0.87
Lessingham	0.08	0.07
GMF 2	4.66	1.53
Waxham	8.38	0.27
Bridge Farm	8.52	0.66

4.1.2 *FLOW VARIATIONS BETWEEN MARSHES*

The Graph below shows the discharge of water from the ditches measured in the respective marshes. This gives an indication of the quantity of salty water transported to the Brograve pumps when the pumps are running.

Table 11: Graph comparing average discharges (m^3/day) measured over 5 day period. (full field data provided in Appendix 3)



Discharge ranges between approximately 845m^3 per day and 2071 m^3 per day during the sampling period. Results represent flow during dry periods.

As seen above discharge in the Lessingham marsh is highest, Hempstead and Bridge Farm discharges are within a close range as are those of Great Moss Fen and Waxham ditches.

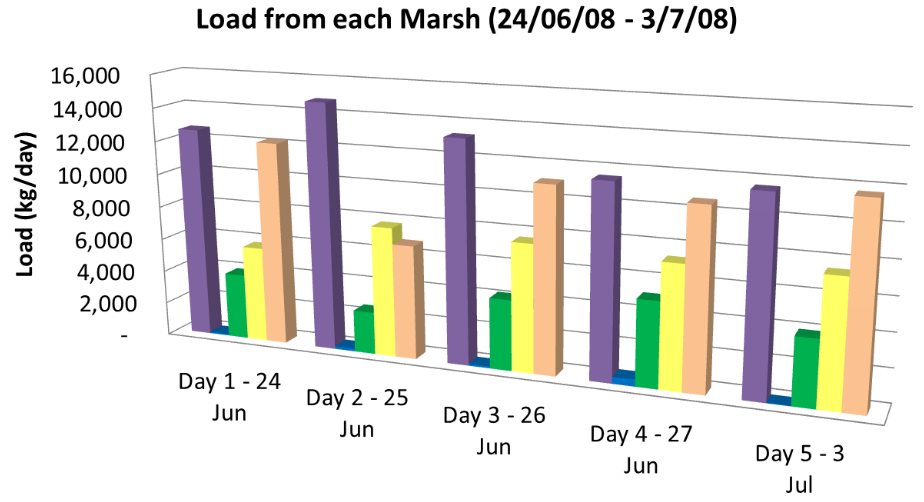
The discharge measurements give a useful indication of the variance of discharge in the catchment. In some marshes mentioned in the original sampling map (the Great Moss Fen and Firtree Marsh) discharge was either so low as to be beyond detection limits or the cloudiness of the water due to ochre deposits made it impossible to use the pooh stick methods, these areas have thus been excluded from the results section.

4.1.3 RESULTS ON LOAD CONTRIBUTIONSOF MARSHES FROM FIELD STUDY

The chart below shows the estimated salt load from the individual marshes calculated as the product of the discharge and chlorinity measurements above. The discharge was calculated for each measurement in kilograms per second and then scaled up to provide an estimate of the daily flow. Where data on flow and chlorinity was missing the average value was taken from the other days of measurement.

Conditions were the same on all days – no precipitation and pumps were inactive.

Figure 15: Graph to show load in kg/day from each marsh measured during field study. Hempstead area and Bridge Farm contribute the highest load when pumps are inactive.



	Day 1 - 24 Jun	Day 2 - 25 Jun	Day 3 - 26 Jun	Day 4 - 27 Jun	Day 5 - 3 Jul
🟪 Hempstead	12,660	14,792	13,275	11,514	11,613
🟦 Lessingham	84	163	110	411	34
🟩 GMF 2	3,942	2,533	4,213	5,079	3,942
🟨 Waxham	5,740	7,754	7,612	7,301	7,462
🟧 Bridge Farm	12,191	6,799	11,072	10,650	11,697

Hempstead marsh is shown to contribute the highest load whereas Lessingham has the lowest. Hempstead Marsh and Bridge Farm show high variation in load values, largely due to much higher scale of discharge, Bridge Farm has unusually high variance in load values particularly on day 2 of the study. Lessingham has an unusually low deviation compared to the other marshes but this is down to much lower discharge levels. (table 12).

Table 12: Table to show variance between load values obtained from Brograve Level field survey

Marsh	Mean (kg/day)	Standard deviation (kg / day)
Hempstead	12,771	1,348.38
Lessingham	160	147.67
GMF 2	3,942	915.42
Waxham	7,174	819.22
Bridge Farm	10,482	2,141.18

Figure 16: Comparison of salt load per marsh per area in ditch shows Waxham contributes a disproportionate amount to the salt load. This indicates surface area of ditches within the marsh is not the only factor governing contribution to salt load

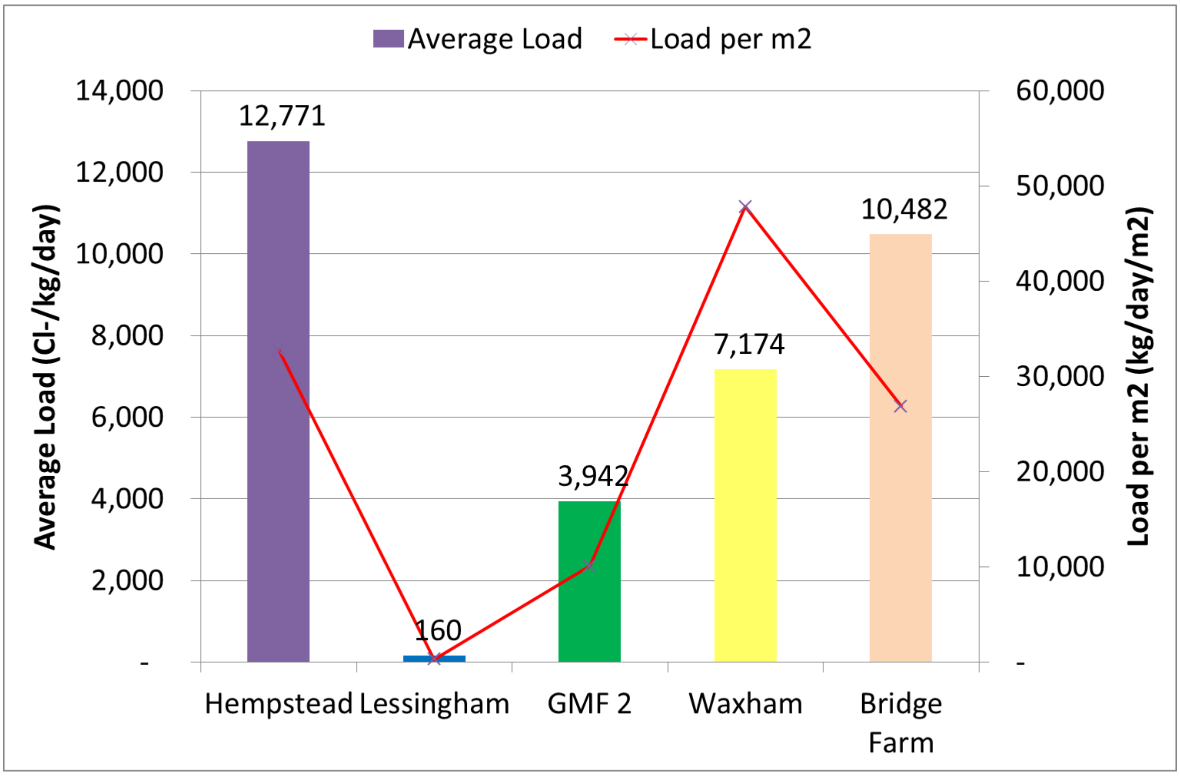


Figure 16 above shows Waxham, a marsh found close to the coastline is shown to be contributing a disproportionate amount to the salt load despite its relatively smaller size.

4.2 BROGRAVE TELEMETRY DATA ANALYSIS

This section of the results chapter presents the outcomes of telemetry data analysis from the Brograve Pumps. Although it doesn't form part of the specific aims of the thesis in terms of assessing spatial variation of load within the Brograve catchment, it does provide additional information on the volume and salinity of water being pumped by the Brograve pump when the pumps are active and provides further justification for intervention. This section provides background information to assist with the final objective for the thesis which was to "Make recommendations on where management changes should be targeted in the Brograve sub-catchment".

The results were analysed according to the following criteria:

1. Chlorinity Levels– to determine the level of saline pollution being transmitted to the Broads within the Brograve catchment and trends in chlorine concentration over 18 year period.
2. Discharge – the volume of water pumped during the year, indicating trends in terms of seasonal changes to pumping levels and the quantities being transmitted
3. Load – calculated as the chlorine concentration multiplied by the discharges, these results indicate the quantities of seawater contributed by each marsh.
4. Further analysis were carried out on the results to assess correlation of other factors such as the correlation between ditch size and load contribution to determine ratio that can be used in determining ditches that potentially contribute disproportionate amounts

4.2.1 CHLORINITY TRENDS IN WATER PUMPED FROM BROGRAVE PUMP

Figure 17: The majority of chlorinity values measured from the Brograve pumps fall between 1500 and 6000 Cl^{-1}mg/l. Values under 1500 and over 6000 are the extremes indicating minimum or maximum values or data anomalies. (Sourced from the IDB, July 2008)

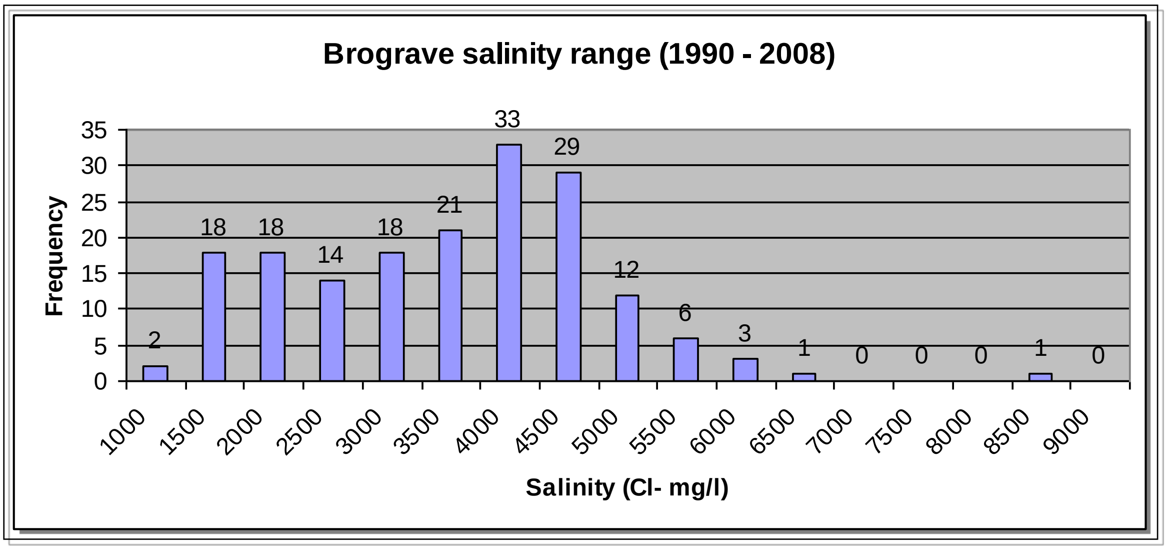
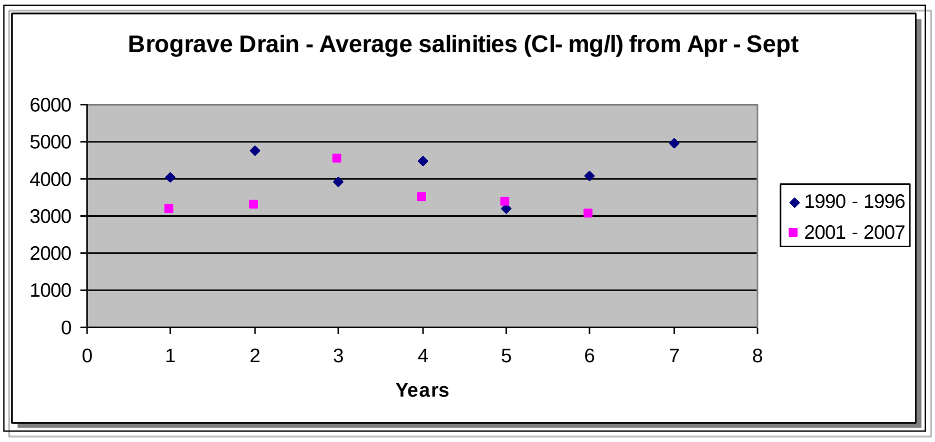


Figure 17 and 18 both show that the Brograve pump is discharging highly brackish → saline water from the catchment. Discharges from the pump have consistently been above 1000mg/L for the past two decades.

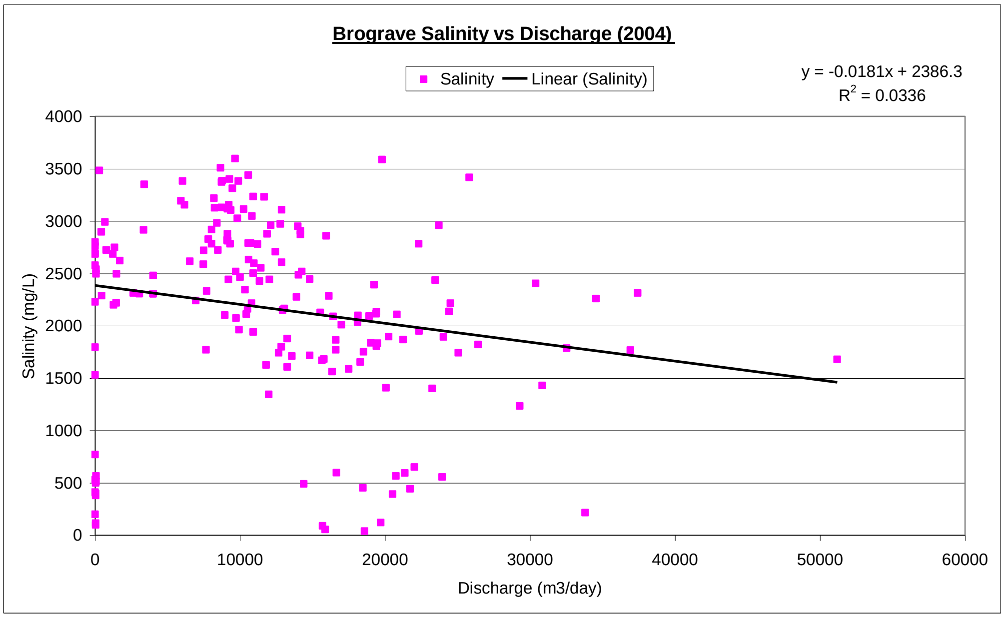
Figure 18: Average salinities [measured in Chloride concentration) in Brograve over past decade have remained within 3000 mg/L→ 5000mg/L. (Source EA 2008).



4.2.2 DISCHARGE FROM BROGRAVE PUMP 2004

Data from 2004 is used to analyse correlations between salinity and discharge as more complete data was available for this year.

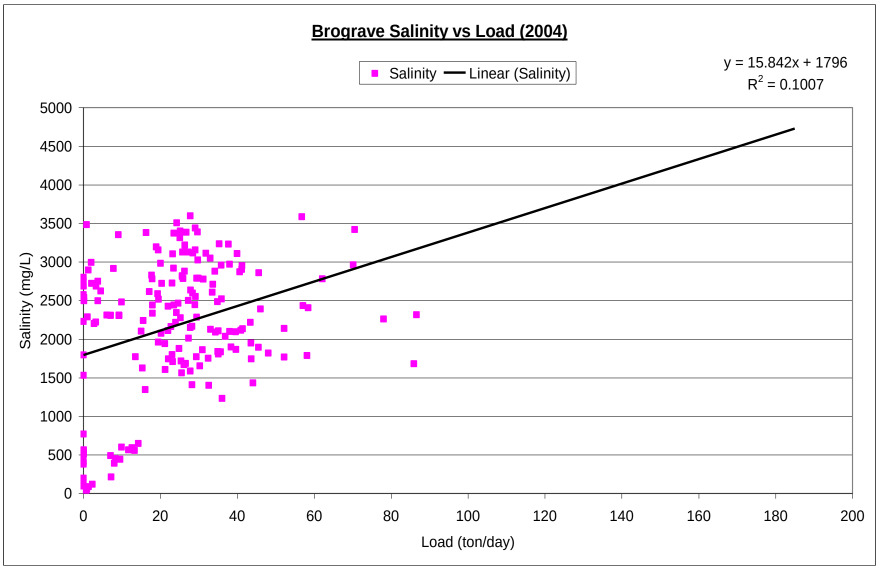
Figure 19: The Chlorinity levels appear to be unrelated to discharge.



4.2.3 LOAD VALUES FOR BROGRAVE PUMP 2004

Chlorinity values range between 1000mg/l and 3500 mg/l. Where the load value doubles there is no corresponding increase in chlorinity demonstrating chlorinity value remains stable despite volumes of water pumped.

Figure 20: Graph to show relation between Chlorinity values and Load from Brograve pump



Load appears to correspond more closely to the volumes of water pumped (figure 21). This confirms the hypothesis of relatively stable salt concentration in water (Figure 21 and 22).

Figure 21: Graph to show relationship between load from Brograve level pump and discharge

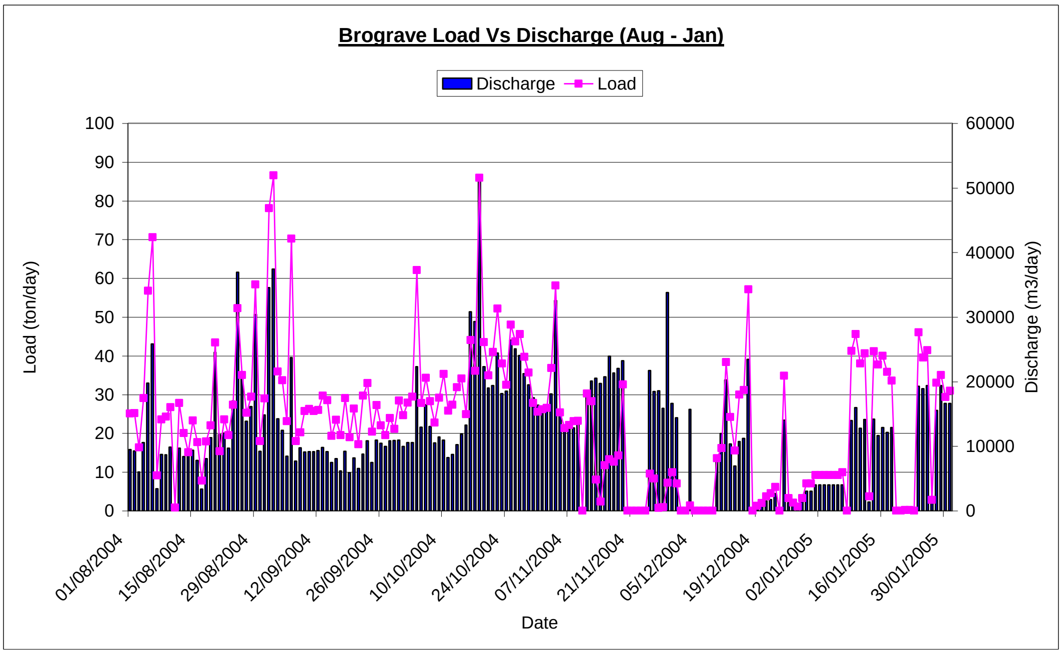
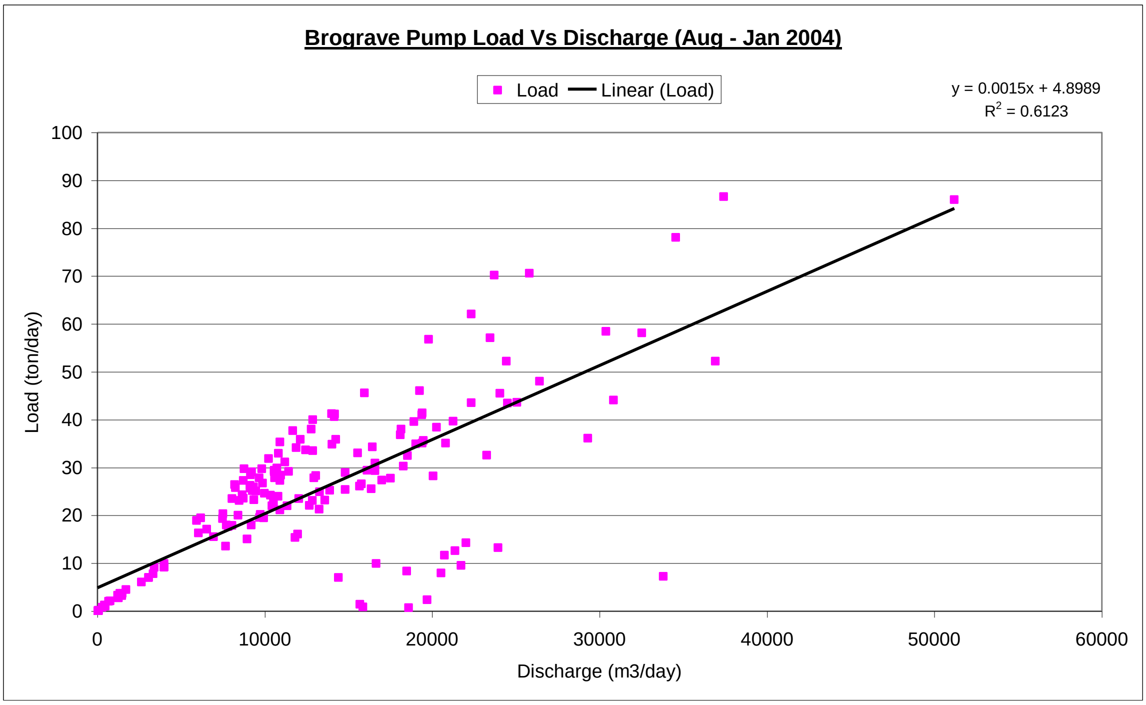


Figure 22: Scatter Graph to demonstrate load versus discharge relationship



The Graphs below show the levels of pumping during the period of the survey, even on dry days there is still some pump activity.

Figure 23: Graph to show salt load discharged from Brograve pump 1st Jun 2008 - 12th Aug 2008. When pumps are active salt load fluctuates between 80 and 8000 kg/l. Zero values indicate when pumps are inactive (Source EA 2008)

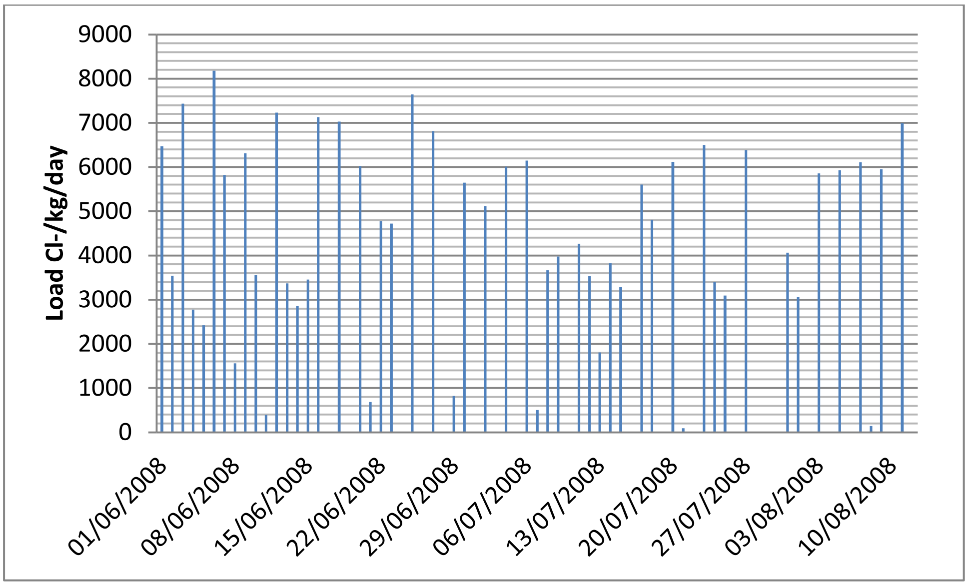
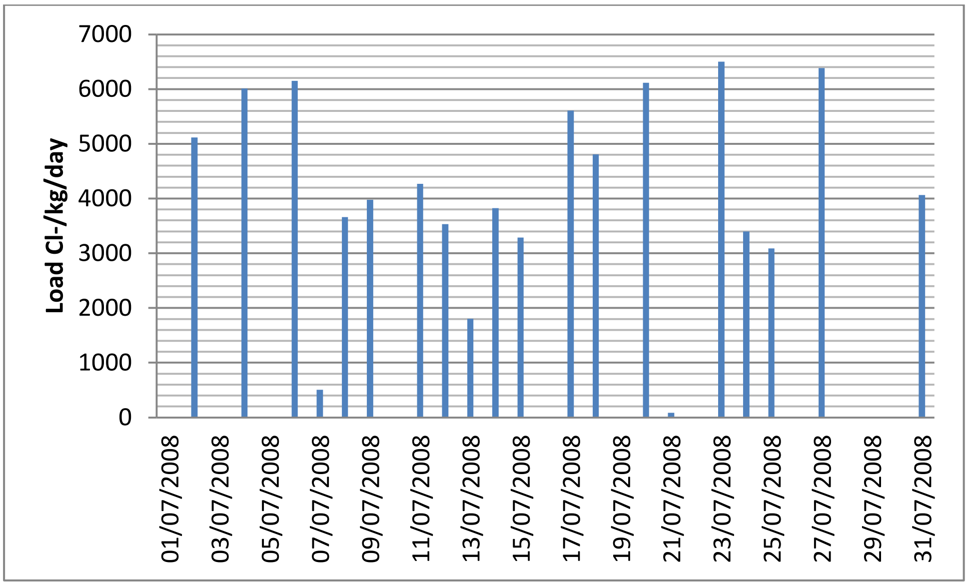


Figure 24: Load discharged from pump during the time of the field survey (load ranges between 0 and 8000 kg/day)



4.3 SOMERTON LEVEL TELEMETRY DATA ANALYSIS

The final objective of this research was to look at how changes to water table management have affected salt load discharges from the Somerton pumps which are adjacent drainage to the Brograve Catchment. If the raising of water levels in the Somerton level drainage area is shown to have been successful this could provide justification for replicating the same in the Brograve level and results from this analysis could also provide an indication of the timescales of response to restorative measures.

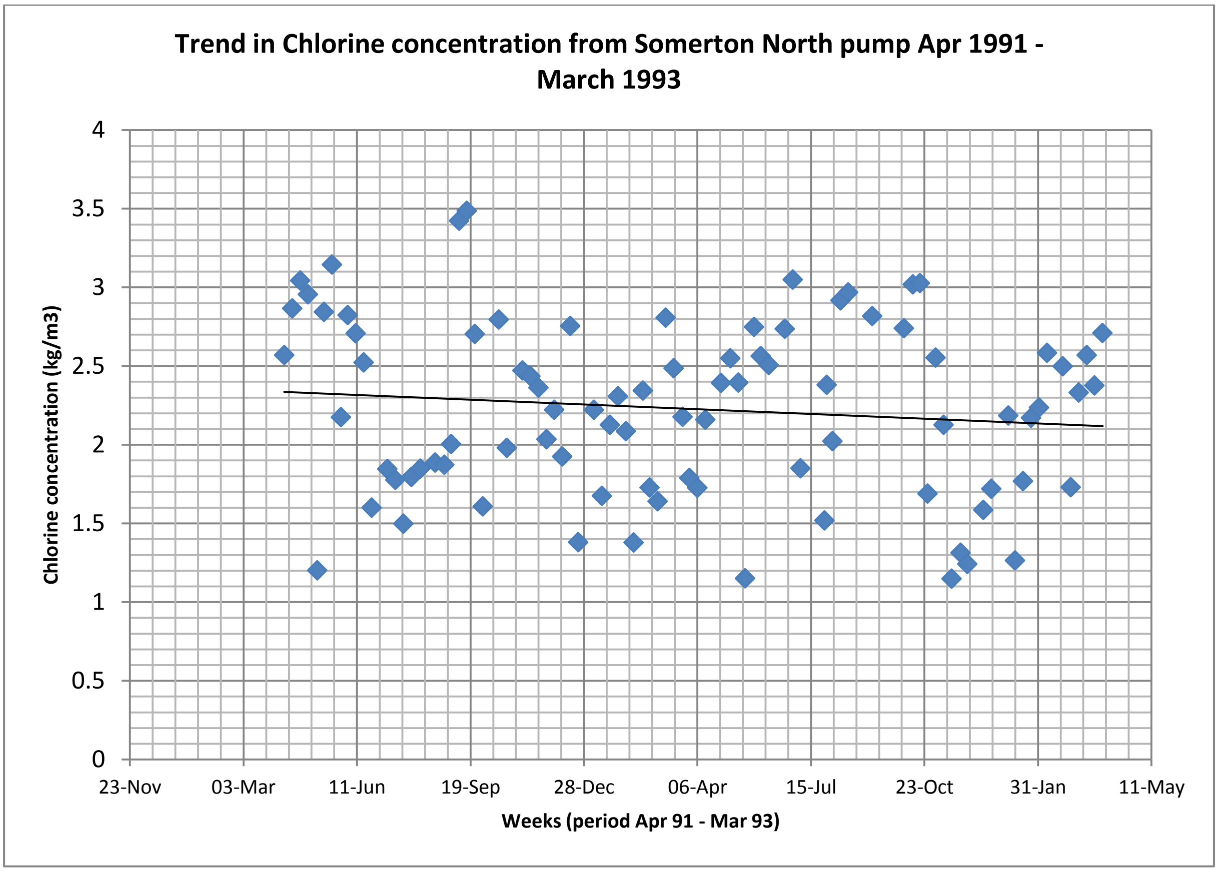
The following graphs therefore assess the chlorinity, discharges and loads from the two Somerton pumps prior to intervention and the same parameters post intervention in 2005. They will show whether or not chlorinity in drainage ditches and the saline loads to the pump shows a significant difference post-intervention.

Pre-Intervention Data Analysis – 1991 - 1992

4.3.1 TRENDS IN CHLORINE CONCENTRATION OF WATER PUMPED FROM SOMERTON NORTH AND OLD PUMPS 1991/1992

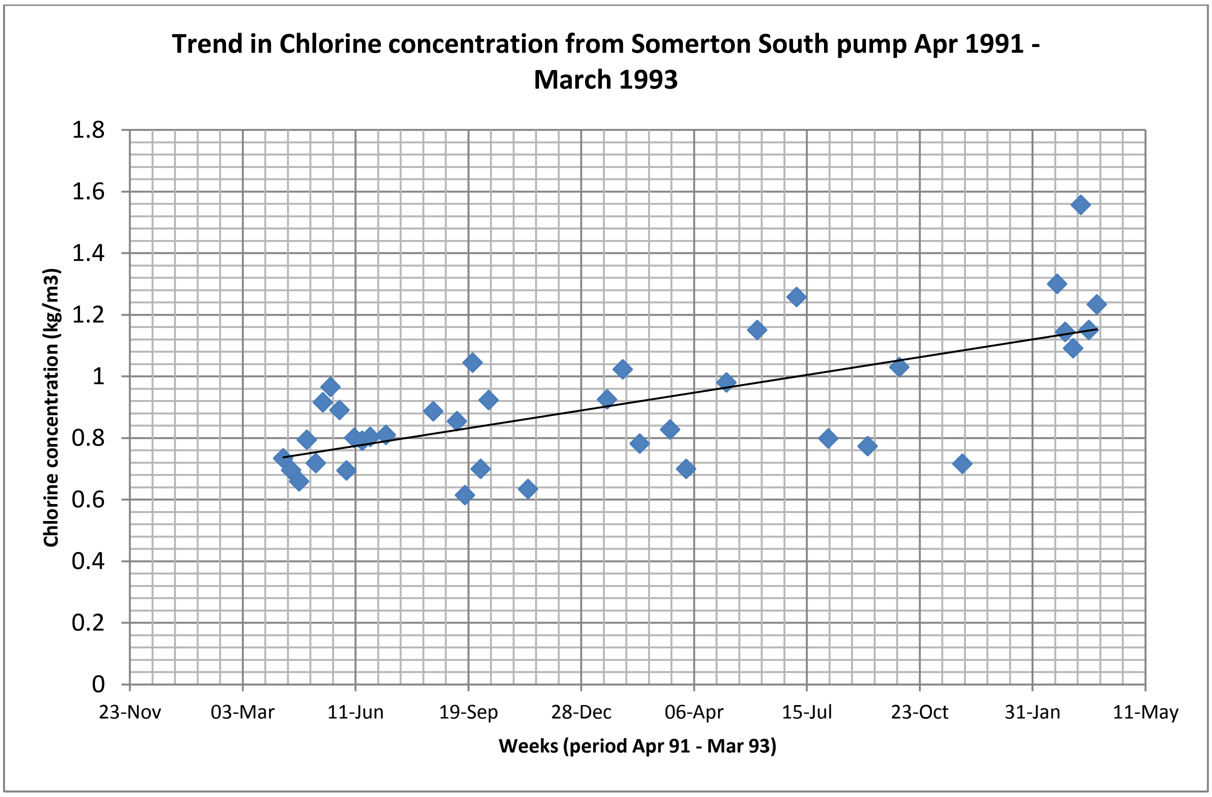
The chlorinity of the water in the Somerton North pump remains within the range of 1kg/m^3 and 3 kg/m^3. No significant changes in this range are observed over the 24 month period (figure 25).

Figure 25: Somerton North pump Chlorinity Apr 91 - Mar '93



The majority of Somerton South Pump Chlorine values range between 0.5 kg/m^3 and 1.5 kg/m^3 with average chlorinity values showing an increase toward the end of the two-year period (Figure 26).

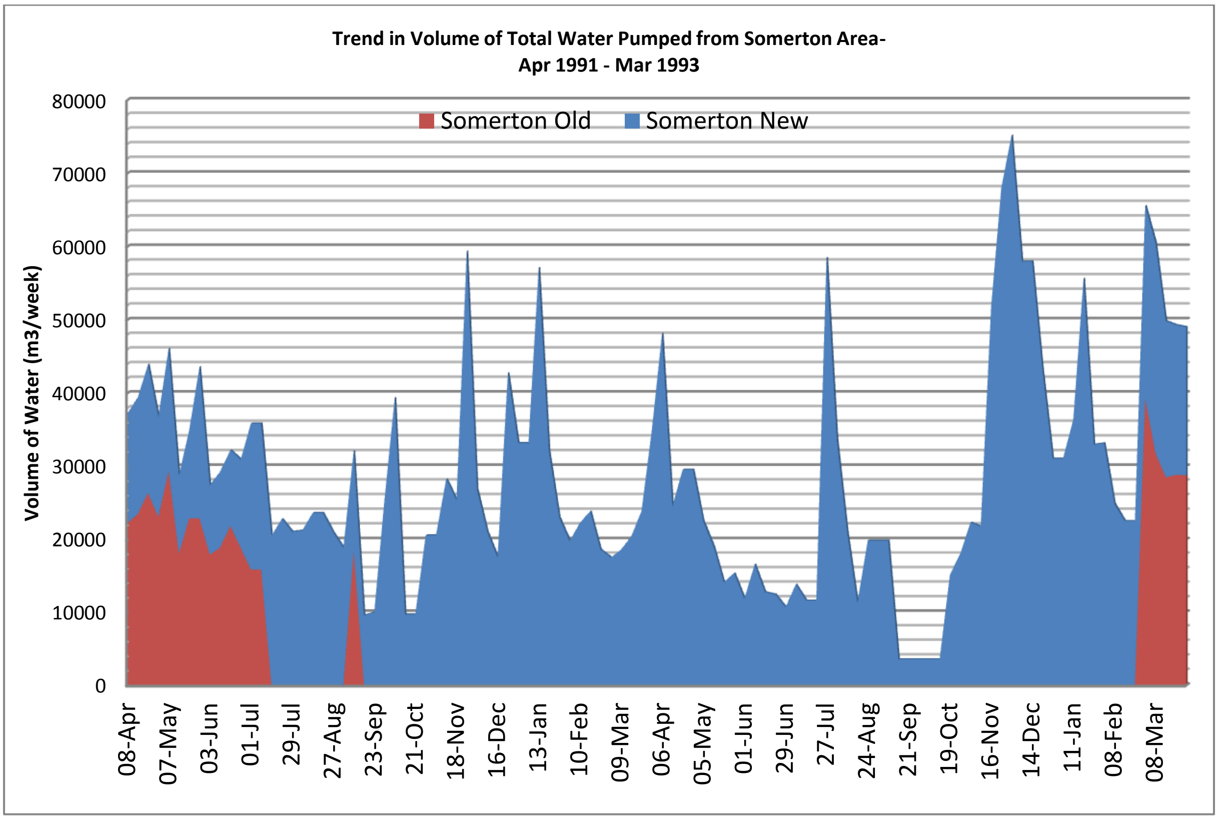
Figure 26: Somerton South Pump Chlorinity Apr'91 - mar '93



4.3.2 *TRENDS IN VOLUMES OF WATER PUMPED FROM SOMERTON NORTH AND SOUTH PUMPS*

The figures below show that prior to intervention the volumes of water pumped from the Somerton North Pump were significantly greater than those pumped from the Somerton South Pump. The total volume of water pumped is extremely high with the average of over 20,000 m^3 per week.

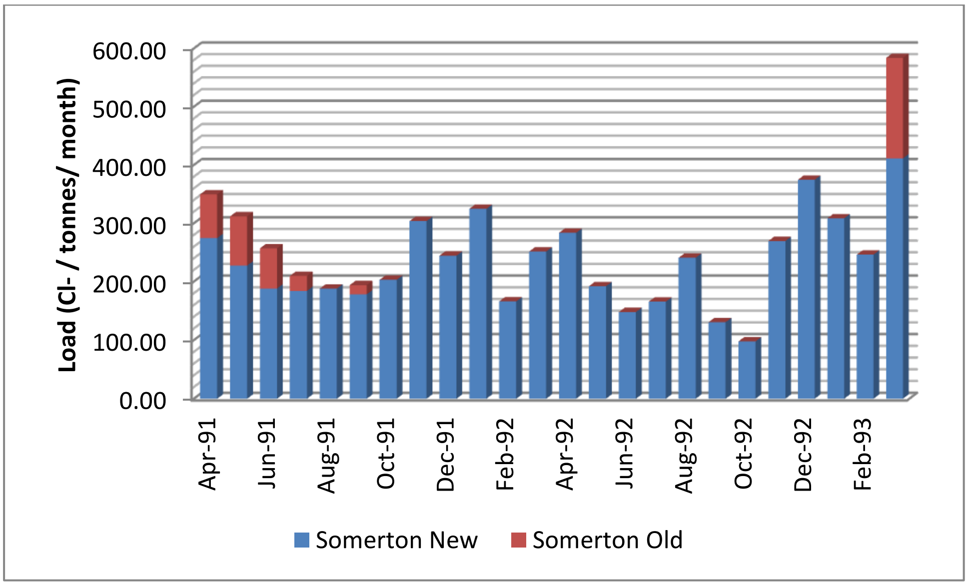
Figure 27 Total Volume of water pumped from Somerton pumps Old and New (cumulative graph)



4.3.3 *TRENDS IN LOAD (KG/MONTH) FOR SOMERTON NORTH AND SOMERTON SOUTH PUMPS:*

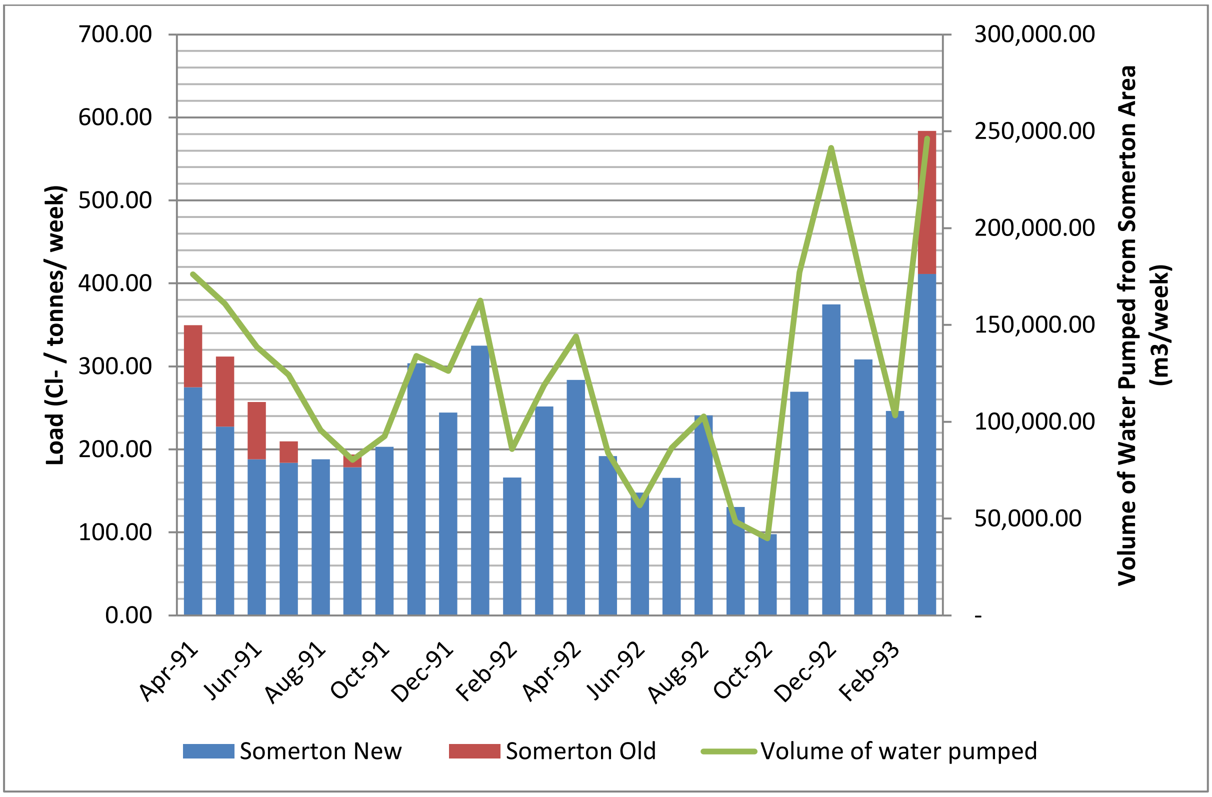
As expected Somerton North contribution to Load is much higher than Somerton South with the Somerton North pump having a significantly higher average chlorinity and the significant difference in the volume of water being pumped.

Figure 28: Trend in Load (tonnes Cl-/month) for Somerton North and Old pumps - Apr'91 - Mar'93



Increase in Load is directly correlated with Increase in volume of water pumped as seen in graph below. This indicates that salt concentrations remain fairly stable and the main factor influencing load is the volume of water discharged.

Figure 29: Graph to show Load from Somerton Area compared with Volume of Water pumped (Apr '91 – Mar '93)



Post-Intervention Data Analysis, Comparison of 1991/92 with 2004/5 data for Somerton South and 2007/8 data for Somerton North

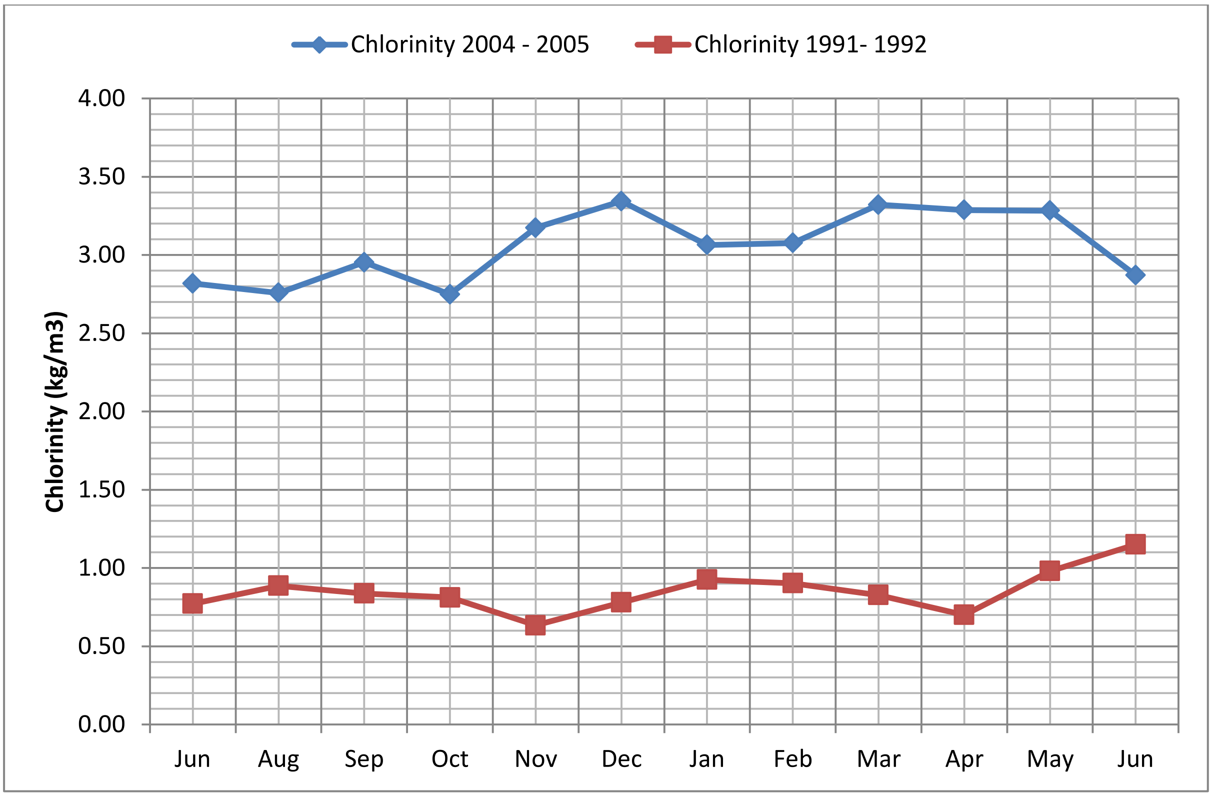
The data for the Somerton South Pump was incomplete for many years with malfunctioning of both the pump and chlorinity meters, thus no reliable data could be obtained for the post-intervention period. The most complete data obtained was for the year 2004/2005 just prior to intervention thus this was used in the telemetry analysis.

Somerton North data was also incomplete in many parts as explained in the methodology section. The most complete data was obtained for 2007 and thus indicates changes in chlorine, discharge and subsequently load two years after water levels were raised in the area. This data gives some indication of the level of success in terms of reducing the load.

4.3.4 TREND IN CONCENTRATION OF CHLORINE IN SOMERTON SOUTH PUMP WATER 1991/92 AND 2004/05

Analysis was made of the average chlorine levels in the Somerton South pump between the two time periods.

Figure 30: Comparison of chlorinity of Water from Somerton South Pump



As can be seen from the figures above, there was a huge increase in chlorinity of water over 11 year period.

4.3.5 COMPARISON OF DISCHARGE DATA FROM SOMERTON SOUTH PUMP 1991/1992 AND 2004/2005

In terms of the discharge at the Somerton South pump, pumping levels significantly increased between the time periods and Somerton South discharge was similar to that of the Somerton North pump prior to intervention – see figures 30 and 31.

Figure 31: Water pumped from Somerton South significantly increased between 1991 and 2004

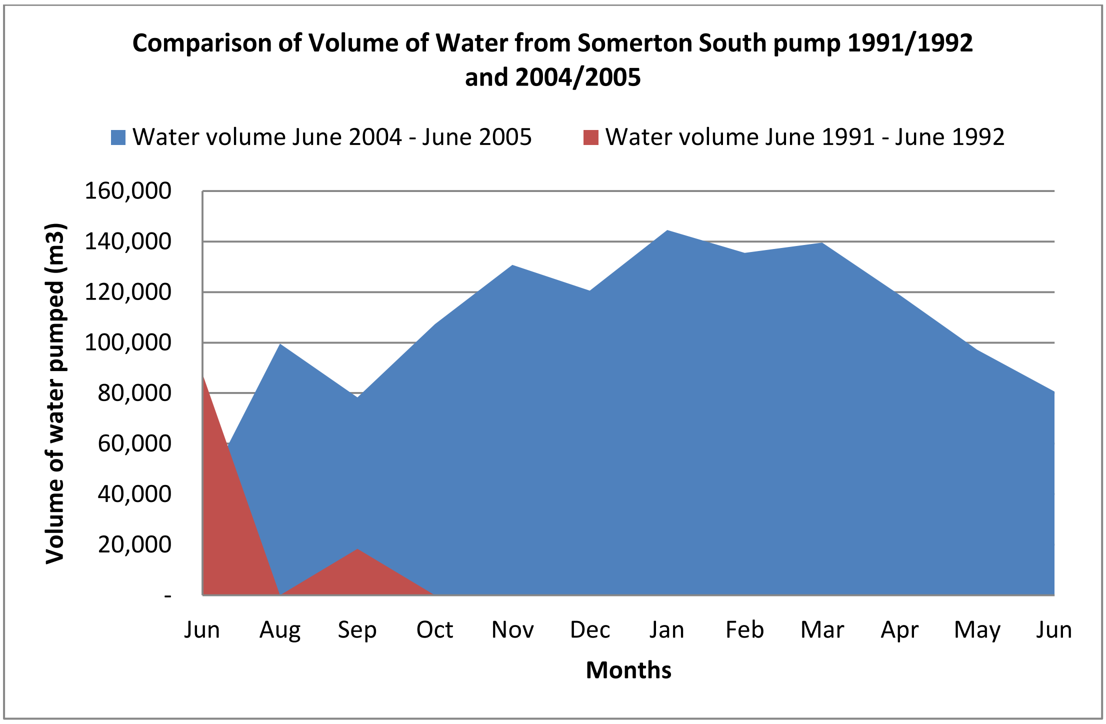
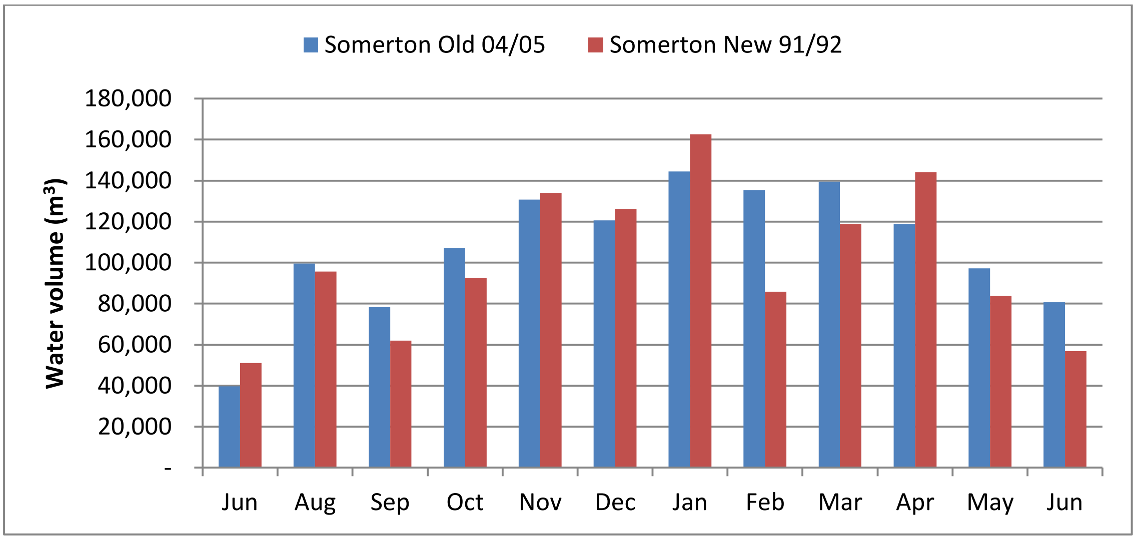


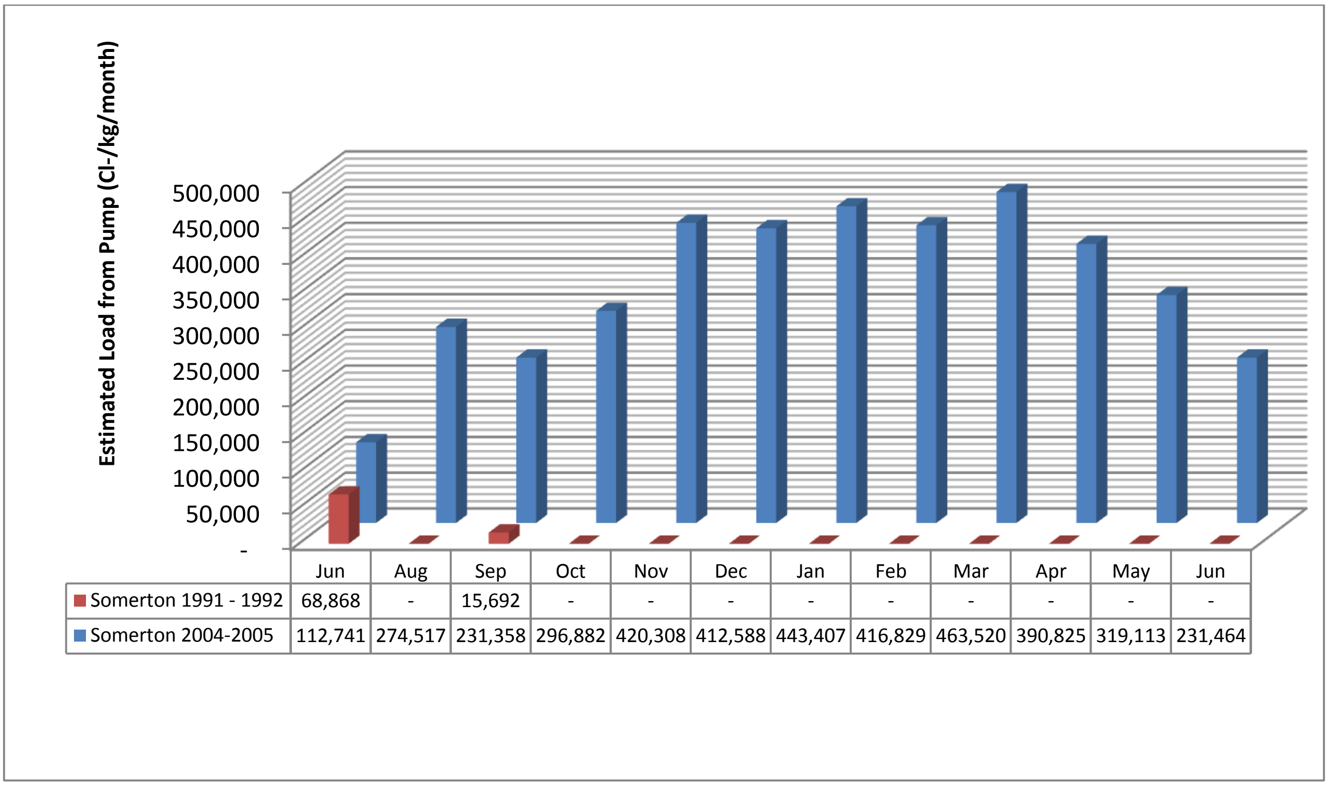
Figure 32: Levels of pumping at Somerton South in 2004/05 grew to similar levels to that of Somerton North Pumping in the 90s



4.3.6 COMPARISON OF LOAD FROM SOMERTON SOUTH PUMP

As expected, due to a significant increase in chloride and water discharge, salt load contribution from the Somerton South pump increased significantly compared to that in 1991.

Table 13: Graph to compare Load (Cl-/kg/month) from Somerton South Pump

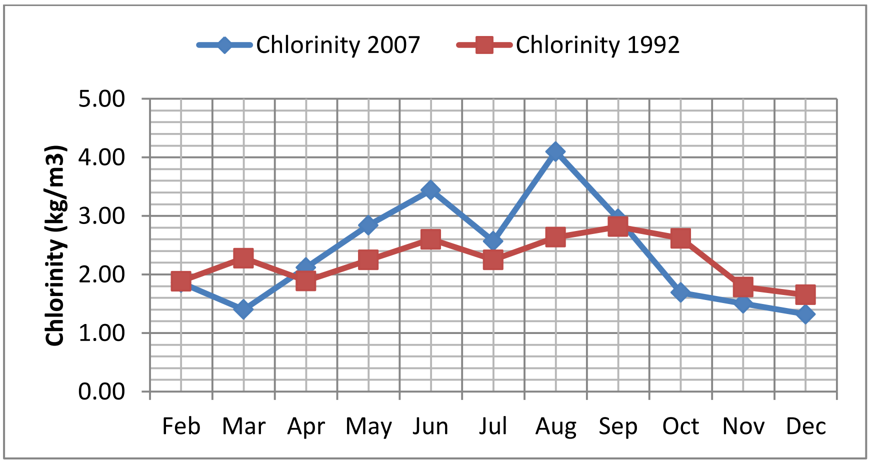


	Jun	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
🟥 Somerton 1991 - 1992	68,868	-	15,692	-	-	-	-	-	-	-	-	-
🟦 Somerton 2004-2005	112,741	274,517	231,358	296,882	420,308	412,588	443,407	416,829	463,520	390,825	319,113	231,464

4.3.7 TREND IN CONCENTRATION OF CHLORINE IN SOMERTON NORTH PUMP WATER 1991/92 AND 2007

Apart from some anomalously high chlorinity values measured in June and August of 2007/2008 period, chlorinity values for Somerton North range between 1.25 and 3 kg /m³ for both time periods, thus no significant change observed in the saline intrusion levels in the catchment area for this pump (Figure 33).

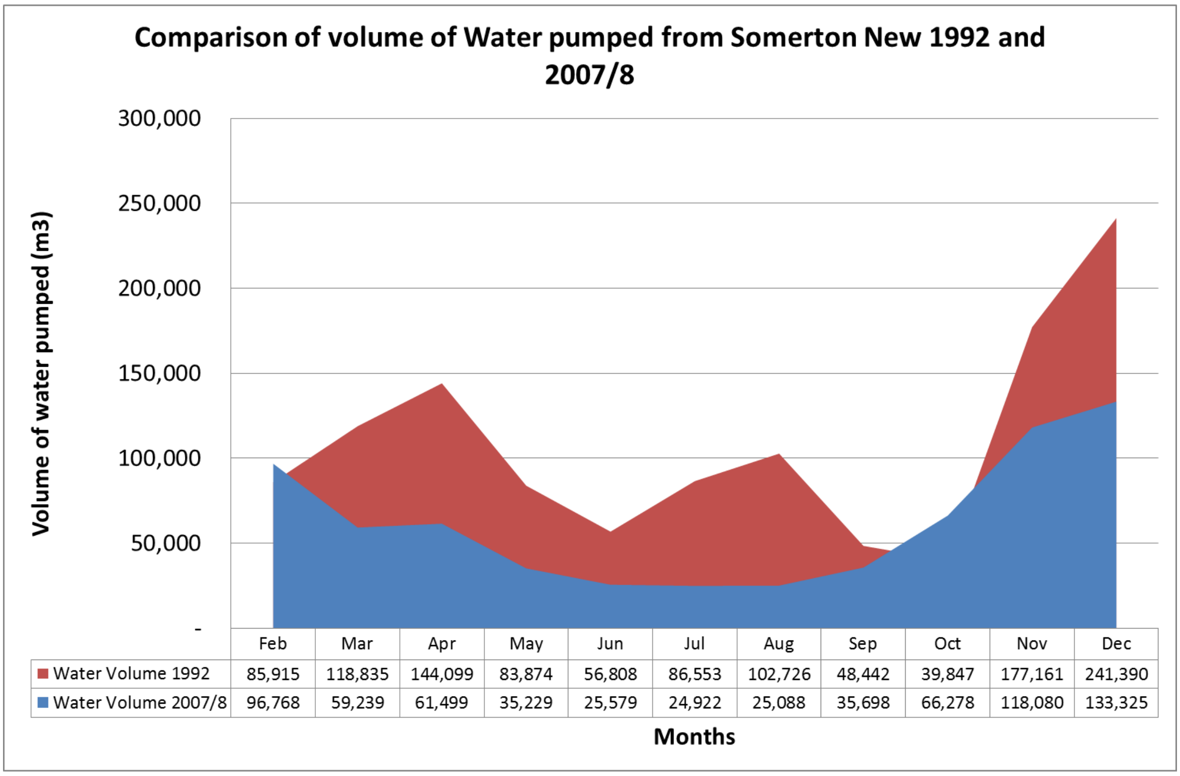
Figure 33: Comparison of chlorinity of Water from Somerton North Pump



4.3.8 COMPARISON OF VOLUME OF WATER PUMPED PRE AND POST INTERVENTION AT SOMERTON NORTH PUMP

The figure below shows that by 2007 pumping levels in Somerton North had been significantly reduced (Figure 34.)

Figure 34: Volume of Water pumped from Somerton North Pump in 1992 and 2007/8



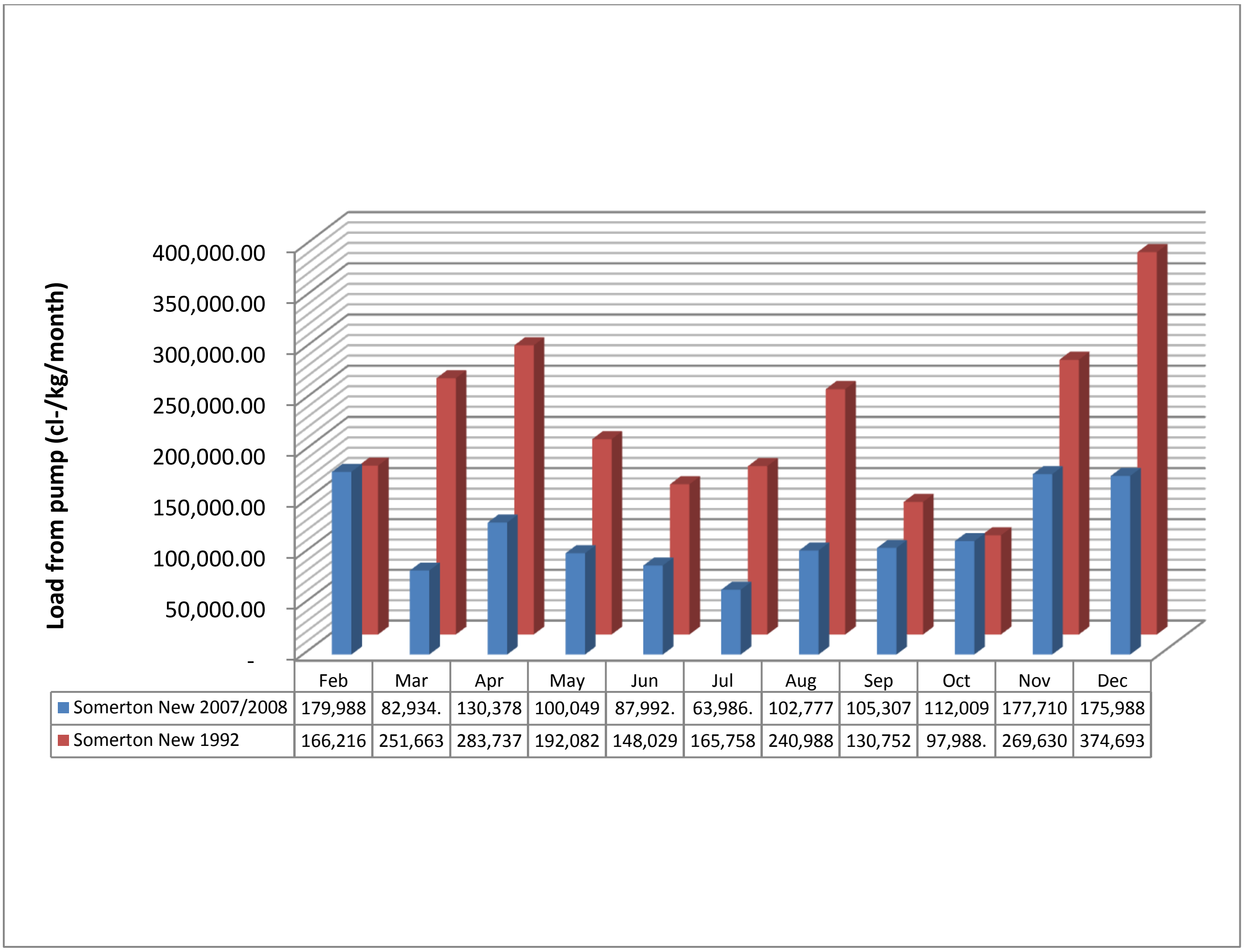
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟥 Water Volume 1992	85,915	118,835	144,099	83,874	56,808	86,553	102,726	48,442	39,847	177,161	241,390
🟦 Water Volume 2007/8	96,768	59,239	61,499	35,229	25,579	24,922	25,088	35,698	66,278	118,080	133,325

The total estimated volume of water pumped for 1992 is 1,185,649.71 and that for 2007/8 is 681,704.45 m^3 representing a reduction in water volume of nearly 40%. The pattern of water pumping between the two periods appears similar with an increase in pumping levels during spring months (March – May) where presumably rainfall is higher and a reduction observed during the winter months.

4.3.9 COMPARISON OF LOAD FROM SOMERTON NORTH PUMP

As expected, load from Somerton North is also significantly reduced.

Figure 35: Graph to showing estimated Load values (Cl-/kg/month) from Somerton North Pump in 1992 and 2007/8



	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Somerton New 2007/2008	179,988	82,934.	130,378	100,049	87,992.	63,986.	102,777	105,307	112,009	177,710	175,988
🟥 Somerton New 1992	166,216	251,663	283,737	192,082	148,029	165,758	240,988	130,752	97,988.	269,630	374,693

Graph shows reduction in ~ 40% reduction in Load following intervention. The estimated load over a 10 month period in 2007/08 in kg of Cl- over 10 month period is approximately 1,319,125 kg whereas the estimated Load over a 10 month period in 1992 in kg of Cl- over 10 month period was 2,321,542 kg representing a difference of over 100,000 tonnes.

5 DISCUSSION

5.1 CHLORINITY AND FLOW SURVEY RESULTS – BROGRAVE LEVEL – JUNE 2008

All ditches measured showed relatively high chlorinity levels indicating that saline water from the aquifer is being directly fed into the ditches.

As the samples were measured during a dry period the assumption can be made that the chloride concentration measured is representative of the groundwater composition in the aquifer. The entry of this salinised groundwater indicates that ditch profiles and water levels in the ditch are still so low as to result in a discharge of groundwater into ditches. The results also show that saline intrusion is generally widespread throughout the marshlands although to different extent in the various areas.

With the exception of the Firtree marsh all the other marshes transport a significant proportion of salty water into the Brograve Main Drain.

Hempstead marsh was shown to contribute the highest load to the system. Waxham was shown to contribute more than average load with respect to its size. This is likely to be due to the high chlorinity observed in the ditches.

5.2 TELEMETRY DATA FROM BROGRAVE LEVEL PUMP

Telemetry data from the Brograve pumps show a high salt load discharge.

Considering that the target chlorinity for the Horsey Mere is 1000mg/L, the results of the analysis of telemetric pump data show how the discharges from the Brograve pump are likely to impede the attainment of low salt levels in the Upper Thurne Broads. It confirms the hypothesis that in order to restore water quality within the Broads, salt levels in the drainage water will have to be lowered.

Pumping activity is linked to a rise in water levels. Therefore in months where there is higher rainfall and the water table rises there is an increase in discharge from the pump. It was expected that as a result of this freshwater input into the water system, salinity of the pumped water would drop in periods of high discharge however this was not the case, and chlorinity did not demonstrate a correlation with the discharge volumes

In some instances on the graph the load value is shown to double yet there is no corresponding response in chlorinity value. This could indicate that the transport of salty water from the marshes to the drainage pump is driven to a large extent by the gradient differential that is created between the main drain and marsh ditches when the pumps are active. Discharges from the pumps could actually be driving discharge from the aquifer into the ditches or alternatively it could be that the drains accumulate salt when the pump isn't running, resulting in a high load being pumped when it is switched on to 'empty' the drains. The very high loads don't appear to be generally in the winter, suggesting that it is not just a question of more water pumped.

5.3 TELEMETRY DATA FROM SOMERTON LEVEL PUMPS – PRE AND POST INTERVENTION ANALYSIS

5.3.1 PRE-INTERVENTION1991/92

Freshwater has a chloride concentration between 0.01 and 0.25 kg/m^3 and Brackish water a concentration ranging between 0.5 – 5 kg/m^3. In general water at the Somerton pump falls within expected values for brackish water and ranges between mildly and moderately brackish (Figure 26).

For the Broads authority, chloride concentration limits are set between 0.6 kg/m^3 and 1kg/m^3 for the lake water to be considered to be of good quality. Water from the Somerton North pump is consistently above this level over the time period measured (figure 25).

5.3.2 POST INTERVENTION 2004/5 AND 2007/8

The significant increase in chlorinity of water from Somerton South indicates either further movement of saline water into the aquifer or that ditches were dug deeper and interacted directly with saline aquifer water.

Chlorinity values in Somerton North pump did not show significant change over the 16 year period measured. This is slightly unexpected as Somerton South showed significant increase in chlorinity over an 11 year period. We could have expected that over a 16 year period thus, a greater increase would be observed. What these results seem to imply is that saline intrusion in the Somerton catchment occurred to different extents within the area but at some point reached a maximum value and then remained stable. It could imply that within the Brograve catchment chlorinity levels may well plateau and reach similar concentration throughout the catchment.

Another explanation for the change in salinity levels is that the ditches in the Somerton South area were re-profiled and dug deeper. The deepening of the profiles of the ditches, as was done in the Somerton area in the late 70s, would place them in direct contact with the salinised aquifer (Holman 1994), this in turn would accelerate the extent of saline intrusion in the drain network. However, as far as has been reported, no physical changes affecting ditch depth or width were carried out to the Somerton ditches between the 1990s and the 2000s, only the volume of water pumped changed during this period. Another influence could also have been changes in which part of the Somerton catchment feeds each pump, if water from the Somerton North Area was diverted to the Somerton South pump this could in part explain the change in chlorine concentration of the water.

6 CONCLUSIONS

This study uses a spatial approach to investigate how seawater intrusion has manifested itself within the different hydrological units within the Brograve level marshlands. Due to the limited sampling over a short space of time, this research can only provide a snapshot of flow characteristics and chlorinity.

The results do however indicate a complexity of flow and storage within the individual marshlands due to a range of hydrological and geological interactions They support the argument that blanket alterations to the water table level management in the area could have varying effects on these units within the catchment.

The differences in the flow and chlorinity recorded in ditches within the marshlands suggest a complex aquifer system, consisting of different compartments which create distinct salt load conditions in the drain network according to their individual hydrodynamic characteristics.

The results also indicate transport of saline water from the aquifer to the pumps is occurring as a direct result of the marsh drain to main drain gradient which occurs when the pumps are active.

The pooh stick method used to estimate the flow conditions provides a useful estimate for comparing flow conditions between the marshes but is limited by observational errors in the field. Additionally there are discharges into the Brograve Main Drain from other marsh areas which were not measured in this field study. Bearing this in mind, estimated load measured from the marshes falls within the same order of magnitude as the load discharged from the Brograve pumps, which indicates measurements can be used to compare salt load contributions between the marshes for the purpose of this research.

The flow variation indicates the speed with which salty water is transported from the marshlands to the main drain. However, it does not give any clear indication of a change in storage that may occur in the ditches. Storage is known to occur in the ditches as water levels varied during the course of the field study. Where ditches are wider this storage capacity is increased.

Transportation of the saline groundwater from individual ditches will therefore vary, not only according to the flow velocity of groundwater discharging into the ditch but also the storage capacity and tendency for water storage in individual ditches. This tendency to store water before discharging in the main drain will also be affected by differences in the topography of the drainage area. Areas with a very flat relief are likely to store more water.

There is also an indication other factors such as proximity of ditches to the coast can have significant impact on their relative contributions of salt load. It was expected that larger ditch size and thus higher discharge would be more significant however the results show that management interventions will have to also have to consider chlorinity and proximity of marsh to the coastline.

This indicates that under a cost-benefit analysis, raising water levels in the Waxham marsh area may provide higher benefits than expected. Raising water table levels in the Hempstead, Waxham and Brograve main marsh areas is likely to have more significant impact on chlorinity levels than raising levels in the Firtree marshes.

This research has shown that when looking at remediative measures for water quality it is important to consider not only the concentrations of the pollutant in question in the water but also how it is transported through the system. It has shown that even when dealing with the same pollutant within one aquifer body, transport characteristics can still show huge variance according to the different hydraulic characteristics of heterogeneous units found in such media. The study has also highlighted the difficulty in managing seawater intrusion in drained catchments and how management strategies require data from both the continuous monitoring of discharges and actual field surveys in order to get a clearer picture of the dynamics of pollutant transport in the area in question.

It has shown how important monitoring of pump discharges is in the catchment and the issues that can arise where data is incomplete – for example in determining the success of implementation measures analysis of data from the Somerton pumps was impeded by an absence of data.

That being said raising of water levels in order to restore the quality of water in Broads fed by the Somerton Pumps does show promising results. The results show that within a 2 year period significant reduction in load is obtainable provided chlorinity levels remain stable. Chlorinity levels tend to remain stable in Brograve and Somerton North pump water but show a significant increase at the Somerton South, potentially due to the huge increase in pumping. It demonstrates that once chlorine levels have obtained a certain level, reduction in pumping does not result in a reversal of the salinisation.

The rise in chlorinity of the Somerton South pump water shows a worrying trend but not totally unexpected. Enormous volumes of freshwater are displaced before the effects of saline intrusion are normally detected in an aquifer. As such the effects of salt intrusion mitigation activities also take a long time for effects to be seen with evidence that this can be between several decades to centuries (Essink 2001).

7 KEY RECOMMENDATIONS:

Further study however is required on flow dynamics when pumps are active in order to ascertain how the proximity of the drains to the Brograve main drain and pump influences their salt load contribution at times of pumping and whether this alters their ranking in terms of overall salt load contribution to the pump discharges.

1. further flow characterisation of ditches in order to ascertain flow regimes during or immediately following pumping of the Brograve catchment
2. Further studies on change in storage observed in drainage ditches that do not flow when pumps are inactive
3. Follow on analysis of Somerton pump telemetric data over a longer timescale.
4. Analysis on the likely impact of climate change to seawater intrusion and the restoration of water quality in the Upper Thurne Catchment.

8 REFERENCES

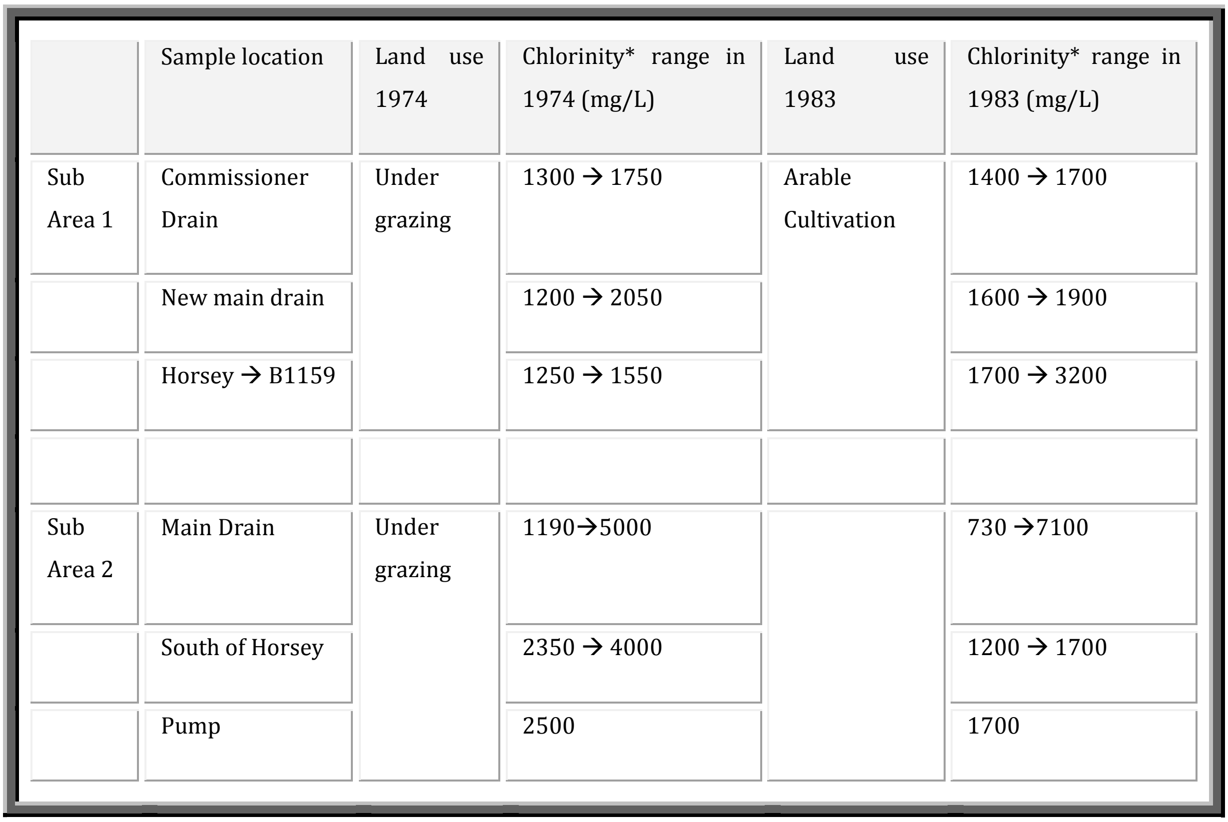
1. Arfib, B., de Marsily, G., Ganoulis, J. (2007) Locating the Zone of Saline Intrusion in a Coastal Karst Aquifer Using Spring flow Data. *Ground Water* **45 (1)** pp28-35
2. Barker, T., Hatton, K., O'Connor, M., Connor, L., Bagnell, L. and Moss, B. (2008). Control of ecosystem state in a shallow, brackish lake: implications for the conservation of stonewort communities Aquatic Conservation: Marine and freshwater ecosystems **18**: pp221–240
3. Bilotta, G. S., Brazier, R. E., Haygarth, P. M., Macleod, C. J. A., Butler, P., Granger, S., Krueger, T., Freer, J., Quinton, J.(2008).Rethinking the Contribution of Drained and Undrained Grasslands to Sediment-Related Water Quality Problems. *Journal of Environmental Quality* **37**:pp 906-914
4. Driscoll, R.J. (1984) Chloride ion concentration in dyke water in the Thurne catchment area in 1974 and 1983. Unpublished Report for NCC, Norwich:
5. Driscoll, R.J. (1985) The effect of changes in land management on the dyke flora at Sommerton and Winterton. Trans. Norfolk Norwich Nat. Soc. **(27)**: 33-41.
6. Ecology, Land and People (ELP) (2004). Feasibility study for solutions to the salinity and ochre issues in the Brograve catchment.
7. Essink, O., Gaulbert, H.P. (2001) Improving fresh groundwater supply—problems and solutions. *Ocean & Coastal Management*,**44(5-6),**pp429-449
8. Holden, J., Evans, M. G., Burt, T. P., Horton, M.(2006) Impact of Land Drainage on Peatland Hydrology. *Journal of Environmental Quality* **35**: pp1764-1778
9. Holdway, P.A., Watson, R.A., Moss, B.(1978). Aspects of the ecology of Prymnesium parvum (Haptophyta) and water chemistry in the Norfolk Broads, England. *Freshwater Biology* **8 (4)** pp295–311.
10. Holman, I.P. (1994) Controls on saline intrusion in the Crag aquifer of north-east Norfolk. University of East Anglia, Unpublished PhD thesis

11. Holman, I et al (1999) Crag aquifer characteristics and water balance for the Thurne catchment, northeast. *Quarterly Journal of Engineering Geology and Hydrogeology*. **32**: pp365-380.
12. The Institute of Food and Agricultural Sciences (IFAS) (2005) Iron Ochre And Related Sludge Deposits In Subsurface Drain Lines. (http://edis.ifas.ufl.edu/pdffiles/AE/AE02600.pdf)
13. Montety, V., Radakovitch , O., Vallet-Coulomb, C., Blavoux, B., Hermitte, D., Valles, V. (2008) Origin of groundwater salinity and hydrogeochemical processes in a confined coastal aquifer: Case of the Rhône delta (Southern France) *Applied Geochemistry* **23** pp2337–2349
14. Moss, B (1983) The Norfolk Broadland: Experiments in the restoration of a complex wetland. *Biological Reviews* **58:4**:pp 521 – 561
15. Moss, B. (1994) Brackish and freshwater shallow lakes - different systems or variations on the same theme? Nutrient Dynamics and Biological Structure in Shallow Freshwater and Brackish Lakes *Hydrobiologia* **275/276:** pp1-14.
16. Narayan,K.A., Schleeberger, C., Charlesworth, P.B., Effects Of Groundwater Pumping On Saltwater Intrusion In The Lower Burdekin Delta, North Queensland
17. Serwan M. J. Harper, D.M., Brierley, B. A.J.D. Ferguson & G. Phillips (eds),(1999), Use of remote sensing and geographical information systems in developing lake management strategies *Hydrobiologia* **395/396**: pp 211–226.
18. Stewart, N.F. (2004).Important Stonewort Areas. An assessment of the best areas for stoneworts in theUnited Kingdom (summary). *Plantlife International*, Salisbury, UK.
19. Vasquez, E.A., Glenn, E.P., Glenn, R., Guntenspergen, J., Brown, J., Nelson, S.G. Salt tolerance and osmotic adjustment of *Spartina alterniflora* (Poaceae) and the invasive M haplotype of *Phragmites australis* (Poaceae) along a salinity gradient

9 APPENDICES

APPENDIX 1: OUTCOMES FROM DRISCOLL SURVEY AND SAMPLE POINTS

Table 14: Driscoll was commissioned by the nature conservancy to carry out a survey of the chlorinity in the Upper Thurne Catchment. The area containing the Brograve Level (sub-Area 1) was surveyed in 1974 and 1983. below are the results of this survey (Driscoll 1984)



	Sample location	Land use 1974	Chlorinity* range in 1974 (mg/L)	Land use 1983	Chlorinity* range in 1983 (mg/L)
Sub Area 1	Commissioner Drain	Under grazing	1300 → 1750	Arable Cultivation	1400 → 1700
	New main drain		1200 → 2050		1600 → 1900
	Horsey → B1159		1250 → 1550		1700 → 3200
Sub Area 2	Main Drain	Under grazing	1190→5000		730 →7100
	South of Horsey		2350 → 4000		1200 → 1700
	Pump		2500		1700

* measured in Chloride concentrations (mg/L)

Driscoll drew the following conclusions from his chlorinity surveys from the two years. Firstly, all the water in these regions were brackish, patterns of chlorinity were very similar between 1974 and 1983 and additionally chlorinity was conclusively shown to be derived from groundwater as all surface water above dyke levels were fresh.. Groundwater is saline under most of the research area (Holman 1997, Simpson 2007).

APPENDIX 2: DATA FROM FIELD STUDY

Table 15: Grid References for Sampling areas

Marsh Represented	Location Description	Grid Ref
Hempstead	Near Boundary Farm	411267
HM + LESSGM	bridge where logger inserted	410264
Lessingham	Near Boundary Farm	409267
Great Moss Fen	Dairy Barns	423256
GMF 2	Lambrigg Mill	423252
Waxham	Brograve Farm	439253
Bridge Farm Main Marsh	Bridge House	443247
Firtree	FT Pig Farm	448239

Table 16: Flow survey for different field sites

Marsh / Day of sampling	speed (s)	average(s)	length (m)	velocity m/s	Final average flow calculated (m/s)
Hempstead					
Day 1	41.97	43.59	2	0.0459	0.046
	42.89				
	43.97				
	45.54				
Lessingham					
Day 1	57.15	42.55	2	0.0470	0.047
	59.91				
	28.10				
	30.56				
	42.77				
	38.35				
	41.00				
Great Moss Fen					
Day 1	39.94	39.94	2	0.0501	0.025
Waxham					
Day 1	27.62	37.33	2	0.0536	0.066
	46.08				
	51.27				

	31.15				
	31.35				
	36.50				
Day 2	23.60	27.09	2	0.0738	
	27.03				
	25.44				
	30.04				
	29.88				
	24.66				
	28.99				
Day 3	28.81	28.89	2	0.0692	
	29.06				
	29.53				
	32.19				
	25.1				
	32.28				
	25.29				
Bridge Farm					
Day1	40.38	44.19	2	0.0453	0.036
	30.39				
	36.57				
	39.36				
	50.07				
	35.63				
	49.19				
	72.47				
	43.92				
	43.92				
Day 2	93.67	79.45	2	0.0252	
	118.97				
	68.69				
	54.42				
	91.27				
	62.00				
	67.13				
Day 3	83.87	52.72	2	0.0379	
	37.1				
	62.61				
	43.55				
	44.92				
	53.35				
	43.61				

Table 17: Data table for Chlorinity, Discharge and Load for field sites

	Day 1 – 24 Jun			Day 2 – 25 Jun			Day 3 – 26 Jun			Day 4 – 27 Jun			Day 5 – 3 Jul		
	Cl- kg/m^3	Vol m^3/day	Load 1	Cl- kg/m^3	Vol m^3/day	Load 2	Cl- kg/m^3	Vol m^3/day	Load 3	Cl- kg/m^3	Vol m^3/day	Load 4	Cl- kg/m^3	Vol m^3/day	Load 5
Hempstead	8.16	1,550.71	12,660	9.54	1,550.71	14,792	8.56	1,550.71	13,275	7.43	1,550.71	11,514	7.49	1,550.71	11,613
Lessingham	0.04	2,071.23	84	0.08	2,071.23	163	0.05	2,071.23	110	0.20	2,071.23	411	0.02	2,071.23	34
Great Moss Fen	3.39	-	-	3.85	-	-	5.57	-	-	6.49	-	-		-	-
GMF 2	4.66	845.83	3,942	2.99	845.83	2,533	4.98	845.83	4,213	6.00	845.83	5,079	4.66	845.83	3,942
Waxham	8.20	699.93	5,740	8.04	964.41	7,754	8.42	904.24	7,612	8.53	856.20	7,301	8.72	856.20	7,462
Bridge Farm	7.91	1,540.69	12,191	7.93	856.93	6,799	8.57	1,291.52	11,072	8.66	1,229.71	10,650	9.51	1,229.71	11,697
Firtree	4.29	-	-	3.44	-	-	4.98	-	-	4.83	-	-	5.62	-	-