A HYDROLOGICAL INVESTIGATION OF THREE DEVON SAND DUNE SYSTEMS; BRAUNTON BURROWS, NORTHAM BURROWS AND DAWLISH WARREN

RACHEL JANE BURDEN

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A HYDROLOGICAL INVESTIGATION OF THREE DEVON SAND DUNE SYSTEMS; BRAUNTON BURROWS, NORTHAM BURROWS AND DAWLISH WARREN

by

RACHEL JANE BURDEN

A thesis submitted to the University of Plymouth in partial fulfilment for the degree of

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Department of Geographical Sciences
Faculty of Science

In collaboration with

English Nature, Environment Agency, Devon County Council, Teignbridge District Council and the Royal North Devon Golf Club

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ABSTRACT

A hydrological investigation of three Devon sand dune systems; Braunton Burrows, Northam Burrows and Dawlish Warren

In 1993 concerns were expressed by English Nature that Devon's three largest sand dune systems Braunton Burrows, Northam Burrows and Dawlish Warren were drying out to the detriment of the dune habitat flora and fauna. Research was therefore required to understand how these systems functioned hydrologically, to determine whether they were drying out and if so to recommend sustainable management options aimed at reinstating former water levels, or preventing any further lowering of the water tables. At Braunton water table elevations have been monitored on a monthly basis by the Nature Conservancy, the Nature Conservancy Council and English Nature since 1972. These data were invaluable in describing the spatial and temporal hydrological characteristics and functioning of the groundwater system. Braunton Burrows was the main study site of the research. At both Northam and Dawlish, at the start of the fieldwork programme a dipwell monitoring network was installed and water table elevations were recorded weekly. Hydrological characteristics of each dune system were related to temporal variability in effective precipitation, the tide, the underlying geology and sediment properties.

The groundwater system at Braunton was mounded, with effective inputs accumulating over an impermeable basal layer close to mean sea level. The system was very sensitive to seasonal variability in effective precipitation. At the centre of the groundwater mound, during the winter months, the elevation of the water table was 10 m above OD. The groundwater mound was asymmetric, with the highest water table elevations occurring along the eastern margin of the system. The transitional zone from dune sands to marshland, of a lower permeability, was restricting the inland lateral drainage regime and was controlling both the shape and elevation of the water table. At Northam the groundwater system was also mounded and again the shape and elevation of the water table were dependent upon effective precipitation. Unfortunately the monitoring network at Dawlish proved insufficient to describe either the shape or elevation of the groundwater table. Within the smaller systems of Northam and Dawlish variable sediment properties lead to intra-site variability in annual cyclical water table fluctuations.

A prominent trend in the long-term water table data for Braunton Burrows was the general overall decline in the elevation of the water table from 1983 to mid 1992. With precipitation as the primary source of groundwater recharge, consecutive years with below average effective precipitation (1983-1992) was undoubtedly the primary cause, but was exacerbated by the drainage improvement works carried out on West Boundary Drain in 1983. Scrub growth, artificial drainage of the golf course and marine erosion were also possibly influencing the groundwater drainage regime. At Northam and Dawlish, without historical data it was not possible to determine if the systems were drying out, however factors influencing annual cyclical water table elevations were identified. Again climate was the key variable controlling the long-term elevation of the water table and undoubtedly the dry spell between 1983 and 1992 would have had repercussions on the elevation of the water table within these two systems. At Northam the drainage ditch network and reduced tidal inundation were the other main factors influencing groundwater levels. At Dawlish the golf course pump drainage system and scrub encroachment were effectively reducing annual groundwater recharge.

At Braunton a numerical groundwater flow model was used as a predictive management tool, to assist in the recommendation of sustainable water level management options. A range of commercial groundwater flow models were reviewed and Visual MODFLOW, incorporating the original United States Geological Survey's MODFLOW code, with a fully integrated pre and post processor, was selected as the most suitable model for the Braunton scenario. The modelling exercise had three objectives; to test whether a commercial model such as Visual MODFLOW could be applied successfully to simulate the hydrology of Braunton Burrows; to gain further detail on the hydrological functioning of the system and ultimately if the model was calibrated to test a set of management scenarios to predict the hydro-ecological consequences of introducing new management practices into the system.

Having identified the most probable factors influencing water table elevations within each dune system, sustainable hydrological management options were recommended with the aim of raising water levels, or preventing any further decline in water table elevations. The management options afforded nature conservation the highest priority, but also took into consideration the long-term requirements of all the other land user groups. At Braunton when formulating the management recommendations the modelling predictions were also taken into consideration.
Potential areas for future research were also identified. Water level monitoring should continue at all three sites, so that the longer-term impact of any water level management strategies implemented as a result of this research can be evaluated. Also at both Northam and Dawlish a more detailed analysis of the geology and sediment properties would be invaluable in providing a more comprehensive hydrological description of the functioning of the groundwater systems. The Braunton groundwater model could be developed further, addressing and overcoming problems encountered in this study and evaluating a wider range of water level management scenarios.

As a result of this research far more is understood about the hydrological functioning of Devon's three largest dune systems and the recommendation of sustainable remedial/restorative water level management options will help to ensure that these ecologically diverse habitats are conserved for future generations. This research has also provided both the applied and theoretical framework to address water resource management problems within small and large scale dune systems around the shores of Great Britain.
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Signed

Date 27/5/95

xxx
Chapter 1
Introduction
Chapter 1

Introduction

1.0 Introduction; the importance of sand dune systems

Coastal sand dune systems are internationally recognised as prime botanical sites, sustaining a rich and diverse range of successional dune plant communities, together with their abundant animal life and invertebrate population (Doody, 1989; Pieters, 1989; Jones, 1993; Stuyfzand, 1993).

Pressures from urban and industrial development, agricultural intensification, afforestation, tourism and recreation, coastal protection, aggregate extraction, military training and water abstraction has resulted in the modification, or destruction of sand dune systems throughout Europe. Governments and individual organisations have recognised the international importance of these systems and the need for controlled management and protection. The nature conservation value of sand dune systems was emphasised at the European Coastal Dune Congress, held in Leiden, the Netherlands, in September 1987 (Van der Meulen et al., 1989). Participants from Belgium, Denmark, France, Great Britain, the Netherlands, Poland, Portugal, Spain, Sweden and West Germany stressed the need to conserve these diverse habitats from future destruction and deterioration by human activity. The result was the formation of the European Union for Dune Conservation and Coastal Management (EUDC), which was a start for future European conservation action.

An international inventory of coastal dunes has been completed by the EUDC in co-operation with the UK Joint Committee for Nature Conservation (Doody, 1991). The inventory is being followed up by investigative research into the quality, threats and development of coastal ecosystems around the shorelines of Europe.
Individual countries also have their own organisations for sand dune conservation. For example, in the Netherlands, which has the greatest extent of dune habitat in Europe, there is an organisation called the Foundation for Dune Conservation (Stichting Duinbehoud) (Salman, 1989). The organisation has been working to provide a better balance between nature conservation and human activity.

In Great Britain there are an estimated 56,300 ha of coastal dunes (Figure 1.1). These habitats are of great importance for their diverse ecology and geomorphology (Doody, 1989). The conservation of these dunes is the remit of a number of organisations, such as the County and Local Councils, County Trusts, the National Trust, Countryside Council for Wales, Scottish Natural Heritage and English Nature (formerly the Nature Conservancy and the Nature Conservancy Council). By 1984, 120 sand dune habitats within Great Britain had been designated as Sites of Special Scientific Interest (SSSI) and 16 sites as National Nature Reserves (Doody, 1989), for their wildlife interests and geomorphology. Furthermore, the Braunton Burrows sand dune system, North Devon, is one of only three sites in England to have international recognition as a Biosphere Reserve (English Nature, 1992).

In 1994, a national inventory of English coastal dune systems was completed identifying the diversity and ecological value of these habitats (Radley, 1994). Vegetation was mapped using the National Vegetation Classification and land use and management were described. Similar inventories were also completed for Scotland and Wales.

In the late 1940s the ecological and geomorphological importance of major sand dune systems around the coastline of England and Wales were described by Steers (1948). This text included a general description of Devon’s three largest sand dune systems Braunton Burrows, Northam Burrows and Dawlish Warren. Subsequently, the ecological value of sand dune systems in Great Britain was documented in detailed research by Willis et al. (1959a; 1959b)
at Braunton Burrows, North Devon and by Ranwell (1959; 1972) at Newborough Warren, Anglesey. These studies were primarily concerned with describing the major dune plant communities and identifying some of the most important factors which influenced their development, distribution and composition. However, these studies were also of fundamental importance in providing a basic semi-quantitative account of the hydrological characteristics and functioning of the groundwater system.

Since the work of Willis et al. (1959a;1959b) and Ranwell (1959; 1972) little further hydrological research has been undertaken on British sand dune systems, but reversing this trend in the last several decades has been the hydro-ecological study at Kenfig Local Nature Reserve, Mid Glamorgan, (Jones and Etherington, 1989; Jones, 1993) and the calculation of a water budget for the Ainsdale dune system, Merseyside (Clarke, 1980). Most other research which has been undertaken on British dune systems has been primarily concerned with vegetation dynamics and rabbit grazing (Ranwell, 1960; Hodgkin, 1984; Garson, 1985; Hope-Simpson, 1985; Oosterveld, 1985; Marrs, 1985; Willis, 1960, 1985a; 1985b, Jones et al., 1995; Edmondson and Gateley, 1996; Jones, 1996).

More recent research carried out on Braunton Burrows has included the work of Sarre (1984; 1989) and Maddock (1991), who analysed the rate and pattern of sand movement within the dune system. Furthermore, a study by Meur (1993) compared the geomorphology, protection and management of sand dunes in Northern Brittany, with dune systems in Devon and Cornwall, including Braunton Burrows and Northam Burrows. In the mid 1990s a morphological survey of Braunton Burrows was carried out by Chisholm (1996). He described areas of sediment gain, loss and stability, compared with the ground survey data collected in the late 1950s by Kidson (1960) and the detailed photogrammetric survey of the dunes in the late 1980s by Kidson et al. (1989). Braunton Burrows is the only known sand
dune system in Great Britain where repeat morphological surveys have been carried out to determine the long term topographical changes that are taking place.

The Coastal Directories Project, co-ordinated by the Joint Nature Conservation Committee (JNCC), has collated existing environmental information on the UK and Isle of Man coastal zone. The project group have produced a series of national and regional reports which describe the relationship between the physical functioning, natural resources and human activities within the coastal zone (Barne et al., 1996a, 1996b; Doody, 1995). The regional reports covering south west England include a section on sand dunes systems, describing the ecological and geomorphological importance of these terrestrial habitats, their conservation status and the impact of human activity (Dargie, 1996a, 1996b).

Prior to the hydrological studies of the late 1950s (Willis et al., 1959a, 1959b; Ranwell, 1959; 1972) the majority of research on British sand dune systems was concerned with vegetation succession, the xerosere, or phytosociological accounts of the dune and slack flora (Hepburn, 1944; Olsen, 1958; Salisbury, 1952; Gillham, 1953).

Outside the British Isles the pioneering work in the late 19th century of Badon-Ghyben (1889) and Herzberg (1901), cited in de Vries (1994), discovered the importance of fresh water pockets floating on salt water in the dune systems of the Netherlands. Since the discovery of this valuable resource, the Dutch dune systems have been intensively drained to provide a water supply to its population.
Figure 1.1 The distribution and area of sand dunes in Great Britain in 1984. Source: Adapted from Doody (1989).
By the 1950s, concerns were growing that the groundwater systems was being over exploited, resulting in saline intrusion and a gradual change in the ecology of the area (Biemond, 1957; Lindenbergh, 1957; Van Dijk, 1989; Stuyfzand, 1993; Bakker and Stuyfzand, 1993). Hydrological research was therefore urgently required to understand the dynamics and characteristics of the groundwater system, and explains the fairly continuous programme of hydrological research undertaken in the Netherlands since the mid 1950s (Biemond, 1957; Beukeboom, 1976; Van der Lann, 1979; Bakker, 1981; Van Dijk, 1989; Bakker, 1990; Bakker and Nienhuis, 1990; Van Dijk and Grootjans, 1993; Stuyfzand, 1993; de Vries, 1994; Geelen, et al., 1995). This literature provided the most comprehensive review of coastal sand dune hydrology, with detailed research on the dynamics and characteristics of groundwater flow, the quality and quantity of groundwater and factors influencing groundwater movement. A comprehensive review of the hydrological literature is included in Section 1.4.

It should be noted at this stage that the Dutch hydrological research has been based upon sand dune systems where the groundwater hydrology has been extensively altered by groundwater abstractions and artificial recharge schemes. In contrast the hydrological functioning of British sand dune systems is best described as 'semi-natural' (Doody, 1991). Although British dune systems have generally not been used for water abstraction, the functioning of the groundwater systems have often been influenced by human activity, in the form of artificial drainage, the planting of tree species and the prevention of tidal inundation.

In the Netherlands there are a number of Dune Water Companies who manage the extraction of fresh water from the dune systems and who have also carried out extensive research into the hydro-ecological functioning of these habitats (Stuyfzand, pers. comm). With the exception of the Dutch research, specific research describing the groundwater hydrology of sand dune systems has received little attention in most other European countries (Bakker, 1990).
It is primarily the Dutch who in recent years have researched the properties of slack soils and
dune sands and have discussed their influence on the hydrology of the dune system (Jungerius,
1990; Dekker and Jungerius, 1990; Dekker and Ritsema, 1994; Ritsema and Dekker, 1994;).
In Great Britain it was only the more recent hydro-ecological research by Clarke (1980) and
Jones (1993) that actually related sediment properties to the movement of soil water through
the dune system. In the semi-arid regions of New Mexico there is currently an ongoing
research programme investigating soil water movement in the unsaturated zone of sand dune
systems (Stephens and Knowlton, 1986; McCord and Stephens, 1987; Ritsema and Dekker,
1994). A comprehensive review of the physical characteristics of dune sands is included in
Section 1.5.

Detailed research has also been carried out to quantify the impact of various management
techniques on the hydrology of the Dutch dune systems (Bakker, 1981; Bakker, 1990;
Stuyfzand, 1993; Van Beckhoven, 1993; Van Dijk and Grootjans, 1993; Geelen, et al., 1995).
These studies describe the effects of scrub encroachment and tree planting, groundwater
abstractions, the lowering of polder levels and the creation and management of drainage
ditches on the hydro-ecology of sand dune systems, as reviewed in Section 1.6. Again, there
was an apparent lack of detailed literature relating to the management of British sand dune
systems from a hydrological perspective.

This introductory section has therefore identified both the importance of sand dune systems
across Europe for nature conservation and, with the exception of the Dutch studies, the
apparent lack of detailed research describing the hydrology of sand dune systems. Relevant
sand dune hydrology literature will be reviewed in greater detail from Section 1.4 onwards, in
relation to the specific aims of this research outlined in Section 1.2.
1.1 The need for research on British sand dune systems.

As described in Section 1.0, British sand dune systems are important sites for nature conservation. Characteristically the water table within the dune slacks remains at, or close to the surface for most of the year, sustaining a rich and diverse range of flora and fauna, which contribute to their conservation value (Van Beckhoven, 1992; Van Zadelhoff, 1981 cited in Bakker and Stuyfzand, 1993; Stuyfzand, 1993; Van Dijk and Grootjans, 1993). Dune slacks are defined as damp or wet hollows left between dune ridges after the process of deflation and where the groundwater table reaches, or approaches, the surface of the sand (Tansley, 1949). Research by Bakker and Stuyfzand (1993) and Van Beckhoven (1992), stressed that plant species found within the Dutch dune slacks were sensitive to long-term hydrological change and as a result of groundwater abstractions slack water table elevations have fallen. Consequently this has caused a marked decline in the most sensitive species. Considering the relationship between nature conservation, species composition and the hydrological regime, it is surprising that so little hydrological research has been carried out on sand dune systems in Great Britain, many of which are described as prime botanical sites (Gibbons, 1990). This emphasised the need for detailed investigative research, to describe and explain the groundwater hydrology and management of British sand dune systems in order to avoid future possible destruction of these ecologically important habitats.

In addition to this research niche, over the past several decades there has been a growing concern over the perceived falling water tables within three Devon sand dune systems. In 1992 English Nature reported that at Braunton Burrows, North Devon (Figure 1.2), the elevation of the water table had fallen by one metre in certain parts of the system since the early 1980s. Similar concerns were also voiced at Northam Burrows, located on the opposite side of the Taw-Torridge Estuary from Braunton (Figure 1.2) and Dawlish Warren, on the south Devon coast (Figure 1.2). Consequently, the perceived changing hydrological regime is endangering the survival of their outstanding wildlife interests. These sites are nationally, or
internationally renowned for their botanical interests and for the study of coastal geomorphology (Section 2.5). Detailed hydrological research was therefore urgently required, to describe and explain the hydrology of these systems to investigate whether they were drying out and if so to identify the most probable causes.

The main research programme was carried out on Braunton Burrows, England's largest sand dune system. Monthly water table elevation data collected by the Nature Conservancy, the Nature Conservancy Council and English Nature (hereafter referred to as NC, NCC and EN) from June 1972 to December 1995 provided the essential data to carry out the detailed hydrological investigation and to determine if the water table had fallen. Setting the research into a wider context, the knowledge gained will provide an invaluable contribution to the understanding of the hydrology of British sand dune systems. Furthermore, if the hydrology of Braunton Burrows can be understood then the scientific knowledge gained can be applied to the understanding of the hydrological characteristics and functioning of the smaller dune systems at Dawlish Warren and Northam Burrows.
Figure 1.2 Location of study sites; Braunton Burrows, Northam Burrows and Dawlish Warren.
1.2 Aims of the research

The aims of this research were;

1. to describe and explain the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Braunton Burrows, Northam Burrows and Dawlish Warren (Section 1.2.1).

2. to assess whether these systems were drying out and if so to determine the most probable causes. At Braunton Burrows this was partially achieved through the use of a hydrological model (Section 1.2.2).

3. to recommend sustainable hydrological management options for each system, aimed at raising water levels or preventing any future lowering of the water table (Section 1.2.3).

Sub-sections 1.2.1-1.2.3 briefly outline each of the research aims.

1.2.1 Aim 1: to describe the spatial and temporal hydrological characteristics and functioning of the groundwater systems

To describe the hydrological characteristics and functioning of the groundwater systems the study sites were spatially and temporally analysed at three investigative scales (Section 3.1);

1. the entire dune system
2. cross sections and flow nets
3. point observations

At Braunton Burrows, because of the sheer size of the system the physical properties of the dune sands were also investigated at a further scale, detailed experimental sites, which consisted of a slack and dune unit (Section 3.1). At Northam and Dawlish the physical
properties of the dune sands were spatially described from point observations, next to each dipwell in the monitoring network.

Water table contour plots and cross-sections were constructed to describe the seasonal variability in the shape and elevation of the water table and also to evaluate the response of the system to effective precipitation (precipitation minus losses through evapotranspiration). Flow nets superimposed on the water table contour plots were used to describe the gradient of the water table. Water table data from individual observation wells were plotted to evaluate intra-site variability in annual cyclical water table fluctuations. The relationship between the elevation of the water table and effective precipitation was also investigated. To help explain the hydrological characteristics described at each scale of investigation the effects of the underlying geology, saline intrusion, the tide and sediment properties on the functional hydrology of the system were considered.

1.2.2 Aim 2: to assess whether the dune systems were drying out and if so to determine the most probable causes

Water table data collected on Braunton Burrows since 1972, were used to determine whether the system was drying out. English Nature believe that the disappearance of the internationally rare fen orchid (*Liparis loeselii*) since 1988 and the decline in the water germander (*Teucrium scordium*) by about 45 % since 1982, was a possible consequence of lower water table elevations on the Burrows (Wolton, 1995). After site visits to Braunton Burrows and much discussion with English Nature at the first sand dune hydrology steering group meeting (August 1993), set up to co-ordinate this research, five possible contributing causes for the perceived changing hydrological regime were identified (Table 1.1).
Table 1.1  Possible factors influencing the elevation of the water table on Braunton Burrows, Northam Burrows and Dawlish Warren.

<table>
<thead>
<tr>
<th>Sand dune system</th>
<th>Possible factors influencing the elevation of the water table.</th>
</tr>
</thead>
</table>
| Braunton Burrows | Climatic trends-long-term changes in precipitation and effective precipitation totals.  
|                   | Marine erosion of the fore dune ridge, altering the groundwater drainage regime.  
|                   | Increased evapotranspiration losses, with the encroachment of scrub species such as willow (*Salix repens*) and Yorkshire fog (*Holcus lanatus*).  
|                   | Saunton golf course drainage system.  
|                   | Land drainage in the adjoining Braunton Marsh system. |
| Northam Burrows  | Climatic trends-long-term changes in precipitation and effective precipitation totals.  
|                   | Marine erosion of the system, altering the groundwater drainage regime.  
|                   | The drainage ditch network.  
|                   | The installation of tidal flaps on the Pill, preventing tidal inundation.  
|                   | The construction of the landfill access road preventing tidal inundation. |
| Dawlish Warren   | Climatic trends-long-term changes in precipitation and effective precipitation totals  
|                   | Marine erosion of the fore dune ridge, altering the groundwater drainage regime.  
|                   | Increased evapotranspiration losses with the encroachment of scrub species such as willow (*Salix repens, Salix cinerea*), birch (*Betula pubescens*) and elder (*Sambucus nigra*).  
|                   | The creation of wildlife ponds within the Local Nature Reserve.  
|                   | An efficient pump drainage system on Dawlish Warren Golf Course. |

At Northam Burrows and Dawlish Warren long-term water table data were not available and so it was impossible to determine whether the systems had been gradually dying out, or whether water levels had fallen suddenly. However, the weekly water table data collected for these sites, during the fieldwork programme (October 1993-March 1996), were analysed to detect possible factors influencing or controlling, annual or seasonal, water table fluctuations. After visits to both Northam Burrows and Dawlish Warren and in depth discussions with the site staff, possible factors influencing the long-term hydrological regime were identified (Table 1.1).
Visual MODFLOW (hereafter referred to as VMODFLOW), a three dimensional finite difference groundwater flow model, created by the United States Geological Survey (USGS), was used as a predictive management tool in the hydrological investigation of Braunton Burrows (Chapter 7). A detailed explanation of the purpose of groundwater modelling in the Braunton water resource management investigation is described in Section 3.4. This section will also describe the history and development of groundwater models and will review a range of commercially available groundwater flow models, with the ultimate aim of selecting the most suitable model for simulating the groundwater hydrology of Braunton Burrows.

A conceptual model of the Braunton groundwater system was created by specifying grid dimensions and boundary conditions, and assigning parameter values to precipitation, evapotranspiration, vertical and horizontal hydraulic conductivity, and storage. Once satisfactorily calibrated to simulate field water table elevations the model was used to predict the hydrological consequences of increasing, or decreasing certain parameter values and introducing, or altering management practices within the system. For example, the groundwater model was used to determine the impact on the elevation of the Burrows water table of changing the drainage regime along the eastern margin of the system and also to predict the hydrological effects of increasing scrub coverage by 100%. The modelling predictions assisted in the final recommendation of sustainable hydrological management options for Braunton, as discussed in Section 1.2.3.

1.2.3 Aim 3: to recommend sustainable hydrological management options aimed at reinstating former water levels, or preventing any future lowering of the water table

Having identified the possible factors which have, or continue to influence the elevation of the water table within the dune systems, the final aim of this research was to recommend
sustainable future hydrological management options. The aim of the management options were to raise water table elevations, or prevent any possible future hydrological change through human mismanagement of the system. It was essential that the final management recommendations were sustainable, and afforded the maximum benefit to nature conservation, but also took into consideration the seasonal requirements of other land users and interest groups. For example any recommended changes to the drainage regime, aimed at raising winter water table elevations, would need to take into consideration factors such as agricultural production and waterlogging of the golf course greens and tees.

1.3 Structure of the thesis

This thesis has been divided into eight chapters. The introduction (Chapter 1) sets the study into perspective, states the aims of the research and reviews existing literature on the hydrology and management of sand dune systems. Chapter 2 describes the location and physical characteristics of each dune system and also describes ways in which human activity has altered the hydrology. Experimental design is evaluated in Chapter 3. This chapter considers the scale of the investigation and both the field and laboratory procedures used within the study. Of primary consideration throughout this chapter is the collection of representative and accurate data, which will help in the hydrological description and future management of the three dune systems. This chapter also reviews groundwater modelling techniques, describing the development of groundwater flow models in water resource management investigations. The modelling section also will critically evaluate a range of commercially available groundwater flow models, with the ultimate aim of demonstrating why VMODFLOW was the most suitable model for simulating the groundwater hydrology of Braunton Burrows.

Chapter 4 will describe and analyse the hydrological characteristics and functioning of the groundwater system at Braunton Burrows. The hydrology will be described at three
investigative scales, before considering the effects of effective precipitation, the underlying
geology, saline intrusion, the tidal cycle and sediment properties on the hydrological
functioning of the system.

Chapter 5 will firstly evaluate whether water levels on the Burrows have fallen by plotting
water table elevation data from selected observation wells. This chapter will also identify the
factors that are influencing the long-term elevation of the water table. Preliminary analysis of
the water table data from Braunton Burrows indicated that a possible cause for the perceived
drying out of the dune habitat was the management of the adjoining Braunton Marsh land
drainage system. The final part of Chapter 5 is therefore devoted to describing the hydrology
and management of this system, which will also provide the essential data to accurately
parameterise the eastern boundary of the groundwater model in Chapter 7.

Chapter 6 is divided into two main parts. The first part describes the hydrology of Northam
Burrows following a similar structure to Chapter 4. Possible factors influencing
annual/seasonal water table fluctuations within the system will also be identified. The second
part of this chapter follows an identical structure to the first part and describes the hydrology
and management of Dawlish Warren.

Chapter 7 firstly describes the parameterisation and calibration of the Braunton Burrows three
dimensional groundwater flow model (VMODFLOW). Model validation and sensitivity
analysis will also be considered. Secondly this chapter will describe how the model is used to
test a set of hydrological management scenarios to evaluate the impact on the elevation of the
Burrows water table of altering certain boundary conditions, or introducing new management
practices. Ultimately the modelling results will assist in the recommendation of future
hydrological management options for Braunton Burrows (Chapter 8).
Having determined the probable factors which are influencing water table elevations within each dune system (Chapters 5 and 6), the penultimate chapter to the thesis (Chapter 8) will recommend sustainable hydrological management options for each of the dune systems. The management recommendations are aimed at raising groundwater levels, or preventing any future changes to the hydrological regime, which could result in further loss or destruction of the dune habitat.

Finally, Chapter 9 will draw the study together presenting a synthesis of the main findings, a critique of the research and a discussion on potential future research. This chapter will also evaluate the implications of this research for the management of other sand dune systems around the shores of Great Britain.

1.4 The hydrology of sand dune systems

1.4.1 Characteristics of the water table

Of fundamental importance to the understanding of the hydrology of sand dune systems is the functioning of the water table. Research at Braunton Burrows (Willis et al., 1959a; 1959b), discovered from contour plots of the water table that the centre of the dune system was maintained at a higher elevation where there was a low water table gradient, than at the landward and seaward margins where the gradients steepened. At the centre of the dune system, the water table was approximately 6 m higher than on the shoreline, or at the inland boundary, forming what Willis et al. (1959a; 1959b) described as a dome shaped water table. These water table characteristics are often associated with isolated catchments, which are chiefly dependent on precipitation for groundwater recharge, with percolating waters accumulating over impermeable sub-surface deposits. Water leaves the dune system by groundwater flow to the sea and to the inner dune fringe (Bakker, 1990) (Figure 1.3). Except for the extreme northern part of Braunton Burrows, which perhaps receives an additional
input from the surrounding hill slopes, the rest of the system has been classed as an isolated catchment with a low-lying hinterland, namely Braunton Marsh (Willis et al., 1959a).

Figure 1.3 Cross-section through a dune system with a low-lying hinterland.

The movement of groundwater in the domed system can be described in mathematical terms by Darcy's Law (Equation 1.1), and assuming the principle of continuity, where volumetric inputs to the system equal volumetric outputs. Moving out from the centre of the dune system, the cumulative increase in groundwater discharge, due to lateral drainage, an increased catchment area and an areal input of precipitation must be balanced by a corresponding increase in groundwater flux, and hence by an increasing gradient.

h: height of groundwater table above mean sea level (m)
H: depth of fresh water below mean sea level (m)
x: distance inland (m)
\[ Q = -K \cdot A \cdot \frac{dh}{dx} \]  

(Equation 1.1)

\[ Q: \quad \text{discharge} \]
\[ K: \quad \text{hydraulic conductivity of the medium (m d}^{-1}) \]
\[ A: \quad \text{area of flow} \]
\[ h: \quad \text{head} \]
\[ x: \quad \text{distance along flow path} \]

Similar water table characteristics and drainage relations were described for the dune system at Kenfig, Mid Glamorgan (Jones, 1993). The highest point of the water table was located east of the geographical centre of the system and from this point the height of the water table declined in all directions. The highest water table elevations were 6 m above the lowest recorded winter water levels around the margins of the system.

At the southern end of Braunton Burrows Willis et al. (1959a) observed smaller water table gradients, a feature related to the presence of a high proportion of shingle within the sandy medium, increasing permeability. Steeper gradients were observed along the eastern edge of the dune system, because of the lower permeability in the transitional zone from dune sands to marshland (Willis et al., 1959a).

The dune systems at Northam Burrows and Dawlish Warren are much smaller in size and are perhaps influenced to a greater extent than Braunton by an input to the system from the adjoining higher-lying hinterland. The feeding of groundwater to such systems can be two fold (Bakker, 1990). Firstly, there is the direct precipitation input and secondly, there is groundwater flow from the higher hinterland, which can be a major input to smaller systems. The consequent effect, dependent upon the size of the surrounding higher land, the
precipitation surplus and the permeability of the inner boundary, is to raise the height of the water table at the inland margin, making it wedge shaped (Figure 1.4).

![Cross-section through a dune system with a high-lying hinterland](image)

- **h**: height of groundwater table above mean sea level (m)
- **hr**: groundwater table at the inland boundary (m above mean sea level)
- **L**: distance between shoreline and inland groundwater boundary (m)
- **x**: distance inland (m)

Figure 1.4 Cross-section through a dune system with a high-lying hinterland. Source: Bakker (1990).

Research on the Kenfig dune system, Mid Glamorgan, by Jones (1993) concluded that the doming of a water table beneath a dune system was a function of distance. The water table did not dome beneath individual dunes and in fact in one case the water table elevation beneath a dune was lower than that measured in the adjoining slack. Similar observations were also noted by Winter (1986), in a study of the configuration of the water table beneath the sandhills of Nebraska. In this research it was suggested that the timing of recharge was
dependent on the thickness of the unsaturated zone. As the depth of the unsaturated zone increased recharge of the system became much slower. Eventually a new water table equilibrium would be reached.

1.4.2 Water table characteristics and tidal fluctuations

When describing the hydrological characteristics and functioning of the groundwater system the possible influence of the tidal cycle on water table fluctuations should be taken into consideration. However, Ranwell (1972) stated that sea water is prevented from penetrating in the groundwater zone by a positive drainage gradient from the dune system. However, the tide may begin to influence the elevation of the water table when a reverse gradient is created, for example by groundwater abstractions. At Newborough Warren, Anglesey, water table observations made within a slack 200 m from the shoreline showed that groundwater levels were not affected by a spring tide, or during the 48 hrs afterwards (Ranwell, 1972). Similar conclusions were also drawn from research carried out on Braunton Burrows, Devon (Willis et al., 1959b) and Ainsdale, Lancashire (Clarke, 1980).

1.4.3 Seasonal fluctuations of the water table

Seasonal fluctuations of the water table should be considered when describing the long-term hydrological characteristics and functioning of the groundwater system at each sand dune complex. There are a number of studies that describe the distinct seasonal fluctuations characteristic of British sand dune habitats. These fluctuations have been described as a three phase cycle (Blanchard, 1952, cited in Jones 1993; Ranwell, 1959; Willis et al., 1959a; Clarke, 1980). The first phase from November to April is characterised by high winter water table elevations, typically resulting in widespread flooding of the dune slacks. At Kenfig, Mid Glamorgan in the winter months up to 34 % of the dune system is covered by standing water (Jones, 1993). At Newborough Warren, Anglesey, in the dune slacks amongst the dune ridges surface pools up to 1.5 m deep have been recorded. Similarly, at Braunton Burrows, North
Devon, flood waters up to one metre deep were recorded in the winter of 1994/1995 (Breeds, pers. comm.). The second phase of the cycle is characterised by a fall in the elevation of the water table from April to August. The autumn recovery from September to November occurs more rapidly. The seasonal fluctuation of the water table is closely correlated with the distribution of precipitation and evapotranspiration losses. Research by Willis et al. (1959a) concluded that the maximum annual range of the water table occurred near the flatter centre of the dome-shaped water table and smaller ranges were evident at the margins of the system where the water table was replenished not only by areal precipitation, but also by groundwater draining from the centre of the water table dome. Research at Braunton Burrows and Newborough Warren showed that the annual cyclical range of the water table was in the order of one metre (Willis et al. 1959a; Ranwell 1959). These water table fluctuations were dependent on annual effective precipitation. Within the sand dune system at Winterton, Norfolk, the annual effective precipitation totals were on average less than at Braunton and hence the annual range of the water table was reduced to 50 cm (Ranwell, 1972).

1.4.4 Erosion of dune systems and sea level rise

Erosion of dune systems by the action of the sea is a world-wide problem. Bird (1985) stated that 20% of the world's coastline consisted of sandy beaches backed by dune systems or depositional barriers. Between 1965 and 1985 approximately 70% of the coastline showed signs of net shoreline erosion. Less than 10% showed net progradation and the rest remained relatively stable. As described by Bakker (1981), erosion of the fore dunes caused an initial increase in the gradient of the water table and ultimately resulted in greater drainage from the seaward margin of the dune system. As a result, there was an overall lowering of the water table until a new equilibrium was reached.

In a recent survey of 121 coastal sand dune systems in the British Isles (Radley, 1992; 1994), 67 of the sites were described as showing signs of net erosion. Net erosion was defined as
those sites where the percentage of the shoreline recorded as either actively eroding, or protected from erosion by sea defences was at least 10% greater than the percentage recorded as prograding. In comparison, only 21 of the sites showed net progradation, which was defined as sites where the percentage of the shoreline prograding was at least 10% greater than that recorded as either eroding, or protected from erosion by sea defences. A further 12 sites were described as being in net equilibrium and at 17 of the sites the situation was not clear. The remaining 4 sites were described as relict, isolated from the action of the sea. Although Radley (1992;1994) stressed that the data were crude, collected during one-off visits to each of the sites, the findings were consistent with other surveys of the British coastline by Bird (1985) and May (1985).

Blackley et al. (1972) stated that erosion has affected the foreshore at Braunton Burrows, between Airy Point and Crow Point (Figure 1.5), on a varying scale for over 100 years. This period is not dissimilar from that during which sand and gravel extraction has been carried out in a sizeable way. From 1960 to 1970 between 60,000 and 100,000 tonnes of sand and gravel were extracted each year. It therefore appeared that a link might be found between the two. In an experiment by Blackley et al. (1972), fluorescent labelled sand was deposited near low water on Instow Beach, off Airy Point and on the bar near Middle Ridge buoy during June 1971 (Figure 1.5). The results from the study showed limited dispersion of the fluorescent labelled sand at Instow Beach, much greater movements off of Airy Point, principally towards Crow Point, and maximum movement at the Middle Ridge bar. Whilst the authors suggested that longer term monitoring was required, the tracer experiment indicated that sediment was transported alongshore to replenish sand extracted from near Crow Point, leading to the increased erosion of the Burrows foreshore.
Figure 1.5 Fluorescent tracer experiments. Source: Blackley et al. (1972).
As described by Bakker (1981) at Bergen aan Zee, the Netherlands, since the mid 1800s erosion of the dune system has varied between 50 m and 100 m. As a result water levels in the fore dunes have dropped by 0.5-1.0 m, in the central dune area by 0.2-0.5 m and by decimetres in the inner part of the dune system. At West Terschelling, the Netherlands, Van Dijk and Grootjans (1993) report of the case where the accretion of the dune system along the coastline since 1859 has increased water levels at the original foot of the dunes by 3 m, by 1 m in the centre of the dune system and 0.2-0.5 m at the inland margin.

In 1990 the Dutch government decided that coastal erosion should be halted using ‘dynamic preservation’ (Loftier and Coosen, 1995). Between 5 and 7 million m$^3$ of sand was deposited along the Dutch coast as part of a beach nourishment scheme. This layer of sand acted as a ‘wearing layer’, to absorb coastal energy and help prevent further erosion of the dune system. The Dutch are aware that beach nourishment is not a definitive solution, but a temporary measure to combat erosion problems (de Ruig, 1995).

The effects of sea level rise and marine erosion on the groundwater hydrology of Braunton, Northam and Dawlish should also be considered. The nearest port for which reliable tide gauge data were available was Newlyn, where the long term record (1916-1982) suggested that relative sea level (RSL) was rising between 1.7-2.2 mm a$^{-1}$ (Heyworth and Kidson, 1982; Woodworth, 1987; Boorman et al., 1989; Whittle, 1990). A study by Warrick and Barrow (1991) found that models predicting changes in sea level around the British coast agreed with the estimates provided by the Intergovernmental Panel on Climatic Change, which suggested a rise in global sea levels of 20±10 cm by AD 2030 and 30±cm by AD 2050. In south west England RSL rise is enhanced by the regional isostatic regime. Land levels are dropping slightly as a result of glacial unloading in Scotland and northern England, since the last glacial maximum ca. 18,000 years ago (Lowe and Walker, 1984). This is causing an accelerated rate of RSL rise compared with the global value. A sea defence report by the former National


Rivers Authority in 1991, cited in Comber et al. (1993) suggested that for the south west the combined effects of climatic change and tectonic activity would produce a RSL rise of 5.0 mm a⁻¹ between AD 1990 and AD 2030.

As described by Comber et al. (1993) the dunes at Braunton will suffer increased frontal erosion under the predicted future rise in RSL. The sand released, together with any sand reserves in the system, would then be available for new dune building along a line further landwards. The extent of the landward migration will depend upon sand supply, the direction and strength of the winds and the general physiography of the site. Erosion of the fore dune ridge may also lead to a change in the groundwater drainage regime, gradually lowering the overall elevation of the water table within the system. At Northam sea level rise will lead to more frequent breaching of the pebble ridge that encompasses and protects the dunes. Increased tidal breaching will consequently lead to more frequent flooding of the coastal plain, recharging the groundwater system with saline waters, which could lead to change in the ecological structure of the habitat. Within the smaller Dawlish system, a RSL rise of the magnitude predicted could result in the major loss of dune habitat.

1.4.5 Saline intrusion

When fresh ground water meets denser sea water in a coastal phreatic aquifer the fresh water tends to float on top of the sea water. This is known as the Ghyben-Herzberg principle, developed from the work of two Dutch engineers Badon-Ghyben (1889) and Herzberg (1901), cited in de Vries (1994). The principle has been described as a steady state geohydrological phenomenon resulting because of differences in the density of salt water (1025 kg m⁻³) and fresh water (1000 kg m⁻³). At the fresh and salt water interface the pressure of the fresh water above equals the pressure of the salt water below. The boundary is assumed to be a sharp defined interface. The depth of the interface can be calculated from the following equation:
\[ z = \frac{Pf}{Ps - Pf} h \]

(Equation 1.2)

- \( z \) depth below sea level to a point on the interface
- \( h \) the elevation of the groundwater table at that point
- \( Pf \) density of fresh water
- \( Ps \) density of salt water

As described by Urish and Ozbilgin (1989), in oceanic islands completely surrounded by sea water, the fresh water will take the form of a lens, thickest at the centre of the landmass and becoming thinner as the coastline. However, in coastal areas where the aquifer extends inland only the margin characteristics of the lens will exist, as described in Section 1.4.1.

The Ghyben-Herzberg principle has been criticised for its oversimplification in assuming that the groundwater head at the water table is the same as the head of the freshwater interface, implying that there are no vertical gradients (Dupuit assumption), (Urish and Ozbilgin, 1989). The relationship between salt water and fresh water was later described as a dynamic system in which the interface was treated as a boundary between two separate flow fields (Hubbert, 1940). Since the pioneering work of Badon-Ghyben and Herzberg there has been a wealth of research investigating various aspects of the salt water, fresh water interface, as reviewed by Reilly and Goodman (1985). The main areas of investigation include hydrodynamic dispersion of the interface, the effects of permeability on salt water intrusion and a comparison of numerical and analytical methods for determining the size and shape of the fresh water lens.
1.5 Characteristics of the slack soils and dune sands

To be able to describe and explain the hydrology of dune systems, the characteristics of the dune sands and slack soils must be considered. Physical properties such as hydraulic conductivity, the structure of the medium, bulk density and particle size will influence the hydrological functioning of the system.

Saturated hydraulic conductivity ($K_{sat}$) is defined as the volume of water that will pass through a unit cross-sectional area of a soil in a unit of time, given a unit difference in water potential (Landon, 1984). The $K_{sat}$ of aeolian sand has been measured in a number of studies (Table 1.2), because this physical property determines the rate and ease with which groundwater moves through the system. The $K_{sat}$ for dune sands ranged from 7.5 m d$^{-1}$ to 11 m d$^{-1}$ (Table 1.2).

<table>
<thead>
<tr>
<th>Location</th>
<th>$K_{sat}$ (m d$^{-1}$)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ainsdale, Lancashire</td>
<td>11.0</td>
<td>(Clarke, 1980)</td>
</tr>
<tr>
<td>Kenfig, Mid Glamorgan</td>
<td>9.2</td>
<td>(Jones, 1993)</td>
</tr>
<tr>
<td>Freisian Islands, the Netherlands</td>
<td>7.5</td>
<td>(Beukeboom, 1976)</td>
</tr>
<tr>
<td>Typical Dutch dune aquifers</td>
<td>8.0</td>
<td>(Van Dijk and de Groot, 1987)</td>
</tr>
<tr>
<td>De Mont Saint Frieux, France</td>
<td>10.0</td>
<td>(Bakker and Neinhuis, 1990)</td>
</tr>
</tbody>
</table>

Bedinger (1961) stated that the magnitude of $K_{sat}$ was partially dependent upon the grain size. The larger the particle size the easier it becomes for soil water movement. At both Ainsdale and Kenfig experimental results have shown that excavated sand samples are of a uniform structure with a highly sorted mean grain size, which allowed the researchers to adopt the assumption that the dune sands formed a homogenous isotropic medium (Clarke, 1980; Jones, 1993). The greater the percentage of silt and clay sized particles in the sample the slower the movement of groundwater through and within the system.
Bulk density has the greatest effect on water movement in the unsaturated zone of dune sands, ultimately influencing the rate of groundwater recharge. Small changes in density as little as 0.02 g cm\(^{-3}\) can produce significant changes in unsaturated hydraulic conductivity (Miles et al., 1988). The measurement of bulk density in dune sands has mainly been calculated for semi-arid environments, but in one case has also been related to a study site in the Netherlands (Dekker and Ritsema, 1994). Water infiltrating dune sands usually passes a cross stratigraphy of thin sandy layers (1-3 mm) deposited by successive wind events and compacted by rainfall (Ritsema and Dekker, 1994). As a result of rain compaction in the bare dune sands at Kootwijk, New Mexico and Terschelling, the Netherlands, Ritsema and Dekker (1994) found that the mean bulk density of the surface layer was higher (1.65 g cm\(^{-3}\)) than the loosely packed sand below which averaged 1.45 g cm\(^{-3}\). Variations in bulk density within a dune profile can ultimately lead to preferential flow paths, which will need to be taken into consideration when describing the recharge characteristics through the unsaturated zone.

McCord and Stephens (1987) working in aeolian sands in New Mexico, found a strong lateral component to unsaturated flow on a hillslope even in the absence of impeding layers. The process was attributed to moisture dependent heterogeneity in hydraulic conductivity. During infiltration and the subsequent redistribution a zone of increased moisture occurred at depth beneath the land surface. This created a zone of relatively high hydraulic conductivity parallel to the sloping land surface. As a result moisture tended to accumulate in the down-slope direction within this wetted region and flowed laterally.
1.6 The management of sand dune systems

1.6.1 The influence of vegetation on the hydrological characteristics of sand dune systems

The encroachment of scrub species onto a dune system may have a subsequent effect on the local water budget through increased rates of transpiration, evaporation and interception. In both British and Dutch sand dune systems, before the outbreak of the human induced disease myxomatosis in the early 1950s, rabbit grazing kept down the growth of grasses, sedges and woody species and helped to develop and sustain a rich and diverse flora (Thomas, 1963). At Braunton Burrows since the outbreak of myxomatosis in the summer of 1954, which decimated the rabbit population, there has been a noticeable change in the dominant species of the site. Scrub species such as willow (Salix repens), birch (Betula pubescens) and Yorkshire fog (Holcus lanatus) have spread into many of the dune slacks. In 1992, English Nature estimated that 12% of the 1,350 ha system was covered by scrub species. Similar changes in vegetation cover have been noticed at Newborough Warren, where Ranwell (pers. comm.) cited in Hodgkin (1984), recalled that before 1954 scrub species were scattered and sparse, because the rabbits chewed upon any young shoots. However, by 1984 scrub had become thinly spread over most of the Warren. Research by Hodgkin (1984) at Newborough Warren, claimed that 95% of the hawthorn and 20 of the 21 birch trees became established after the outbreak of myxomatosis.

Evapotranspiration losses from a dune system are determined by the climate, the dominant vegetation species and their percentage cover. Data from lysimeter studies at Castricum and Zandvoort, the Netherlands, have been used by Stuyfzand (1993) to determine a mean annual water balance for a coastal dune system with different vegetation coverages (Table 1.3). In this case evapotranspiration included evaporation losses by leaf interception, soil evaporation and plant transpiration.
Table 1.3 Mean annual water balance for coastal dunes with different vegetation covers. Source: Stuyfzand (1993).

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Gross precipitation mm/year</th>
<th>Precipitation excess mm/year</th>
<th>Evapotranspiration mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>bare dune sand</td>
<td>820</td>
<td>623</td>
<td>197</td>
</tr>
<tr>
<td>bare, some marram</td>
<td>820</td>
<td>613</td>
<td>207</td>
</tr>
<tr>
<td>poor, dry dune vegetation</td>
<td>820</td>
<td>459</td>
<td>361</td>
</tr>
<tr>
<td>sea buckthorn (Hippophae rhamnoides) &lt;50% grass</td>
<td>820</td>
<td>394</td>
<td>426</td>
</tr>
<tr>
<td>wet, dune slack vegetation</td>
<td>820</td>
<td>238</td>
<td>582</td>
</tr>
<tr>
<td>dune shrub, sea buckthorn</td>
<td>820</td>
<td>345</td>
<td>475</td>
</tr>
<tr>
<td>oaks (Quercus robur)</td>
<td>820</td>
<td>305</td>
<td>515</td>
</tr>
<tr>
<td>pines (Pinus nigra)</td>
<td>820</td>
<td>140</td>
<td>680</td>
</tr>
<tr>
<td>open water</td>
<td>820</td>
<td>49</td>
<td>771</td>
</tr>
<tr>
<td>reeds in dune lake</td>
<td>820</td>
<td>205/-580</td>
<td>615/1400</td>
</tr>
</tbody>
</table>

The research by Stuyfzand (1993) showed that annual evapotranspiration losses from wet dune slack vegetation were greater than those from oaks and dune shrub (Table 1.3). The highest annual evapotranspiration losses were from open water bodies and reeds (Table 1.3). Unfortunately Stuyfzand (1993) does not provide a comparative value for willow. The main research examining evapotranspiration losses from willow has been carried out in Sweden (Grip, 1981; Grip et al., 1989; Halldin and Lindroth, 1989; Lindroth et al., 1994). These studies found that evapotranspiration losses from willow were greater than from most other vegetation types. Grip (1981) stated that evapotranspiration rates from willow exceeded those calculated from Penman's (1948) formula for grass by between 5% and 40% in the summer and autumn months. Similarly, Persson and Jansson (1989) measured an evapotranspiration
rate for willow of between 3 and 3.4 mm d$^{-1}$, which exceeded the Penman formula for grass by between 10% and 25%. These studies do not provide either an annual evapotranspiration rate for willow, or a monthly breakdown of the data necessary to make this calculation. Therefore, a direct comparison of evapotranspiration losses from willow with other vegetation types was not possible.

In the Netherlands on the Schoorl Dunes, the planting of pine trees has caused the water table in the central dune area to drop by one metre (Bakker, 1981). Other dune systems along the western coast of the Netherlands have recorded a less dramatic drop of 10 to 20 cm as a result of the newly planted trees (Van Dijk and Grootjans, 1993).

1.6.2 The influence of drainage and groundwater abstractions on the hydrological characteristics of sand dune systems

Artificial drainage and groundwater abstractions are effectively net losses from the groundwater system and may therefore contribute to lower water table elevations. Long-term changes in the elevation of the water table will in turn influence the ecological diversity and composition of the dune slack habitat, which are the areas most sensitive to hydrological change (Van Beckhoven, 1992; Geelen et al., 1995).

Since the mid 1800s, the Dutch have been extracting a water supply from their sand dune systems to meet the consumption requirements of the population (de Vries, 1989; Stuyfzand, 1993). Today almost all of the sand dune environment in the Netherlands is being used for water abstraction, pumping approximately 40 million m$^3$ of fresh water each year for human consumption (Udo de Haes, 1982, cited in Van Dijk and Grootjans 1993). Such large scale continuous abstraction programmes have resulted in the loss of many rare and unique dune slack species, that cannot adapt to the changing hydrological regime (Van Beckhoven, 1992; Geelen et al., 1995). Between 1850 and 1978, in the dune system to the north of Noordwijk,
the Netherlands, the water table fell by between 1 and 2 m, which was almost completely attributed to water abstractions (Bakker, 1981). Further to this, Bakker (1981) reported that near Texel, the Netherlands, an additional problem was that water abstractions were increasing groundwater velocities five fold from 0.1-0.2 m d\(^{-1}\) to 0.5-1.0 m d\(^{-1}\), resulting in greater drainage from the system.

In 1955, an artificial recharge programme was put into action with the aim of reinstating former water table elevations within some of the dune systems and to enhance the ecological diversity of the dune slack (Van Beckhoven, 1992; Geelen et al., 1995). The results from the remedial programme were disappointing, former water tables were reinstated, but few of the original dune slack species returned. Research suggested that the quality of the recharge water was poor. Concentrations of chloride, potassium, sodium, magnesium, nitrate and sulphate were increased one hundred fold, or more (Bakker, 1990). This research clearly demonstrated the difficulties associated with attempting to artificially reinstate former water table elevations and ecological diversity after the damage has been done.

Within the Dutch dune systems research has been carried out to identify the effects on the elevation of the dune system water table of lowering water levels within adjoining polders (Van Dijk and Grootjans, 1993). Polder is the Dutch term referring to flat tracts of coastal land reclaimed from the sea and protected from inundation by embankments (Whittow, 1984). The results from this research can perhaps be related to the drainage characteristics and management of the reclaimed marshland at Braunton, as described in Chapter 5. Van Dijk and Grootjans (1993) found that a lowering of the polder water level by 0.25-0.50 m caused a reduction in groundwater levels in the adjoining dune area by a value decreasing almost linearly from 0.25-0.50 m at the inner dune ridge to 0 m in the fore dunes.
Golf courses are one of the major land uses of sand dune systems in Great Britain. In a survey of 65 dune systems in England, Radley (1994) reported that a golf course existed on 31 of these sites. The golf courses form an integral part of the dune and slack system and are often subject to surface flooding in the winter months. Many golf courses therefore have been artificially drained by open drainage ditches, or submerged pipe drainage, removing water from the system. Willis et al. (1959a) reported that drainage of the golf course on Braunton Burrows had undoubtedly lowered the elevation of the water table in the northern part of the system (Section 5.2.4). However, data were not collected to substantiate this statement. In the Dutch dune systems the construction of drainage ditch networks have caused a significant drop in the elevation of the water table, in the order of decimetres, over extensive areas of the dune system (Van Dijk and Grootjans, 1993). The drainage of dune slacks poses a threat on the most sensitive plant species, which depend upon a high water table throughout the year.

In the summer months to allow the continuation of play, greens and tees are sometimes irrigated, which if pumped from the dune system would again contribute to an overall lowering of the water table. On the other hand if the irrigation water is from an alternative source not connected to the dune system aquifer the irrigation water will be an additional input to the system.

1.7 Hydrological modelling of sand dune systems

Computer-based numerical groundwater flow models are often used to develop an understanding of the functioning of a groundwater system and to make predictions about future groundwater flows under different management practices (Anderson and Woessner, 1992). Groundwater models are now widely used in water resource management investigations in all kinds of environments, including river basins (Michl, 1996), wetlands (McNamara, et al., 1992; Bradley, 1994 and 1996; Bromley and Robinson, 1995; Ishemo, pers. comm.) and even sand dune systems (Olsthoorn, et al., 1993; Bergkamp, pers. comm.).
Two models in particular have been used to mathematically model and resolve water resource management problems within sand dune systems. Olsthoom et al. (1993) used MODFLOW a three dimensional groundwater flow model, developed by the USGS, to simulate a 35 km² area of dune system along the North-Sea coast of the Netherlands. The model was used to develop and test a set of hydrological scenarios to optimise the interests of both groundwater abstraction and nature conservation. The second model, developed by a consultancy firm in the Netherlands, is known as Micro-Fern (Bergkamp, pers. comm.). This is a saturated three dimensional groundwater flow model, which has been widely used by dune water companies, government agencies and universities in the Netherlands. The model has been used to predict the hydro-ecological consequences of changing groundwater abstraction rates, or the impact on groundwater levels of artificially recharging the system.

The history and development of groundwater models, and the purpose of modelling in the hydrological investigation of Braunton Burrows will be discussed in Section 3.4. This Section will also review a range of groundwater flow models including MODFLOW and Micro-Fern, describing their features and capabilities, and their relative successes in previous groundwater modelling investigations. The critical review of numerical groundwater models will ensure that the most appropriate model is chosen for the Braunton modelling scenario.

1.8 Conclusion

The introductory chapter of this thesis has identified the need for investigative research into the hydrology of British sand dune systems in order to conserve their ecological diversity from future destruction primarily by human activity. Furthermore, English Nature have expressed their concerns that Devon’s three largest sand dune systems are drying out, jeopardising the flora and fauna for which these sites are nationally, or internationally renowned. Detailed hydrological research was therefore urgently required. Braunton Burrows, Northam Burrows and Dawlish Warren were the study sites used in this hydrological investigation.
Broadly the aims of this study were to describe and explain the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Braunton Northam and Dawlish; to determine if the systems were drying out and if so, to identify the most probable causes, and finally to recommend sustainable management options aimed at raising water levels, or preventing any future lowering the water table.

In this chapter a literature review provided valuable theory on the hydrological functioning of sand dune systems and also showed how natural factors and human management, including the effects of marine erosion, vegetation change, groundwater abstractions and artificial drainage may influence water table elevations.
Chapter 2
The sand dune systems of Braunton Burrows, Northam Burrows and Dawlish Warren
Introduction

Braunton Burrows, Northam Burrows and Dawlish Warren were the chosen study sites for this investigative research, into the hydrology and management of sand dune systems. These study sites were chosen primarily because of increasing concerns that the systems were drying out, ultimately endangering the survival of their diverse wildlife interests. In order to describe the hydrology of each site and to recommend future hydrological management options, aimed at raising water levels or preventing any future lowering of the water table, it was essential to describe both the physical characteristics of the landscape and the impact of human activity on the hydrological functioning of the systems. Chapter 2 will therefore describe the geographical location, climate, geology, geomorphology, soils, vegetation, drainage regime, conservation status and land use of each dune system.

Geographical location of the study sites

Braunton Burrows

Braunton Burrows occupying 1350 ha, which includes all land to the mean low water mark, is located 10 km to the west of Barnstaple on the north Devon coast (Figure 1.2). The Burrows form a coastal dune belt running north-south from Saunton Down to the mouth of the Taw-Torridge Estuary, a distance of 5.5 km (Figure 2.1). The dune system extends inland for a further 2 km. Braunton Burrows is bordered to the east by the low-lying reclaimed agricultural land of Braunton Marsh and to the north by the higher-lying land of Saunton. Characteristics of Braunton Marsh will be described in Section 5.3.
Figure 2.1 Geographical setting of Braunton Burrows and physical characteristics of the landscape.
Northam Burrows

Northam Burrows, a smaller site of 423 ha, is situated on the adjacent side of the Taw-Torridge Estuary from Braunton Burrows, 12 km to the south west of Barnstaple, (Figure 1.2). The 423 ha includes all land down to the mean low water mark. To the south and south-east of Northam Burrows are the higher-lying towns of Appledore, Northam and Westward Ho! (Figure 2.2).

Dawlish Warren

Dawlish Warren covers approximately 200 ha of a coastal sand spit (includes all land down to the mean low water mark) and is located 14 km south of Exeter on the south Devon coast (Figure 1.2). The site is joined to the mainland at its western end and extends eastwards for 2 km, into the mouth of the Exe Estuary (Figure 2.3).

2.2 Climate - precipitation and evapotranspiration

This section will describe the seasonal distribution of precipitation and monthly variations in evapotranspiration losses, which will ultimately influence the recharge characteristics of the groundwater systems. These variables will be considered throughout the thesis when describing annual cyclical water table fluctuations and long-term trends in the elevation of the water table.

At all three study sites meteorological data were analysed on a monthly basis from 1972-1995. This range of data were chosen primarily to relate to the long-term water table data available from Braunton Burrows. Monthly precipitation data, from RAF Chivenor, Bideford King George Fields (Bideford KGF) and Exmouth were supplied by the Environment Agency. Monthly actual evapotranspiration data were also supplied by the Environment Agency and were calculated using the 'Meteorological Office Rainfall and
Figure 2.2 Geographical setting of Northam Burrows and physical characteristics of the landscape.
Figure 2.3 Geographical setting of Dawlish Warren and physical characteristics of the landscape.
Evaporation Calculation System' (MORECS). The core of the scheme is a system which uses daily synoptic weather data as inputs to estimate weekly and monthly potential and actual evapotranspiration rates from various vegetation types and land surfaces, averaged over a 40 x 40 km area around the site of investigation (Woodley, 1991). Evapotranspiration rates are calculated from sunshine hours, wind speed, temperature, vapour pressure and the state, and height of the vegetation (Thompson et al., 1981). MORECS uses a slightly modified version of the Penman-Monteith equation to directly calculate both potential and actual evapotranspiration rates, in the latter case adjusting the bulk surface resistance according to the magnitude of the soil moisture deficit (Woodley, 1991). A description of the MORECS calculation process is included in Thompson et al., (1981). Throughout this thesis actual evapotranspiration rates were used in any hydrometeorological descriptions or calculations.

Braunton Burrows and Northam Burrows

The meteorological station at RAF Chivenor (SS 494 347) 4 km to the east of Braunton Burrows and at an altitude of 6 m, was identified as the most representative station, to reflect the prevailing climatic conditions at both Braunton Burrows and Northam Burrows. Data from this station were in fact used in the hydrological description of Braunton Burrows in the 1950s (Willis et al., 1959a). RAF Chivenor ceased monitoring from September 1975 to September 1980 and so a comparative site at Bideford KGF (SS 454 271) was used as an overlap, corrected for site variations in location and altitude.

Precipitation Characteristics

The analysis of precipitation data from RAF Chivenor and Bideford KGF, gave a long-term average (1972-1995) annual precipitation total of 878.3 mm, varying from a maximum of 1065.4 mm in 1994, to a minimum of 670.7 mm in 1975. Willis et al., (1959a) calculated
a similar annual average of 889 mm for the earlier period of 1935-1959. Precipitation of the area was seasonal and on average the autumn and winter months were wetter than the spring and early summer months (Figure 2.4). From 1972-1995, on average December was the wettest month of the year and May was the driest (Figure 2.4).

**Evapotranspiration rates**

Monthly rates of actual evapotranspiration are chiefly dependent upon temperature. The greatest evapotranspiration losses occurred in the warmer summer months (Figure 2.5), which coincided with the driest months in terms of precipitation (Figure 2.4). In July for example the average (1972-1995) total precipitation for the month was 53.97 mm and the average actual evapotranspiration losses were 86.2 mm, leading to a soil moisture deficit of 32.23 mm. At Northam and Braunton, from April through to August monthly actual evapotranspiration rates exceeded monthly precipitation totals, resulting in soil moisture deficits and a gradual decline in the elevation of the water table, as groundwater was released from storage. However, from September through to March, for the period 1972-1995, monthly precipitation totals were in excess of actual evapotranspiration losses, which typically would have resulted in an increase in groundwater storage and a rise in the elevation of the water table.

The importance of actual evapotranspiration losses to the groundwater budgets of the Braunton and Northam systems will also depend upon the dominant vegetation species. As explained in Section 1.6.1, tree species have higher evapotranspiration rates than grasses, typically leading to greater soil moisture deficits throughout the summer months.
Figure 2.4  Long-term average monthly precipitation totals for Braunton Burrows and Northam Burrows (1972-1995).

Figure 2.5  Long-term average monthly evapotranspiration losses for Braunton Burrows and Northam Burrows (1972-1995).
Dawlish Warren

The most comprehensive meteorological data, representative of the prevailing climatic conditions at Dawlish Warren were from Exmouth (SY 013 827). This meteorological station is located 2 km to the north east of Dawlish Warren, at an altitude of 53 m.

Precipitation characteristics

The long-term average (1972-1995) annual total precipitation for Dawlish Warren was 776.3 mm, ranging from a maximum of 949.6 mm in 1995, to a minimum annual total of 526.3 mm in 1975. Again the distribution of precipitation was seasonal and on average the autumn and winter months were wetter than the spring and early summer months (Figure 2.6). From 1972-1995 on average December was the wettest month of the year and July was the driest month (Figure 2.6). Monthly variability in precipitation should be related to monthly actual evapotranspiration rates to determine the possible annual cyclical effects on the Dawlish groundwater budget.

Evapotranspiration rates

Actual evapotranspiration losses for Dawlish Warren (Figure 2.7) demonstrated a similar seasonal pattern of distribution to those described for Braunton and Northam (Figure 2.5). Monthly actual evapotranspiration losses, based on calculations for grass, were greatest in the summer months when temperatures were the highest. This coincided with the months receiving the least precipitation. On average between 1972 and 1995 soil moisture deficits occurred within the Dawlish system from April through to August, leading to a reduction in groundwater storage and a gradual decline in the elevation of the water table. From September through to March monthly precipitation totals were on average (1972-1995) in excess of actual evapotranspiration losses, which lead to an increase in groundwater storage and a gradual recovery of water table elevations.
Figure 2.6  Long-term average monthly precipitation totals for Dawlish Warren (1972-1995).

Figure 2.7  Long-term average monthly evapotranspiration losses for Dawlish Warren (1972-1995).
As described in Section 1.6.1, monthly evapotranspiration rates would be higher from both the scrub species encroaching into Greenland Lake and from the open water bodies (wildlife ponds), leading to greater monthly soil moisture deficits in these areas.

2.3 Geology

It is important to have a knowledge of the underlying geology at all three study sites, because the structure, permeability and depth to bedrock are all important geological characteristics which may influence the properties of the overlying dune sands and the hydrological functioning of the groundwater systems.

Braunton Burrows

The geology of Braunton Burrows has been described by Edmonds et al. (1979) and Durrance and Laming (1993). The site is underlain by Pilton Shales, which were formed during the transition from Devonian to Carboniferous (Edmonds et al. 1979). The Pilton Shales outcrop in an east-west belt from the Devon and Somerset border to the Taw-Torridge Estuary. These rocks are soft grey shales, with localised bands and lenses of fossiliferous limestone, composed of shell debris, and medium to coarse grained quartzitic sandstone. Seismic research by McFarlane (1955) showed that the rock platform occurs at six to nine metres below mean sea level. A description of a single borehole on Braunton Burrows (SS 4579 3248) stated that the rock platform is overlain by silt and clay at approximately mean sea level (Edmonds et al., 1979). The wind blown sands which overlie the Pilton Shales and the marine silts and clays are believed to be of local origin, based on the similarity of their mineralogical composition (Greenwood, 1970). The main sources are from Bideford Bay, cliff erosion at Saunton Down and estuarine deposits from the Rivers Taw and Torridge (Figure 2.1). A study by Willis (1960) described the dune sands at Braunton as calcareous, with the calcium carbonate content accounting for 12 % by sample weight in the dunes near the sea, where there is much comminuted shell of
molluscs. As a result of leaching calcium carbonate content values of 7 to 9 %, by sample weight, were recorded on the Inland Plain and in the older parts of the dune system.

Northam Burrows

Northam Burrows is part of an alluvial plain deposited at the mouth of the Taw-Torridge Estuary. The site is underlain by Culm Sandstones and Pilton Shales of Upper Devonian and Carboniferous age (Dartington Amenity Trust, 1970). The alluvial plain is overlain by wind blown sand, the depth of which decreases from west to east.

Dawlish Warren

The geological structure of Dawlish Warren has been described in detailed seismic studies and borehole investigations by Kidson (1950) and Durrance (1969; 1980). The Warren is underlain by New Red Sandstone, of Permian and Triassic age, which dips gently from about 3 m below high water medium spring tide (HWMS) near the western end of the Warren, to 23 m below HWMS near Warren point (Kidson, 1950), (Figure 2.8). The rock surface is complicated by a number of incised channels reaching a maximum depth of 45.7 m below HWMS and run north-west, south-east across the Warren. These channels suggest that the River Exe has changed its position and in fact the spit may have originally been attached to the eastern side of the Estuary (Sims et al., 1995). The formation of Dawlish Warren spit is described in Section 2.4.

The rock surface and incised channels are partially overlain and infilled by Middle Devensian gravel, which merges into clay and sand deposits (Figure 2.9). The main body of the exposed spit consists of wind blown sands. These sands are often described as 'fossil', originating from offshore deposits first made available during the Pleistocene
Figure 2.8  Contour map of the New Red Sandstone surface beneath Dawlish Warren. (The line X-Y marks the position of the cross-section shown in Figure 2.9.) Source: Durrance (1980).

Figure 2.9  Profile through Dawlish Warren along the line X-Y (Figure 2.8) to show the stratigraphic structure. Source: Durrance (1980).
Sims et al., 1995). Under the present rate of sea level rise no new sediment is being brought to the coast from offshore sources. The other main source of sediment is from the River Exe.

The extent of the silt and clay beneath Dawlish Warren will influence the hydrological functioning of the groundwater system and will need to be considered carefully when describing the hydrological functioning of the system in Part 2 of Chapter 6.

2.4 Geomorphology

Braunton Burrows and Northam Burrows

Sediment transport is described within the context of coastal cells and sub-cells, which divide the coastline into sections (British Geological Survey, 1996a). Braunton Burrows and Northam Burrows form part of the Barnstaple Bay sub-cell, within which erosion and accretion are interrelated and are largely independent of other cells. Within the Barnstaple Bay sub-cell two major spits, Braunton Burrows and Northam Burrows, appear to have developed from opposing directions across the mouth of the Taw-Torridge Estuary (Kidson, 1963). A study of these two spits by Kidson (1963) stated that no record exists which suggested that the breach hypothesis needed to be invoked to interpret these geomorphological features. Research by Stuart and Hookway (1954) showed that marked pebbles on the ridge at Northam moved steadily northwards. All the evidence from the Braunton side of the estuary pointed to drift in a southerly direction (Kidson, 1963). Counter drifting was therefore the most probable cause of the Taw-Torridge Estuary double spit formation. Research by Sims (pers. comm.) suggested that counter drifting was possibly the result of a sudden change in the dominant wind and wave approach, but may also be related to sediment movement in rotating tidal streams. Wind blown sand dunes have been superimposed on the sites and Northam is protected by a naturally forming
The topography of Braunton comprises of three main sand dune ridges, running north-south parallel to the shoreline and separated by lower lying slacks (Figure 2.10). The dune ridges break down in the extreme north and south into a less defined double ridge (Willis et al., 1959a).

As described from the Braunton Burrows habitat map (Nature Conservancy Council, 1990), the fore dunes along the seaward margin of the system reach a maximum height of 8 m above Ordnance Datum (OD). Behind the fore dunes is a belt of dunes reaching a maximum height of 15 m above OD. Some of the dunes in the main ridge tower to 38 m above OD. Braunton Burrows has the highest range of dunes of any west coast system (English Nature, 1992). Landwards of the main dune ridge, covering approximately half of the total area of the Burrows the dunes are lower and more fragmented, amongst a relatively flat sand plain. Saunton Sands (Figure 2.10) forms a gently sloping beach along the eastern margin of the system, which at low tide is up to 1 km wide (Sarre, 1984).

The aerial view of a transect across the Burrows, from Saunton Sands inland to Braunton Marsh, shows the variation in topographical features across the system (Plate 2.2).

To the north of the system is Saunton Down, where the land rises to 160 m above OD. Along the eastern margin of the system is Braunton Marsh, where the land lies between 2-6 m above OD.
Plate 2.1 The pebble ridge at Northam Burrows.

Figure 2.10 Topographical characteristics of the Braunton dune system.
Source: Edmonds et al. (1979).
Plate 2.2  Aerial view of a transect across Braunton Burrows.
As described by Comber *et al.*, (1993), sand and gravel has been extracted from the northern side of the Taw-Torridge Estuary since the late eighteenth century. Erosion along the southern flanks of Braunton Burrows was recorded as early as the mid-nineteenth century. This period is not dissimilar from that during which sand and gravel extraction has been carried out in a sizeable way. Despite these obvious erosion problems extraction was allowed to continue and between 1960-1970 approximately 600,000 tonnes of sand and gravel were removed from the southern side of the estuary (Carr *et al.*, 1972). At the turn of the century extraction figures peaked at 150,000 tonnes per annum. A licence entitling the annual extraction of 15,000 tonnes of gravel from Crow Point has been in place since 1982 (Comber, *et al.*, 1993). Possibly as a result of sediment extraction Braunton spit, a valuable natural flood defence barrier, was breached in 1984 (Comber, *et al.*, 1993). Research by Blackley *et al.* (1972), using fluorescent labelled sand, suggested that sediment was being transported alongshore to replenish sand and gravel extracted from near Crow Point. The possible effects of sediment extraction on the long-term hydrological functioning of Braunton Burrows will be evaluated further in Section 5.2.2.

The geomorphological characteristics of Northam Burrows are best identified with reference to Figure 2.2 and Plate 2.3. The dunes at Northam cover only 83 ha of the total 258 ha site, extending in a narrow belt northwards from Sandymere before widening in the area around the landfill site (Comber *et al.*, 1993). The dunes reach a maximum height of 20 m above OD halfway along the ridge (Corrin, pers. comm.). The Burrows are protected from the sea by a naturally formed pebble ridge, which runs along the seaward margin of the system, before recurving around Greysand Hill (Plate 2.1). High tide reaches the base of the pebble ridge, but at low tide a beach of 550 m is exposed (Terpstra and Butterfield, 1969).

South of Greysand Hill is an area of transition from sandy plain to saltmarsh. This area is known as the Skern and at low tide forms a flat of sand and silt. The western shore of the
Skern has been scarred by refuse tipping and was developed as a landfill access road from 1937 (Terpstra and Butterfield, 1969).

Inland of the dune belt and pebble ridge the landscape forms a low lying coastal sand plain (Plate 2.4) stretching from the Skern in the north, to Westward Ho! in the south and inland as far as Appledore Bridge (Figure 2.2). The land gently slopes from the south east to the north west, but undulates more in the vicinity of the main dune ridge.

Plate 2.4   The coastal plain at Northam Burrows.

Dawlish Warren

As described by the British Geological Survey (1996b), sediment transport at Dawlish Warren occurs within the coastal sub-cell which extends from Dawlish Warren to Start Point, which is to the east of Salcombe. There is a weak northward movement of sediment within this cell and the beaches are subject to strong seasonal changes in drift direction.
Dawlish Warren and Exmouth Point form a double spit at the mouth of the Exe Estuary. The work by Kidson (1963) suggested that the double spit was the result of counter drifting. The geomorphological characteristics of Dawlish Warren are illustrated in Figure 2.3 and Plate 2.5. Dawlish Warren runs parallel to the shoreline, extending north-eastwards from the west side of the Exe Estuary for 2 km. The Warren was developed during the Flandrian rise in sea level, which ended about 5,000 years ago (Mottershead, 1986). Sea level rise lead to sediments being swept into the mouth of the estuary through the process of longshore drift. As described in Section 2.3 it is likely that the course of the River Exe has changed and consequently so has the position of the spit. Research in the 1950s and 1960s showed that the Warren spit was rapidly eroding (Kidson, 1950, 1964; Hydraulics Research Station, 1963), but since then has remained relatively stable (Redfern, 1993). The sea defence works at Dawlish Warren have helped to stabilise the spit. These coastline changes will be considered further when evaluating the possible causes for the perceived changing hydrological regime at Dawlish Warren (Section 6.17).

The outer spit along the seaward margin, known as the 'Outer Warren', forms a discontinuous ridge of mobile dunes reaching a maximum height of 7 m above OD and 25-50 m wide. The dune ridge is fronted at low tide by a stretch of beach varying in width from 100-300 m (Mottershead, 1986). Inland of the fore dunes is a ridge of generally lower semi-fixed dunes. The inner spit, known as the 'Inner Warren', forms a stabilized dune ridge reaching 3-4 m above OD at its eastern point. The spits are separated by Greenland Lake, an area of lower lying land formerly a tidal creek (Plate 2.6) The entrance to the creek became blocked in 1947, through the natural accretion of sand (Lawrence, 1991). Gradually this part of the system dried out and the vegetation species changed to form a wet meadow area, often mistaken for dune slack.
Plate 2.6 Greenland Lake and the Outer Warren.
(Photograph taken from the Inner Warren facing south.)

The former National Rivers Authority infilled part of Greenland Lake in the late 1970s, with waste rubble and boulders from the sea defence scheme (de Lemos, 1992). In the sheltered lee of the Inner Warren an area of mudflats and saltmarsh have built up.

2.5 Soil characteristics

The physical properties of the dune sands and slack soils will ultimately control water movement through the medium and therefore descriptive profiles for each study site were included.
Braunton Burrows

Findlay et al. (1984) classified Braunton Burrows as part of the Sandwich association 361, which consists of calcareous and non-calcareous sandy soils. In general this association contains a variety of soils types, with soil profile development dependent upon the degree of dune stabilization and the vegetation cover. For example, on the seaward margin of the system the dunes are more mobile prohibiting soil development. However, inland with the stabilizing effect of the dune vegetation two distinct soil types can be recognized, the first occurring in the dune slacks and the second on the dry dunes. Both soil types have been described by Willis et al. (1959a) and were observed in the field when digging soil observation pits. Representative profiles from field observations are described in Tables 2.1 and 2.2.

In comparison to the dry dunes, soil development and humus accumulation is greater in the dune slacks, particularly where the ground surface is colonized by scrub species, which increase the amount of organic matter added to the soil (Table 2.2). The majority of the slacks are subject to waterlogging throughout the winter and spring months. This results in anaerobic conditions, causing a reduction of iron oxides in the soil and giving a distinctive grey/blue colour to the profile, known as gleying (Knapp, 1979), (Table 2.2). A feature of the slack soils observed by Willis et al. (1959a) was that at 30 cm depth from the surface a compact layer occurred, almost impenetrable to a spade. This layer was attributed to the aggregation of fine particles possibly under the influence of salts being carried upwards by the fluctuating water table. However, the compact layer was not found when digging soil observation pits on Braunton Burrows, which would suggest this is a far more localized characteristic than implied by Willis et al. (1959a).
Table 2.1  Representative soil profile on a dry dune.  
(Personal field observations).

<table>
<thead>
<tr>
<th>Horizons</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3 cm Ah</td>
<td>Dark brown (Y 4/3) sand, high organic matter content; structure-less; stoneless; porous abundant fine fibrous roots; merging undulating boundary. (Beneath dry dune scrub humus accumulation is greater with an organic layer of 3-5 cm depth.)</td>
</tr>
<tr>
<td>3-15 cm Cu 1</td>
<td>Brown (Y 5/3) humus stained sand horizon; structure-less; stoneless; porous; low organic matter content; few fibrous roots; merging undulating boundary.</td>
</tr>
<tr>
<td>14-45 cm Cu 2</td>
<td>Yellowish brown (Y 5/4) sand; structure-less; stoneless; porous; low organic matter content; few fibrous roots; merging boundary.</td>
</tr>
<tr>
<td>45 cm + Cu 3</td>
<td>Brown (Y 5/5) sand; structure-less; stoneless; porous; low organic matter content; moist; shell fragments noticeable; odd fibrous root.</td>
</tr>
</tbody>
</table>

No further changes in sand characteristics were observed to a depth of 1.5 m.
Table 2.2  Representative soil profile within a dune slack.  
(Personal field observations).

<table>
<thead>
<tr>
<th>Locality: Braunton Burrows, North Devon</th>
<th>Grid Reference: SS 459 353</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizons:</td>
</tr>
<tr>
<td>0-10 cm Ah</td>
<td>Dark brown (Y 4/3) sand; high organic matter content; structure-less; stoneless; porous; abundant fibrous rooting; merging undulating boundary.</td>
</tr>
<tr>
<td>10-25 cm A(g)</td>
<td>Brown (Y 5/3) humus stained sand; structure-less; stoneless; shell fragments&lt;1 mm; porous; lower organic matter content; sporadic grey and red mottling; few roots; merging undulating boundary.</td>
</tr>
<tr>
<td>25-80 cm Cg1</td>
<td>Yellowish brown (Y 5/4) sand; structure-less; stoneless; low organic matter content; distinct grey and red mottling; a few roots; smooth boundary.</td>
</tr>
<tr>
<td>80 cm + Cg2</td>
<td>Light grey (5YR 6/1) sand; structure-less; stoneless; low organic matter content; gleyed. (Prolonged waterlogging causes anaerobic conditions and the reduction of iron oxides).</td>
</tr>
</tbody>
</table>

Northam Burrows

The soils at Northam Burrows are also broadly classified as Sandwich association 361 (Devon County Council, 1993). Again the younger seaward dunes have less well developed soil characteristics than those found on the stable vegetated inland plain. The soil characteristics are similar to those described for Braunton Burrows (Tables 2.1 and 2.2). The estuarine origin of the site explains the prominence of clay within the sediment profiles, particularly in the immediate vicinity of the Pill, where the accumulation of wind blown sand is the least. A representative profile of this area is described in Table 2.3.
Table 2.3  Representative soil profile within 10 m of the Pill at Northam Burrows. (Personal field observations).

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Within 10 m of the Pill</td>
<td></td>
</tr>
<tr>
<td>Elevation: 3.8 m (above OD).</td>
<td>Relief: Flat</td>
</tr>
<tr>
<td>Geology: Overburden-alluvium</td>
<td>Parent Material: Pilton Shales</td>
</tr>
<tr>
<td>and wind blown sand</td>
<td></td>
</tr>
<tr>
<td>Vegetation: Dune grassland</td>
<td></td>
</tr>
<tr>
<td>Horizons:</td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>Dark yellowish brown (10YR3/3) sand; high organic matter content; structure-less; stoneless; porous; abundant fine rooting; merging undulating boundary.</td>
</tr>
<tr>
<td>Ah</td>
<td></td>
</tr>
<tr>
<td>10-19 cm</td>
<td>Brown (Y 5/3) humus stained sand; low organic matter content; structure-less; stoneless; few fine roots; undulating boundary.</td>
</tr>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>19-45 cm</td>
<td>Yellowish brown (Y 5/5) sand; low organic matter content; red mottling; smooth clear boundary.</td>
</tr>
<tr>
<td>B(g)1</td>
<td></td>
</tr>
<tr>
<td>45-60 cm</td>
<td>Grey (5YR 4/1) sand layer comparatively coarser; gleyed; shell fragments; low organic matter content; sharp boundary; absence of roots.</td>
</tr>
<tr>
<td>B(g)2</td>
<td></td>
</tr>
<tr>
<td>60-95 cm</td>
<td>Grey (5YR 4/1) sand and clay layer; gleyed; waterlogged; structure-less; stoneless; absence of roots.</td>
</tr>
<tr>
<td>C(g)1</td>
<td></td>
</tr>
<tr>
<td>95+</td>
<td>Dark grey (5YR 3/1) clay; compact; stoneless; absence of roots.</td>
</tr>
<tr>
<td>C(g)2</td>
<td></td>
</tr>
</tbody>
</table>

Dawlish Warren

The Sandwich association 361 is also broadly mapped at Dawlish Warren, with similar soil characteristics to those described for Braunton Burrows (Tables 2.1 and 2.2). Within Greenland Lake the soils have been classified as Formby series, which are groundwater gleys with similar profile characteristics to those described under a dune slack at Braunton (Hall and Folland, 1967; Findlay et al., 1984), (Table 2.2). The area has also been mapped with the Beckfoot series, which are typical sandy rankers (Findlay et al., 1984), with similar characteristics to those described on a dry dune at Braunton (Table 2.1).
2.6 Vegetation

This section will describe the vegetation of each study site. The rarity and importance of the flora to the conservation status of the sites will be considered, alongside the possible detriment to these prime botanical sites if the perceived drying out process continues. It should be stressed at this stage that it is not within the scope of this thesis to determine the tolerance levels of individual species to long-term changes in the elevation of the water table.

**Braunton Burrows**

Braunton Burrows is described as a prime botanical site (Gibbons, 1990), sustaining a rich and diverse range of flora. Successional dune plant communities range from pioneer species on the mobile dunes, to invading scrub species inland on the fixed dunes. Apart from the blanket bog on Dartmoor, the plant communities at Braunton Burrows form the only priority habitat in Devon for conservation under the EC Habitats Directive. The dune slacks at Braunton are characteristically rich in highly specialised wetland plant communities and the site contains about one third of all dune slack in England (English Nature, 1992). Concerns have been expressed that the slacks are gradually being invaded by scrub species, such as creeping willow (*Salix repens*) and Yorkshire fog (*Holcus lanatus*). Similarly, the dune grasslands, inland of the main dune ridge, once characteristically rich in lichens and low growing plants are gradually becoming dominated by coarse grasses and sporadic dense low level scrub. The changing species composition is believed to be the result of either a lack of rabbit grazing, since the advent of myxamotosis in 1954, or a consequence of the perceived falling water table (Breeds, pers. comm.). In 1992 scrub species covered approximately 12 % of the dune system (English Nature, 1992). The presence of these hydrophilous species should be taken into consideration when describing the temporal variability in the elevation of the water table.
at Braunton Burrows (Section 5.2.3).

Table 2.4 lists some of the rare species found on the Burrows, all of which are characteristic of the dune slack habitat and are dependent on a high water table throughout the year. These are the rarities for which the site is renowned, but at the same time are also those most jeopardised by the perceived changing hydrological regime. English Nature attribute lower water levels on the Burrows to the disappearance of the internationally rare fen orchid \textit{(Liparis loeselii)} since 1988 and the decline in the water germander \textit{(Teucrium scordium)} by about 45% since 1982. The fen orchid \textit{(Liparis loeselii)}, early gentian \textit{(Gentianella anglica)} and water germander \textit{(Teucrium scordium)} are protected species under schedule 8 of the Wildlife and Countryside Act 1981 (Wolton, 1995). Further details of the species found on Braunton Burrows are described in the SSSI citation sheet included in Appendix A.

**Table 2.4 Rare species of Braunton Burrows**


<table>
<thead>
<tr>
<th>Species</th>
<th>Rarity of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>water germander \textit{(Teucrium scordium)}</td>
<td>Braunton Burrows is one of only 3 sites in Great Britain for this rarity (protected species).</td>
</tr>
<tr>
<td>early gentian \textit{(Gentianella anglica)}</td>
<td>This declining endemic plant now occurs at only 49 localities in Britain (protected species).</td>
</tr>
<tr>
<td>clustered club-rush \textit{(Scirpus holoschoenus)}</td>
<td>This species occurs only at Braunton Burrows and one other location in Great Britain.</td>
</tr>
<tr>
<td>fen orchid \textit{(Liparis loeselii)}</td>
<td>Braunton Burrows is one of only five sites in Great Britain for this rarity (protected species).</td>
</tr>
<tr>
<td>sharp rush \textit{(Juncus acutus)}</td>
<td>Braunton Burrows and Northam Burrows are two of only five sites in Great Britain for this rarity.</td>
</tr>
<tr>
<td>petalwort \textit{(Petalophyllum ralfsii)}</td>
<td>Braunton Burrows is one of only 12 sites in Great Britain for this rare liverwort.</td>
</tr>
<tr>
<td>variegated horsetail \textit{(Equisetum variegatum)}</td>
<td>Braunton Burrows is the only site in Devon for this nationally rare species.</td>
</tr>
<tr>
<td>round-leaved wintergreen \textit{(Pyrola rotundifolia)}</td>
<td>Braunton Burrows is the only site in Devon for this nationally rare species.</td>
</tr>
</tbody>
</table>
Northam Burrows

At Northam Burrows the diverse range of species makes the site a valuable ecological resource. The existence of various species within the system are dependent upon factors such as the underlying soil, topography and the drainage regime. On this basis the Burrows can be classified into distinct habitats, such as the coastal grasslands, which make up approximately half of the site, the intervening rush communities, the fixed dunes, the open channel ditches and the saltmarsh environment (Figure 2.2).

A number of species found within these habitats are nationally important for their existence (Table 2.5). A more detailed description of the species found on Northam Burrows are described in the SSSI citation sheet included in Appendix A.

Table 2.5 Rare species of Northam Burrows.
Source: Adapted from Devon County Council (1993) and Wolton (1995).

<table>
<thead>
<tr>
<th>Species</th>
<th>Rarity of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>water germander</td>
<td>Northam Burrows is 1 of only 3 sites in Great Britain for this rarity.</td>
</tr>
<tr>
<td>(Teucrium scordium)</td>
<td></td>
</tr>
<tr>
<td>fen orchid</td>
<td>Northam Burrows is 1 of only 5 sites in Great Britain for this rarity (protected species).</td>
</tr>
<tr>
<td>(Liparis loeselii)</td>
<td></td>
</tr>
<tr>
<td>sharp rush</td>
<td>Northam Burrows is 1 of only 5 sites in Great Britain for this rarity (protected species).</td>
</tr>
<tr>
<td>(Juncus acutus)</td>
<td></td>
</tr>
</tbody>
</table>

As mentioned when describing the rare flora of Braunton, the water germander (Teucrium scordium) is a particular rarity and protected species. This species requires open and wet conditions, and is found in the Inland Sea at Northam Burrows (Figure 2.2). The staff at Northam are concerned that if the perceived drying out of the system continues, then site conditions may no longer be suitable for its successful colonisation. A further concern is that as a result of lower water levels, bramble (Rubus fruticosus) is encroaching and taking over many clumps of sharp rush (Juncus acutus). A GIS survey of the site in 1991, showed that since 1964 the rush communities have declined by 50% (Jollands, 1991).
Dawlish Warren

Dawlish Warren with its various habitat types, including mobile dunes, semi-fixed dunes, fixed dunes, saltmarsh, freshwater wetland and ponds, has been colonized by a diverse range of plant species. Around 350 species of flowering plants have been recorded on Dawlish Warren (de Lemos, 1992). The nationally important species are listed in Table 2.6.

<table>
<thead>
<tr>
<th>Species</th>
<th>Rarity of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warren crocus ( (Romulea columnae var. occidentalis) )</td>
<td>Dawlish Warren is the only mainland Britain site where this species is found.</td>
</tr>
<tr>
<td>petalwort ( (Petalophyllum ralfsii) )</td>
<td>Dawlish Warren is one of only 12 sites in Great Britain for this national rarity and was only discovered on the Warren in July 1997.</td>
</tr>
<tr>
<td>bulbous meadow grass ( (Poa infirma) )</td>
<td>Nationally scarce.</td>
</tr>
<tr>
<td>shepherd's cress ( (Teesdalia nudicaulis) )</td>
<td>Nationally scarce.</td>
</tr>
</tbody>
</table>

The Warren crocus \( (Romulea columnae var. occidentalis) \), shepherd's cress \( (Teesdalia nudicaulis) \) and bulbous meadow grass \( (Poa infirma) \) are all found on the golf course and are threatened by the drainage regime and pressures from human recreation.

The area most threatened by the apparent falling water table is Greenland Lake, where the encroachment of scrub species such as birch \( (Betula pubescens) \), elder \( (Sambucus nigra) \) and willow \( (Salix cinerea, Salix repens) \) are replacing the damp loving species such as the southern marsh orchid \( (Dactylorhiza praetermissa) \), autumn lady's tresses orchid \( (Spiranthes spiralis) \), yellow bartsia \( (Parentucellia viscosa) \), greater birds-foot trefoil \( (Lotus uliginosus) \) and the michaelmas daisy \( (Aster novi-belgii) \) (de Lemos, 1992). A more detailed account of the flora of Dawlish Warren is described in the SSSI citation sheet (Appendix A).
2.7 Land drainage

This section will describe the land drainage regime operating within each of the dune systems, because ultimately drainage losses via ditches, tile drains and into ponds may influence, or control the long-term elevation of the water table.

**Braunton Burrows**

The 18 hole links course to the north of the Braunton system is drained by an open channel ditch and a tile drain system. The drainage waters collect in the ditch and drain into the adjoining Braunton Marsh system (Figure 2.1). These drainage waters effectively become a net loss from the dune system. The seasonal effect of the golf course drainage system on the elevation of the water table within Braunton Burrows will be discussed further in Section 5.2.4.

Drainage ditches also dissect the fields to the North of Sandy Lane car park (Figure 2.1), and drain into the Braunton Marsh system. West Boundary Drain forms the inland boundary between the dune and marsh systems (Figure 2.1). The possible effects of the management of this channel on the elevation of the water table on the Burrows will be discussed further in Section 5.2.5.

**Northam Burrows**

At Northam Burrows a network of ditches, drain surface water and possibly groundwater from the south eastern part of the system (Figure 2.2) in order to prevent widespread surface flooding. These drainage waters ultimately feed into an arterial channel, the Pill, which drains out into the Skern. The flow regime of the Pill is not managed and with tides greater than 5.8 m saline waters inundate the channel and flow up as far as Goosey Pool (Figure 2.2). These waters drain as the tide recedes.
Goosey Pool is a shallow water area (Figure 2.2) subject to large water level fluctuations caused by tidal inputs. Before the area was infilled with sediment dredged from the Pill, Goosey Pool was an extensive surface water body up to one metre deep and attracting a diverse range of wildlife (Corrin, pers. comm.).

Sandymere and Greysand Lake are both artificial surface water features, which characteristically flood during the winter months (Figure 2.2). The water level in Greysand Lake is controlled by an overflow pipe and penstock. With tides greater than 5.8 m and when the penstock on the overflow pipe is open, tidal waters replenish the pool. Sandymere is not really a drainage feature merely a perched ephemeral surface pool, which contains brackish waters. A major input to the pool is from tidal breaching of the pebble ridge.

**Dawlish Warren**

The golf course at Dawlish Warren is artificially drained by a herring-bone system of underground clay drainage pipes, which feed into a main drainage channel (Figure 2.11). These drainage waters either flow directly out into the estuary, or collect in a pond at the eastern tip of the golf course. The pond is the sink of the system and water levels on the golf course are partially controlled by the elevation of standing water in the pond. Water is pumped directly from the holding pond out into the Exe Estuary and again is effectively a net loss from the groundwater system, as discussed further in Section 6.17.1e.

Two more ponds were created on the Local Nature Reserve in 1983, not for drainage purposes, but to attract wildlife (Figure 2.3). The largest pond, situated to the east of the interpretation centre is approximately 0.6 ha and a smaller pond located at the easterly point of the reserve covers a maximum of 80 m² depending upon the time of year.
Figure 2.11 Drainage characteristics of Dawlish Warren golf course.
2.8 Conservation status

Table 2.7 summarises the conservation status of each dune system, which clearly illustrates the ecological and geomorphological importance of these ecosystems. The conservation value attributed to these sites also stresses why there is the need to understand how these systems function hydrologically, in order to prevent any future loss or damage to the dune habitat.

Table 2.7 Conservation status of the study sites.
Source: Keddie (1996a; 1996b), Wolton (pers. comm.) and Walsh (pers. comm.).

<table>
<thead>
<tr>
<th>Site name</th>
<th>Conservation status</th>
<th>Date Designated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brauton Burrows</td>
<td>Site of Special Scientific Interest</td>
<td>1976</td>
</tr>
<tr>
<td></td>
<td>UNESCO Biosphere Reserve (One of only three sites in England to have this international conservation status).</td>
<td>1977</td>
</tr>
<tr>
<td></td>
<td>Candidate 'Special Area of Conservation' (EC Habitats Directive)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Part of the Hartland Heritage Coast</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>Area of Outstanding Natural Beauty</td>
<td>1960</td>
</tr>
<tr>
<td>Northam Burrows</td>
<td>Country Park</td>
<td>1974</td>
</tr>
<tr>
<td></td>
<td>Site of Special Scientific Interest</td>
<td>1981</td>
</tr>
<tr>
<td></td>
<td>Part of the Hartland Heritage Coast</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>Area of Outstanding Natural Beauty</td>
<td>1960</td>
</tr>
<tr>
<td>Dawlish Warren</td>
<td>Local Nature Reserve</td>
<td>1978</td>
</tr>
<tr>
<td></td>
<td>Site of Special Scientific Interest</td>
<td>1981</td>
</tr>
<tr>
<td></td>
<td>Part of the Exe Estuary Ramsar site (wetland of international importance).</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>Part of the Exe Estuary 'Special Protection Area' (EC Birds Directive)</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>Part of the Warren is a Devon Wildlife Trust Reserve</td>
<td>-</td>
</tr>
</tbody>
</table>
In September 1996 English Nature withdrew National Nature Reserve Status from Braunton Burrows, as a consequence of being unable to manage the site to the maximum benefit of nature conservation (Wolton. pers comm). However, as Braunton is a proposed 'Special Area of Conservation' site, English Nature continues to work closely with the Ministry of Defence (MOD) and the land owners to ensure that the future management of the site is sustainable and that nature conservation is of primary consideration.

The SSSI citation sheets for Braunton, Northam and Dawlish (Appendix A) describe the importance of these systems for their ecological diversity and geomorphology.

2.9 Land use and management

Although the final hydrological management recommendations will afford primary consideration to nature conservation, the requirements of other land users and interest groups must also be taken into consideration. This section will therefore describe the varied land uses of each dune system.

Braunton Burrows

As described by English Nature (1993), the entire site of Braunton Burrows, with the exception of the foreshore (406 ha), is owned by the Christie Devon Estate Trusts. The foreshore (Saunton Sands) forms part of the Crown Estate and is leased to Braunton Parish Council. With reference to Figure 2.1, the Christie Devon Estate Trusts lease the northern 113 ha of the Burrows to Saunton Golf Club. The MOD lease the southern two thirds (604 ha) as a military training ground. Between 1964 and September 1996 English Nature sub-leased this land from the MOD and it was designated as a National Nature Reserve. To the east of the American Road three small areas of land known as Southern Flat, Middle Flat
and Northern Flat are leased to local people for grazing. The only land currently in the hands of the Estate is 155 ha between the golf course and Saunton Sands. Braunton Burrows is also of major importance for recreation, education and research.

**Northam Burrows**

Devon County Council has held the freehold of Northam Burrows since 1974 (Devon County Council, 1993). The existence of Rights of Common on the Burrows has allowed generations of local residents access to free grazing. Grazing has helped produce the unique grassland habitat that now exists. Since the late 1800s part of the site has been leased to the Royal North Devon Golf Club (Figure 2.2). The 18 hole course has been described as the most natural links course in Great Britain after St. Andrews (Linaker, pers.comm.). Since the designation of Northam Burrows as a Country Park in 1974 the site has been popular with local people and tourists for leisure and recreation. To the north of the Burrows, in the area around Greysand Hill 11.1 ha has been infilled by landfill tipping since 1942 (Devon County Council, 1993). Today an active landfill to the south west of this area covers an additional 4.4 ha (Devon County Council, 1993).

**Dawlish Warren**

At Dawlish, the Outer Warren and Greenland Lake are owned by Teignbridge District Council (Figure 2.3) and are heavily used for leisure, recreation and educational purposes. The Inner Warren is leased by Devon Wildlife Trust to Dawlish Golf Club, who have established an 18 hole golf course (Teignbridge District Council, 1992).
2.10 Conclusion

Table 2.8 summaries the key physical characteristics of Braunton Burrows, Northam Burrows and Dawlish Warren and describes the impact of human activity on the hydrological functioning of the systems.

<table>
<thead>
<tr>
<th>Landscape characteristics</th>
<th>Braunton Burrows</th>
<th>Northam Burrows</th>
<th>Dawlish Warren</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>1,350 ha</td>
<td>423 ha</td>
<td>200 ha</td>
</tr>
<tr>
<td>Climate</td>
<td>The annual average precipitation (1972-1995) is 878.3 mm. Autumn and winter months receive the most precipitation. Evapotranspiration losses are highest from May to August.</td>
<td>Similar seasonal precipitation and evapotranspiration characteristics as for Braunton and Northam. The annual average precipitation (1972-1995) is 776.3 mm.</td>
<td></td>
</tr>
<tr>
<td>Geomorphology</td>
<td>Three main dune ridges reaching a maximum of 40 m above OD. Inland of the dune ridges is a undulating coast plain with fragmented dunes and wet slacks.</td>
<td>Coastal plain, with a single dune ridge along its seaward margin, reaching a maximum of 15 m above OD. The site is partially protected by the Pebble Ridge.</td>
<td>Consists of two main dune ridges. Outer Warren: mobile fore dunes backed by a semi fixed dune ridge, 6-8 m above OD. Inner Warren: fixed dune ridge, 4-6 m above OD Former tidal creek separating the Inner and Outer Warren.</td>
</tr>
<tr>
<td>Characteristics of the slack soils and dune sands</td>
<td>Dry dunes; Sandy rankers. Slacks; gleyed soils.</td>
<td>As described for Braunton. Near the Pill silt and clay is prominent in the soil profile.</td>
<td>Dry Dunes; sandy rankers. Greenland Lake: gleyed soils.</td>
</tr>
<tr>
<td>Vegetation</td>
<td>12 % of system covered by invading scrub. Rare plant species include the water germander, fen orchid and sharp rush.</td>
<td>Bramble invasion. Rare species include the water germander and the sharp rush.</td>
<td>Scrub encroachment into Greenland Lake. Rare species include the sand crocus, shepherds cress and bulbous meadow grass.</td>
</tr>
<tr>
<td>Land drainage characteristics</td>
<td>Tile drains and a drainage ditch on the golf course. Drainage ditches dissect the agricultural fields to the north of Sandy Lane car park and West Boundary Drain runs along the eastern margin of the dune system.</td>
<td>Drainage ditch network discharging into the Pill.</td>
<td>Herring bone drainage network on the golf course. Drainage waters collect in a pond and drain into the Exe.</td>
</tr>
<tr>
<td>Conservation status</td>
<td>SSSI, Biosphere Reserve, formerly a National Nature Reserve, proposed SAC site and part of the Hartland Heritage Coast, and an Area of Outstanding Natural Beauty.</td>
<td>Country Park, SSSI and part of the Hartland Heritage Coast, and an Area of Outstanding Natural Beauty.</td>
<td>SSSI, Local Nature Reserve, part of the Exe Estuary Ramsar Site and Special Protection Area. Part of the Warren is a Devon Wildlife Trust Reserve.</td>
</tr>
<tr>
<td>Land use</td>
<td>Nature conservation, golf course, military training ground, grazing and leisure activities</td>
<td>Nature conservation, golf course, grazing land and leisure activities.</td>
<td>Nature conservation, golf course and leisure activities.</td>
</tr>
</tbody>
</table>
Chapter 3
Experimental design
Chapter 3

Experimental Design

3.0 Introduction

Experimental design was of paramount importance to the successful fulfilment of the aims of this research; to describe the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Braunton Burrows, Northam Burrows and Dawlish Warren; to assess whether these systems were drying out and if so, to determine the most probable causes, and finally to recommend sustainable hydrological management options for each system, aimed at raising water levels, or preventing any future lowering of the water table. The experimental design controls the scale of the investigation, the representativeness of individual monitoring or sampling sites, the types of observations made, the validity of the collected data and its subsequent usefulness in fulfilling the outlined aims of this research.

This chapter therefore aims to describe the experimental design developed in order to successfully undertake the detailed hydrological investigation of three Devon sand dune systems. The chapter will firstly consider the scale of the research, before describing the field and laboratory procedures used to ensure the collection of representative and accurate data.

Data collected on Braunton Burrows will also be used in the parameterisation and calibration of a groundwater model. Chapter 3 will therefore include a detailed section on the history and development of groundwater models in water resource management investigations. This section will also establish the purpose of modelling at Braunton and will evaluate the applicability of selected models to simulate the hydrogeology of the site, and to predict the long-term behaviour of the groundwater system.
3.1 Scale of investigation

As first described in Section 1.2.1, the spatial hydrological characteristics and the functioning of the groundwater systems were considered at three investigative scales, in order to build up a detailed picture of the hydrological complexity of each dune system (Table 3.1). At Braunton, because of the sheer size of the dune system (1,350 ha) the physical properties of the dune sands were investigated at an additional scale, which is described throughout the thesis as a detailed experimental site (Table 3.1).

Table 3.1 Scale of the hydrological investigation at Braunton, Northam and Dawlish.

<table>
<thead>
<tr>
<th>Level of investigation</th>
<th>Scale of Analysis</th>
<th>Generality of the hydrological interpretation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrology of the entire dune system described with the aid of water table contour plots</td>
<td>General</td>
</tr>
<tr>
<td>2</td>
<td>Flow-nets and cross sections used to describe spatial and temporal variability in the elevation, shape and gradient of the water table.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Detailed experimental sites used to characterise the physical properties of the dune sands at Braunton.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Individual water table monitoring sites used to describe intra-site variability in the annual cyclical response of the groundwater system.</td>
<td>Specific</td>
</tr>
</tbody>
</table>

At Braunton five detailed experimental sites were investigated (Figure 3.1), four consisting of dune and slack units and the fifth was a peripheral site within an area of dune turf and scrub. To ensure spatial representation the sites were chosen with consideration to their geographical location within the dune system. As shown in Figure 3.1, two of the detailed experimental sites were located within the high dune ridges, along the eastern side of the system (Horse Breakers Slack and Round Slack). In
comparison, a further two sites were within the Inland Plain surrounded by fragmented dunes reaching a maximum height of 16 m above OD (Cotton Slack and J-Lane Slack) (Figure 3.1). The final site, Bridle Path was at the inland margin of the dune system (Figure 3.1).

At both Northam and Dawlish physical properties of the dune sands were analysed next to each water table observation site within the monitoring network (Section 3.2.3b). This sampling strategy ensured a detailed spatial analysis of sediment properties and was also essential to explain intra-site variability in the annual cyclical response of the groundwater system.

The requirement to describe the hydrology and physical properties of the dune sands at the described investigative scales was of paramount importance when designing and supplementing the water table monitoring networks (Section 3.2.3).

3.2 Field procedures

3.2.1 The measurement of ground water levels

Water table data provide records of short-term changes and long-term trends of storage fluctuations within a specific aquifer (Alexander, 1983) and were required to successfully fulfil the aims of this research. The scale and design of the water table monitoring network and the validity of the collected water level data, with regards to well design characteristics and installation procedures were all important factors to be taken into consideration.
Figure 3.1 Experimental sites at Braunton Burrows.
The water table can be defined as the level at which water pressure is equal to atmospheric pressure and hence is the level at which water will stand in a well that is hydraulically connected with the ground water body (Brassington, 1993; Gilman, 1994). In an unconfined aquifer any change in barometric pressure can be transmitted directly to the water table both in the aquifer and in the well, so that heads remain equal and no measurable change in the water level occurs (Todd, 1959; Price, 1996).

At all three sites water table elevations were monitored through the use of dipwells, which consisted of perforated plastic piping, screened to avoid sedimentation. At Braunton Burrows observation pits, retained in the monitoring network from the earlier hydrological study by Willis et al. (1959a), were also used to monitor water table elevations. These pits were a maximum of 1 m deep, with an area of 0.25 m². Consecutive measurements of the phreatic water level were made from the same position on the edge of the observation pit, to limit any measurement error.

In addition piezometers were installed within each of the detailed experimental sites to determine the $K_{sat}$ of the dune sands. Only the lower section of the piezometer casing is perforated to allow flow into the well. The length of the perforated casing is therefore the depth over which $K_{sat}$ is determined.

3.2.2 Dipwell and piezometer design considerations

The well diameter, casing and screening characteristics, and the installation procedures will determine the representativeness and accuracy of any collected water table data, or hydraulic measurements.

Research by Price (1996) and Ward (1963;1975) concluded that the validity of the water
level readings in a well will increase as the diameter of the well decreases. Basically the wider the well the more it departs in size from the interstices in which ground water is naturally held and the more likely it is to improve artificial flow conditions, which ultimately result in a lowering of the water table in the well. Further to this, Kruseman and de Ridder (1977) and Gilman (1994) state that if the diameter is large the volume of water contained within the well may cause a time lag in changes of draw down, particularly when the water table is varying rapidly. Considering the requirements of this research, to monitor short-term water table responses in permeable dune sands, such as in a slug test (Section 3.2.6a), plastic piping with a diameter of 3.5 cm was used to construct any new dipwells, or piezometers installed during the fieldwork programme (September 1993-March 1996). Similar sized dipwells and piezometers have been successfully used by Clarke (1980), Alexander (1983) and Jones (1993) in the collection of representative water level data.

A further consideration was the possibility of head loss caused by the well casing, which had the purpose of supporting the sides of the hole, but allowing a maximum volume of water to enter the well with a minimum of hydraulic resistance (Todd, 1959). Head loss through a perforated well casing is controlled by the percentage of open area. Kruseman and de Ridder (1977) state that the well should be slotted, or perforated over no more than 30 to 40 % of its circumference to keep the entrance velocities less than 0.03 m s⁻¹. At this velocity the friction losses through the well casing are negligible. This percentage open area was therefore ensured when constructing dipwells and piezometers for use within this research.
3.2.3 The observation well network

a) The existing observation well network at Braunton Burrows

At Braunton Burrows, the Nature Conservancy, the Nature Conservancy Council and English Nature (NC, NCC and EN) have been monitoring water table elevations at 26 locations, on a monthly basis since June 1972 (Figure 3.2). Water table observation pits maintained from the earlier hydrological study of Willis et al. (1959a) were found at 14 of these sites and dipwells had been installed at the other 12 sites. For the purpose of the hydrological investigation at Braunton, the observation pits and dipwells were collectively described as observation wells. The monitoring network was revised in June 1992. Some of the less accessible southerly monitoring sites were abandoned and a transect of six observation wells was installed to the north of the monitoring network (coded 1N-6N on Figure 3.2).

The observation wells were located along environmental gradients from east to west and north to south (Figure 3.2), mainly in the southern part of the dune system, within the boundaries of the former National Nature Reserve. Although the inherited observation well network provided exceptionally valuable long-term (1972-1995) water table elevation data, there was notably a lack of observation wells in the central third of the system and on the golf course to the north (Figure 3.2). This meant that the hydrological interpretation of the site (Chapters 4 and 5) was based primarily on water table data collected in the southern part of the dune system. The spatial distribution of observation wells within the inherited monitoring network also made it difficult to evaluate the possible effects that factors such as the golf course drainage system were having on the long-term elevation of the water table (Section 5.2).
Figure 3.2 Location of observation wells on Braunton Burrows.
Using the inherited observation well monitoring network and the available long-term water table elevation data, the hydrological characteristics and functioning of the groundwater system were evaluated at the three investigative scales described in Table 3.1.

The existing observation wells were positioned with consideration to the following points:

1. to monitor the hydrology of the slacks at varying elevations within the dune system. These are the areas of prime botanical interest and the most susceptible to long-term hydrological change.

2. to avoid the high the dunes where it was difficult to reach the water table.

3. accessible for regular monitoring.

These criteria ensured that comprehensive water table elevation data were collected. At both Northam and Dawlish similar criteria were adopted, although because the monitoring networks were being developed from scratch greater consideration could be given to the spatial representativeness of individual dipwells (Section 3.2.2b).

b) The dipwell monitoring network at Northam Burrows and Dawlish Warren

Water table elevations had not been monitored on either Northam or Dawlish prior to the start of this research. In September 1993, at the very start of the fieldwork programme, a monitoring network of 14 dipwells were installed at Northam Burrows (Figure 3.3) and six at Dawlish Warren (Figure 3.4). Three more dipwells were added to the Dawlish monitoring network between February and May 1995, when it was realised that more detailed water table data were required on the golf course and within
Figure 3.3 Location of dipwells on Northam Burrows.
Figure 3.4 Location of dipwells on Dawlish Warren.
(Exploratory boreholes refer to Section 3.2.7)
Greenland Lake. Early installation of the dipwells was essential to monitor the rise in the water table through the autumn and winter months of 1993/1994. Also, the low water table elevations at the start of the research in September 1993 were beneficial when manually installing the dipwells. The dipwells were installed to a depth of between 1.2-2.5 m, with the primary aim of positioning them below the lower limit of any annual cyclical water table fluctuations. The liquid nature of saturated sand made hand augering below the water table impossible. To build up a detailed picture of the temporal hydrological characteristics of these systems water levels were monitored weekly.

The dipwells at both Northam and Dawlish (Figures 3.3 and 3.4) were located with consideration to the following points;

1. spatially distributed to evaluate any intra-site variability in the annual cyclical response of the water table and also to build up a picture of the shape and elevation of the groundwater system.

2. to identify possible factors influencing annual/seasonal water table fluctuations, such as artificial drainage or scrub encroachment.

3. to monitor the sites where the rare plant species are most threatened by the changing hydrological regime, such as in the Inland Sea at Northam Burrows and within Greenland Lake at Dawlish Warren.

4. accessible for regular monitoring.

5. out of direct view of the public, to avoid vandalism and the subsequent loss of valuable weekly water table readings.
Also at Dawlish Warren in the main pond to the east of the interpretation centre (Figure 2.3) a stage board was installed and levelled to OD to record weekly water level fluctuations.

3.2.4 Surveying

At each study site the dipwells, piezometers and observation pits, were levelled to OD (Newlyn) using an electronic distance measurer (EDM). Principally, the EDM measures the time difference between a transmitted and reflected laser beam of radiation (Gordon et al., 1992). The target is a reflective surface. The EDM was used in this research to measure distances between monitoring sites and their elevation differences. By converting water table measurements to metres above OD the water table data collected from individual observation wells could be related to each other to describe the hydrological characteristics of each system.

At Northam and Dawlish additional spot height measurements were taken to build up topographical maps of the sites. A detailed land surface contour map was published for Braunton Burrows by the Nature Conservancy Council in 1990.

The maintenance and management of West Boundary Drain, located along the eastern margin of the dune system, was identified by English Nature as a possible contributing cause for the perceived lower water levels on Braunton Burrows. An EDM survey of this drain was therefore undertaken to describe the geometry of the channel and ultimately from a management perspective to evaluate the potential for raising seasonal water levels within this ditch without causing widespread flooding of the surrounding agricultural land (Section 5.3.3). Cross-sections of West Boundary Drain similar to those shown in Figure 3.5 were drawn up for each of the survey points shown on Figure
3.6. These data were also used to simulate the drain when modelling the Braunton groundwater system (Chapter 7).

Figure 3.5 West Boundary Drain cross-section measurements

3.2.5 The tidal cycle

The literature reviewed in Section 1.4.3 clearly stated that there was no relationship between water table fluctuations and the height of the tide at Braunton (Willis et al., 1959a), Newborough Warren (Ranwell, 1959) or Ainsdale (Clarke, 1980). However, the literature does not describe the method of observation, or the degree of accuracy. Therefore, it was thought necessary to substantiate these results with the use of highly sensitive water level recorders. Any tidal influence would need to be taken into consideration when describing spatial and temporal differences in annual cyclical water table fluctuations.

At Braunton water table fluctuations were monitored over a 24 hr period, during a spring tide, in dipwell 6N (Figure 3.1), which was located in a slack 250 m inland from
the seaward edge of the fore dune ridge. The monitoring equipment included a Druck pressure transducer, connected to a 21X Campbell data logger. The pressure transducer, designed to measure water level changes according to the head above it, was secured in the dipwell, at a point below the elevation of the water table. The data logger was programmed to monitor changes in head every 10 minutes.

A similar experiment was carried out at Northam Burrows on dipwells 11 and 12 (Figure 3.3), which were within 150 m of the High Water Mark (HWM), situated in a former area of saltmarsh. Preliminary analysis of the water table data from dipwell 11 displayed irregular weekly fluctuations throughout the period of monitoring (October 1993-March 1996), which was possibly a tidal influence (Section 6.7). Dipwells 11 and 12 were monitored simultaneously for an initial period of 8 hrs. Dipwell 11 was monitored in total for 72 hrs, with the loan of an additional data logger and pressure transducer from Devon County Council. Insurance problems with university equipment meant that the data logger on dipwell 12 had to be removed after the initial 8 hrs.

To determine whether the tide was influencing water table fluctuations at Dawlish Warren the main pond next to the interpretation centre (Figure 2.3) was monitored for a period of 72 hrs, during which time a high spring tide occurred. A dipwell was temporarily installed in the centre of the pond and was monitored every ten minutes with the use of the data logger and pressure transducer.
Figure 3.6 Survey points on Braunton Marsh.
(Discharge measurement sites refer to Section 3.2.10.)
3.2.6 Saturated hydraulic conductivity ($K_{sat}$)

$K_{sat}$ measures the ease of water movement through the dune sands, as defined in Section 1.5. This hydraulic property was considered when describing intra and inter-site variability in the annual cyclical functioning of the groundwater systems.

a) $K_{sat}$ below the water table

There are a number of well documented field methods which will give a representative measurement of $K_{sat}$ below the water table. The auger hole method developed by Hooghoudt (1936) and described in Luthin and Kirkham (1949) involved augering holes of a known dimension and then adding water and observing water table fluctuations. This method was impractical in this research because of the non-cohesive nature of the dune sands. The auger hole method was later improved by Kirkham (1945), Kirkham and Van Bavel (1948) and Van Beers (1958) and the hole was lined with an open ended cylinder. However, Bonell (1972) and Jones (1993) both working in a sandy medium had major problems with removing upwelling saturated sand, which quickly filled the liner.

An alternative method, described by Cooper et al. (1967), Papadopulus et al. (1973), Bouwer and Jackson (1974), Bouwer and Rice, (1976), Van der Kamp (1976) and Black (1978) was the slug test. A slug test calculates $K_{sat}$ from the rate of rise of a water level in a lined and capped auger hole after a certain volume or 'slug' of water has been removed or added to the well (Bouwer and Rice, 1976). This was thought to be the most appropriate method for the determination of $K_{sat}$ in saturated dune sands and was successfully employed at Kenfig by Jones (1993).

At Braunton, slug tests were carried out on the nested piezometers installed in the
detailed experimental sites (Section 3.1). $K_{sat}$ was measured at a depth of 0.70-1.0 m, 2.70-3.0 m and 5.50-6.0 m from the ground surface. At Northam screened piezometers were temporarily installed within 3 m distance of each dipwell in the monitoring network, measuring $K_{sat}$ at various depths from the ground surface, to a maximum of 2.50 m. Similarly at Dawlish screened piezometers were also temporarily installed within 3 m distance of dipwells 1, 2, 3A, 5, 6 and 8 to facilitate measuring $K_{sat}$ at various depths to a maximum of 0.95-1.25 m. Again the liquid nature of saturated sand limited the depth to which the piezometers could be installed.

To avoid non-representative $K_{sat}$ measurements the piezometers were flushed to remove any sediment accumulating in the bottom of the pipe and to minimise smearing around the outer wall of the piezometer. A pressure transducer was then lowered into the piezometer and secured at a point that would be below the water level after the slug was removed. The steady head in the piezometer was recorded before the slug of water was removed. The pressure transducer was connected to a Campbell data logger and programmed to measure the recovery of the water table on a ten second interval. A slug of water was then rapidly removed using a bailer and the progressive recovery recorded. A problem faced in this experiment was that the removal of the slug did not sufficiently lower the water table, because of the high permeability of the dune sands. A stirrup pump was therefore used to remove 30-50 cm depth of water, pumping for approximately 20 seconds.

An experimental design consideration was the number of slug tests to be carried out on each well to ensure a representative value of $K_{sat}$. As recommended by Van Beers (1958), Boersma (1965a) and Bonell (1972) it was more important to gain a representative spatial value for $K_{sat}$ carrying out tests on more holes, rather than
repeating the test numerous times on the same hole. If human error was suspected, or if the data logger water table recovery measurements were irregular then the slug test was repeated on the same auger hole.

At a later stage the water table recovery data were down loaded from the data logger and used to determine values of $K_{sat}$ using the computer package AQTESOLV, developed by Geraghty and Miller Inc. (1991). A full description of the analysis method is provided in Section 4.8.3.

b) $K_{sat}$ above the water table (well permeameter)

The determination of $K_{sat}$ above the water table was only determined at Braunton. The purpose of this experiment was to determine the degree of $K_{sat}$ variability within the system and also to compare the well permeameter $K_{sat}$ results with those measured in the slug test experiments.

$K_{sat}$ above the water table can be determined by either field or laboratory based methods. However, it is well documented in the literature that laboratory determination of $K_{sat}$ often incurs considerable error (Christiansen, 1944; Kirkham, 1945; Sillanpaa, 1959; Jones, 1993). Transportation of a sediment core from the field to the laboratory may considerably alter the properties of the sample and was a particular problem with non-cohesive dune sands.

Field methods for determining $K_{sat}$ are based on the measurement of the rate of flow of water from a lined, or unlined auger hole. However, there are a number of limitations to many of these methods. The double-tube method, the shallow-well pump in method and the cylinder permeameter methods, described by Boersma (1965b), are all time
-consuming, require large quantities of water, considerable manpower, specialised equipment and have been used with varying degrees of success.

For these reasons, it was therefore decided to use an alternative method known as the simplified well permeameter technique, which required less water and could easily be operated by one person. The technique was developed by Talsma and Hallam (1980) and was essentially a refinement of the shallow-well pump in method for determining $K_{sat}$ above the water table. The simplified well permeameter technique calculated $K_{sat}$ by measuring the rate of flow from an unlined auger hole, whilst maintaining a constant head (Bonell et al., 1983). The principal problem with this method was that because of the non-cohesive nature of the dune sands a liner was required. Liners, perforated the length of the hole and open ended, but screened with a fine netting to avoid blockage were installed for the measurements. Bonell (1972), stated that if the liner was sufficiently perforated (30 to 40 % of its circumference) its use should not cause any restriction of flow during the recovery and may therefore successfully be used to support the hole in the simplified well permeameter experiment.

The simplified well permeameter consists of two concentric acrylic tubes and adjustable legs, as illustrated in Figure 3.7. The principle of this experiment was to measure the rate of water infiltration from the permeameter in order to maintain a constant head (H in Figure 3.7) in the lined auger hole. A pre-wetting phase of a minimum of twenty minutes was required in an attempt to saturate the area immediately around the auger hole and to develop a constant head within the liner. The formulae used to analyse the well permeameter data are described in Appendix B.
The well permeameter experiment was carried out on dunes adjoining four of the detailed experimental sites, namely Cotton Slack, Round Slack, Horse Breakers Slack and J-Lane Slack (Figure 3.1). $K_{sat}$ was calculated at the base of the dune, mid-slope and at the top of the dune. At each of these locations the well permeameter test was carried out on three separate augur holes to ensure a representative $K_{sat}$ value for the site. The lined auger holes were 0.5 m deep and the base of the well permeameter was set at 0.4 m. Therefore the constant head (H) and the determination of $K_{sat}$ were determined for the depth 0.4-0.5 m (Figure 3.7).

3.2.7 Depth to bedrock or an impermeable layer - seismic hammer and drilling rig

To calculate the depth of the salt water, fresh water interface (Sections 4.6, 6.6 and 6.14) and to parameterise the groundwater model (Chapter 7), data on the depth to bedrock or an impermeable layer that would form the lower boundary of the groundwater systems were required.
The most economic method for the determination of the depth to a consolidated underlying substrate, such as clay, or rock was the seismic hammer. This technique worked on the principle that energy being passed into the ground would be reflected when it encountered a less penetrable layer. The deflected signal was detected by a series of geophones connected to a seismograph. The time interval between the original and reflected energy wave was a function of the depth to a less penetrable layer.

However, when using the seismic hammer at Braunton Burrows, up over Warble Fly Hill and down into Horse Breakers Slack (Figure 3.1), inconclusive results were obtained. The high sensitivity of the seismograph in the sandy medium detected a wetting front 2-4 m from the ground surface (Figure 3.8).

An alternative method was to drill down through the sand dune profile to bedrock, or a continuous impermeable layer. In unconsolidated material, such as dune sands, Todd (1959) suggested that the most appropriate drilling technique was the rotary method. With the use of the Squirrel Drilling Rig from the Department of Geological Sciences, University of Plymouth, this method was employed on both Braunton Burrows and Northam Burrows (Plate 3.1). Auger flights were rotated vertically into the ground, coiling up the excavated material. A total of 15 auger flights were available allowing a maximum drilling depth of 13.50 m.
Figure 3.8 Seismic profile up over Warble Fly Hill and down into Horse Breakers Slack.
At Braunton depth to bedrock or an impermeable clay layer was quantified at five sites, (labelled Pt1-Pt5 on Figure 3.1). As described in Section 2.4, Northam Burrows forms an alluvial plain overlain by wind blown sand. The depth to the silt and clay material was investigated at six locations within the dune system (Figure 3.9). The sheer size of the Braunton and Northam systems, economic constraints and problems of accessibility limited the number of sites where depth to bedrock or an impermeable layer could be investigated. Therefore, the data presented in Sections 4.5 and 6.5 should only be taken as a probable indicator of the depth and continuity of the lower basal layers of the groundwater systems.
Figure 3.9 Locations on Northam Burrows where depth to bedrock or an impermeable layer were determined.
Limited access to the Warren golf course, infilling of parts of Greenland Lake with boulders and rubble from the sea defence works and financial constraints, prevented a detailed geological survey of the Warren. However, geological surveys of the site have been carried out by Kidson (1950) and Durrance (1969; 1980) and will be reviewed in Section 6.13. Also eight exploratory boreholes were hand augered on the golf course to a maximum depth of 2 m (Figure 3.4), to describe the characteristics of the underlying sediment.

3.2.8 Particle size sampling

Variations in the average grain size will ultimately influence water movement in both the saturated and unsaturated zones. At Braunton to determine the homogeneity of the dune sands with depth samples were collected from four profiles on Warble Fly Hill (coded DR Profile I-IV on Figure 3.1), sampling every 0.90 m to a maximum depth of 12.60 m with the use of the drilling rig. Before each additional auger flight (0.90 m in length) was added to the drill the hydraulic pressure was released and the drill was allowed to rotate on the spot. Material from the lowest auger flight was coiled to the surface for sampling and returned to the laboratory for the determination of particle size distribution (Section 3.3.1). Using this sampling method the depth from which the samples were excavated was only an approximation. Taylor (pers. comm.) stated that with this sampling method there could be a 10 % error in the calculated depth from which the sediment was taken. Dune sands were not sampled beneath the water table, because the liquid nature of saturated sand made even an approximation of the sample excavation depth impossible. To evaluate spatial variability in particle size characteristics within the Braunton system samples were taken at 0.90 m depths above the water table at the sites where the drilling rig was used to determine depth to bedrock or an impermeable layer (coded Pt1-Pt5 on Figure 3.1) and during the installation of the
nested piezometers in the detailed experimental sites (Figure 3.1).

At both Northam and Dawlish samples for particle size analysis were collected by hand augering. At Northam, to evaluate the spatial variability in particle size characteristics the dune sands were sampled at 0.50 m depths above the water table within 2.5 m distance of each dipwell within the monitoring network (Figure 3.3). Preliminary analysis of the material on the golf course at Dawlish, during the installation of the dipwell network, identified a silty/clay layer less than one metre from the ground surface. Therefore, to build up a detailed picture of the complexity of the sediment properties in this part of the system sediment was sampled at 0.20 m depths above the water table next to dipwells 5, 6, 6A, 7 and 8 (Figure 3.4). At a more detailed scale of investigation sediment was sampled every 0.20 m above the water table, on a 30 m x 30 m grid across Greenland Lake (Figure 3.10). The purpose of this exercise was to determine whether the functioning of the groundwater system in Greenland Lake, a former tidal creek, was influenced by variable particle size characteristics.

3.2.9 Bulk density sampling

Bulk density is one of the main characteristics which describes the relative proportions of solid and void in a soil (Pitty, 1979). Bulk density was considered at Braunton Burrows, to identify compaction, or the presence of an impeding layer that would cause variability in the rate of groundwater recharge.
There are three basic methods for determining bulk density; the excavation method, the clod method and the coring method (Blake, 1965, Smith and Atkinson, 1975). The basic principle of these methods is weighing and drying a known volume of soil (Blake, 1965). Working in dune sands measuring the volume of a soil clod was not possible because of the lack of structural stability. Excavation of a known volume also proved impossible because of the non-cohesive nature of the dune sands, with the side walls of a soil pit collapsing. The most practical method for obtaining a known volume sample was therefore coring. Sampling took place during the wetter winter months when the
surface 0-50 cm were more cohesive, but not saturated. A cylindrical metal sampler with a plastic liner was pressed into the ground to the desired depth removing a known volume of sample in situ. No samples were taken below the water table, because of the lack of suitable equipment to remove a saturated sand sample of a known volume. Bulk density samples were successfully taken at depths of 0-5 cm and 45-50 cm, at the same locations as the simplified well permeameter experiments were carried out (Section 3.2.6b).

3.2.10 Discharge calculations

Discharge is defined as the volume of water passing through a given cross-sectional area of the channel, during a given period of time (Rantz, 1982). An extensive survey of channel discharge was undertaken on Braunton Marsh, primarily because of concerns expressed by English Nature that the water level management of the drainage ditch network and in particular West Boundary Drain was influencing water levels on the Burrows. To compare and contrast summer and winter discharge characteristics and to ensure representative measurements discharge readings were taken during four separate hydro-metric surveys, July 1994, January 1995, July 1995 and January 1996.

Also on ten separate occasions during the hydro-metric surveys of January 1995 and 1996, discharge from the golf course drainage ditch, on its entrance into Braunton Marsh was quantified. The purpose of these measurements were to quantify net winter drainage losses from the northern part of the dune system. Drainage losses from the golf course are considered further when evaluating the impact of the golf course drainage system on the elevation of the water table within the Burrows (Section 5.2.4).

As described by Petts (1983), the mean velocity of a channel cross-section is determined
from a number of point measurements. The basic procedure is to select a series of verticals, spaced at known intervals across the channel and to determine the depth and velocity at each. According to Dingman (1984) the standard procedure for hydrologists is to use a minimum of 20 verticals per channel. However, Linsley et al. (1975) stated that if the purpose of the survey was to relate the discharge from one channel to another, then it was more important to complete the survey to an acceptable degree of accuracy within the shortest time possible, thus avoiding changes in the discharge caused by additional inputs to the system from precipitation. According to the size of the drainage ditch, the majority of which on Braunton Marsh were less than 2.5 m wide at water level, between 5 and 10 verticals were measured. At each vertical water depth (D) was recorded and the mean velocity (V) was measured at four tenths of the depth from the channel bed, or six tenths below the surface (Ingle Smith and Stopp, 1978; Rantz, 1982), (Figure 3.11). This method of determining mean velocity is used by the USGS where the maximum depth of water in the channel is less than 0.76 m, or if the scale of the survey is large and discharge characteristics within individual channels are to be related to each other (Rantz, 1982). Flow measurements were converted into discharge values using the simple mid-section method (Figure 3.11). Each vertical was viewed as being in the centre of a subsection; the discharge of each subsection is calculated and the total channel cross-sectional discharge is the sum of the subsection discharges.

Within each subsection velocity was calculated with the use of an electromagnetic current meter. The instrument works on the principle that a conducting fluid moving through a magnetic field would induce a voltage, providing a direct measurement of velocity (Gordon et al., 1992). The electromagnetic current meter has a calibrated velocity range of 0.000 m s\(^{-1}\) to 1.500 m s\(^{-1}\). The machine also has the capability of measuring velocity within a vegetated channel.
Figure 3.11  The mid-section method for calculating discharge.

Locations within the marsh drainage ditch system where discharge measurements were taken are shown on Figure 3.6. Discharge measurements were made a minimum of 10 m distance from the convergence or divergence of drainage ditches (Figure 3.6), to avoid measuring irregular flows that could ultimately lead to misinterpreting the seasonal drainage regime of the system.

3.2.11 The pump drainage system at Dawlish Warren

As described in Section 2.9 the golf course at Dawlish Warren is pump drained during the wetter winter months to avoid widespread flooding. During the winter of 1995/1996 the green keeper was asked to keep a log of the times when the pump was switched on and off, so that effective losses from the system could be calculated. Unfortunately the
data supplied at the end of the winter season were unreliable.

3.3 Laboratory procedures

3.3.1 Particle size analysis

As described in Section 3.2.8 samples were taken at each of the dune systems for particle size analysis. A traditional method of particle size analysis is by wet or dry sieving (BS 1796) (Allen, 1993). A representative sub-sample is passed through a stack of sieves, which become progressively finer, separating the particles into group sizes. The weight of the sample retained on each sieve is weighed and expressed as a percentage of the total sieved sample. This method can be time consuming and becomes difficult when measuring dry powders under 38 μm (Day, 1965). An alternative technique for determining the particle size characteristics of a silt and clay rich sample is the pipette method (BS 1377), (McCave and Syvitski, 1991).

In this research, particle size distribution was determined by a combination of dry sieving (particles >1.7 mm) and laser diffraction (particles <1.7 mm). Organic matter was removed from the samples by adding hydrogen peroxide, which when heated oxidized a large part of the organic matter to carbon dioxide (Day, 1965). The modern method of particle size analysis by laser diffraction has been described by McCave et al. (1986) and McCave and Syvitski (1991). Particles of a given size diffract light through a given angle, which increases as the size of the particle decreases. The parallel beam of monochromatic light, when passed through the suspended sample, diffracts and focuses onto a detector. The detector then calculates the angular distribution of the scattered light intensity, from which a computerised output of particle size distribution is displayed.
This method of particle size analysis has numerous advantages, as outlined in the Malvern Instruments Ltd (1993) handbook;

1. it is non-intrusive, using a low power laser beam to produce the particle size.

2. typically each sample will take less than one minute to analyse.

3. gives a high resolution size discrimination.

4. there are a number of lens ranges, chosen to suit the size range of the sample. The overall measurement range of the machine is from 0.1μm to 2000 μm (2 mm).

5. no calibration is required. The instrument is based on fundamental physical properties.

Research has been carried out by Hartley (pers. comm.) to determine the accuracy of the laser diffraction method of particle size analysis. When analysing beach sands, using the sieving and laser diffraction methods, very similar particle size frequency distribution curves were obtained. However, when analysing a predominantly silt and clay sample the laser diffraction method consistently underestimated the percentage volume of particles less than 62μm compared with the pipette method. A correction calibration graph has been produced (Hartley, pers. comm.), which was used when analysing predominantly silt and clay samples in this study.
3.3.2 Bulk Density

To calculate bulk density the samples were oven dried, at a constant temperature of 105°C, for 24 hrs. Dry bulk density (BD) is the ratio of the mass of dry solids to the bulk volume (Rowell, 1994), expressed as;

\[
\text{BD} = \frac{M_d}{V} \quad \text{(g cm}^3\text{)}
\]

(Equation 3.1)

where \(M_d\) is the total mass of dry soil (g) and \(V\) is the total volume of soil (cm\(^3\)).

3.4 Groundwater modelling techniques

3.4.1 The development of groundwater modelling

A model is any device that represents an approximation of a field situation (Anderson and Woessner, 1992). The application of groundwater models to practical problems has inevitably been controlled by developments in modelling techniques and the increasing power and sophistication of computing systems (Ashley, 1994). Several types of models have been used to study groundwater flow systems, which can be divided into three broad categories.

The first category are described as physical models, which include sand tank models, consisting of a tank filled with an unconsolidated porous medium through which water is induced to flow (Freeze and Cherry, 1979; Wang and Anderson 1982; Ashley 1994). A major drawback with this type of model is scaling down from the field situation to the dimensions of the laboratory model. Phenomena measured at the scale of a sand tank model are often different from conditions observed in the field. It is also difficult to modify boundary conditions and parameter values. Accordingly this type of model can only be applied to simple defined problems requiring little or no calibration, or groundwater flow problems in simple layered aquifers.
The second category are described as analogue models, which includes viscous flow models (the Hele Shaw model) and electrical models (Freeze and Cherry, 1979; Wang and Anderson, 1982; Ashley, 1994). This category of model was widely used in the 1950s before high-speed computers were available. The Hele-Shaw model is based on viscous flow between parallel glass plates, and electrical analogue models work on the principle that groundwater flow is analogous to the flow of electricity around a circuit. Voltage changes in the electrical analogue model are analogous to changes in groundwater head. A drawback with this category of model is that each one is designed for a unique aquifer system and parameter values, and boundary conditions cannot be easily changed.

The third category is the mathematical model, which can be either an analytical or numerical solution. As computing became more widely available during the 1970s most physical and analogue models became redundant, due to the power of the mathematical model (Ashley, 1994). Analytical models are based on analytical flow equations, which are solved by graphical means, whereas numerical models are based on numerical flow equations and are solved by computers (Anderson and Woessner, 1992). A numerical model is a replica of a real-world system (National Research Council, 1990). As described by Peters (1987), analytical models are more appropriate for aquifer test analysis, or prediction over short periods of time, in simple geologic settings and at a local scale (typically hectares to several square kilometres). Numerical models are used for long-term groundwater assessments of large areas, with a range of aquifer properties, boundary conditions and water budget fluxes (Mercer and Faust, 1980). Commercial numerical models were readily available from the late 1970s, however, the simplicity of their conceptual basis meant that in most situations it was preferable for a modeller to code a model from scratch, to suit the particular requirements of the groundwater
modelling problem (Freeze, 1971; Narasimhan and Witherspoon, 1976; Frind and Verge, 1978). Since the 1970s there has been steady progress in the development of more sophisticated commercially available numerical groundwater models, designed to simulate confined, unconfined and semi-confined multi-aquifers in one, two, or three dimensions (Anderson and Woessner, 1992). These commercial model codes have been thoroughly tested and evaluated. Today the ease of use of commercial software makes numerical modelling a more routine tool for the analysis of groundwater resource management problems (Ashley, 1994; National Research Council, 1990). Numerical models can now readily be used to examine the behaviour of groundwater systems, which are too complex to examine by analytical methods (Walton, 1991; Wood, 1993). However, the basic problem remains that no matter how sophisticated the numerical model is, the ability to predict groundwater behaviour depends on the initial conceptualisation of the problem.

Prediction models, employing numerical simulation techniques and homogenous/heterogenous aquifer parameters, have been widely used in groundwater resource management problems, as reviewed by Bradley (1994;1996). A numerical model of the Braunton groundwater system would be ideal for this purpose and would have three main objectives;

1. to investigate whether it was possible to apply a commercial groundwater flow model to the Braunton aquifer and calibrate it satisfactorily to simulate the complex hydrogeology, and domed water table of the Burrows.

2. to gain a better insight in the hydrological functioning of the Braunton groundwater system and,
3. if the model can be calibrated, use it to test a set of hydrological management scenarios to predict the hydro-ecological consequences of altering boundary conditions, or introducing new management practices into the system.

At Braunton a numerical model of the groundwater system would help provide quantitative answers to water resource management questions, which could not easily be answered with analytical solutions. For example, the model could be used to evaluate the impact that an increase in scrub coverage, or the deepening of the drainage ditches on Braunton Marsh, would have on the elevation of the water table. Specific water resource management questions relating to the Braunton scenario are listed in Section 7.1.

3.4.2 Model criteria for Braunton Burrows

Today there are many well tested and developed commercial models, which can simulate many different hydrogeological scenarios and so numerical models are rarely, if ever, developed from scratch. However, the successful application of an 'off-the-shelf' model is dependent upon the applicability of the selected model to the groundwater regime. At this stage in the modelling process it was therefore essential to set the Braunton scenario into basic context so that a suitable model could be chosen. As described in Sections 2.3 and 2.4 the Braunton dune system is a multi-layered aquifer. The unconfined aeolian sands are underlain by layers of silt, clay and sand. Also to the east of the Burrows is Braunton Marsh, which will need to be modelled as semi-confined, or confined aquifer layers. Detailed quantitative accounts of the site hydrogeology will be described in Chapter 4, before conceptualising the system for modelling in Chapter 7. The chosen groundwater model must therefore be capable of simulating all aquifer types, confined, unconfined and semi-confined.
As described by Aral (1990a) in such a multi-layered system the main aquifer layers may lose or gain water through either, or both of the geologic formations bounding the main aquifers. The leakage between layers cannot be ignored due to the large horizontal contact areas involved and the large piezometric head differences that may exist between the main aquifer layers. This pressure difference is the principle driving force for leakage. Thus in a typical layered geologic formation the overall flow picture is that of a three-dimensional coupled, interactive groundwater flow system (Aral, 1990b). In most cases proper analysis of such systems must reflect this nature of flow. In contrast two dimensional groundwater flow models assume the Dupuit Forchimer principle, that no vertical flow occurs between boundaries (Freeze and Cherry, 1979), which can introduce error into the modelling predictions.

Furthermore, two dimensional areal models that use the Dupuit assumptions calculate the head at the water table (Anderson and Woessner, 1992), but in two dimensional profile and three dimensional simulations the water table forms part of the upper model boundary. Head is equal to the sum of pressure and elevation head (Freeze and Cherry, 1979). At the water table pressure is equal to atmospheric pressure and pressure head is set to zero. The water table is the most difficult of all boundaries to simulate and often, as in the case of Braunton Burrows, is the very feature that needs to be calculated, in order to recommend future water level management options to prevent any further lowering of the water table. Therefore, to be of maximum benefit in the Braunton modelling scenario the selected model should calculate the water table elevation as part of the modelling solution.

Fluctuations in the elevation of the Braunton water table, caused by changes in the drainage regime or the encroachment of hydrophilic species, is a time dependent
problem (Dowd, pers. comm). The selected model should therefore also be capable of handling transient simulations.

From the outlined model criteria for the Braunton scenario, the most suitable type of groundwater flow model would be a three dimensional model, which would take into account vertical drainage between layers, calculate the elevation of the water table in the top model layer and simulate transient groundwater flow scenarios. The decision that a three dimensional groundwater flow model was the most appropriate type of numerical model to simulate the groundwater flow regime of the Braunton multi-layered aquifer was confirmed by discussion with experienced groundwater modellers from the University of Georgia (Dowd, pers. comm.), the Amsterdam Water Supply (Olsthoom, pers. comm.) and the University of Birmingham (Mackay, pers. comm.).

Other considerations when selecting a model include the need to check that the accuracy of the model code has been verified and to demonstrate that the numerical solution is relatively free of round-off and truncation errors, which if uncontrolled can lead to an unstable solution (National Research Council, 1990; Anderson and Woessner, 1992). It is also important to determine whether the code has been used in other case studies, thus establishing its track record in coping with various hydrogeological settings and water resource management problems.

Sections 3.4.2a-e describe the features, capabilities and application of the most popular and well tested three dimensional groundwater flow models, which have been used worldwide in groundwater resource management studies (Walton, 1991; Anderson and Woessner 1992; Olsthooorn, pers. comm; Dowd pers. comm.). A critical evaluation of the suitability of each model in simulating the groundwater hydrology of Braunton
Burrows will follow in Section 3.4.2f.

a) MODFLOW and Visual MODFLOW

As introduced in Section 1.7 MODFLOW is a three dimensional saturated groundwater flow model developed by the United States Geological Survey (USGS), (McDonald and Harbaugh, 1988). MODFLOW simulates steady-state and transient groundwater flow, in confined and unconfined aquifers with heterogeneous, anisotropic porous media and with variable layer thicknesses (Scientific Software Group, 1997). The groundwater flow equation is solved using the finite difference approximation (Wood, 1993; McDonald and Harbaugh, 1988) and the model domain is divided into blocks, in which the medium properties are assumed to be uniform. As described by Anderson and Woessner (1992) finite difference models are easier to program and in general fewer data are required to construct a finite difference grid. Finite difference models calculate a value for the head at the node, which also is the average head for the cell that surrounds the node (Wood, 1993).

Input parameters to be specified in MODFLOW include grid dimensions, layer elevations, vertical and horizontal hydraulic conductivity ($K_{sv}$), storage parameters, boundary conditions (constant head, no-flow or general head boundaries) and precipitation. There is also a package which takes into account losses from the system through the process of evapotranspiration. The model has other optional modules, which simulate the hydrological functioning of rivers, drains and wells. Compatible preprocessors are available to help with data assembly and postprocessors can assist in viewing the model's output. MODFLOW is a public domain model and official versions of the USGS modelling software are available for electronic retrieval via the World Wide Web (http://water.usgs.gov/software/ground_water.html).
A valuable feature of MODFLOW is the ease with which the model can be integrated with a GIS system, as described in the groundwater modelling research carried out by Olsthoorn et al. (1993), Stibitz et al. (1993), Kamps and Olsthoorn (1996), Hardisly et al. (1996), Juan and Kolm (1996) and Michl (1996). The integration of MODFLOW and a GIS system reduces both data entry time and the post-processing of the modelling results.

MODFLOW is described as one of the most widely used groundwater models in the world (McDonald and Harbaugh, 1988; Hake and Cuhadroglu, 1993). Its frequent usage comes from its modular nature, ease of use, good documentation, and its verified open code, which can be modified by the modeller to suit the requirements of a particular modelling scenario. The USGS MODFLOW code has international recognition and support.

MODFLOW is continually being developed and new packages added to the code, to increase its scope of applicability to different groundwater modelling scenarios. In 1996 an updated version called MODFLOW-96 was released, which has the same computational methods, but is designed to be more user friendly (Harbaugh and McDonald 1996). Furthermore, in 1995, Waterloo Hydrogeologic Software released Visual MODFLOW 2.0 (hereafter referred to as VMODFLOW), which is a fully integrated pre and post processor for the official USGS MODFLOW code. VMODFLOW is often described as a graphical interface for MODFLOW (Guiger, 1995). In VMODFLOW when the modeller has finished preparing the input, the preprocessor prepares the MODFLOW input files, calls up the MODFLOW executable program and runs the model, before returning the modeller to the postprocessor to visualize the results. The VMODFLOW output module allows the modeller to contour
the modelling results to show heads, drawdown, water table elevations, head differences between layers, flow pathlines and the flux between layers (Guiger, 1995). VMODFLOW also allows the modeller to graphically assign the input parameters, run the analysis, calibrate the model and visualise the results in either plan view, or full cross-sections. The ability to quickly switch between plan and cross-section display of the model is a powerful feature of VMODFLOW that allows the modeller to gain a better perspective on three dimensional groundwater modelling (Winston, 1996). Guiger (1995) described VMODFLOW as a user friendly modelling package, that even an intermediate modeller would find easy to use, performing simulations of a professional quality and using the world's most widely used USGS MODFLOW code. The fully integrated VMODFLOW modelling package, with its powerful and intuitive graphical interface, allows individual model runs and the overall modelling project to be completed much faster than if using MODFLOW with a separate pre and post processor.

There are many more examples in the literature describing the use of the MODFLOW code in groundwater resource management scenarios than with any other model in the world (Olsthoorn, pers. comm). Rojstaczer (1994) stated that MODFLOW has been applied so frequently that the model has near brand-name recognition. MODFLOW has been used in a range of environments, evaluating groundwater resource management problems at both a local scale (1.5 ha) and regional scale (1,300 km²), (Table 3.2).

The modelling studies listed in Table 3.2 describe the process of model design, calibration, validation and prediction, and are valuable sources of reference when setting up a new groundwater modelling study. However, these modelling examples fail to describe any problems with the model's capabilities, or the stability and sensitivity of the final calibrated model. As described by Rojstaczer (1994) the danger with using
predictive numerical groundwater models is to interpret the models results and recommend future water resource management strategies without taking into consideration the assumptions made, or the sensitivity of the model.

Table 3.2 Examples of the use of MODFLOW in groundwater resource management investigations.

<table>
<thead>
<tr>
<th>Author of study</th>
<th>Transient or steady-state simulations</th>
<th>Area modelled</th>
<th>Discretisation of model cells</th>
<th>Purpose of modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ishemo (pers. comm.)</td>
<td>Steady-state and transient</td>
<td>500 ha</td>
<td>50 m x 50 m</td>
<td>Modelling the water table response to changing evapotranspiration rates and drainage on Goss Moor, Cornwall.</td>
</tr>
<tr>
<td>Juan and Kolm (1996)</td>
<td>Steady-state</td>
<td>1,300 km²</td>
<td>500 m x 500 m</td>
<td>To more fully understand the groundwater functioning of the Jackson Hole aquifer, Wyoming.</td>
</tr>
<tr>
<td>Michl (1996)</td>
<td>Steady-state and transient</td>
<td>4,500 ha</td>
<td>Ranging from 25m x 25 m to 250 m x 250 m</td>
<td>To determine future management strategies for groundwater withdrawal in the lower River Sieg, near Bonn, Germany.</td>
</tr>
<tr>
<td>Bromley and Robinson (1995)</td>
<td>Steady-state and transient</td>
<td>58 ha</td>
<td>50 m x 50 m</td>
<td>Modelling the effects of peat cutting on water levels at Tythorne Moor, National Nature Reserve, South Yorkshire</td>
</tr>
<tr>
<td>Ashley (1994)</td>
<td>Transient</td>
<td>1.5 ha</td>
<td>Ranging from; 10 m to 50 m side length</td>
<td>Modelling the impact of excavation works for road construction, on groundwater levels at West Bromwich.</td>
</tr>
<tr>
<td>Bradley (1994,1996)</td>
<td>Steady-state and transient</td>
<td>5.4 ha</td>
<td>10 m x 10 m</td>
<td>Modelling the water table response of Narborough Bog, Leicestershire, (wetland habitat)</td>
</tr>
<tr>
<td>Gilvear et al. (1993)</td>
<td>Steady-state</td>
<td>1,050 ha</td>
<td>i) 250 m x 250 m, ii) 125 m x 125 m</td>
<td>Modelling the groundwater contribution to a small wetland.</td>
</tr>
<tr>
<td>Olsthoom et al. (1993)</td>
<td>Steady-state and transient</td>
<td>3,500 ha</td>
<td>100 m x 100 m</td>
<td>The effects of water abstraction on the elevation of the water table within a sand dune system.</td>
</tr>
<tr>
<td>Mayo and Slosson (1992)</td>
<td>Steady-state and transient</td>
<td>2,238 km²</td>
<td>1,600 m x 1,600 m</td>
<td>Modelling to predict water table elevation changes resulting from groundwater abstractions from Fish Springs Ranch, Nevada.</td>
</tr>
<tr>
<td>McNamara et al. (1992)</td>
<td>Steady-state</td>
<td>12 ha</td>
<td>Not stated</td>
<td>Modelling groundwater flow through a wetland in a small kettle hole, New York, USA</td>
</tr>
<tr>
<td>Hensel and Miller (1991)</td>
<td>Steady-state</td>
<td>58 ha</td>
<td>28 m x 28 m</td>
<td>Modelling the wetlands on the floodplain of the Des Plaines River, Illinois, to evaluate the effect of wetland creation on groundwater flows</td>
</tr>
</tbody>
</table>
For all of the above reasons MODFLOW is the main numerical groundwater flow model used by the 'Amsterdam Water Supply Company', hydrological consultants and government agencies, to simulate the hydrology of sand dune systems in the Netherlands (Olsthoorn, pers. comm.). As described in Section 1.7, MODFLOW was used with a compatible pre and post processor to model a 35 km² area of sand dunes along the North-Sea coast, to the south of Zandvoort. The aim of the modelling exercise was to optimise the interests of both groundwater abstractions and nature conservation (Olsthoorn, et al. 1993). Again any problems encountered when using this model were not described in the published paper. However, Olsthoorn (pers. comm.) stated that the main problem with this regional scale finite difference model, consisting of 64 x 128 rectangular cells, each measuring 100 m x 100 m, was that it was difficult to accurately simulate the scale of individual recharge features and drainage channels. To solve this problem a smaller scale model was created, which was then embedded into the regional model. This was a time consuming procedure.

The description of the features and capabilities of the MODFLOW code and the VMODFLOW modelling package appear to fulfil the modelling criteria set out for the Braunton groundwater modelling scenario (Section 3.4.2). The MODFLOW code will be critically compared with the other models reviewed in Sections 3.4.2b to 3.4.2e, to determine whether it is the most suitable model for the Braunton groundwater resource management investigation (Section 3.4.3).

b) Micro-Fem

As briefly outlined in Section 1.7, Micro-Fem is a three dimensional, finite element, saturated groundwater flow model, based on a computer code initially written for a regional groundwater research project in the Netherlands in 1986/1987 (Hemker and
The model is primarily used in the Netherlands by government agencies, consultants and universities to optimise groundwater abstraction rates from the Dutch dune systems, and to evaluate the possible long-term effects on water table elevations, and the dune habitat ecology. Micro-Fem can model, confined, semi-confined, phreatic and leaky multiple-aquifer systems (Scientific Software Group, 1997). The model can handle both steady-state and transient simulations. Micro-Fem is based on the finite element method, which is mathematically described in Wood (1993). The modelling domain is discretised into a triangular irregular network, with variable spacing. Finite element models are better able to approximate irregularly shaped boundaries than finite difference models and it is also easier to adjust the size of individual elements, as well as the location of boundaries (Wood, 1993). As described by Anderson and Woessner (1992) finite element models precisely define the variation in head within an element by means of interpolation (basis) functions. Heads are calculated at the nodes for convenience, but head is defined everywhere by means of basis functions.

Micro-Fem is a set of eleven programs, which lead the modeller through the whole process of groundwater modelling from the generation of a grid, preprocessing, groundwater calculations, postprocessing, graphical interpretation and the plotting of the results. Input parameters include transmissivity, vertical hydraulic resistance of the aquitard, discharge (if not zero), storativity, areal precipitation and evapotranspiration. Boundaries can be assigned as either fixed head, no-flow or fixed flow (by injection) boundaries. The model can also simulate rivers and drains.

Although Micro-Fem has been used in the Netherlands there was an apparent lack of published research which evaluated the limitations and merits of the model, and its value as a predictive groundwater management tool. The only published research described
how interface programs have been developed to integrate Micro-Fem and GIS (Biesheuvel and Hemker, 1993). The integration of these two systems makes pre and post processing of the modelling data easier and quicker and reduces the possibility of human input error. The lack of Micro-Fem groundwater modelling examples makes it extremely difficult for a modeller to find solutions to problems encountered whilst using the model and also to evaluate the relative successfulness of Micro-Fem in past modelling studies of sand dune systems. Furthermore, Micro-Fem has only been used to model the Dutch dune systems, where aquifers are typically 500-600 m deep and cover thousands of hectares of the coastline (Stuyfzand and Bruggeman, 1994). It is therefore not known whether Micro-Fem could model the scale of the Braunton dune system, where the saturated zone is a maximum of 10-12 m deep, 2.5 km wide and 5 km in length.

Micro-Fem is not a public domain model and the code is only supplied in an executable format, which prevents the modeller from altering the model set-up to suit the requirements of a particular modelling scenario. Many modellers are apprehensive about using such 'closed' model codes (Olsthoorn, pers. comm).

The physical features and capabilities of Micro-Fem appear to fulfil the criteria of a suitable model to simulate the hydrology and behaviour of the Braunton groundwater system. However, Micro-Fem will be critically compared against the other models in Section 3.4.3, before deciding on the most appropriate model for the Braunton groundwater resource management investigation.
AQUIFEM-N, a multi-layered quasi-three dimensional finite element groundwater flow model, was developed by Townley (1990). AQUIFEM-N uses linear triangular finite elements to represent the geometry of an aquifer. The model can be used to simulate steady-state and transient groundwater flow in unconfined, confined and semi-confined aquifers. A quasi-three dimensional model can simulate a sequence of aquifers with intervening confining layers, however the confining layers are not explicitly represented, nor are the heads in the confining beds calculated. In a quasi-three dimensional model the effect of a confining bed is simulated by means of a leakage term representing vertical flow between two aquifers (Aral, 1990a; Anderson and Woessner, 1992).

AQUIFEM-N input parameters include areal precipitation, aquifer bottom elevation, aquifer thickness, hydraulic conductivities or tranmissivities, specific yield, an aquifer storage coefficient and a leakage coefficient to and from adjacent aquitards. Boundary conditions are of three types, prescribed head, prescribed flux, or mixed and can vary in space and time. AQUIFEM-N can also represent rivers, streams, lakes, ponds, pumping wells, flowing artesian wells, distributed recharge and evapotranspiration.

AQUIFEM-N is supplied together with a number of ancillary programs for grid generation and graphical output, although they are not as easy to use as most model graphical interfaces (Scientific Software Group, 1997; Anderson and Woessner, 1992). AQUIFEM-N is only available in an executable form, thus allowing the integrity of the model to be maintained, but preventing the modeller from adapting the FORTRAN code to accommodate specific requirements of individual modelling case studies.

Despite this model being described as a well used and popular three dimensional groundwater flow model (Anderson and Woessner, 1992; Dowd, pers. comm.), again
there was an apparent lack of published research in scientific journals and texts, describing scenarios where the model has been used and its limitations. This makes it more difficult for the modeller to evaluate what problems may be encountered when modelling the Braunton groundwater system.

From the description of the features and capabilities of AQUIFEM-N (Townley, 1990), this model would appear to fulfil the criteria of a model suitable for simulating the groundwater hydrology of Braunton Burrows. However, the relative merits and limitations of the configuration and application of this model in groundwater resource management studies must be compared with the other three dimensional models reviewed (Sections 3.4.2a, 3.4.2b, 3.4.2d, 3.4.2e), to ensure that the most appropriate model is selected (Section 3.4.3).

d) AQUA3D

AQUA3D is described as a popular three dimensional finite element groundwater flow model (Scientific Software Group, 1997). First released in 1983 as a two dimensional model, AQUA has been continuously updated and has been used worldwide in groundwater resource management investigations. Up until four years ago AQUA3D was only a single layer model, but can now handle multi-layered systems, solving both steady state and transient groundwater flow problems, with heterogeneous and anisotropic flow conditions. Compared with the other models reviewed in this section, the multi-layered version of AQUA3D is a relatively new addition to the range of commercially available three dimensional groundwater flow models. This explains the apparent lack of published modelling examples describing groundwater resource management scenarios where AQUA3D has been used to simulate multi-layered systems. This model has never been used by consultants or government agencies in the
Netherlands to model sand dune systems (Olsthoorn, pers. comm). Furthermore, AQUA3D is not public domain and is therefore only available at considerable cost.

e) 3DFEMFAT

3DFEMFAT is a finite element model of flow and solute transport through saturated and unsaturated heterogeneous and anisotropic media. Although this model can simulate three dimensional flow only, the model has often been used for solute and pollutant transport modelling (Scientific Software Group, 1997). The 3DFEMFAT input module therefore required detailed quantitative accounts of a wide range of soil characteristics for each soil type, or geologic unit, as described in full by the Scientific Software Group, (1997). The complex parameterisation of this model made it much less suitable for modelling the Braunton system.

3.4.3 Model selection

Having described the capabilities and applications of the most popular and well tested three dimensional groundwater flow models, the most suitable models for fulfilling the objectives of the Braunton groundwater modelling exercise, are MODFLOW and the VMODFLOW package, Micro-Fem and AQUIFEM-N. These models each have their own merits and limitations, relating to their features and capabilities, as summarised in Table 3.3. Table 3.3 reviews the USGS MODFLOW code as part of the VMODFLOW modelling package.

Although all three models appeared suitable for modelling the Braunton domain, VMODFLOW, incorporating the original MODFLOW code with a fully integrated and graphically controlled pre and post processor, appeared to be the latest in a line of developments in three dimensional groundwater modelling. This fully integrated
Table 3.3 A comparison of the features and capabilities of VMODFLOW, Micro-Fem and AQUIFEM-N.

<table>
<thead>
<tr>
<th>Model</th>
<th>VMODFLOW</th>
<th>Micro-Fem</th>
<th>AQUIFEM-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>3D finite difference (less data required to construct a finite difference grid. More difficult to simulate irregularly shaped boundaries)</td>
<td>3D finite element (better able to approximate irregularly shaped boundaries. Easier to adjust the size of individual elements and boundary locations)</td>
<td>Quasi 3D finite element (better able to approximate irregularly shaped boundaries. Easier to adjust the size of individual elements and boundary locations).</td>
</tr>
<tr>
<td>Model code</td>
<td>Verified 'open' code, which can be altered by the modellers to suit the specific requirements of individual model case studies.</td>
<td>Available in executable format only.</td>
<td>Available in executable format only.</td>
</tr>
<tr>
<td>Preprocessor</td>
<td>The VMODFLOW modelling package comes with a fully integrated preprocessor with interactive graphics input.</td>
<td>Micro-Fem is supplied with own its own preprocessor which allows the graphical interactive input of model parameters.</td>
<td>Model supplied with a preprocessor which is not as easy to use as most. Input to preprocessor in the form of ASCII text files.</td>
</tr>
<tr>
<td>Postprocessor</td>
<td>The VMODFLOW package comes with a fully integrated postprocessor with graphical output of model results.</td>
<td>Model supplied with a built in post processor which graphically displays the model simulations</td>
<td>ASCII text output files from AQUIFEM-N are imported into a separate postprocessor. Not as easy to use as most postprocessors.</td>
</tr>
<tr>
<td>Model application</td>
<td>The MODFLOW code has been used worldwide to simulate a range of environments, including dune systems in the Netherlands.</td>
<td>Used in the Netherlands.</td>
<td>Described as a popular model used worldwide in groundwater management scenarios (Anderson and Woessner, 1992).</td>
</tr>
<tr>
<td>Documentation of use</td>
<td>A wide range of modelling examples describing scenarios where MODFLOW has been used. International support.</td>
<td>Used primarily by Dutch government agencies, consultants and universities. Lack of published Micro-Fem modelling examples.</td>
<td>Technical information about the models capabilities limited. Also a lack of modelling examples describing scenarios where AQUIFEM-N has been used.</td>
</tr>
</tbody>
</table>

modelling package, with a powerful graphical interface, allows model runs and modelling projects to be completed much quicker than if using the original USGS
MODFLOW code with a separate pre and post processor. MODFLOW was by far the best documented model, which has been used worldwide to model a range of environments. It is also the preferred groundwater model used by hydrogeologists and consultants to model sand dune systems in the Netherlands. Modellers using MODFLOW are described as being part of an international community, because of the model's worldwide recognition and support (Dowd pers. comm). Also the existing MODFLOW examples (Table 3.2) would be an excellent source of reference when modelling Braunton Burrows, providing guidance on model design, overcoming calibration and validation problems and assisting in the presentation and interpretation of the model's predictions.

With Micro-Fem and AQUIFEM-N, there was an apparent lack of published modelling examples. The user manuals were the primary source of reference, merely guiding the modeller through each stage of the modelling protocol. It would therefore be more difficult when modelling Braunton to evaluate the relative successes and failures of these models in past water resource management scenarios, and in particular establishing how valuable Micro-Fem had been as a predictive management tool when modelling the Dutch sand dune systems. Also the graphically controlled pre and post processors attached to AQUIFEM-N are known to be more difficult to use than those incorporated in VMODFLOW (Anderson and Woessner, 1992).

Furthermore, at the time of modelling the Braunton groundwater system unlimited technical support and advise on the use of VMODFLOW was readily available.

For all of the positive reasons identified in this critical review VMODFLOW, incorporating the USGS MODFLOW code was selected to evaluate whether a model of
the Braunton groundwater system could be successfully calibrated and used as a predictive management tool to recommend future water level management strategies for the Burrows. The advantages of VMODFLOW over the other models reviewed in this section (Table 3.3) would help ensure that the final model predictions were of a professional standard.

3.5 Data handling and analysis

At Braunton Burrows monthly water table data (from 1972-1995), for each observation well in the monitoring network, along with corresponding monthly precipitation totals and actual evapotranspiration rates were collated in an Excel spreadsheet. The meteorological data were supplied in the required format by the Environment Agency. Quality control of these data had already been undertaken by the Meteorological Office, Bracknell. The water table elevation readings collected by the NC, the NCC and EN were comprehensive and consistent. Data from all of the observation wells in the monitoring network were used in the hydrological description of Braunton Burrows (Chapters 4 and 5). When the elevation of the water table fell beneath the bottom of an observation well measurements were recorded as 'dry' and missing data were recorded as 'not measured', rather than extrapolating average values and introducing false trends into the time series. To describe annual and seasonal, spatial and temporal characteristics of the groundwater system (Chapters 4 and 5), the meteorological data and the water table elevation data were statistically analysed in Excel, or Minitab, using descriptive statistics (mean standard deviation), times series analysis, Mann-Whitney significance tests, and correlation. The statistical analysis tools used to analyse the data will be described in full as they are used in the results chapters (Chapter 4 and 5). \( K_{sat} \) values were calculated from the slug test data using the automated package of AQTESOLV (Section 4.8.3). These data, along with hydraulic conductivity values calculated from the
well permeameter experiment, bulk density measurements, particle size characteristics and the geological data were collated in an Excel spreadsheet. Characteristics of the dune sands were graphically presented, or statistically analysed using descriptive statistics (mean and standard deviation). These data were not transformed in any way. Careful consideration to the experimental design ensured that the data were accurate, representative and applicable to the hydrological interpretation of the system.

At both Northam and Dawlish water table elevation data, the meteorological variables, and the data describing the physical properties of the dune sands were organised and managed in the same way as at Braunton (Chapter 6).

At Braunton and Northam to construct seasonal water table contour plots and flow nets the required monthly water table elevation data were imported into the mapping package SURFER (described in Section 4.2). The comprehensive data sets collected at Braunton were also confidently used to parameterise and calibrate a three dimensional model of the groundwater system (Chapter 7).

3.6 Conclusion

The field and laboratory techniques used in this research and the sampling strategy adopted, in order to collect the data required to fulfil the aims of the research, are summarized in Tables 3.4 and 3.5. Throughout this chapter particular consideration was given to the experimental design to ensure that the data collected were spatially representative and of a high degree of accuracy.

The experimental design chapter also included a detailed section on groundwater modelling techniques. The history and development of groundwater modelling was described, from the physical models of the 1950s (sand tank and analogue models), to
the more sophisticated modern day analytical and numerical groundwater flow models. There were three objectives to the Braunton groundwater modelling exercise; to determine whether a commercial model could be successfully calibrated to simulate the Braunton groundwater hydrology; to gain a better understanding of the hydrological functioning of the system and ultimately to use the model to test a set of water level management scenarios, to predict the hydro-ecological consequences of altering boundary conditions, or introducing new management practices into the system.

Section 3.4 demonstrated that the best tool available to meet the needs of prediction was a numerical groundwater flow model. The model criteria for the Braunton scenario included a model which would handle transient simulations for unconfined, confined and semi-confined aquifers. The chosen model would also need to simulate vertical leakage between layers and calculate the elevation of the water table in the top model layer, rather than groundwater head. A three dimensional model would fulfil all of these criteria. A range of the most popular and well tested commercial three dimensional models were therefore critically evaluated, including MODFLOW/VMODFLOW, MicroFem, AQUIFEM-N, AQUA3D and 3DFEMFAT. VMODFLOW was selected as the most suitable model for simulating the Braunton groundwater system. VMODFLOW is a finite difference model and is the latest in a line of developments in three dimensional groundwater modelling. Incorporating the USGS MODFLOW code with a fully integrated pre and post processor, VMODFLOW formed a complete, user friendly, modelling package. In this study MODFLOW was preferred to other models because of its international recognition and support, and its world wide documented use in a range of environments, including sand dune systems. In the Braunton scenario the existing MODFLOW modelling examples would provide valuable information on model design, parameterisation, calibration and the interpretation of the model's predictions.
<table>
<thead>
<tr>
<th>Field data acquisition</th>
<th>Experimental technique</th>
<th>Observation period/sampling procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land and water table elevation, above OD.</td>
<td>Electronic distance measurer.</td>
<td>At all three sites water table monitoring sites were levelled to OD. Spot height measurement were taken at Northam and Dawlish to build up topographical maps. The geometry of West Boundary Drain, Braunton Marsh was surveyed.</td>
</tr>
<tr>
<td>Tidal fluctuations.</td>
<td>Druck pressure transducer, connected to a data logger and then secured to a dipwell to measure water level fluctuations.</td>
<td><strong>Braunton</strong>: dipwell 6N was monitored for 24 hrs. <strong>Northam</strong>: dipwell 11 was monitored for 72 hrs and dipwell 12 for 8 hrs. <strong>Dawlish</strong>: water levels in the main pond were monitored for 72 hrs.</td>
</tr>
<tr>
<td>K̂ below the water table.</td>
<td>Slug test - using the data logger and Druck pressure transducer to monitor water level recovery.</td>
<td><strong>Braunton</strong>: 15 slug tests were carried out on the nested piezometers in the detailed experimental sites (Figure 3.3). <strong>Northam</strong>: 14 slug tests were carried out on the piezometers temporarily installed next to each dipwell in the monitoring network (Figure 3.4). <strong>Dawlish</strong>: 6 slug tests were carried out next to dipwells 1, 2, 3A, 5, 6, and 8 (Figure 3.5).</td>
</tr>
<tr>
<td>K̂ above the water table.</td>
<td>Well permeameter - measures the rate of flow from a lined auger hole whilst maintaining a constant head.</td>
<td><strong>Braunton</strong>: one off observations. Carried out on dunes adjoining four of the detailed experimental sites (Figure 3.1). Three K̂ tests at base of dune, three mid slope and three at the top of dune.</td>
</tr>
<tr>
<td>Aquifer characteristics.</td>
<td>Drilling rig.</td>
<td>Depth to bedrock or an impenetrable layer was investigated at 5 sites on Braunton (Figure 3.1) and 6 sites at Northam (Figure 3.9).</td>
</tr>
<tr>
<td>Particle size sampling.</td>
<td>Samples collected with the aid of the drilling rig and by hand augering.</td>
<td>Sampling above the saturated zone. <strong>Braunton</strong>: sampling every 0.90 m in four profiles on Warble Fly Hill, during the installation of the nested piezometers and the sites where depth to bedrock was determined (Figure 3.1). <strong>Northam</strong>: sampling every 0.50 m, next to each dipwell in the monitoring network (Figure 3.3). <strong>Dawlish</strong>: sampling every 0.20 m next to dipwells 5, 6, 6A, 7 and 8 (Figure 3.4). At a more detailed scale sampling at 0.20 m depths on a 30 x 30 m grid within part of Greenland Lake (Figure 3.10).</td>
</tr>
<tr>
<td>Bulk density.</td>
<td>Coring method.</td>
<td><strong>Braunton</strong>: sampling at 0-5 cm and 45-50 cm at the site of each well permeameter experiment, in the detailed experimental sites.</td>
</tr>
</tbody>
</table>
Table 3.5 Summary of laboratory procedures.

<table>
<thead>
<tr>
<th>Laboratory procedures</th>
<th>Equipment</th>
<th>Analysis technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>Oven.</td>
<td>Oven drying to determine weight loss.</td>
</tr>
<tr>
<td>Particle size analysis</td>
<td>Malvern Mastersizer and a nest of sieves.</td>
<td>Laser diffraction and dry sieving.</td>
</tr>
</tbody>
</table>
Chapter 4
Hydrological characteristics and the functioning of the groundwater system at Braunton Burrows
4.0 Introduction

As an introduction to the hydrology of Braunton Burrows the first part of Chapter 4 will begin by describing the spatial hydrological characteristics and functioning of the groundwater system. The spatial dimension will involve describing the hydrological regime at three investigative scales. The largest scale of investigation will evaluate the hydrology of the entire dune system, from the analysis of slack water table data and the construction of water table contour plots. At the second scale of investigation the shape, elevation and gradient of the water table will be described from cross-sections and flow nets. At the smallest investigative scale, individual observation wells will be considered, to determine whether geographical location within the dune system influences annual cyclical water table fluctuations.

The hydrology of the groundwater system, described from the three investigative scales, may be influenced by annual and seasonal variability in effective precipitation, the underlying geology, saline intrusion, the tide and the physical properties of the dune sands. The influence of these parameters on the hydrological functioning of the Braunton system will also be considered in this chapter.

4.1 General hydrological characteristics of the dune system

At the largest scale of investigation the hydrological characteristics of the entire dune system were examined from two perspectives. The first perspective described both the long-term (1972-1995) variability in the response of the water table and the flooding potential of inland and coastal slacks (Section 4.1.1). The slacks were considered first in the
hydrological description of Braunton Burrows for three reasons. Firstly, the slacks were the main water table observation sites, which have been monitored over the past 25 years to provide the water level data used throughout this research. Secondly, the water table data collected from the slacks were absolute rather than interpolated values extracted from the water table contour plots (Section 4.1.2). Thirdly, dune slacks are the sites of greatest ecological value and are the most susceptible to long-term hydrological change (Van Beckhoven, 1992).

The second perspective of the hydrological investigation at this scale involved the construction of water table contour plots, using water level data from the observation well network (Section 3.2.3a). The contour plots were used to describe the shape and elevation of the water table and its response to effective precipitation.

4.1.1 Hydrological characteristics of the groundwater system from slack water table elevations

The diversity of the dune slack habitat is the primary reason why there is an urgent need to evaluate whether the dune system is drying out and if so, to determine the most probable causes. From field observations and the preliminary analysis of slack water table elevation data, collected from September 1994 through to the end of June 1995, there were noticeable spatial and temporal differences in the hydrological functioning of these areas. In part this appeared to be related to the geographical location of the slacks within the dune system. Slacks less than 750 m from Sandy Lane or the American Road appeared to flood before those within the high dune ridges, nearest the seaward margin of the system (Figure 4.1). Furthermore, the water table remained at or above the surface for a longer period in the inland slacks. After the winter of 1994/1995, which was described as the wettest winter on record for Britain since 1869 (Marsh and Turton, 1996), surface pools were still evident
in four of the inland slacks by the third week of June.

Based on the field observations described above, the hydrological functioning of the wet
dune slacks could be spatially divided into two categories; those associated with the high
dune ridges along the western margin of the system and those closer to the inland margin
of the system, within the Inland Plain. The system was therefore divided long ways through
the geographical centre (Figure 4.1), to determine whether the observed spatial variations
in groundwater levels were statistically different on an annual basis and were not just a one
off occurrence. For the purpose of this exercise the American Road was taken as the inland
boundary of the dune system and the fore dune ridge as the seaward limit of the dune
complex. Water table elevations measured within eight observation wells sited in slacks
closest to the seaward margin of the dune system were compared with water levels
measured in eight observation wells closest to the inland boundary of the system (Figure
4.1). Water levels in these two groups of slacks were statistically compared for the
beginning of January and the beginning of July from 1972 to 1995. The analysis of slack
water table elevation differences was limited to the southern half of the dune system, where
the Nature Conservancy, the Nature Conservancy Council and English Nature (NC, NCC
and EN) have monitored water levels since 1972 (Figure 4.1). Mann-Whitney significance
tests were carried out on the data. This is a non-parametric test making no assumptions
about the distribution of the sample populations and determines whether the populations
are significantly different (Hammond and McCullagh, 1975).
Figure 4.1 Distribution of slacks within the Braunton dune system.
The results from the Mann-Whitney tests showed that with the exception of 1975 and 1976, between 1972 and 1995 water table elevations at the beginning of January and July were significantly higher at a 95 % confidence level in the inland slacks. A feasible explanation was that the adjoining marsh system was less permeable than the dune sands, consequently restricting lateral drainage from the eastern margin of the dune system and causing the groundwater to mound. Willis et al. (1959a) also arrived at the same explanation that Braunton Marsh was controlling the long-term functioning of the Burrows groundwater system. By contrast groundwater outflow from the seaward side of the system drained through dune sands of a relatively higher permeability (Section 4.8.3), which in part accounted for the lower water table elevations recorded in the seaward slacks. The higher water table elevations along the eastern side of the dune system will be examined further when describing the water table contour plots (Section 4.1.2) and cross-sections of the groundwater system (Section 4.2.1).

In the exceptionally dry years of 1975 and 1976 there was no significant difference between inland and seaward slack water table elevations. The drought of 1975/1976 possibly caused the groundwater mound to decay more than usual and hence water table elevation differences were less apparent.

Slacks are described by Ranwell (1959) to represent the approximate elevation of the water table. Reference to Figure 4.1 shows that generally the ground surface elevation of the inland slacks are higher than those on the seaward side of the dune system. This suggests that since the formation of the dune system the water table along the eastern margin of the system has always been higher, probably as a result of the adjoining marsh system restricting the inland lateral drainage regime and causing the groundwater to mound.
4.1.2 Short-term hydrological characteristics of the groundwater system; based on seasonal water table contour plots

Except for the extreme northern part of the system, which is possibly receiving a secondary source of groundwater from the higher lying land of Saunton, Braunton Burrows is an isolated catchment dependent upon precipitation for recharge (Willis et al., 1959a). Water table contour plots were constructed for September 1994, February 1995, September 1995 and January 1996, using water table elevation data from the revised observation well network (Section 3.2.3a). The revised observation well network incorporated a wider distribution of monitoring sites, including a northern transect of observation wells (Figure 3.2), which assisted in the construction of more accurate contour plots. The dates of the contour plots would also demonstrate the variable response of the groundwater system to extreme and average conditions in terms of long-term average (LTA) effective precipitation. Effective precipitation was calculated as precipitation minus losses through evapotranspiration, which were taken from MORECS data. Throughout this chapter LTA refers to the years of 1972-1995, which covers the period of water table monitoring at Braunton by the NC, the NCC and EN.

The water table contour plot for the beginning of September 1994 represented average summer recharge characteristics (Figure 4.2). In the summer months evapotranspiration losses exceeded precipitation inputs to give negative values of effective precipitation. From May to August preceding the September 1994 water table contour plot, total effective precipitation (-91.2 mm) was only 2.5 % greater than the LTA for the site. In comparison, May to August preceding the September 1995 plot (Figure 4.4) were exceptionally hot and dry months. Total effective precipitation for this summer period was -310.6 mm, which was 232 % less than the LTA. Although the summer of 1995 was extremely dry, the previous winter (1994/1995) was the wettest winter in Britain since 1869 (Marsh and
Turton, 1996). From October 1994 to January 1995 Braunton Burrows received 43% more effective precipitation (418.4 mm) than the LTA. In fact water levels recorded on the Burrows during the winter of 1994/1995 were the highest on record. The contour plot for February 1995 (Figure 4.3) was therefore constructed to illustrate the effect on the elevation of the water table of this exceptionally wet winter. By contrast the three months preceding the January 1996 contour plot (Figure 4.5) were exceptionally dry and Braunton Burrows received only 68.3% (145.8 mm) of the seasonal LTA effective precipitation. The January 1996 plot also followed the dry and warm summer months of 1995.

The water table was mapped in the form of a two dimensional contour plot, using the computer package SURFER (SURFER, 1987). The program creates a regular grid of spatial coordinates, from the supplied X and Y national grid coordinates of known water table elevations (Jones, 1993). The interpolation method of kriging was used to interpolate the height of the water table for each node of the grid. In the kriging technique data carry different weights based on their position, both in relation to the estimated point and to one another (Oliver and Webster, 1991). Kriging only uses those data that are spatially related to the kriging location, which includes those samples within the range of spatial dependence, as determined through the use of a variogram (Trangmar et al., 1985). Data points occurring in clusters will carry less weight in the kriging equation than lone points and data points lying between kriging points (Trangmar et al., 1985). The interpolation technique of kriging has been widely used in hydrological research (de Marsily, 1986; Pucci and Murashige, 1987; Jones, 1993).

The contour plots (Figures 4.2-4.6) extend from the northerly observation well transect, south to Crow Point, as shown on Figure 4.2. It was not possible to accurately interpolate the water table contours to the north of this transect, because of the absence of known
water table elevations.

Mean sea level Newlyn, denoted by the 0 m surface elevation contour on the Braunton Burrows habitat map (Nature Conservancy Council, 1990), was used as a datum taken to represent approximately zero water table elevation. A similar assumption was also made in the calculation of a water balance for the Ainsdale dune system (Clarke, 1980). Furthermore, Ordnance Survey, Southampton, stated that mean sea level was probably the best datum from which to build up a contour map of the water table surface (Lamb, pers. comm). Taking mean sea level as zero water table elevation is only an approximation, which in fact may either over or under exaggerate the elevation of the water table at this point as the system is not in steady-state. Therefore, the contour plots (Figures 4.2-4.6) should only be taken as an indication of the possible seasonal differences in the shape and elevation of the Braunton groundwater system.

**Interpretation of the contour plots**

Both the summer (February 1995 and January 1996) and winter (February 1994 and February 1995) plots of the water table show a similar contour pattern (Figures 4.2-4.6). For these particular dates the contours run parallel to the seaward boundary of the system, curving south-eastwards around the southern part of the dune complex before running parallel to West Boundary Drain, which forms the inland boundary between the dune and marsh systems. A similar contour pattern was also interpolated in the earlier hydrological study of Braunton Burrows by Willis *et al.* (1959a), as illustrated in Figure 4.6.
Figure 4.2  Contour plot of the water table at Braunton Burrows, September 1994. (Contour elevations are in metres above OD. Cross-sections refer to Section 4.2.1 and Figures 4.7-4.10.)
Figure 4.3 Contour plot of the water table at Braunton Burrows, February 1995. (Contour elevations are in metres above OD. Cross-sections refer to Section 4.2.1 and Figures 4.7-4.10.)
Figure 4.4  Contour plot of the water table at Braunton Burrows, September 1995.  
(Contour elevations are in metres above OD. Cross-sections refer to Section 4.2.1 and Figures 4.7-4.10.)
Figure 4.5  Contour plot of the water table at Braunton Burrows, January 1996. (Contour elevations are in metres above OD. Cross-sections refer to Section 4.2.1 and Figures 4.7-4.10.)
Figure 4.6 Contour plot of the water table at Braunton Burrows, June 1952. Adapted from Willis et al. (1959a). (Contour elevations are in metres above OD. Cross-sections refer to Section 4.2.1 and Figures 4.7-4.10.)
In each contour plot the groundwater system was mounded. Taking West Boundary Drain as the inland boundary of the Burrows and the 0 m water table contour as the seaward limit of the system, the groundwater mound in September 1994, February 1995, September 1995 and January 1996 was asymmetric, particularly to the south of Sandy Lane Plain (Figures 4.2-4.5). The highest water table elevations were recorded closest to the inland boundary of the system. The asymmetric nature of the groundwater mound again suggested that in the transitional zone from dune sands to marshland the permeability was lower, restricting the inland drainage regime and causing the groundwater to mound. The hydrology of this area will be investigated further in Section 4.2.1, when describing cross-sections of the water table.

In September 1994 the maximum elevation of the water table was approximately 9 m above OD (Figure 4.2). With the exceptionally wet winter (1994/1995) that followed, by February 1995 the water table had risen a further metre (Figure 4.3), but rapidly decayed with the drought conditions that prevailed during the summer of 1995 (Figure 4.3). In September 1995 the maximum elevation of the groundwater mound was 9 m, but the area enclosed by the 8 m and 9 m water table contours was 18 % less than that measured in September 1994 (Figure 4.2), highlighting the impact of the summer drought on the elevation of the water table. The extent of the 9 m contour had increased again by January 1996 (Figure 4.5), but the development of the groundwater mound had perhaps been dampened by the dry and warm summer of 1995 and the below average effective precipitation totals between October and December 1995 (31.7 % less than the LTA - 145.8 mm).

The maximum elevation of the water table on the June 1952 plot (Figure 4.6), redrawn from the earlier work of Willis et al. (1959a), was approximately one metre higher than maximum water table elevations recorded on the contour plots for September 1994 (Figure
4.2), September 1995 (Figure 4.4) and January 1996 (Figure 4.5). The June 1952 water table elevations were however, similar to those recorded in February 1995 which followed the exceptionally wet winter of 1994/1995. There are several possible explanations for the higher water table elevations recorded in the summer of 1952 compared with those more recently measured from the contour plots of 1994, 1995 and 1996 (Figures 4.2-4.5).

Firstly, an analysis of the weather conditions preceding the June 1952 contour plot may help to explain the higher water table elevations. Although meteorological data were not available from RAF Chivenor for 1952, the World Climate Disc CD-ROM (University of East Anglia, 1992) provided absolute precipitation data from 1932-1990 for a number of meteorological stations in Devon (Table 4.1), including Plymouth, Mount Batten (SX 486, 532), Exeter Airport (SY 002, 936) and Bideford, St. Jennetts (SS 440, 246), which was less than 5 km to the south east of Braunton Burrows. In this section only LTA refers to data for the years between 1932-1990.

<table>
<thead>
<tr>
<th>Meteorological Station</th>
<th>Precipitation characteristics for the winter months of December 1951, January and February 1952.</th>
<th>Precipitation characteristics for the spring months of March, April and May 1952</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total precipitation for the winter period and as a percentage of the LTA (1932-1990)</td>
<td>LTA winter precipitation (1932-1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total precipitation for the spring period and as a percentage of the LTA (1932-1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTA spring precipitation (1932-1990)</td>
</tr>
<tr>
<td>Bideford</td>
<td>238.1 mm (82 %)</td>
<td>289.5 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>233.7 mm (130 %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>180.33 mm</td>
</tr>
<tr>
<td>Exeter Airport</td>
<td>129.3 mm (52 %)</td>
<td>248.8 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>209.2 mm (121 %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>173.23 mm</td>
</tr>
<tr>
<td>Plymouth</td>
<td>218.8 mm (72 %)</td>
<td>303.7 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>219.5 mm (121 %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>180.72 mm</td>
</tr>
</tbody>
</table>

The winter months (December, January and February) of 1951/1952 for the meteorological stations listed in Table 4.1 received between 18-48 % less precipitation than the LTA.
However, during the spring months (March, April and May) of 1952 these same meteorological stations received between 21-30 % more precipitation than the calculated LTA. The meteorological station at Bideford, which was the nearest to Braunton, received 30 % more precipitation than the LTA for the 1952 spring period (Table 4.1). Unfortunately the World Climatic Disc did not provide long-term evapotranspiration data, which could have been analysed to determine the percentage of precipitation that was lost to evapotranspiration. Above average total precipitation from March to May 1952 may therefore partially account for the higher water levels recorded on the Burrows in June 1952.

The second explanation was that the higher water levels measured in June 1952 were an indication of former water table elevations on the Burrows, before the perceived drying out process began.

Summary

In summary, Figures 4.2-4.6 emphasised the dependence of the Braunton system on precipitation as a primary source of groundwater recharge. Effective precipitation partially controlled both the shape and elevation of the water table. The other main factor influencing the hydrological functioning of the groundwater system was Braunton Marsh. The lower permeability of the marsh sediment compared with the dune sands was probably restricting the inland lateral drainage regime and causing the groundwater system to mound along the eastern margin of the system.

4.2 Characteristics of the groundwater system from cross-sections and flow nets

At the second scale of investigation characteristics of the groundwater system were evaluated from cross-sections (Section 4.2.1) and flow nets (Section 4.2.2), derived from
the two dimensional water table contour plots described in Section 4.1.2.

4.2.1 Characteristics of the groundwater system from cross-sections

Characteristics of the groundwater system were described from three cross-sections running east to west across the dune system. The cross-sections were located 1,075 m (cross-section A), 2,200 m (cross-section B) and 3,600 m (cross-section C) north of the most southerly tip of the 0 m water table contour, in the vicinity of Crow Point (Figures 4.2-4.6). These locations were chosen to highlight any intra-site variability in the form and seasonal functioning of the groundwater system. A fourth water table cross-section extended from cross-section B, south to the 0 m water table contour (Figures 4.2-4.6) and was included to evaluate the north-south drainage regime.

Cross-sections of the water table were derived from the contour plots described in Section 4.1.2 and therefore illustrated both extreme and average conditions of the groundwater system in terms of effective inputs. It should also be stressed at this stage that the cross-sections incur a large vertical exaggeration, which will become apparent when examining the hydraulic gradients in Section 4.2.2.

a) Cross-section A

Cross-section A extends from the 0 m contour on the seaward side of the system, inland 2,000 m to West Boundary Drain. This artificial drainage channel forms a physical boundary between the dune and marsh systems.

Both the summer (September 1994 and 1995) and winter (February 1995 and January 1996) profiles showed that the groundwater system was mounded (Figure 4.7). The cross-section of the surface topography, derived from the Braunton Burrows habitat map (Nature
Conservancy Council, 1990), showed that the highest land elevations occurred on the seaward side of the system (Figure 4.7). By contrast the highest water table elevations were recorded closest to the inland boundary (Figure 4.7).

Figure 4.7 Cross-section A; the shape and elevation of the water table. (Location of cross-section A is shown on Figures 4.2-4.6. X-axis on the graph refers to distance inland from the 0 m water table contour.)

Figure 4.7 shows that for each profile the elevation of the water table reached a maximum elevation between 1,200 and 1,400 m inland from the 0 m water table contour and only 600-800 m from the inland boundary of the dune system. The asymmetric nature of the groundwater system again identified the importance of the transitional zone to marshland as a major factor controlling the inland lateral drainage regime and the functioning of the groundwater system, as described in Section 4.1.2. These groundwater characteristics also suggest that the high dune ridges, to the west of the system, have less influence on the groundwater hydrology than the inland/seaward drainage regime and the $K_{sat}$ of both the
dune sands and the adjoining marsh sediment.

Water table profiles at cross-section A clearly show the dependence of the dune system on precipitation as a primary source of groundwater recharge as previously described when interpreting the water table contour plots in Section 4.1.2. The sensitivity of the groundwater system to effective precipitation can also be seen at cross-sections B, C and D (Figures 4.8-4.10).

The scale of Figure 4.7 is not detailed enough to determine any seasonal lateral shift of the groundwater mound, resulting because of monthly variations in the distribution of effective precipitation. However, between summer and winter seasons the whole groundwater system fluctuated, with the greatest range of water table fluctuations generally occurring at the highest point of the groundwater mound. In the summer (September 1994 and 1995) with decreasing inputs to the dune system the top of the groundwater mound began to decay. The margins of the system fluctuated less as these sites were recharged not only by areal precipitation, but also by groundwater draining from the centre of the decaying mound. These hydrological characteristics can also be seen at cross-sections B, C and D (Figures 4.8-4.10). Variability in the range of annual cyclical water table fluctuations within the groundwater mound will be described and evaluated further in Section 4.3.

b) Cross-section B

Cross-section B was a further 980 m north of cross-section A (Figure 4.2-4.6) and extended from the 0 m water table contour on the west of the system, inland 2,400 m to West Boundary Drain.
As shown in Figure 4.8, the summer and winter water table profiles follow the shape of the surface topography more closely than those described for cross-section A (Figure 4.7).

However, the water table mound was still asymmetric. Maximum water table elevations were recorded approximately 1,500-1,700 m inland from the 0 m water table contour and less than 700 m from West Boundary Drain. As explained for cross-section A (Section 4.2.1a), these higher water table elevations on the inland side of the hydrological system emphasised the importance of changes in permeability in the transitional zone to marshland in controlling the groundwater hydrology. Figure 4.8 also shows that as a result of these inland drainage restrictions steeper hydraulic gradients occurred in order to maintain groundwater flow. The hydraulic gradient of the water table will be quantified and discussed further in Section 4.2.2.

![Figure 4.8 Cross-section B; the shape and elevation of the water table. (Location of cross-section B is shown on Figures 4.2-4.6. X-axis on the graph refers to distance inland from the 0 m water table contour.)](image-url)
c) Cross-section C

Cross-section C was a further 1,550 m north of cross-section B. The dune system extends inland 2,600 m from the 0 m water table contour. At the inland boundary the dunes are bordered by agricultural fields, that merge into the northern part of Braunton Marsh within a distance of 800 m.

So far in the hydrological description of Braunton Burrows Braunton Marsh has been identified as the most probable cause for the asymmetric nature of the groundwater mound. The greater distance of cross-section C from Braunton Marsh therefore possibly explained why the groundwater mound was more central within the dune system and closely followed the shape of the surface topography. Furthermore, the inland hydraulic gradient of the water table appeared less steep (Figure 4.9). An alternative explanation was that the water table profiles at cross-section C were derived from an area of the dune system where there were no water table elevation monitoring sites and so relied upon kriging (Section 4.1.2) to interpolate the elevation of the water table in this area. This in part may therefore account for the different shaped water table profiles.

d) Cross-section D

Cross-section D extended north-south from the centre of the groundwater mound to the 0 m water table contour (Figures 4.2-4.6), which explained the wedge shaped appearance of the groundwater system (Figure 4.10).

Cross-section D emphasised the radial drainage pattern of the groundwater system. At cross-section D groundwater drained from the centre of the mound south, whereas at cross-sections A, B and C groundwater drained east and west from the highest point of the mound.
Figure 4.9  Cross-section C; the shape and elevation of the water table. 
(Location of cross-section C is shown on Figures 4.2-4.6. X-axis on the graph refers to distance inland from the 0 m water table contour.)

Figure 4.10  Cross-section D; the shape and elevation of the water table. 
(Location of cross-section D is shown on Figures 4.2-4.6. X-axis on the graph refers to distance inland from the 0 m water table contour.)
e) Summary

A detailed analysis of the cross-sections have highlighted three main characteristics of the groundwater system at Braunton Burrows;

1. in cross-sections A and B (Figure 4.7 and 4.8) the groundwater mound was asymmetric. The most probable explanation was that the lower permeability of the transitional zone to marshland was restricting the inland drainage regime and causing the groundwater to mound along the eastern margin of the system. Cross-section C was less influenced by proximity to Braunton Marsh and hence the water table showed a greater degree of symmetry.

2. groundwater mounding along the eastern margin of the system suggested that the high dune ridges along the seaward margin had less influence on the groundwater hydrology than the landward lateral drainage regime and the $K_{sat}$ of the transitional zone to marshland.

3. the water table profiles demonstrated the dependence of the groundwater system on precipitation as a primary source of groundwater recharge. Both the shape and elevation of the water table were partially a function of monthly antecedent effective precipitation totals.

4.2.2 Hydraulic gradients calculated from flow nets

The contour plots shown in Figures 4.2-4.6 depict lines of equal groundwater potential. Intersecting these equipotentials at right angles are flow lines (Figures 4.11-4.15), which are paths followed by groundwater as it moves through the aquifer in the direction of the decreasing head (Walton, 1970). From the flow lines, drawn at right angles to the water
table contours, it was possible to calculate and analyse differences in hydraulic gradients on the seaward and landward side of the drainage system. Hydraulic gradients were calculated for September 1994, February 1995, September 1995, and January 1996. These hydraulic gradients were also compared with those from June 1952, which were derived from the contour plot redrawn from the earlier work of Willis et al. (1959a).

As described in Section 4.1.2, the assumption of using mean sea level as zero water table elevation is only an approximation, which may either over or under exaggerate the elevation of the water table at that point as the system is not in steady-state. Therefore, data shown in Tables 4.2-4.5 only act as a guide to the likely hydraulic gradients of the water table.

a) **Hydraulic gradients on the seaward side of the groundwater system from the highest water table contour (9 m or 10 m) to the 0 m contour**

Average hydraulic gradients on the seaward side of the hydrological system, from the highest groundwater contour (9 m or 10 m) to the 0 m contour, ranged from 0.68m per 100m to 0.77m per 100m (Table 4.2). The gradients calculated for June 1952 were marginally steeper (0.80m per 100m), but comparable to those measured in February 1995 when water table elevations were high because of the exceptionally wet winter of 1994/1995. As already mentioned in Section 4.1.2 the steeper hydraulic gradients in June 1952 were possibly an indication of former water table elevations and drainage conditions on the Burrows, but also may be partially related to the above average effective precipitation in the three months preceding June 1952 (Table 4.2). The reliance on kriging to interpolate the elevation of the water table for each node of the grid may have also influenced the accuracy of the calculated hydraulic gradients, particularly in areas of the plot where input data were sparse.
Figure 4.11  September 1994 flow net for Braunton Burrows.  
(Contour elevations are in metres above OD. Flow line identification labels refer to Tables 4.2-4.5.)
Figure 4.12  February 1995 flow net for Braunton Burrows.
(Contour elevations are in metres above OD. Flow line identification labels refer to Tables 4.2-4.5.)
Figure 4.13 September 1995 flow net for Braunton Burrows. (Contour elevations are in metres above OD. Flow line identification labels refer to Tables 4.2-4.5.)
Figure 4.14 January 1996 flow net for Braunton Burrows.
(Contour elevations are in metres above OD. Flow line identification labels refer to Tables 4.2-4.5.)
Figure 4.15 June 1952 flow net for Braunton Burrows. (Adapted from Willis et al. (1959a). Contour elevations are in metres above OD. Flow line identification labels refer to Tables 4.2-4.5.)
As described by Clarke (1980) in the study of Ainsdale, variations between summer and winter hydraulic gradients result because of the variability in the seasonal distribution of effective precipitation (Section 2.8). In the summer the elevation of the water table falls, due to groundwater drainage exceeding inputs into the system. This in turn reduces the hydraulic gradients to both the sea and the inland boundary and the rate of groundwater drainage from the system. In the winter months, with increased precipitation, the volume of water held in storage by the system will increase, consequently increasing the hydraulic gradients and the rate of groundwater drainage in order to regulate both the shape and elevation of the water table.

The calculated hydraulic gradients in Table 4.2 were partially a function of antecedent effective precipitation totals. Hydraulic gradients observed in February 1995, following the exceptionally wet winter of 1994/1995, were steeper than those calculated for January 1996, which was a dry winter and followed the drought conditions that prevailed over Britain in the summer of 1995. Amounts of effective precipitation therefore have to be sufficiently greater than drainage to increase storage, build up the elevation of the mound and increase the gradient of the water table. Of primary consideration when evaluating groundwater gradients was therefore the rate at which the input of water must occur to maintain the position of the water table. Of secondary consideration were the changes in inputs, or losses, from the system that would explain the observed changes in storage levels and hence the groundwater gradients (Clarke, 1980).
Table 4.2 Hydraulic gradients on the seaward side of the groundwater system, from the highest groundwater contour (9 m or 10 m) to the 0 m contour. (The hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 4.11-4.15). Flow line identification labels to Figures 4.11-4.15).

<table>
<thead>
<tr>
<th>Location of flow lines (refer to Figures 4.11-4.15)</th>
<th>Hydraulic gradients on the seaward side of the groundwater system from the highest water table contour (9 m or 10 m) to the 0 m contour.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sept 1994 (Gradients in metres per 100 m)</td>
</tr>
<tr>
<td>A</td>
<td>0.56</td>
</tr>
<tr>
<td>B</td>
<td>0.62</td>
</tr>
<tr>
<td>C</td>
<td>0.63</td>
</tr>
<tr>
<td>D</td>
<td>0.62</td>
</tr>
<tr>
<td>E</td>
<td>0.62</td>
</tr>
<tr>
<td>F</td>
<td>0.62</td>
</tr>
<tr>
<td>G</td>
<td>0.59</td>
</tr>
<tr>
<td>H</td>
<td>0.56</td>
</tr>
<tr>
<td>I</td>
<td>0.55</td>
</tr>
<tr>
<td>J</td>
<td>0.57</td>
</tr>
<tr>
<td>K</td>
<td>0.62</td>
</tr>
<tr>
<td>L</td>
<td>0.67</td>
</tr>
<tr>
<td>M</td>
<td>0.69</td>
</tr>
<tr>
<td>N</td>
<td>0.75</td>
</tr>
<tr>
<td>O</td>
<td>0.82</td>
</tr>
<tr>
<td>P</td>
<td>0.86</td>
</tr>
<tr>
<td>Q</td>
<td>0.90</td>
</tr>
<tr>
<td>R</td>
<td>0.92</td>
</tr>
<tr>
<td>S</td>
<td>0.95</td>
</tr>
<tr>
<td>T</td>
<td>0.92</td>
</tr>
<tr>
<td>U</td>
<td>-</td>
</tr>
<tr>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Antecedent effective precipitation (EP), or precipitation (P), characteristics

| May-Aug preceding Sept 1994 EP was 2.5% above LTA (-91.2mm) | May-Aug preceding Sept 1995 EP 232% below LTA (-310.6mm) | Oct-Jan preceding Feb 1995 Braunton received 43% more EP than LTA (418.4 mm) | Oct-Dec preceding Jan 1996 Braunton received only 68.3% of the LTA EP (148.8 mm) | Apr-Jun preceding June 1952 Braunton received 30% more P than the LTA (233.7 mm) |
b) **Hydraulic gradients along the seaward margin of the groundwater system, from the 4 m contour to the 0 m contour**

A feature of the groundwater system also noted by Willis et al. (1959a) was that the hydraulic gradients along the seaward margin of the groundwater system, between the 0 and 4 m water table contours (Table 4.3) were steeper than hydraulic gradients measured anywhere else in the system. As previously mentioned the hydraulic gradients at the edge of the system in particular only provide a likely indication of the characteristics of the groundwater system, because of the assumption that mean sea level represented approximately zero water table elevation (Section 4.1.2). Also the lack of water table monitoring sites along the fore dune ridge and on Saunton Sands may have also effected the accuracy of the original contour plots in this area.

Research by Willis et al. (1959a) suggested that the volume of water percolating through the system increased from the centre to the margins, the steeper water table gradients at the margins were therefore required to move greater volumes of water through the sand.

As described in Section 4.2.2.a, an analysis of antecedent monthly precipitation totals again assisted in the explanation of the seasonal differences in the observed average hydraulic gradients. Winter hydraulic gradients (February 1995 and January 1996) were generally steeper than those measured in the summer (September 1994 and 1995), (Table 4.3).

c) **Hydraulic gradients on the seaward side of groundwater system from the highest water table contour (9 m or 10 m) to the 4 m contour**

Both the summer and winter hydraulic gradients for 1994, 1995 and 1996, between the highest water table contour (9 m or 10 m) and the 4 m contour on the seaward side of the groundwater system (Table 4.4), were less steep than those described in Section 4.2.1b
Hydraulic gradients on the seaward side of the groundwater system, from the 4 m contour to the 0 m contour. (The hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 4.11-4.15). Flow line identification labels refer to Figures 4.11-4.15).

<table>
<thead>
<tr>
<th>Location of flow lines (refer to Figures 4.11-4.15)</th>
<th>Hydraulic gradients along the seaward margin of the groundwater system, from the 4 m contour to the 0 m contour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: A</td>
<td>Sept 1994 (Gradients in metres per 100 m)</td>
</tr>
<tr>
<td>Location: B</td>
<td>1.14</td>
</tr>
<tr>
<td>Location: C</td>
<td>1.14</td>
</tr>
<tr>
<td>Location: D</td>
<td>0.94</td>
</tr>
<tr>
<td>Location: E</td>
<td>0.94</td>
</tr>
<tr>
<td>Location: F</td>
<td>0.94</td>
</tr>
<tr>
<td>Location: G</td>
<td>0.94</td>
</tr>
<tr>
<td>Location: H</td>
<td>0.89</td>
</tr>
<tr>
<td>Location: I</td>
<td>0.90</td>
</tr>
<tr>
<td>Location: J</td>
<td>1.14</td>
</tr>
<tr>
<td>Location: K</td>
<td>1.00</td>
</tr>
<tr>
<td>Location: L</td>
<td>0.94</td>
</tr>
<tr>
<td>Location: M</td>
<td>0.89</td>
</tr>
<tr>
<td>Location: N</td>
<td>0.89</td>
</tr>
<tr>
<td>Location: O</td>
<td>0.89</td>
</tr>
<tr>
<td>Location: P</td>
<td>0.89</td>
</tr>
<tr>
<td>Location: Q</td>
<td>1.00</td>
</tr>
<tr>
<td>Location: R</td>
<td>1.00</td>
</tr>
<tr>
<td>Location: S</td>
<td>1.00</td>
</tr>
<tr>
<td>Location: T</td>
<td>1.00</td>
</tr>
<tr>
<td>Location: U</td>
<td>-</td>
</tr>
<tr>
<td>Location: V</td>
<td>-</td>
</tr>
<tr>
<td>Average:</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Antecedent effective precipitation (EP), or precipitation characteristics:
- May-Aug preceding Sept 1994, EP was 2.5% above LTA (-91.2mm)
- May-Aug preceding Sept 1995, EP 232% below LTA (-310.6mm)
- Oct-Jan preceding Feb 1995, Braunton received 43% more EP than LTA (418.4 mm)
- Oct-Dec preceding Jan 1996, Braunton received only 68.3% (148.8 mm) of the LTA EP
- Apr-Jun preceding June 1952, Braunton received 30% more P than the LTA (233.7 mm)
Table 4.4: Hydraulic gradients on the seaward side of the groundwater system, from the highest groundwater contour (9 m or 10 m) to the 4 m contour. (The hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 4.11-4.15). Flow line identification labels refer to Figures 4.11-4.15.)

<table>
<thead>
<tr>
<th>Location of flow lines (refer to Figures 4.11-4.15)</th>
<th>Hydraulic gradients on the seaward side of the groundwater system, from the highest water table contour (9 or 10 m) to the 4 m contour.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sept 1994 (Gradients in metres per 100 m)</td>
</tr>
<tr>
<td>A</td>
<td>0.40</td>
</tr>
<tr>
<td>B</td>
<td>0.45</td>
</tr>
<tr>
<td>C</td>
<td>0.50</td>
</tr>
<tr>
<td>D</td>
<td>0.50</td>
</tr>
<tr>
<td>E</td>
<td>0.49</td>
</tr>
<tr>
<td>F</td>
<td>0.49</td>
</tr>
<tr>
<td>G</td>
<td>0.45</td>
</tr>
<tr>
<td>H</td>
<td>0.43</td>
</tr>
<tr>
<td>I</td>
<td>0.43</td>
</tr>
<tr>
<td>J</td>
<td>0.41</td>
</tr>
<tr>
<td>K</td>
<td>0.48</td>
</tr>
<tr>
<td>L</td>
<td>0.54</td>
</tr>
<tr>
<td>M</td>
<td>0.59</td>
</tr>
<tr>
<td>N</td>
<td>0.67</td>
</tr>
<tr>
<td>O</td>
<td>0.77</td>
</tr>
<tr>
<td>P</td>
<td>0.83</td>
</tr>
<tr>
<td>Q</td>
<td>0.83</td>
</tr>
<tr>
<td>R</td>
<td>0.87</td>
</tr>
<tr>
<td>S</td>
<td>0.90</td>
</tr>
<tr>
<td>T</td>
<td>0.87</td>
</tr>
<tr>
<td>U</td>
<td>-</td>
</tr>
<tr>
<td>V</td>
<td>-</td>
</tr>
<tr>
<td>Average:</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Antecedent effective precipitation (EP), or precipitation (P) characteristics:
- May-Aug preceding Sept 1994, EP was 2.5% above LTA (-91.2mm)
- May-Aug preceding Sept 1995, EP 232% below LTA (-310.6mm)
- Oct-Jan preceding Feb 1995 Braunton received 43% more EP than LTA (418.4 mm)
- Oct-Dec preceding Jan 1996 Braunton received only 68.3% (148.8 mm) of the LTA EP
- Apr-Jun preceding June 1952 Braunton received 30% more P than the LTA (233.7 mm)
(Table 4.3) along the seaward margin of the system. Average hydraulic gradients ranged from 0.58m per 100m in September 1995, to 0.70m per 100m in June 1952. The less steep gradients allowed the characteristic water table mound to develop and for higher water table elevations to be maintained more central within the groundwater system.

Hydraulic gradients calculated for June 1952 were steeper for the possible reasons already explained in Section 4.2.2a and were again more comparable to the hydraulic gradients measured in February 1995. Again the close relationship between hydraulic gradients and antecedent monthly effective precipitation totals was apparent (Table 4.4).

d) Hydraulic gradients on the marshward side of the groundwater system from the highest water table contour (9 m or 10 m) to the 4 m contour

With the exception of the hydraulic gradients derived from the earlier work of Willis et al. (1959a), the hydraulic gradients from the highest water table contour (9 m or 10 m) to the 4 m contour on the marshward side of the groundwater system (Table 4.5) were steeper than those calculated for the same location on the seaward side of the groundwater system (Table 4.4). These steeper gradients were possibly related to the lower permeability of the sediment in the transitional zone to marshland, restricting groundwater drainage. Also on the seaward side of the groundwater system sedimentological factors such as particle size distribution and packing may be causing variations in $K_{sat}$, resulting in less steep hydraulic gradients.

The shorter and steeper flow paths on the marshward side of the groundwater system were arguably more sensitive to long-term changes in effective precipitation and changes to the marsh drainage system.
Table 4.5 Hydraulic gradients on the marshward side of the groundwater system, from the highest groundwater contour (9 m or 10 m) to the 4 m contour. (The hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 4.11-4.15). Flow line identification labels refer to Figures 4.11-4.15.)

| Location of flow lines (refer to Figures 4.11-4.15) | Hydraulic gradients on the marshward side of the groundwater system, from the highest water table contour (9 m or 10 m) to the 4 m contour. |
|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------
|                                                   | Sept 1994 (Gradients in metres per 100 m) | Sept 1995 (Gradients in metres per 100 m) | Feb 1995 (Gradients in metres per 100 m) | Jan 1996 (Gradients in metres per 100 m) | Willis et al., June 1952 (Gradients in metres per 100 m) |
| A1                                                | 0.43                                      | 0.57                                      | 0.62                                      | -                                         | 0.44                                         |
| B1                                                | 0.50                                      | 0.71                                      | 0.73                                      | 0.34                                      | 0.44                                         |
| C1                                                | 0.80                                      | 0.71                                      | 0.80                                      | 0.38                                      | 0.48                                         |
| D1                                                | 0.77                                      | 0.67                                      | 0.56                                      | 0.45                                      | 0.51                                         |
| E1                                                | 0.50                                      | 0.67                                      | 0.73                                      | 0.50                                      | 0.55                                         |
| F1                                                | 0.57                                      | 0.71                                      | 0.80                                      | 0.61                                      | 0.60                                         |
| G1                                                | 0.58                                      | 0.74                                      | 0.86                                      | 0.80                                      | 0.63                                         |
| H1                                                | 0.66                                      | 0.74                                      | 0.90                                      | 1.00                                      | 0.63                                         |
| I1                                                | 0.68                                      | 0.74                                      | 0.86                                      | 1.00                                      | 0.71                                         |
| J1                                                | 0.68                                      | 0.74                                      | 0.80                                      | 0.95                                      | 0.73                                         |
| K1                                                | 0.67                                      | 0.63                                      | 0.86                                      | 0.83                                      | 0.71                                         |
| L1                                                | 0.71                                      | 0.54                                      | 0.60                                      | 1.11                                      | 0.71                                         |
| M1                                                | 0.63                                      | 0.48                                      | 0.38                                      | 1.11                                      | 0.65                                         |
| N1                                                | 0.56                                      | 0.40                                      | -                                         | 1.00                                      | 0.57                                         |
| O1                                                | 0.50                                      | -                                         | -                                         | 1.00                                      | 0.44                                         |
| P1                                                | 0.42                                      | -                                         | -                                         | 0.80                                      | -                                            |
| Q1                                                | -                                         | -                                         | -                                         | 0.71                                      | -                                            |
| R1                                                | -                                         | -                                         | -                                         | 0.69                                      | -                                            |
| S1                                                | -                                         | -                                         | -                                         | 0.63                                      | -                                            |
| T1                                                | -                                         | -                                         | -                                         | 0.61                                      | -                                            |
| U1                                                | -                                         | -                                         | -                                         | 0.63                                      | -                                            |
| V1                                                | -                                         | -                                         | -                                         | 0.71                                      | -                                            |
| W1                                                | -                                         | -                                         | -                                         | 0.83                                      | -                                            |
| X1                                                | -                                         | -                                         | -                                         | 0.77                                      | -                                            |
| Y1                                                | -                                         | -                                         | -                                         | 0.80                                      | -                                            |
| Average:                                          | 0.62                                      | 0.65                                      | 0.73                                      | 0.76                                      | 0.59                                         |

Notes:
- **Antecedent effective precipitation (EP)**, or precipitation (P), characteristics:
  - May-Aug preceding Sept 1994: EP was 2.3% above LTA (-91.2 mm)
  - May-Aug preceding Sept 1995: EP 232% below LTA (-310.6 mm)
  - Oct-Jan preceding Feb 1995: Braunton received 43% more EP than LTA (148.8 mm) of the LTA EP
  - Oct-Dec preceding Jan 1996: Braunton received only 68.3% more P than the LTA (233.7 mm)
  - Apr-Jun preceding June 1952: Braunton received 30% more P than the LTA
e) Summary

The following points summarise the main characteristics of the groundwater system interpreted from the flow nets;

1. the hydraulic gradients on the seaward side of the system between the highest water table contour and the 4 m contour were less steep than those measured between the 0 m and 4 m water table contours, because the volume of water percolating through the dune sands increased from the centre to the margins. Steeper hydraulic gradients were therefore observed at the margins where there were greater movements of water through the medium.

2. temporal differences in hydraulic gradients were a function of antecedent monthly effective precipitation totals.

3. the hydraulic gradients on the marshward side of the groundwater system were steeper than those on the seaward side, possibly as a result of the less permeable adjoining marsh restricting groundwater drainage. Following Darcy's Law the increased hydraulic gradients were essential to drain water from the groundwater system. Furthermore, the less steep gradients on the seaward side of the groundwater system may possibly be related to differences in particle size distribution or packing, giving rise to variations in $K_{sat}$.

4.3 Hydrological characteristics explained from point observations

The aim of this section was to identify any variability in the annual cyclical response of the water table in relation to geographical location within the groundwater system. Water table data from two groups of four observation wells were analysed. The first group of observation wells (7, 23, 39 and 42) formed an east to west transect across the dune system (Figure 3.2). Observation well 42 was 300 m from the seaward edge of the fore dune ridge,
whereas observation wells 7 and 39 were more central within the dune complex. Observation well 23 was located at the inland boundary of the dune and marsh systems. The second group consisted of observation wells 2, 11, 38 and 58 (Figure 3.2). Observation wells 11 and 58 were within 250 m of the seaward edge of the fore dune ridge. Taking West Boundary Drain as the inland boundary of the dune system and the fore dune ridge as the seaward boundary, wells 2 and 38 were more central within the dune system. The annual cyclical response of the water table in these two groups of wells was described for two periods January 1981-January 1985 and January 1988-January 1992. The period January 1981-January 1985 was chosen because this was the time when concerns were first expressed that the water table on Braunton Burrows was falling. The second analysis period, January 1988-January 1992, was chosen to set the discussion into the wider context.

During both periods of analysis Figures 4.16 and 4.17 show that hydrologically observation wells 7 and 39, both more central within the dune system, respond similarly on an annual cyclical basis. With the exception of between the summer of 1989 and the winter of 1989/1990, water levels in these wells fluctuated by between 0.39 m and 1.0 m. In contrast, with the exception of the water table fluctuations recorded in 1983, observation well 23 located at the inland boundary of the system fluctuated less (Figures 4.16 and 4.17). Seasonal fluctuations ranged from 0.16 m to 0.63 m (Tables 4.6 and 4.7). Between the winter of 1982/1983 and the summer of 1983 the water table at well 23 fell by 1.25 m. This drop in the water table coincided with the drainage improvement works on Braunton Marsh. The possible causes for the sudden drop in the water table at observation well 23 will be investigated further in Sections 5.1.4 and 5.2.5. With the exception of during 1983, observation wells 42, which was within 300 m of the seaward edge of the fore dune ridge, fluctuated less than wells 7 and 39, but generally more than well 23 (Figures 4.16 and 4.17;
The general trend evident from the analysis of these four observation wells was that water levels in observation wells near to the margins of the system (wells 23 and 42) fluctuated less between seasons than water levels in observation wells more central within the dune system (wells 7 and 39) (Figures 4.16 and 4.17; Tables 4.6 and 4.17). Similar spatial differences in seasonal water table fluctuations were also described by Willis et al. (1959a), who stated that the water table along the seaward and inland margin of the system is recharged not only by precipitation, but also by water draining from higher elevations within the groundwater mound. Also the sea and the managed water levels in West Boundary Drain act as constant head boundaries, thus reducing the range of water table fluctuations at the edge of the dune system. In 1983 greater water table fluctuations were recorded at the edge of the system (wells 23 and 42) compared with the centre (wells 7 and 39), (Tables 4.6 and 4.7). Differences in the functioning of the groundwater system during 1983 will be investigated further in Chapter 5.

For the second group of observation wells up until mid 1983 spatial differences in the seasonal response of the water table were not so readily apparent (Table 4.8). However, from the summer of 1983, up until the winter of 1984/1985, again significant spatial differences in water table fluctuations were apparent, with the wells at the edge of the system (wells 11 and 58) fluctuating less than those further inland (wells 2 and 38) (Figure 4.18 and Table 4.8). These spatial differences were also apparent throughout the second period of analysis (Figure 4.19 and Table 4.9). During this period observation wells 2 and 38 on average fluctuated 0.88 m and 0.89 m respectively. In comparison observation well 11 on average fluctuated 0.64 m and observation well 58 (situated at the seaward margin of the system) on average fluctuated 0.58 m (Table 4.9).
Figure 4.16 Annual cyclical water table fluctuations at observation wells 7, 23, 39 and 42 between January 1981 and January 1985. 
(The locations of the observation wells are shown on Figure 3.2).

Table 4.6 Maximum fluctuation of the water table at observation well 7, 23, 39 and 42 between seasons.

<table>
<thead>
<tr>
<th>Observation Well</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (central)</td>
<td>0.67</td>
</tr>
<tr>
<td>23 (inland margin)</td>
<td>0.49</td>
</tr>
<tr>
<td>39 (central)</td>
<td>0.69</td>
</tr>
<tr>
<td>42 (seaward margin)</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Figure 4.17 Annual cyclical water table fluctuations at observation wells 7, 23, 39 and 42 between January 1988 and January 1992. (The locations of the dipwells are shown on Figure 3.2).

Table 4.7 Maximum fluctuation of the water table at observation well 7, 23, 39 and 42 between seasons.

<table>
<thead>
<tr>
<th>Observation Well</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (central)</td>
<td>0.51</td>
</tr>
<tr>
<td>23 (inland margin)</td>
<td>0.19</td>
</tr>
<tr>
<td>39 (central)</td>
<td>0.39</td>
</tr>
<tr>
<td>42 (seaward margin)</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Figure 4.18 Annual cyclical water table fluctuations at observation wells 2, 11, 38 and 58 between January 1981 and January 1985. (The location of the dipwells are shown on Figure 3.2).

Table 4.8 Maximum fluctuation of the water table at observation well 2, 11, 38 and 58 between seasons.

<table>
<thead>
<tr>
<th>Observation Well</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (central)</td>
<td>0.83</td>
</tr>
<tr>
<td>11 (seaward margin)</td>
<td>0.66</td>
</tr>
<tr>
<td>38 (central)</td>
<td>0.66</td>
</tr>
<tr>
<td>58 (seaward margin)</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Figure 4.19 Annual cyclical water table fluctuations at observation wells 2, 11, 38 and 58 between January 1988 and January 1992. (The location of the observation wells are shown on Figure 3.2).

Table 4.9 Maximum fluctuation of the water table at observation well 2, 11, 38 and 58 between seasons.

<table>
<thead>
<tr>
<th>Observation Well</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (central)</td>
<td>0.40</td>
</tr>
<tr>
<td>11 (seaward margin)</td>
<td>0.23</td>
</tr>
<tr>
<td>38 (central)</td>
<td>0.27</td>
</tr>
<tr>
<td>58 (seaward margin)</td>
<td>0.15</td>
</tr>
</tbody>
</table>
The results from this section suggest that water levels at the centre of the groundwater mound would be most affected by long-term changes in the climate, or the groundwater drainage regime.

4.4 The relationship between the elevation of the water table and effective precipitation

As identified in Sections 4.1 and 4.2, precipitation was the main factor controlling the elevation of the water table within the isolated dune system at Braunton. Research by Willis et al. (1959a) and Jones (1967) both working on sand dune systems have attempted to quantify the relationship between the elevation of the water table and monthly precipitation totals, through correlation and regression analysis. Both studies concluded that the elevation of the water table was most closely correlated with precipitation of the three months preceding measurement. At Kenfig the correlation coefficients were poor and only explained between 5% and 54% of the association between the two variables at the 95% significance level. The strength of the correlation coefficients calculated by Willis et al. (1959a) were not described. These studies did not take into account evapotranspiration losses, which would have improved the correlations. A detailed study on the Dutch dune systems by Stuyfzand (1993), assuming piston flow and a scanty vegetation cover, found that to reach a water table 2 m from the ground surface transit time in the vadose zone was four months.

In this section Spearman's rank correlation (rₚ) was used to determine the relationship between water table elevation and discrete periods of antecedent monthly effective precipitation. The relationship between these two variables was investigated for the period December 1993 to December 1995, in order to make a direct comparison with the response characteristics of the water table at Northam and Dawlish (Section 6.4 and 6.12), where water table elevations have only been monitored since the start of the research in October
1993. At Braunton monthly water table elevations from 12 observation wells in the monitoring network (Table 4.10) were correlated with discrete periods of antecedent monthly effective precipitation.

Analysis of the results (Table 4.10) showed that between December 1993 and December 1995 the elevation of the water table in ten of the observation wells was most closely correlated with total antecedent effective precipitation of the 91-120 day period previous. The correlation coefficients were significant at 95% and ranged from 0.809 to 0.905, with $r^2$ explaining between 65% and 82% of the relationship between these two variables. These correlation coefficients were stronger than those calculated by Jones (1967) at Kenfig.

Independent variables which may have influenced the strength of the relationship include variability in the sediment properties and differences in evapotranspiration losses associated with areas of scrub growth. Also MORECS evapotranspiration data used in the calculation of monthly effective precipitation totals were measured over a 40 x 40 km area and therefore only provided an averaged monthly rate. Also evapotranspiration losses from a coastal environment would possibly be greater than the majority of inland measurements used in the calculation of MORECS evapotranspiration data.

Wells 25 and 27 took longer to respond and were most closely correlated with antecedent effective precipitation from the preceding 121-150 day period. The correlation coefficients were significant at 95% and explained 76% (well 25) and 56% (well 27) of the association between the two variables. The slower response of these wells was possibly related to their location with the dune ridges surrounded by a greater volume of unsaturated sand, which would reduce the response rate of the water table to effective inputs.
Table 4.10  The relationship between water table elevation and effective precipitation between December 1993 and December 1995, for selected observation wells on Braunton Burrows (For observation well location refer to Figure 3.2. Shaded boxes indicate the strongest correlations at a 95 % significance level. \( r_s \) - Spearman's correlation coefficient. \( r^2 \) - measure of association between the two variables.)

<table>
<thead>
<tr>
<th>Obs. well (and correlation coefficient value required to be significant at 99%)</th>
<th>0-30 days</th>
<th>31-60 days</th>
<th>61-90 days</th>
<th>91-120 days</th>
<th>121-150 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (( r_s =0.485 ))</td>
<td>0.032</td>
<td>0.474</td>
<td>0.706</td>
<td>0.883 (( r^2 =78 % ))</td>
<td>0.819</td>
</tr>
<tr>
<td>2 (( r_s =0.485 ))</td>
<td>0.135</td>
<td>0.574</td>
<td>0.802</td>
<td>0.809 (( r^2 =65 % ))</td>
<td>0.778</td>
</tr>
<tr>
<td>3 (( r_s =0.485 ))</td>
<td>0.058</td>
<td>0.472</td>
<td>0.715</td>
<td>0.871 (( r^2 =76 % ))</td>
<td>0.800</td>
</tr>
<tr>
<td>6 (( r_s =0.485 ))</td>
<td>0.124</td>
<td>0.346</td>
<td>0.675</td>
<td>0.873 (( r^2 =76 % ))</td>
<td>0.871</td>
</tr>
<tr>
<td>7 (( r_s =0.485 ))</td>
<td>0.036</td>
<td>0.483</td>
<td>0.748</td>
<td>0.895 (( r^2 =80 % ))</td>
<td>0.832</td>
</tr>
<tr>
<td>23 (( r_s =0.485 ))</td>
<td>0.246</td>
<td>0.638</td>
<td>0.788</td>
<td>0.839 (( r^2 =70 % ))</td>
<td>0.712</td>
</tr>
<tr>
<td>25 (( r_s =0.485 ))</td>
<td>-0.148</td>
<td>0.276</td>
<td>0.639</td>
<td>0.858</td>
<td>0.874 (( r^2 =76 % ))</td>
</tr>
<tr>
<td>27 (( r_s =0.485 ))</td>
<td>-0.016</td>
<td>0.293</td>
<td>0.477</td>
<td>0.625</td>
<td>0.750 (( r^2 =56 % ))</td>
</tr>
<tr>
<td>36 (( r_s =0.485 ))</td>
<td>0.295</td>
<td>0.606</td>
<td>0.785</td>
<td>0.823 (( r^2 =67 % ))</td>
<td>0.681</td>
</tr>
<tr>
<td>37 (( r_s =0.485 ))</td>
<td>0.065</td>
<td>0.521</td>
<td>0.788</td>
<td>0.905 (( r^2 =82 % ))</td>
<td>0.805</td>
</tr>
<tr>
<td>38 (( r_s =0.485 ))</td>
<td>0.079</td>
<td>0.493</td>
<td>0.739</td>
<td>0.860 (( r^2 =74 % ))</td>
<td>0.758</td>
</tr>
<tr>
<td>39 (( r_s =0.508 ))</td>
<td>0.137</td>
<td>0.468</td>
<td>0.768</td>
<td>0.836 (( r^2 =70 % ))</td>
<td>0.717</td>
</tr>
</tbody>
</table>

4.5 The lower geological boundary or impermeable layer of the groundwater system

A quantitative account of the depth and continuity of the lower geological boundary, or impermeable layer of the groundwater system was essential in this study to accurately parameterise the groundwater flow model (Chapter 7). These geological data were also required when calculating the depth of the fresh water, salt water interface (Section 4.6). The depth to the lower geological boundary or impermeable layer was quantified from five borehole investigations (coded Pt1-Pt5 on Figure 3.1).
The depth to the underlying basal material ranged from 0.96 m below OD to 1.10 m above OD (Table 4.11), which was a similar depth to that described in the single borehole log by Edmonds et al. (1979). In each borehole the silty/clay layer was very compact, causing the hydraulic drilling rig to jam. Except for site 4, in Rowan Plain (coded Pt 4 on Figure 3.1), this silty/clay basal layer contained both pebbles (2-8 mm diameter) and shale fragments from the underlying bedrock. Given the possible error in the sampling technique (Section 3.2.7) and the natural undulations in the basal material, from these results it was concluded that a relatively impermeable layer occurs close to OD. For the purpose of this research, in both groundwater calculations and the groundwater modelling exercise, this layer was used as the lower boundary of the groundwater system.

Table 4.11 Characteristics of the basal material from borehole investigations. (Measurements are in metres above or below OD. Particle size classification according to the scale of Friedman and Sanders (1978). Experimental sites are shown on Figure 3.1, coded Pt1-Pt5.)

<table>
<thead>
<tr>
<th>Drilling rig profile</th>
<th>Location</th>
<th>Characteristics of basal material</th>
<th>Depth to base material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton Slack</td>
<td>Silt/clay layer - 86 % &lt;62μm</td>
<td>0.96 m below OD</td>
</tr>
<tr>
<td>2</td>
<td>Next to observation well 56, eastern margin of the dune system</td>
<td>Silt/clay layer- 85 % &lt;62μm</td>
<td>0.33 m above OD</td>
</tr>
<tr>
<td>3</td>
<td>Next to observation well 23, eastern margin of dune system</td>
<td>Silt/clay layer- 75 % &lt;62 μm</td>
<td>0.37 m above OD</td>
</tr>
<tr>
<td>4</td>
<td>Rowan Plain</td>
<td>Silt/clay layer- 86 % &lt;62 μm</td>
<td>0.63 m below OD</td>
</tr>
<tr>
<td>5</td>
<td>High Ridge Plains</td>
<td>Very coarse sand and a fine pebble (&lt;4 mm) horizon, causing drill to stop</td>
<td>1.10 m above OD</td>
</tr>
</tbody>
</table>
4.6 Saline intrusion

A problem in the hydrological description of groundwater flow systems unique to coastal areas concerns the effect of subsurface landward encroachment of saline water on the seaward flow of freshwater (Reilly and Goodman, 1985). Saline intrusion was important in this research because if the perceived drying out of the Burrows continued it could result in the progressive intrusion of salt water. In the Netherlands over abstraction of fresh waters from the dune systems has resulted in increased saline intrusion and consequently the loss of rare and unique dune habitat flora (Van Beckhoven, 1992; Van Dijk and Grootjans, 1993).

As explained in Section 1.4.1 the work of Ghyben (1889) and Herzberg (1901), cited in de Vries (1994) independently formulated the principle that salt water occurred beneath the dune systems along the coasts of the Netherlands, not at mean sea level, but at a depth of about 40 times the fresh water head above mean sea level (Todd, 1959). Freeze and Cherry (1979) state that in most real situations the Ghyben-Herzberg principle underestimates the depth to the salt water interface.

At Braunton the lower boundary of the local groundwater system, consisting of a relatively impermeable continuous silty/clay layer (Section 4.5), was a maximum of one metre below mean sea level and water table elevations measured in the most seaward observation wells ranged from 3.8-6.9 m above OD. Applying these hydrological parameters to the Ghyben-Herzberg principle (40:1 ratio) salt-water intrusion was not a problem within the Braunton sand dune aquifer, as the fresh water head above mean sea level was not greater than 40 times the depth of the lower boundary of the groundwater system. The Ghyben-Herzberg principle was based upon the Dutch dune systems where aquifers typically extend 500-600 m below mean sea level (Stuyfzand, pers. comm.).
Similar conclusions were made at Kenfig (Jones, 1993). The lowest recorded water table elevations in the fore dunes were approximately 4.5 m above OD and impermeable clay deposits occurred within 25 m depth of the phreatic surface. Therefore, landward penetration of sea water was considered unlikely.

4.7 The influence of the tide on water table elevations

As described in Section 3.2.5, pressure waves from the tide may cause short-term fluctuations in the elevation of the water table. It was essential to identify the impact of such fluctuations before using the water level data to identify long-term trends in the elevation of the water table (Chapter 5).

Water levels in dipwell 6N, situated in a slack 250 m inland from the seaward edge of the fore dune ridge, were monitored every 10 minutes for a period of 24 hrs, during which time a predicted high spring tide of 7.8 m above Chart Datum occurred. It should be stressed that barometric pressure and the winds may have significantly altered the actual height of the tide experienced at Braunton during the monitoring. The results from the data logger showed the water levels in dipwell 6N did not rise or fall with the tide. Similarly, no tidal influence was recorded in the study of Braunton Burrows by Willis et al. (1959b), who monitored water levels in a slack 200 inland from the seaward edge of the fore dune ridge over a period of 10 days. The long-term water table elevation data from the Braunton observation well network was therefore suitable for interpreting the temporal variability in the elevation of the water table on Braunton Burrows.

4.8 Physical characteristics of the dune sands

A comprehensive description of the physical properties of the dune sands, including particle size distribution, bulk density and K_vt was important in this research in explaining the
hydrological characteristics described in Sections 4.1-4.3. Spatial variability in $K_{sat}$ also had to be quantified before parameterising the groundwater model (Chapter 7).

### 4.8.1 Particle size analysis

Grain size has been described as a fundamental independent variable controlling permeability in unconsolidated sediments (Reyes, 1966; Beard and Weyl, 1973, Fairbridge and Finkl, 1979). In fact, hydrologists have developed semi-empirical formulae to estimate $K_{sat}$ from the square of the grain size diameter, including the work of Schlichter, (1905), Fair and Hatch, (1933) and Krumbein and Monk, (1943).

As described in Section 3.2.8, to describe particle size variability with depth sediment was sampled at 0.90 m intervals to a maximum depth of 12.60 m, at four sites down over Warble Fly Hill (coded DR Profile I to IV on Figure 3.1). To evaluate the spatial variability in particle size distribution within the dune system samples were collected at 0.90 m depths above the elevation of the water table at the drilling rig sites coded Pt1-Pt5 (Figure 3.1) and during the installation of the nested piezometers in the detailed experimental sites (Figure 3.1). According to the particle size classification scale of Friedman and Sanders (1978) sediment was categorised into five distinct classes, silt and clay (<62 µm), fine sand (62µm-250µm), medium grained sand (250µm-500µm), coarse grained sand (500µm-1mm) and particles greater than 1 mm.

#### a) Variability in particle size distribution with depth

Warble Fly Hill rises to 40 m above OD and has been built up of successive layers of wind blown sand over the last 5,000-6,000 years (Comber et al., 1993). The physical nature of the formation of a sand dune will therefore assist in identifying any variability in particle size distribution with depth, which would ultimately affect the hydrological functioning of
As highlighted in both Figures 4.20-4.23 and Table 4.12, for each profile on Warble Fly Hill, the percentage content of particles in each size category were fairly constant with depth. The silt and clay content (<62 µm) ranged from 1.6-8.5 % of the sample volume. The majority of the sediment formed a medium to fine grained sand and at the extreme end of the particle size distribution scale coarse sand (500 µm-1 mm) and particles greater than 1 mm constituted a maximum of 7.3 % of the sample volume. A study by Greenwood (1978) also described the dune sands at Braunton as well sorted, with a uniform particle size distribution.

![Particle size frequency distribution curves for sediment sampled at various depths from the ground surface at profile 1, Warble Fly Hill. (The location of the sampling site is shown on Figure 3.1.)](image)

Figure 4.20  Particle size frequency distribution curves for sediment sampled at various depths from the ground surface at profile 1, Warble Fly Hill. (The location of the sampling site is shown on Figure 3.1.)
Figure 4.21  Particle size frequency distribution curves for sediment sampled at various depths from the ground surface at profile II, Warble Fly Hill. (The location of the sampling site is shown on Figure 3.1.)

Figure 4.22  Particle size frequency distribution curves for sediment sampled at various depths from the ground surface at profile III, Warble Fly Hill. (The location of the sampling site is shown on Figure 3.1.)
Figure 4.23  Particle size frequency distribution curves for sediment sampled at various depths from the ground surface at profile IV, Warble Fly Hill. (The location of the sampling site is shown on Figure 3.1.)
Table 4.12 Variability in particle size distribution with depth, profiles I-IV
Warble Fly Hill.
(Sampling sites are shown on Figure 3.1. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay (<62μm), FS-fine sand (62μm-250μm), MS-medium sand (250μm-500μm), CS-coarse sand (500μm-1mm), >1mm-very coarse sand and fine pebbles.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Profile I</th>
<th>Profile II</th>
<th>Profile III</th>
<th>Profile IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S/C</td>
<td>S/C</td>
<td>S/C</td>
<td>S/C</td>
</tr>
<tr>
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<td>1.8%</td>
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<tr>
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<td>FS 57.5%</td>
<td>FS 62.5%</td>
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</tr>
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<td>S/C 8.5%</td>
<td>S/C 1.6%</td>
</tr>
<tr>
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<td>FS 48.6%</td>
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</tr>
<tr>
<td></td>
<td>MS 47.2%</td>
<td>MS 44.0%</td>
<td>MS 37.0%</td>
<td>MS 48.5%</td>
</tr>
<tr>
<td></td>
<td>CS 1.0%</td>
<td>CS 1.0%</td>
<td>CS 2.0%</td>
<td>CS 1.5%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm 1.0%</td>
<td>&gt;1mm 1.0%</td>
<td>&gt;1mm -</td>
</tr>
</tbody>
</table>
Table 4.12 cont. Variability in particle size distribution characteristics with depth, profiles I-IV Warble Fly Hill.
(Sampling sites are shown on Figure 3.1. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay (<62μm), FS-fine sand (62μm-250μm), MS-medium sand (250μm-500μm), CS-coarse sand (500μm-1mm), >1mm-very coarse sand and fine pebbles.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Profile I</th>
<th>Profile II</th>
<th>Profile III</th>
<th>Profile IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.90 m</td>
<td>S/C 8.0%</td>
<td>S/C 4.0%</td>
<td>S/C 7.3%</td>
<td>S/C 1.8%</td>
</tr>
<tr>
<td></td>
<td>FS 52.0%</td>
<td>FS 51.0%</td>
<td>FS 55.2%</td>
<td>FS 47.2%</td>
</tr>
<tr>
<td></td>
<td>MS 39.5%</td>
<td>MS 42.0%</td>
<td>MS 36.7%</td>
<td>MS 48.8%</td>
</tr>
<tr>
<td></td>
<td>CS 0.5%</td>
<td>CS 1.5%</td>
<td>CS 0.8%</td>
<td>CS 1.8%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm 1.5%</td>
<td>&gt;1mm -</td>
<td>&gt;1mm 0.4%</td>
</tr>
<tr>
<td>10.80 m</td>
<td>S/C 6.0%</td>
<td>S/C 2.0%</td>
<td>S/C 10.0%</td>
<td>S/C 2.0%</td>
</tr>
<tr>
<td></td>
<td>FS 50.0%</td>
<td>FS 55.0%</td>
<td>FS 49.0%</td>
<td>FS 52.0%</td>
</tr>
<tr>
<td></td>
<td>MS 43.0%</td>
<td>MS 40.0%</td>
<td>MS 39.0%</td>
<td>MS 42.4%</td>
</tr>
<tr>
<td></td>
<td>CS 1.0%</td>
<td>CS 2.5%</td>
<td>CS 1.5%</td>
<td>CS 2.6%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm 0.5%</td>
<td>&gt;1mm 0.5%</td>
<td>&gt;1mm 1.0%</td>
</tr>
<tr>
<td>11.70 m</td>
<td>S/C 7.5%</td>
<td>S/C 4.0%</td>
<td>S/C 8.4%</td>
<td>S/C 2.5%</td>
</tr>
<tr>
<td></td>
<td>FS 51.5%</td>
<td>FS 54.0%</td>
<td>FS 52.6%</td>
<td>FS 48.5%</td>
</tr>
<tr>
<td></td>
<td>MS 35.0%</td>
<td>MS 39.0</td>
<td>MS 36.4%</td>
<td>MS 46.7%</td>
</tr>
<tr>
<td></td>
<td>CS 3.0%</td>
<td>CS 0.5%</td>
<td>CS 1.8%</td>
<td>CS 0.9%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 3.0%</td>
<td>&gt;1mm 2.5%</td>
<td>&gt;1mm 0.8%</td>
<td>&gt;1mm 1.4%</td>
</tr>
<tr>
<td>12.60 m</td>
<td>S/C 7.5%</td>
<td>S/C 2.0%</td>
<td>S/C 8.0%</td>
<td>S/C 2.7%</td>
</tr>
<tr>
<td></td>
<td>FS 49.5%</td>
<td>FS 54.0%</td>
<td>FS 47.0%</td>
<td>FS 52.5%</td>
</tr>
<tr>
<td></td>
<td>MS 42.5%</td>
<td>MS 42.0%</td>
<td>MS 45.0%</td>
<td>MS 44.0%</td>
</tr>
<tr>
<td></td>
<td>CS 0.5%</td>
<td>CS 2.0%</td>
<td>CS 0.8%</td>
<td>CS 0.8%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
</tr>
</tbody>
</table>

b) Variability in particle size distribution within the dune system

As shown in Table 4.13 and Figure 4.24, with the exception of sediment sampled in J-Lane and next to observation well 23 the particle size distribution of sediment sampled spatially within the dune system was similar to that measured with depth on Warble Fly Hill (Table 4.12 and Figures 4.20-4.23). The majority of the sediment formed a medium to fine grained sand, with silts and clays constituting between 2.4-10.1% of the sample volume. Samples from the detailed experimental site in J-Lane and next to observation well 23 (drilling rig site Pt3, Figure 3.1) contained a higher percentage of medium (250-500 μm) and coarse (500μm-1mm) grained sand, but no significant increase in silt and clay fractions, which would have helped to explain the groundwater mounding along the eastern margin of the system (Sections 4.1-4.3). The liquid nature of saturated sand prevented sampling beneath the water table and so therefore any change in texture with depth is unknown.
Table 4.13  Particle size characteristics across the dune system at Braunton Burrows. (Sampling sites are shown on Figure 3.1. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay (<62μm), FS-fine sand (62μm-250μm), MS-medium sand (250μm-500μm), CS-coarse sand (500μm-1mm), >1mm-very coarse sand and fine pebbles.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Round Slack (Detailed experimental site)</th>
<th>Cotton Slack (Detailed experimental site)</th>
<th>Bridle Path (Detailed experimental site)</th>
<th>Horse Breakers Slack (Detailed experimental site)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90 m</td>
<td>S/C 5.3%</td>
<td>S/C 7.9%</td>
<td>S/C 10.1%</td>
<td>S/C 3.4%</td>
</tr>
<tr>
<td></td>
<td>FS 49.3%</td>
<td>FS 56.1%</td>
<td>FS 46.2%</td>
<td>FS 53.1%</td>
</tr>
<tr>
<td></td>
<td>MS 44.1%</td>
<td>MS 36.0%</td>
<td>MS 43.7%</td>
<td>MS 38.4%</td>
</tr>
<tr>
<td></td>
<td>CS 1.3%</td>
<td>CS</td>
<td>CS</td>
<td>CS 2.9%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm</td>
<td>&gt;1mm</td>
<td>&gt;1mm</td>
<td>&gt;1mm 2.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>J-Lane (Detailed experimental site)</th>
<th>Next to Obs. well 56 (Drilling rig site Pt 2)</th>
<th>Next to Obs. well 23 (Drilling rig site Pt 3)</th>
<th>50 m east of Warble Fly Hill (Drilling rig site Pt4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90 m</td>
<td>S/C 3.5%</td>
<td>S/C 9.0%</td>
<td>S/C 5.0%</td>
<td>S/C 2.4%</td>
</tr>
<tr>
<td></td>
<td>FS 34.8%</td>
<td>FS 50.5%</td>
<td>FS 32.5%</td>
<td>FS 55.2%</td>
</tr>
<tr>
<td></td>
<td>MS 55.7%</td>
<td>MS 38.5%</td>
<td>MS 52.5%</td>
<td>MS 38.8%</td>
</tr>
<tr>
<td></td>
<td>CS 4.6%</td>
<td>CS 0.8%</td>
<td>CS 8.3%</td>
<td>CS 3.1%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 1.4%</td>
<td>&gt;1mm 1.2%</td>
<td>&gt;1mm 1.7%</td>
<td>&gt;1mm 0.5%</td>
</tr>
</tbody>
</table>

Samples for particle size analysis were not collected from the private land to the east of the American Road (Figure 3.1). This area forms a transitional zone between the dune and marsh systems, where a change in the texture of the sediment and a decrease in permeability probably occurs. This zone of lower permeability would help explain the characteristics and functioning of the groundwater system described throughout Sections 4.1-4.3.
Figure 4.24 Particle size frequency distribution curves for sediment within the Braunton sand dune system at a depth of 0.90 m.

a) Frequency distribution curves for sediment sampled in Round Slack, Cotton Slack, Bridle Path and Horse Breakers Slack.

b) Frequency distribution curves for sediment sampled in J-Lane, at observation well 56 and 23, and 50 m east of Warble Fly Hill.

(Locations of sampling sites are shown on Figure 3.1.)
Section 4.8.1 has shown that with the exception of the coarser dune sands in J-Lane Slack and in the vicinity of observation well 23 the sediment at Braunton has a uniform particle size distribution, both with depth and spatially within the dune complex. The apparent homogenous nature of the dune sands will simplify the parameterisation of the groundwater model in Chapter 7.

4.8.2 Bulk density

Bulk density was determined at the site of each well permeameter experiment, at three locations rising up from a slack, to the top of a dune (Section 3.2.9). Samples were taken at a depth of 0-5 cm and 45-50 cm.

As summarised in Table 4.14, the average surface bulk density (0-5 cm) ranged from 1.38 g cm\(^{-3}\) to 1.57 g cm\(^{-3}\). In general, the surface densities were less than those calculated at depth (45-50 cm). At the 45-50 cm depth average bulk densities ranged from 1.48 g cm\(^{-3}\) to 1.59 g cm\(^{-3}\). The lower bulk densities in the surface layer occur because of the greater content of organic matter and root channels. The calculated values of bulk density were of a similar range to those quoted by Landon (1984), who stated that dune sands usually have a dry bulk density of between 1.20-1.80 g cm\(^{-3}\). The bulk density measurements from Braunton were also comparable to values reported by Ritsema and Dekker (1994) for the Dutch dune systems, which ranged from 1.55-1.58 g cm\(^{-3}\). Average bulk densities calculated at the 45-50 cm depth varied by 0.11 g cm\(^{-3}\). As described in Section 1.5, research by Miles et al. (1988) stated that in the unsaturated zone changes in bulk density as small as 0.02 g cm\(^{-3}\) resulted in significant changes in unsaturated hydraulic conductivity and rates of groundwater recharge. Variability in the bulk density measurements at Braunton (Table 4.14) will partly the less than perfect correlations between water table elevation and
effective precipitation (Section 4.4).

Table 4.14. Mean values for dry bulk density (units g cm$^{-3}$). 
(Experimental sites are shown on Figure 3.1.)

<table>
<thead>
<tr>
<th>Dune location (mean bulk density of 3 auger holes)</th>
<th>Dune base, edge of slack.</th>
<th>Mid slope of dune.</th>
<th>Top of dune.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune rising up from Cotton Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (n=3)</td>
<td>1.43</td>
<td>1.59</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>1.48</td>
<td>1.58</td>
<td>1.54</td>
</tr>
<tr>
<td>Dune rising up from Round Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (n=3)</td>
<td>1.40</td>
<td>1.53</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
<td>1.55</td>
<td>1.56</td>
</tr>
<tr>
<td>Dune rising up from Horse Breakers Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (n=3)</td>
<td>1.57</td>
<td>1.50</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>1.52</td>
<td>1.48</td>
<td>1.54</td>
</tr>
<tr>
<td>Dune rising up from J Lane Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (n=3)</td>
<td>1.38</td>
<td>1.58</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>1.48</td>
<td>1.56</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Bulk density variability may also occur because of the way in which the dune sands were deposited, as thin layers less than a few millimetres thick. Each layer may therefore have very different density and texture characteristics. Also some of these layers may have been compacted by the kinetic energy of rainfall (Tackett and Pearson, 1965). Bulk density variations within the Braunton system may also occur because of the intensive use of the area as a bombing range throughout World War II and since then its continual use for military training.

4.8.3 $K_{sat}$ below the water table (slug test)

As identified in the hydrological study of Ainsdale (Clark, 1980), $K_{sat}$ and its spatial variability was a key parameter governing groundwater flow through the dune system. A detailed account of $K_{sat}$ was essential in this research to successfully calibrate the
groundwater flow model of Braunton Burrows (Chapter 7).

In this study the slug test was the most appropriate method for the determination of \( K_{\text{sat}} \) in dune sands (Section 3.2.6a). Methods for the analysis of slug test data have been developed for both confined (Hvorslev, 1951; Cooper et al., 1967) and unconfined aquifers (Bouwer and Rice, 1976). The dune system at Braunton Burrows consists of well sorted wind blown sands, without any major confining silt or clay lenses (Section 4.8.1) and is therefore classified as an unconfined aquifer.

The Bouwer and Rice (1976) method of slug test analysis (hereafter referred to as the B-R model) calculated \( K_{\text{sat}} \) from the flux of water to or from a well, after the removal or injection of a known volume of water. Through the use of electric analogue experiments Bouwer and Rice (1976) improved the accuracy of determining \( K_{\text{sat}} \) values from slug test data by defining a shape factor, which is the effective radius (\( Re \)) over which the head loss (\( y \)) is dissipated in the flow system.

For the purpose of this research a computer based model AQTESOLV, developed by Geraghty and Miller Inc. (1991), was used to calculate \( K_{\text{sat}} \) using the B-R model. A comparison of \( K_{\text{sat}} \) values obtained by hand calculations with those from the use of AQTESOLV have been shown to agree to within three percent for all soil types, including sandy soils (Brown et al., 1995). Although AQTESOLV automatically calculated \( K_{\text{sat}} \), it was still important to have a basic understanding of the mathematical principles behind the solution (Appendix B).
There are a number of assumptions employed by the B-R model when mathematically describing flow to a well in an unconfined formation;

1. the aquifer is homogenous and isotropic with respect to $K_{sat}$.
2. the specific storage of the aquifer is negligible.
3. drawdown of the water table around the well can be ignored (drawdown is unlikely to be a problem in highly permeable dune sands).
4. flow above the water table can be ignored.
5. hydraulically the well is 100 % efficient.

Although not commonly employed by field hydrogeologists additional methods of slug test analysis for unconfined aquifers have been developed, including the analytical solution of Dagan (1978) and the numerical extension of Dagan's work by Widdowson et al. (1990). Both of these methods are based on the same set of simplifying assumptions outlined by Bouwer and Rice (1976).

The B-R model may contain a percentage error ranging from 10-25 % (Bouwer, 1989; Brown et al. 1995). Generally the model tends to underestimate $K_{sat}$, the greatest errors occurring in the presence of a damaged zone around the well, or when the top of the piezometer screen is close to the water table. A skin forming around the well casing can also introduce error into the $K_{sat}$ measurements, although this was unlikely to be a problem in dune sands.

As described in Section 3.2.6a, $K_{sat}$ below the water table was determined for each nest of piezometers installed within the detailed experimental sites (Figure 3.1). The experimental sites were located to highlight variability in $K_{sat}$ within the dune system.
4.8.3a Interpretation of slug test results

The results from the slug tests are presented in Table 4.15. The duration of the slug test was very short often less than two minutes, which meant that the determined $K_{sat}$ values were only representative of the water bearing material close to the well (Ferris et al., 1962). Furthermore, because innovative changes were made to the slug test experiment (pumping water from the piezometer rather than removing a 'slug'), a slight cone of depression may have been created in the medium immediately surrounding the piezometer, introducing some error into the slug test results (Kruseman and de Ridder, 1977).

Table 4.15 $K_{sat}$ results for Braunton Burrows using the Bouwer and Rice (1976) solution. ($K_{sat}$ measurement sites are shown on Figure 3.1.)

<table>
<thead>
<tr>
<th>Location (Figure 3.1)</th>
<th>Depth of $K_{sat}$ measurement from the ground surface (m)</th>
<th>$K_{sat}$ (m d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton Slack</td>
<td>0.70 - 1.0 2.60 - 3.0 5.50 - 6.0</td>
<td>7.88 8.24 10.50</td>
</tr>
<tr>
<td>Round Slack</td>
<td>0.70 - 1.0 2.60 - 3.0 5.50 - 6.0</td>
<td>8.30 7.95 8.18</td>
</tr>
<tr>
<td>Horse Breakers Slack</td>
<td>0.70 - 1.0 2.60 - 3.0 5.50 - 6.0</td>
<td>7.60 7.16 7.46</td>
</tr>
<tr>
<td>J-Lane Slack</td>
<td>0.70 - 1.0 2.60 - 3.0 5.50 - 6.0</td>
<td>7.44 7.65 6.80</td>
</tr>
<tr>
<td>Bridle Path</td>
<td>0.70-1.0 2.60-3.0 5.50-6.0</td>
<td>8.24 7.44 8.28</td>
</tr>
<tr>
<td>Average $K_{sat}$</td>
<td>0.70-1.0 2.60-3.0 5.50-6.0</td>
<td>7.89 7.69 8.24</td>
</tr>
<tr>
<td>Average $K_{sat}$ for all depths ($\sigma$)</td>
<td></td>
<td>7.94 (0.84)</td>
</tr>
</tbody>
</table>

At Braunton, considering all three measurement depths $K_{sat}$ ranged from 6.80 m d$^{-1}$ to 10.50 m d$^{-1}$, with an overall mean of 7.94 m d$^{-1}$. The similarity of the average calculated values of $K_{sat}$ with depth (Table 4.15) emphasised the homogenous nature of the sand dune
aquifer. These $K_{sat}$ values were comparable to those quoted from other studies on European sand dune systems (Table 1.3), where $K_{sat}$ measurements ranged from 7.5-11.0 m d$^{-1}$ (Beukeboom, 1976; Clarke, 1980; Van Dijk and de Groot, 1987; Bakker and Neinhuis 1990; Jones 1993). $K_{sat}$ values greater than 3.0 m d$^{-1}$ are classified as very rapid draining by the FAO (1963).

The slug test results presented in Table 4.15 show that $K_{sat}$ values measured in J-Lane Slack were lower than the overall average for the system. Furthermore, at a depth of 5.5-6.0 m $K_{sat}$ was calculated as 6.80 m d$^{-1}$, which was the lowest $K_{sat}$ value recorded on the Burrows and therefore may indicate a change in the texture of the sediment not identified in Section 4.8.1.

The apparent homogeneity of the aquifer simplifies the parameterisation of the Braunton groundwater flow model in Chapter 7, but does not however, help in the explanation of the groundwater mounding along the eastern side of the system (Sections 4.1 and 4.2). The relatively uniform values of $K_{sat}$ (Table 4.15) suggest that the zone of lower permeability lies outside the experimental area to the east of the American Road. Access to this area was prohibited and therefore no slug tests measurements were undertaken.

### 4.8.4 $K_{sat}$ above the water table (well permeameter)

As described in Section 3.2.7b, the method used to determine $K_{sat}$ in situ without the presence of a water table was the simplified well permeameter developed by Talsma and Hallam (1980). The mathematical solution for the calculation of $K_{sat}$ using this technique is described in Appendix B.

As detailed in Section 3.2.6b the well permeameter experiment was carried out on the
dunes adjoining four of the detailed experimental sites, namely Cotton Slack, Round Slack, Horse Breakers Slack and J-Lane Slack (Figure 3.1). $K_{sat}$ was determined at the depth of 40-50 cm. The well permeameter $K_{sat}$ results are summarised in Table 4.16.

### Table 4.16

<table>
<thead>
<tr>
<th>Experimental site and auger hole number</th>
<th>$K_{sat}$ measurements at the dune base (m d$^{-1}$)</th>
<th>$K_{sat}$ measurements mid dune slope (m d$^{-1}$)</th>
<th>$K_{sat}$ measurements at top of dune (m d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.44</td>
<td>3.50</td>
<td>4.63</td>
</tr>
<tr>
<td>2</td>
<td>4.56</td>
<td>3.75</td>
<td>4.26</td>
</tr>
<tr>
<td>3</td>
<td>5.78</td>
<td>4.35</td>
<td>4.31</td>
</tr>
<tr>
<td>Round Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.54</td>
<td>4.31</td>
<td>4.38</td>
</tr>
<tr>
<td>2</td>
<td>5.82</td>
<td>5.10</td>
<td>5.84</td>
</tr>
<tr>
<td>3</td>
<td>4.25</td>
<td>4.85</td>
<td>4.14</td>
</tr>
<tr>
<td>Horse Breakers Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.43</td>
<td>4.44</td>
<td>3.98</td>
</tr>
<tr>
<td>2</td>
<td>5.00</td>
<td>4.87</td>
<td>4.34</td>
</tr>
<tr>
<td>3</td>
<td>4.55</td>
<td>5.39</td>
<td>4.56</td>
</tr>
<tr>
<td>J-Lane Slack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.44</td>
<td>3.77</td>
<td>6.33</td>
</tr>
<tr>
<td>2</td>
<td>4.89</td>
<td>3.85</td>
<td>12.57</td>
</tr>
<tr>
<td>3</td>
<td>3.88</td>
<td>4.86</td>
<td>5.20</td>
</tr>
</tbody>
</table>

The $K_{sat}$ values determined from the well permeameter experiments ranged from 3.50 m d$^{-1}$ to 6.33 m d$^{-1}$, with one extreme measurement of 12.57 m d$^{-1}$ (Table 4.16). Rabbit burrowing evident in the experimentation area was the probable cause of the extreme value of 12.57 m d$^{-1}$. Although the $K_{sat}$ values calculated from the well permeameter (Table 4.16) were generally lower than those calculated from the slug tests (Table 4.15) conductivities of between 3.50 m d$^{-1}$ and 6.33 m d$^{-1}$ are still classified as very rapid draining by the FAO (1963).

The difference in $K_{sat}$ values determined for below and above the water table may relate
to differences in the techniques adopted. The well permeameter technique has been consistently criticised for its underestimation of hydraulic conductivity (Talsma and Hallam, 1980; Bonell et al., 1983; Reynolds et al., 1983; Chappell, 1990). The most likely explanation was that this technique did not actually measure $K_{\text{sat}}$, but near saturated hydraulic conductivity as a result of air entrapment during the saturation of the material surrounding the auger hole (Reynolds et al., 1983). Although in this study a constant head was maintained in each of the auger holes the achievement of saturation in the dune sands was questionable and may therefore explain some of the variability between these two methods (Tables 4.15 and 4.16). A study by Bouwer (1966) showed that $K_{\text{sat}}$ was approximately twice that calculated in experiments which measured near saturated hydraulic conductivity. Also it should be noted that innovative changes were made to the standard well permeameter experiment, the auger hole was supported with a perforated liner (Section 3.2.6b). Therefore, some hydraulic resistance may have occurred as groundwater entered through the liner (Kruseman and de Ridder, 1977).

From field observations it was apparent that in the top 50 cm of the sand dune profile the amount and size of roots varied considerably. Variable rooting characteristics at each of the well permeameter experimental sites may therefore also explain some of the variability in the near saturated hydraulic conductivity results (Table 4.16).

Research by Bedinger (1961) showed that particle size distribution and packing had a considerable influence on hydraulic conductivity. However, the particle size analysis (Section 4.8.1) showed that the samples analysed at the site of the well permeameter experiments showed little spatial variability either with depth, or across the dune system.
4.8.5 Unsaturated hydraulic conductivity

Unsaturated dune sands have the ability to transmit water at rates several orders of magnitude lower than saturated sand. Research by Taylor and Ashcroft (1972) stated that when the water content of sand is reduced to field capacity moisture content, hydraulic conductivity commonly decreased to 1/100 or 1/1000 of its value at saturation. At Braunton, the dune ridges along the western side of the system form a large volume of unsaturated material (Figure 2.6). The lower rates of hydraulic conductivity associated with unsaturated dune sands will consequently influence the rate of groundwater recharge (Berger, 1992) and should be taken into consideration when simulating the Braunton groundwater system in VMODFLOW (Chapter 7). The rate of groundwater recharge is a function of the depth to the water table.

4.9 Conclusion

As stressed in Section 1.1, there is an apparent lack of research on the hydrology of sand dune systems in Great Britain. This chapter has therefore provided a detailed description and analysis of the hydrological characteristics of England's largest sand dune habitat, Braunton Burrows. The data presented in this chapter will be used in Chapter 5 when describing the long-term variability in the elevation of the water table at Braunton Burrows and in Chapter 7 when parameterising, and calibrating the groundwater flow model.

In Chapter 4, the hydrology of the system was investigated at three scales; the entire dune system; water table cross-sections and flow nets, and point observations. To explain the key hydrological characteristics described at each scale of investigation this chapter also evaluated the influence of effective precipitation, saline intrusion, the tide, the underlying geology and sediment properties on the functional hydrology of the system.
4.9.1 Characteristics of the water table

The groundwater system at Braunton was mounded. To the south of Sandy Lane Plain the groundwater mound was asymmetric. Maximum water table elevations were recorded closest to the inland boundary of the system. At each scale of investigation Braunton Marsh appeared to be partially controlling both the shape and elevation of the groundwater system. The most probable explanation was that along the eastern margin of the system in the transitional zone from dune sands to marshland, a zone of lower permeability was restricting lateral drainage and causing the groundwater system to mound. In comparison drainage to the sea was unrestricted, draining through dune sands of a comparatively higher permeability. The inland/seaward lateral drainage regime and the $K_{sat}$ of the dune and marsh sediments appeared to have more influence on the groundwater hydrology than the high dune ridges along the western margin of the system.

In the mounded Braunton groundwater system the volume of water percolating through the system increased from the centre to the margins (Willis et al., 1959a). Steeper gradients were therefore observed along the seaward margin where greater volumes of water move through the system. Towards the centre of the mound the gradients were less in order to maintain both the shape and elevation of the groundwater mound. Comparatively steeper hydraulic gradients were measured on the marshward side of the drainage system, probably as a result of the lower permeability of the transitional zone from sand dunes to marshland.

At Braunton the annual cyclical range of water fluctuations were typically less than one metre. The greatest water table fluctuations occurred near the centre of the groundwater mound. Towards the margins of the system water levels were replenished not only by areal recharge, but also by groundwater draining from higher elevations within the mound.

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When evaluating the relationship between the elevation of the water table and effective precipitation, water levels in the majority of observation wells were most significantly correlated with antecedent effective precipitation of the 91-120 day period.

4.9.2 Depth to bedrock or an impermeable basal layer

The geological logs from five boreholes revealed a compact, relatively impermeable, silty/clay layer beneath Braunton Burrows at approximately mean sea level. For the purpose of the research this layer was taken as the lower boundary of the groundwater system.

4.9.3 Saline intrusion and the influence of the tide on water table fluctuations

Considering the depth to the basal layer and the fresh water head in the most seaward observation wells saline intrusion was not a problem within the Braunton system.

In agreement with the earlier hydrological study on Braunton by Willis et al. (1959a), the tides were shown to have no effect on the elevation of the water table. This meant that the monthly water table data collected by the NC, the NCC and EN since 1972 could be used to both describe long-term trends in the elevation of the water table and to evaluate whether the system was drying out.

4.9.4 Physical characteristics of the dune sands

With the exception of bulk density the physical properties of the dune sands showed minimal variability both with depth and across the sampling field. The analysis of sediment for particle size distribution, both with depth and spatially within the dune system, showed that the dune sands formed a medium (250 μm-500μm) to fine grained (62 μm-250 μm) sand, with silt and clay fractions (<62μm) constituting less than 10.1 % of the sample volume. The slug test results gave an average $K_{sat}$ of 7.94 m d⁻¹, which according to the
FAO (1963) classification forms a very rapid draining medium. Although the well permeameter results gave lower measurements of $K_{sat}$ the results were still in the same order of magnitude. The apparent homogenous nature of the dune sands does not however, help in the explanation of the groundwater mounding along the eastern margin of the system. This suggested that the transitional zone from dune sands to marshland, of a comparatively lower permeability, was outside the sampling field to the east of the American Road. Alternatively an increase in silt and clay fractions occurred at depths below which samples were taken in the most inland sampling sites. The only sediment property to show any variability was bulk density, which would affect rates of groundwater recharge.
Chapter 5
Long-term variability in the elevation of the water table on Braunton Burrows
Chapter 5

Long-term variability in the elevation of the water table at Braunton Burrows

5.0 Introduction

Chapter 5 has been divided into two parts. The first part will describe the temporal variability in the elevation of the water table on Braunton Burrows. English Nature believe that in some parts of the dune system, water levels have fallen by one metre since the early 1980s (Wolton, pers. comm). Water table data collected on the Burrows will be invaluable in both describing the general water table trends from 1972 to 1995, and in determining whether the system has been gradually drying out, or whether the water table has fallen suddenly as a result of human mismanagement of the groundwater system. The possible causes for any identified trends in the long-term water table elevation data will also be discussed.

As described from the outset of this research (Section 1.3), preliminary analysis of the Braunton water table data stressed the importance of the adjoining Braunton Marsh drainage system in possibly influencing the elevation of the water table on the Burrows in the early 1980s. The second part of this chapter will therefore describe the hydrology and management of Braunton Marsh and in particular West Boundary Drain, which forms the inland boundary between the dune and marsh systems and was subject to major drainage improvement works in 1983. The hydrological description of West Boundary Drain will provide the essential data to accurately parameterise the inland boundary of the Braunton groundwater model (Chapter 7). Ultimately the model will be used to determine how water level management and the maintenance of West Boundary Drain may have influenced the groundwater drainage regime from the Burrows.
5.1 The changing hydrological regime at Braunton Burrows

In the 1992 management plan for Braunton Burrows English Nature expressed their concerns that the dune system was drying out (English Nature, 1992). Lower water levels were endangering the survival of many rare dune slack species (Table 2.4), which were dependent on a high water table throughout the year. After site visits to Braunton Burrows and much discussion with English Nature, and the Environment Agency possible causes for the apparent drying out of Braunton Burrows were identified and included climatic change, coastal erosion, scrub invasion and artificial drainage (Section 1.2.2).

For the purpose of this section data from 19 observation wells in the monitoring network were plotted from 1972-1995, to describe the temporal variability in the long-term elevation of the water table on Braunton Burrows and to evaluate whether the system was drying out. These observation wells provided the most complete monthly water table records since the start of monitoring in June 1972. The locations of these wells are shown on Figure 5.1. Some of the observation wells were only monitored up until June 1992, when the observation well network was revised (Section 3.2.3a).
To analyse the underlying trends in the long-term water table elevation data, the data were seasonally adjusted to eliminate the effects of the seasons (Chatfield, 1987). A 12 month moving average was then applied to the data. The elevation of the water table at Braunton is dependent upon precipitation as a primary source of groundwater recharge (Sections 4.1 and 4.2), therefore the long-term water table elevation data were directly related to monthly effective precipitation data. Effective precipitation was calculated as monthly precipitation totals minus losses through evapotranspiration (based on MORECS data). Effective precipitation is defined as that which actually recharges the groundwater system. In order to analyse the underlying trends in the long-term effective precipitation data, the values were seasonally adjusted and a 12 month moving average was applied to the data (Chatfield, 1987).
Analysis of the annual cyclical response of selected observation wells in Section 4.3 demonstrated that the annual range of water table fluctuations decreased from the centre of the groundwater mound to the margins of the system. At the margins of the system water levels were not only replenished by areal precipitation, but also by groundwater draining from higher elevations within the mound. Before analysing the water table elevation time series plots it was necessary therefore to divide the observation wells into groups, based on their geographical location within the groundwater drainage system (Figure 5.1). This would ensure that annual differences in water table fluctuations caused by location could be distinguished from those caused by long-term variability in effective precipitation, or human activity. The observation wells were divided into four groups;

1. **Group 1** - observation wells that were less than 350 m from the seaward edge of the fore dune ridge.

2. **Group 2** - observation wells that were less than 600 m from the seaward edge of the fore dune ridge.

3. **Group 3** - observation wells that were central within the dune system (greater than 600 m from the seaward edge of the fore dune ridge and more than 500 m from West Boundary Drain, or any tributary drainage ditches).

4. **Group 4** - observation wells that were located along the eastern margin of the system (less than 500 m from West Boundary Drain, or any tributary drainage ditches).

### 5.1.1 Group 1 observation wells

Observation wells that were less than 350 m from the seaward edge of the fore dune ridge included wells 10, 11, 15, 27, 42 and 58 (Figure 5.1). The long-term water table data for each observation well are presented in Figures 5.2-5.7.
Figure 5.2 Long-term (1972-1995) water table elevation data for observation well 10. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.3 Long-term (1972-1995) water table elevation data for observation well 11. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.4 Long-term (1972-1995) water table elevation data for observation well 15. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.5 Long-term (1972-1995) water table elevation data for observation well 27. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.6 Long-term (1972-1995) water table elevation data for observation well 42. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.7 Long-term (1972-1995) water table elevation data for observation well 58. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Observation wells 11, 15, 42 and 58 (Figures 5.3, 5.4, 5.6 and 5.7) responded similarly throughout the time series and emphasised the close relationship between the elevation of the water table and effective precipitation. The lowest water table elevations were recorded during the 1975/1976 drought. From late 1976, as effective precipitation increased, the elevation of the water table began to recover, but fell again between 1978 and 1980 as a result of a dryer period. The water table reached a maximum elevation in 1982, but from early 1983 through to the early 1990s the elevation of the water table showed a general overall decline, which appeared to be related to effective precipitation variability. English Nature believe that as a consequence of a changing hydrological regime since the early 1980s rare and unique species within the dune slacks have been lost, or are declining (Section 5.1). Therefore, a more detailed analysis of effective precipitation data was required to evaluate whether climate was the primary cause for the general overall decline in water levels, or whether other natural and human inferred causes had also contributing to the trend. The general decline in water levels from the early 1980s also coincided with the major drainage improvement works on West Boundary Drain and the reinstatement of field drainage ditches within 5 m of observation well 23, which will be discussed further in Section 5.2.5. It was essential to identify all the possible factors influencing long-term water table elevations in order to help prevent any future lowering of the water table on the Burrows.

Throughout the monitoring period long-term water table fluctuations recorded at observation well 27 were more pronounced (Figure 5.5). These greater fluctuations may be related to site specific characteristics, including the location of the well along a groundwater flow path, localised variability in the sediment properties and the effects of the surface vegetation. This well also responded very differently after the mid 1970s drought and the water table showed no signs of sustained recovery until 1980. In contrast,
all the other observation wells in this group began to recover in late 1976 with the increase in effective precipitation totals. The water table at observation well 27 declined from 1983 to 1986, to an elevation which was below that recorded during the exceptional drought conditions of the mid 1970s. Again this water table characteristic may be related to site specific characteristics, but on the other hand could indicate that other factors were also influencing water table elevations on the Burrows. From 1986 to 1995 water levels at observation well 27 showed a general overall rise, which was related to effective precipitation variability.

5.1.2 Group 2 observation wells

Observation wells less than 600 m from the seaward edge of the fore dune ridge included wells 7, 12, 13 and 14 (Figure 5.1). The long-term water table data for each observation well are presented in Figures 5.8-5.11.

Within group 2 there was some variability in the range of long-term water table fluctuations, which may be related to site specific characteristics including the location of the wells along a groundwater flow path, localised variability in the sediment properties and the effects of the surface vegetation.

The long-term water table elevation trends for observation wells 7, 12, 13, and 14 (Figures 5.8-5.11) were similar to those described in detail for group 1 observation wells (Section 5.1.1). Temporal variability in the elevation of the water table appeared to closely reflect long-term variability in monthly effective precipitation totals. Again from 1983 through to mid 1992 water levels measured in these wells demonstrated a general overall decline (Figures 5.8-5.11), which coincided with a decrease in monthly effective precipitation totals. However, other factors may have also contributed to this trend and will be identified
Figure 5.8 Long-term (1972-1995) water table elevation data for observation well 7. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.9 Long-term (1972-1995) water table elevation data for observation well 12. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.10 Long-term (1972-1995) water table elevation data for observation well 13. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.11 Long-term (1972-1995) water table elevation data for observation well 14. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
and discussed further in Section 5.2. At observation well 7 (Figure 5.8) the final rise in
the elevation of the water table from the summer of 1992 coincided with the increase in
effective precipitation.

5.1.3 Group 3 observation wells

Observation wells classed as central within the dune system included wells 2, 3, 6, 25, 37
and 38 (Figure 5.1). The long-term water table data for each observation well are
presented in Figures 5.12-5.17.

Again observation wells 2 (Figure 5.12), 3 (Figure 5.13), 37 (Figure 5.16) and 38 (Figure
5.17) showed similar long-term water table elevation trends to those described for the
majority of observation wells in groups 1 and 2 (Sections 5.1.1 and 5.1.2). Water table
elevation data from these wells also demonstrated the sensitivity of the system to variability
in effective precipitation. In contrast, observation wells 6 (Figure 5.14) and 25 (Figure
5.15) demonstrated more pronounced long-term water table fluctuations. The magnitude
of the fluctuations were in fact similar to those previously described for observation well
27 (Section 5.1.1 and Figure 5.5). The elevation of the water table in observation wells 6
and 25 did not show any sustained recovery from the mid 1970s drought until 1980,
whereas most other wells on the Burrows began to recover with the increase in effective
precipitation from the autumn of 1976. Again this was similar to the functioning of
observation well 27 (Section 5.1.1 and Figure 5.5). Furthermore, during the summer of
1986, 1989 and 1992 water levels recorded in observation wells 6 and 25 were at a similar
elevation or below those recorded at the height of the mid 1970s drought. Again this may
be related to the site specific characteristics, but however may also indicate that other
factors were influencing the long-term elevation of the water table. It should also be noted
that wells 6, 25 and 27 were located less than 500 m from each other, forming an east to
Figure 5.12 Long-term (1972-1995) water table elevation data for observation well 2. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.13 Long-term (1972-1995) water table elevation data for observation well 3. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.14 Long-term (1972-1995) water table elevation data for observation well 6. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.15 Long-term (1972-1995) water table elevation data for observation well 25. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.16 Long-term (1972-1995) water table elevation data for observation well 37. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.17 Long-term (1972-1995) water table elevation data for observation well 38. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
west transect across the dune system (Figure 5.1).

5.1.4 Group 4 observation wells

Observation wells in group 4 were located along the eastern margin of the dune system, within 500 m of West Boundary Drain or a tributary drainage ditch and included wells 1, 23 and 36 (Figure 5.1). The long-term water table data for each of these observation wells are presented in Figures 5.18-5.20.

Observation wells 1 (Figure 5.18) and 36 (Figure 5.20) displayed similar long-term water table elevation trends between 1972 and 1995 to those already described for the majority of observation wells in groups 1, 2 and 3 (Sections 5.1.1-5.1.3). However, one significant difference was that the water levels recorded in these wells began to show an overall decline from 1981 or 1982 (Figures 5.18 and 5.20). In comparison water levels measured in the majority of observation wells analysed in groups 1, 2, and 3 (Section 5.1.1-5.1.3) showed a general overall decline from early 1983, coinciding with the decrease in effective precipitation totals. Also water levels in observation well 1 fell below those recorded at the peak of the 1975/1976 drought during the summer of 1992. The long-term water table elevation trends for these wells will need to be considered alongside a more detailed analysis of effective precipitation data (Section 5.2.1) before determining what other factors may have influenced the long-term elevation of the water table.

The long-term water table elevation trends for observation well 23 (Figure 5.19) were very different. From 1972 to 1983 there was a gradual overall increase in the elevation of the water table, but suddenly in 1983 the water table fell. From the actual field data (Figure 5.19) a maximum drop in the elevation of the water table of 1.25 m was recorded. The water table began to recover in 1984 to a new equilibrium which was significantly lower
Figure 5.18 Long-term (1972-1995) water table elevation data for observation well 1. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

Figure 5.19 Long-term (1972-1995) water table elevation data for observation well 23. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)
Figure 5.20 Long-term (1972-1995) water table elevation data for observation well 36. (Location of the observation well is shown on Figure 5.1. Water table elevations are in metres above OD.)

than pre-1983 water levels. Again from 1984 to 1995 the elevation of the water table showed a slight overall increase. These long-term water table elevation trends were unique to this well. Human measurement error was ruled out, as monthly water table readings were taken by the same warden throughout the 1980s and the well was not moved (Breeds, pers. comm.). The initial drop in the water table coincided with a decrease in effective precipitation during the spring and summer months of 1983 (Figure 5.19), however at this time the Internal Drainage Board also carried out extensive drainage improvement works along the eastern margin of the system. The impact of the drainage improvements on the elevation of the Burrows water table will be analysed further in Section 5.2.5.

5.1.5 Discussion

The majority of observation wells on the Burrows demonstrated similar long-term water table elevation trends, that could be related to variability in effective precipitation totals,
although other natural and human inferred causes may also have been influencing the long-
term water table elevations. Of greatest concern was the general overall decline in the
elevation of the water table from the early 1980s through to mid 1992. English Nature
attribute changes in the hydrological regime since the early 1980s to the loss and decline
of nationally rare and protected dune slack species. A more detailed analysis of
precipitation and effective precipitation data was therefore required to determine exactly
how climate changed between 1972 and 1995 (Section 5.2.1). From the time series plots
it was difficult to differentiate between the controls of climate and other factors such as
scrub encroachment, marine erosion, and artificial drainage on the long-term elevation of
the water table. However, Section 5.2 will consider each of these factors in turn to
determine how they may have influenced the groundwater hydrology on the Burrows and
how they should be managed in the future to prevent further hydrological change.

5.2 Possible factors influencing the long term elevation of the water table

5.2.1 The impact of long-term changing climatic trends on the elevation of the water table
Section 5.1 has already shown how long-term trends in the elevation of the Burrows water
table mirror imaged long-term variability in monthly effective precipitation. This section
will therefore present a more detailed analysis of the climate data from 1972 to 1995, in
order to evaluate the significance of any long-term variability and to determine what
fluctuations in precipitation and effective precipitation occurred to contribute to the changes
in storage shown by the water table elevation time series plots (Figures 5.2-5.20).
Throughout this section LTA refers to the period 1972 to 1995.

The LTA annual total precipitation for Braunton was 878.3 mm. However, not all
precipitation that entered the system reached the groundwater table, some would have been
lost through the process of evapotranspiration. At Braunton Burrows Willis et al. (1959a)

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calculated that annually only 25-35% of precipitation reached the water table, the rest was lost through evapotranspiration. The analysis of long-term precipitation data from RAF Chivenor and MORECS evapotranspiration data for short grass showed that between 1972 and 1995 on average only 32% of annual precipitation recharged the water table. The calculated LTA annual effective precipitation for the site was 273.4 mm. This figure took no account of the greater evapotranspiration losses associated with scrub and tree species. Unfortunately annual evapotranspiration rates for the different vegetation types found on Braunton were not available, as discussed in Section 1.6.1. This is an area for potential future research, setting up long-term lysimeter experiments under different vegetation units.

In the dunes near Castricum, the Netherlands, such experiments have been running since 1941, describing the variability in evapotranspiration losses from a range of vegetation types during their growth and after reaching maturity (Stuyfzand, 1993).

Also the MORECS evapotranspiration rates used in the calculation of effective precipitation were averaged over a 40 x 40 km area around the study site (Thompson et al., 1981). With precipitation as a primary source of groundwater recharge these figures emphasised the sensitivity of the groundwater system to reductions in precipitation and increased evapotranspiration rates.

Figure 5.21 and Table 5.1 show that between 1972 and 1995 the driest years were recorded in the mid 1970s. In 1973, 1975 and 1976 annual precipitation totals were 21% (692.8 mm), 23.7% (670.7 mm) and 19% (711.7 mm) less than the calculated LTA. During these years below average precipitation, coupled with warm temperatures resulted in below average effective precipitation totals (Figure 5.22 and Table 5.2). In fact in 1975 Braunton only received 20.6 mm of effective precipitation, 92.5% less than the LTA. The repercussions on the elevation of the water table were prominent in all of the water table
Figure 5.21  Annual precipitation totals (1972-1995) for Braunton Burrows

Table 5.1  Annual total precipitation as a percentage of the LTA (1972-1995)
(The LTA annual precipitation is 878.74 mm)

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<td>5.7% &gt; (924.8 mm)</td>
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Figure 5.22 Annual effective precipitation totals (1972-1995) for Braunton Burrows.

Table 5.2 Annual effective precipitation as a percentage of the LTA (1972-1995).
(The LTA annual effective precipitation is 273.4 mm)

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<td>139% &gt; (654.1 mm)</td>
<td>92.5% &lt; (20.6 mm)</td>
<td>69% &lt; (84.6 mm)</td>
<td>54% &lt; (124.4 mm)</td>
<td>32% &lt; (186.1 mm)</td>
<td>25% &gt; (341.0 mm)</td>
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<td>444.08 mm</td>
<td>39.5% &gt; (139.5 mm)</td>
<td>39% &gt; (381.1 mm)</td>
<td>18% &lt; (224.9 mm)</td>
<td>19% &lt; (221.6 mm)</td>
<td>2% &lt; (269.7 mm)</td>
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<td>59% &gt; (434.1 mm)</td>
<td>72% &gt; (470.3 mm)</td>
<td>67% &lt; (91.5 mm)</td>
</tr>
</tbody>
</table>
time series plots presented in Section 5.1. With a break in the dry spell in the autumn of 1976 effective precipitation totals increased (Figure 5.22 and Tables 5.2), leading to a gradual recovery of water levels measured in the majority of observation wells on the Burrows. Between 1980 and 1982 the system experienced extreme opposite conditions and annual effective precipitation totals were between 39 % and 62 % above the LTA (Figure 5.22 and Table 5.2). However, in Section 5.2.4 it was shown that water levels recorded in observation wells 1 and 36 (Figures 5.19 and 5.21) started to fall during this wet period, perhaps indicating that other factors were controlling the elevation of the water table.

This wet period was short lived and in 1983 and 1984 effective precipitation totals were 18 % (224.9 mm) and 19 % (221.6 mm) respectively less than the LTA. Below average effective precipitation in these two consecutive years coincided with the start of the overall decline in water levels recorded in the majority of observation wells on Braunton Burrows. Between November 1985 and February 1986 effective precipitation was 55.2 % less (168.0 mm) than the seasonal LTA (375.2 mm). This may partially explain why water levels on the Burrows continued to fall until the late summer of 1986 (Figures 5.2-5.20). A comparison of effective precipitation totals in the mid 1970s with those recorded from 1983 to 1986 (Figure 5.22 and Table 5.2) would not however immediately explain why water levels in observation wells 6, 25 and 27 fell below those recorded at the height of the 1975/1976 drought. However, these wells also responded very differently after the break in the dry spell in the autumn of 1976 and did not shown any sustained recovery until 1980. The irregular characteristics of these wells were therefore more likely to be explained by site specific characteristics influencing the long-term functioning of the groundwater system. In eight of the years between 1983 and 1992 annual effective precipitation totals were between 2 % and 36 % less than the LTA (Table 5.2). The other two years 1986 and 1988 were comparatively wetter. In 1986 Braunton received 34 % (366.7 mm) more
effective precipitation than the LTA and in 1988 effective inputs to the system were 33 %
(364.4 mm) more than the LTA. Furthermore, as described by Marsh and Turton (1996),
from May 1990 to August 1992 England and Wales had the driest 28 month sequence on
record since 1850. Although there were several wet interludes during this period sustained
groundwater recharge did not occur until the autumn of 1992. This may partially explain
why water levels on the Burrows continued to show a general overall decline up until mid
1992. In fact, during the summer of 1992 water levels recorded in observation wells 1, 7,
6, 25, 27 and 38 were at a similar elevation or below those measured at the peak of the
mid 1970s drought. However, as previously discussed (Sections 5.1.2 and 5.2.3) the time
series plots for observation wells 6, 25 and 27 have displayed irregular long-term
fluctuations throughout their period of monitoring. A wet period occurred in 1993 and
1994 (Figure 5.21) and effective precipitation totals were 59 % (434.1 mm) and 72 %
(470.3 mm) respectively above the LTA. As described in Section 4.1 the winter of
1994/1995 was the wettest since 1869 (Marsh and Turton, 1996) and water levels recorded
in some of the dune slacks were the highest on record. Again this demonstrated the
sensitivity of the groundwater system to effective precipitation.

The sustained period of below average annual effective precipitation from 1983 to mid
1992 undoubtedly was a primary factor controlling water table elevations on the Burrows
and may also explain why in 1992 concerns were raised by English Nature that the system
was drying out and the composition and diversity of the wet slack habitat was changing.
However, marine erosion, scrub growth and artificial drainage systems may have also
contributed to the decline in the elevation of the water table and will therefore be
considered in Sections 5.2.2-5.2.5.
5.2.2 The impact of marine erosion on the elevation of the water table

As described in Section 1.4.5 marine erosion of the fore dune ridge may gradually alter the hydraulic gradient of the water table and the groundwater drainage regime. Studies by Bakker (1981) have shown that marine erosion has resulted in water levels falling by up to one metre in the fore dunes of the Dutch systems. In an inventory of sand dune systems in England, Radley (1994) stated that Braunton Burrows was a site experiencing net fore dune erosion. The dunes at Braunton will also suffer increased frontal erosion with the predicted relative rise in sea levels of 5 mm a\(^{-1}\) for south west England (Comber et al., 1993). From periodic observations made by the former warden on Braunton Burrows, it is also known that beach levels are constantly changing (Breeds, pers. comm.). No long term records of major storm events, or erosion rates have been kept at Braunton and therefore it was not possible to establish, with any degree of confidence, whether marine erosion had in any way contributed to the long-term water table elevation trends described in Section 5.1. From a management perspective it should be acknowledged that marine erosion is a natural ongoing process, which without human intervention in the form of high technology coastal defence schemes will gradually continue to alter the groundwater drainage regime.

However, marine erosion exacerbated by aggregate extraction can be managed. Research by Blackley et al. (1972) stated that marine erosion has affected the foreshore between Airy Point and Crow Point, Braunton Burrows (Figure 1.5) since the 1870s. This period is not dissimilar from that during which sand and gravel has been extracted from the Taw-Torridge Estuary (Section 1.4.4). Research showed that the general movement of sediment in this area was along the shore to replenish sand and gravel removed from near Crow Point (Figure 1.5). The effects of aggregate extraction from the Estuary may be more significant than realised, suggesting that future extractions will need to be managed...
and monitored closely to prevent any further loss, or damage to the dune habitat.

5.2.3 The impact of scrub invasion on the elevation of the water table

In the 1992 Braunton Burrows management plan, it was estimated that scrub species covered approximately 12% of the dune system (English Nature, 1992). Although Plates 5.1 and 5.2 were not taken from identical view points, they indicate the extent of vegetation change which has taken place between 1966 and 1996, with scrub species rapidly encroaching onto the dune habitat. In 1966 the system appeared more mobile with greater areas of bare sand and much less scrub growth.

As described in Section 1.6.1, scrub species such as willow have much higher evapotranspiration rates than grasses and low level shrubs. With the encroachment of scrub species since the outbreak of myxomatosis in 1954, English Nature have been concerned that increased evapotranspiration losses may be contributing to lower water levels on the Burrows. As described in Section 5.2.1 precipitation is the primary input to the system and with a LTA (1972-1995) annual effective precipitation of only 273.4 mm (calculated from MORECS evapotranspiration data for short grass) additional losses through increased evapotranspiration rates, associated with scrub encroachment would be detrimental to an already finely balanced groundwater system.

An increase in scrub growth on the Burrows since the mid 1950s has therefore possibly caused a gradual, but progressive lowering of the water table. However, from the time series plots presented in Section 5.1 it was not possible to determine the extent to which scrub growth has contributed to the long-term variability in the elevation of the water table. The best means of determining the effects of scrub encroachment on the hydrology of Braunton Burrows is through the use of a groundwater flow model (Chapter 7).
Plate 5.1 Scrub growth on Braunton Burrows (August 1966)
(Photograph taken facing north east towards the coast)

Plate 5.2 Scrub growth on Braunton Burrows (March 1996).
(Photograph taken in the vicinity of observation well 1 (Figure 5.1) facing west.)
5.2.4 The impact of the golf course drainage system on the elevation of the water table

Drainage of Saunton golf course was identified as a further possible factor influencing water levels on the Burrows. As far back as the semi-quantitative hydrological description of Braunton Burrows by Willis et al. (1959a) concerns were expressed that the artificial drainage system was lowering the elevation of the water table within the northern part of the system. The golf course drainage system was in excess of 2 km from any of the water table monitoring sites. The closest transect of observation wells (1N-6N, Figure 3.2) were only installed in June 1992. Therefore, from such a relatively short run of water level data it was not possible to evaluate the long-term impact of the golf course drainage system on the elevation of the water table. This section will therefore identify ways in which the present management of the drainage system may have repercussions on the elevation of the Burrows water table.

No new drainage ditches have been dug since the completion of the golf course in 1908 (Stephens, pers. comm.). The main drainage channel is less than 1 m wide, but up to 2 m deep. In the winter months the tile drains and the drainage ditch prevent widespread flooding. Evidently the golf course is managed to cater for the seasonal requirements of the golfers and to the possible detriment of nature conservation. The discharge of the golf course drainage ditch at its entrance into Braunton Marsh was quantified on ten separate occasions during the hydro-metric surveys of both January 1995 and 1996 (Section 3.2.10) and ranged from 50-100 l s⁻¹, depending upon antecedent weather conditions. In effect these drainage waters were a net loss from the system. During the hydro-metric surveys of both July 1994 and 1995 the golf course ditch at its entrance onto Braunton Marsh was dry.

In the summer of 1995 the golf club deepened and widened parts of the drainage system, in order to prevent the recurrence of widespread flooding that prevented golfers playing on
certain tees and greens during the winter of 1994/1995. Incidentally the winter of 1994/1995 was described as the wettest winter on British records since 1869 (Marsh and Turton, 1996) and water levels across the whole of the Burrows were exceptionally high (Breeds, per. comm.). The extent of the surface flooding on the golf course was therefore an exceptional random occurrence. Water levels in the ditch are not managed and therefore in such a highly permeable aquifer changes to the channel geometry will undoubtedly have repercussions on the elevation of the water table in this part of the system and in the longer term possibly affecting a wider area of the Burrows groundwater system. Such drainage improvements would also possibly jeopardise the survival of the dune slack habitat, which is dependent on a high water table throughout the year. Careful management of this area is required to prevent any future possible lowering of the water table, but at the same time the seasonal requirements of the golfers must be considered.

In a site visit to Saunton golf course during the winter of 1995 it was evident that some of the surface flooding was the result of compaction. Future management options to alleviate such problems will be addressed in the final management recommendations (Section 8.4.1).

In the summer months the greens and tees are irrigated using rain water from a purpose built storage reservoir, which is not hydraulically connected with the dune aquifer.

5.2.5 The impact of the drainage improvement works on Braunton Marsh on the elevation of the water table within Braunton Burrows

The deepening of West Boundary Drain and the reinstatement of field drainage ditches on the land adjacent to observation well 23 were identified as further possible contributing causes for the decline in water levels on the Burrows. These drainage improvements were
carried out during the spring and summer months of 1983.

Group 4 observation wells (wells 1, 23 and 36) were the closest to the drainage improvements (Figure 5.1) and would therefore be expected to show the greatest response to changes in the drainage regime along the eastern margin of the system. As described in Section 5.1.4 analysis of the long-term water table elevation data for observation well 23 identified trends that were unique to this well. The most prominent characteristic was the sudden drop in the water table in 1983 (Figure 5.19), which coincided with the deepening of West Boundary Drain and the reinstatement of field drainage ditches with 5 m of observation well 23. Also, both prior and after the sudden drop in the elevation of the water table at observation well 23 (Figure 5.19) water levels showed a general overall increase, which could be related to the decreasing efficiency of the field drains, as with time they become blocked with sediment and aquatic weed growth.

Observation wells 1 and 36 were also within 500 m of West Boundary Drain. However, analysis of the long-term water table elevation data from these wells (Figures 5.18 and 5.20) did not show the same dramatic drop in 1983. This emphasised the importance of the reinstatement of the field drainage ditches in controlling the elevation of the water table in the vicinity of well 23. In fact the long-term water table elevation data for observation wells 1 (Figure 5.18) and 36 (Figure 5.20) showed that the general overall decline in the water table through the 1980s and into the early 1990s began prior to the commencement of the drainage improvement works. This suggested that other factors were influencing the elevation of the water table at observation wells 1 and 36.

Although the general decline in the elevation of the water table recorded on the Burrows from 1983 coincided with a decrease in effective precipitation (Section 5.1), this trend may
have been exacerbated by changes in the drainage regime along the eastern margin of the system. The impact of these drainage improvements on the elevation of the Burrows water table would have depended upon the hydraulic connection between the dune and marsh systems. The hydraulic connection between the two systems was questioned throughout Sections 4.1 and 4.2, when contour plots, flow nets and cross-sections suggested that the inland drainage regime was being restricted, causing the groundwater system to mound along the eastern margin of the system. The hydraulic connection between these two systems and the impact of deepening West Boundary Drain on the elevation of the water table will be investigated further in Chapter 7, through the use of VMODFLOW. The model will be used to gain a better understanding of how this part of the groundwater system functions and ultimately will also be used in the final recommendation of sustainable water level management options for West Boundary Drain.

5.2.6 Concluding comments

Long-term variability in effective precipitation appeared to be the single most important factor controlling the elevation of the water table on the Burrows. However, other factors such as scrub encroachment, artificial drainage and marine erosion have also possibly contributed to the long-term water table elevation trends described in Section 5.1. Although the general overall decline in the elevation of the water table from the early 1980s reflected a decrease in effective precipitation totals, this decline also coincided with the drainage improvement works on Braunton Marsh. In Chapter 7 VMODFLOW will be used to examine further the effects of the drainage improvements and scrub encroachment on the elevation of the water table within Braunton Burrows.
Part 2 - Braunton Marsh

5.3 An introduction to Braunton Marsh

The interpretation of the Braunton water table elevation time series plots, identified the importance of Braunton Marsh and in particular West Boundary Drain in influencing the groundwater drainage regime from the Burrows (Section 5.2.5). The second part of this chapter will therefore describe and explain the hydrology and geometric characteristics of West Boundary Drain as part of the larger Braunton Marsh land drainage system. The plans of the 1983 West Boundary Drain improvement scheme will also be presented and discussed. Ultimately the Braunton Marsh data will be used to calibrate the eastern boundary of the groundwater model and to predict the consequences that changes in the base elevation of West Boundary Drain will have on the groundwater drainage regime from the Burrows (Chapter 7).

5.3.1 The hydrology and management of Braunton Marsh

The Internal Drainage Board (IDB), an independently elected local drainage authority, have the statutory duty on Braunton Marsh to control and maintain the drainage regime, including that of West Boundary Drain. The IDB have a duty under section 48 of the Wildlife and Countryside Act 1981 and the Water Acts of 1973 and 1989 to exercise their function in a way in which to further the conservation and natural beauty of the area (Slade, pers. comm.). Before carrying out any maintenance works that could be harmful to the conservation value of the surrounding area the IDB must consult with English Nature.

The drainage ditches on Braunton Marsh vary in depth and width, depending upon the discharge which needs to be removed from certain parts of the system. The majority of the ditches are less than 2.5 m wide at water level. The main exception is Sir Arthur's Pill
(Figure 5.23), which is a mained river and in places is up to 5 m wide. During the summer months the ditches are used as wet fences and water levels are penned at a maximum height to prevent groundwater drainage from the fields. During the hydro-metric surveys of 1994 and 1995 (Section 3.2.10) the depth of water in the ditches ranged from 0.3 m to 2.0 m. In the winter months the main purpose of the ditches is drainage. Water levels are therefore kept at a minimum to avoid flooding and to encourage grass growth for the following summer's grazing requirements. The winter season is therefore the time when maximum drainage from the land occurs.

Water levels within the drainage system are controlled by a series of sluices managed by the IDB. The main inputs to the system are from the River Caen at Velator Bridge and Sir Arthur's Pill (Figure 5.23), both of which are sluice controlled. Inputs to the system from these sources vary from summer to winter, as described in Sections 5.3.2a and 5.3.2b. Water leaves the system via the Great Sluice (Figure 5.23), which is controlled by the IDB, but maintained by the Environment Agency. The Great Sluice is controlled according to the time of year to maintain certain ditch water levels throughout the system.
Figure 5.23  Braunton Marsh land drainage system.
(Chainage measurements refer to Figure 5.26.)
5.3.2 Seasonal drainage characteristics

In order to model the eastern margin of the marsh drainage system and ultimately recommend sustainable hydrological management options to prevent any further possible lowering of the water table on Braunton Burrows, it was essential to have a comprehensive understanding of the drainage regime of the entire system, but in particular focusing upon the seasonal variability in the management of water levels in West Boundary Drain. As described in Section 3.2.10, to compare and contrast summer and winter discharge characteristics a hydro-metric survey was carried out in July 1994 and January 1995. Furthermore, to ensure that these surveys provided representative data the measurements were repeated in July 1995 and January 1996.

The discharge rates calculated in the two summer hydro-metric surveys were similar and so were the measurements from the two winter surveys. Braunton Marsh is a managed system and therefore antecedent weather conditions have less effect on the drainage regime because the IDB sluice control the system to ensure that penning levels are constantly maintained. The following description of the seasonal drainage characteristics of Braunton Marsh are based upon measurements and observations from the July 1994 and January 1995 surveys, which were representative of typical summer and winter drainage regimes.

Figures 5.24 and 5.25 show that there were unexplained losses and gains in discharge measured within the drainage system. This was attributed to the geometry of the channel and the gradient of the bed, which caused drainage waters to pond, or back-up in certain sections of the ditch network.

a) Summer drainage characteristics

The summer drainage ditch penning levels are in force from March to October. The main
input to Braunton Marsh during the summer is from the River Caen at Velator Bridge (Figure 5.24). The flow divides to the north of the Toll House, with the northern part of Boundary Drain feeding both the ditch network of the Inner Marsh and Sir Arthur's Pill, which is the second major input to the system (Figure 5.24). The sluice on Sir Arthur's Pill at its entrance into the system (Figure 5.24) is controlled by the IDB. In the summer months the sluice is closed, so that water ponds behind the sluice and feeds into West Boundary Drain (Plate 5.3). This appeared to be the main input to West Boundary Drain during the summer months. Careful management of the sluice is therefore critical to water levels in West Boundary Drain. As suggested in Section 5.2.5 water levels in West Boundary Drain may be hydraulically connected with the groundwater drainage regime of the higher-lying sand dune system and will be investigated further with the use of the groundwater model in Chapter 7. If the sluice is raised during the summer months water would take the most direct route increasing the discharge of Sir Arthur's Pill and at the same time starving West Boundary Drain of its major water supply.

b) Winter drainage characteristics

The winter drainage ditch penning levels are in force from October to March. The discharge and flow regime are very different on Braunton Marsh during the winter months (Figure 5.25). All the sluices are left open in order to retain minimal drainage waters within the system. Sir Arthur's Pill, a mained river is the main input to the marsh, but with the exception of feeding the Inner Marsh Pill the discharge of this river flows straight through the system and out into the Taw-Torridge Estuary via the Great Sluice (Figure 5.25).

As a consequence of managing the system to allow maximum drainage, during the hydro-metric surveys of both January 1994 and 1995, stretches of West Boundary Drain contained less than 5 cm of water. Low ditch water levels within West Boundary Drain would not
only effectively prevent surface flooding of the surrounding agricultural land, but would also possibly affect the groundwater drainage regime from the adjoining sand dune system.

The impact of water level management in West Boundary Drain on the Burrows water table will be investigated further with the aid of the groundwater flow model in Chapter 7.

Plate 5.3 Sluice controlling Sir Arthur's Pill to supply water to West Boundary Drain. (Dashed arrows on Sir Arthur's Pill and West Boundary Drain indicate direction of flow.)
Figure 5.24 Discharge from the Braunton Marsh system in July 1994.
Figure 5.25 Discharge from the Braunton Marsh system in January 1995.
5.3.3 The West Boundary Drain improvement scheme

The deepening of West Boundary Drain was identified as a possible contributing cause for the decline in water levels measured on the Burrows from the early 1980s. This section will therefore describe both the extent of the drainage improvements and the present day characteristics of the channel. The data presented in this section will be used to parameterise the eastern boundary of the groundwater flow model (Chapter 7).

Drainage improvement works during 1983 were carried over a 3.5 km stretch of West Boundary Drain (Figure 5.23 and 5.26). The aim of the scheme was to achieve a bed gradient of 1:400 m, which would increase the drainage efficiency of the channel during the winter months, when the rapid removal of discharge was essential to avoid surface flooding. A smooth regular channel would carry up to three times the discharge of a channel of a similar cross-sectional area and gradient, with an irregular bed profile and choked with plant growth (Linsley et al., 1975).

To obtain a bed gradient of 1:400 m the lower reaches of West Boundary Drain, between chainage 13.00 and 28.25 hundred metres, were substantially deepened (Figure 5.26). In sections of the channel almost one metre of sediment was removed. The plans do not indicate whether the channel was widened at the same time. In a report to the nature Conservancy Council, Breeds (1983) described how the deepening of West Boundary Drain in the summer of 1983 had caused subsequent slumping of the ditch sides and further material had to be excavated until the channel was stable. The plans shown in Figure 5.26 are therefore only an indication of the extent of the improvement works that were carried out.
West Boundary Drain

Figure 5.26  Cross-section of the West Boundary Drain improvement scheme.
Annual maintenance of West Boundary Drain is carried out mechanically and although the intention of the IDB is only to remove aquatic weed growth and sediment accumulations from the channel bed a site visit to Braunton Marsh in March 1995 suggested otherwise. Blue lias clay and shell fragments had been scraped from the bottom of the channel, showing how the use of mechanical machinery for ditch maintenance was unintentionally deepening and widening the drain. Depending on the hydraulic connection between the two systems further changes to the channel geometry could be detrimental to water table elevations on the Burrows, as discussed further in Chapter 7.

A detailed EDM survey of the geometry of West Boundary Drain in July 1994 (Section 3.2.4) showed that the channel became progressively deeper along its course south. From the top of the channel bank to bed level depths ranged from 1.3-2.5 m. The lower sections of West Boundary Drain were the deepest having been extensively altered during the 1983 drainage improvement works. The maximum depth of water in West Boundary Drain was measured during the summer surveys (July 1994 and 1995) and ranged from 0.45-0.70 m. In effect therefore, water levels were up to 1.8 m below bankfull stage. In the winter surveys (January 1995 and 1996) the maximum recorded depth of water in any one cross-section of the channel was 0.35 m. From the preliminary analysis of the channel cross-sections, together with a consideration of maximum recorded seasonal water depths in the drain, it would appear feasible to sluice control the channel and raise ditch water levels throughout the year. This would help reduce groundwater drainage losses from the adjoining Braunton Burrows system. Such future management strategies will be explored further using the groundwater model in Chapter 7. Water levels in West Boundary Drain should be carefully managed to cater not only for the needs of nature conservation, but also other land users.
5.4 Conclusion

The first part of Chapter 5 described the temporal variability in the elevation of the water table on Braunton Burrows from 1972-1995. Identified trends in the data were related to possible causes, which included changes in the climate, marine erosion, scrub growth and artificial drainage. A detailed account of the hydrology and management of West Boundary Drain as part of the wider Braunton Marsh land drainage system was included in the second part of this chapter, in order to understand how changes in the drainage regime may have affected groundwater levels on the Burrows. The hydrology and geometry data from West Boundary Drain will also be used to parameterise the eastern boundary of the groundwater model in Chapter 7.

Analysis of the water table data from Braunton Burrows (1972-1995) demonstrated that the long-term variability in the elevation of the water table was closely related to variability in effective precipitation. A prominent trend in the water table data was the general overall decline in the elevation of the water table from 1983. English Nature attribute a changing hydrological regime from the early 1980s to the loss and decline of nationally rare and protected species from within the wet slack habitat. With precipitation as the primary source of groundwater recharge a LTA (1972-1995) annual effective precipitation total of 273.4 mm emphasised the sensitivity of the system to reductions in precipitation and increased rates of evapotranspiration and also highlighted the significance of the dry spell between 1983 and 1993, when in eight of the ten years effective precipitation totals were below the LTA. Climate was identified as the primary factor controlling the long-term elevation of the water table on Braunton Burrows.

Although the general overall decline in the water table from early 1983 coincided with a decline in effective precipitation totals this was also the time when the Internal Drainage Board...
carried out extensive drainage improvement works on West Boundary Drain and reinstated field drainage ditches on the marshland within 5 m of observation well 23. The general decline in water levels on the Burrows from 1983 may therefore have been exacerbated by changes in the drainage regime along the eastern margin of the system. Undoubtedly the sudden drop in the elevation of the water table at observation well 23 in 1983 was related to the reinstatement of the field drainage ditches. Water levels at well 23 fell by 1.25 m, recovering in 1984 to a new equilibrium significantly lower than pre-1983 water table elevations. This was the only well in the monitoring network to show such a dramatic change in the overall elevation of the water table.

A long-term average (1972-1995) annual effective precipitation total of 273.4 mm emphasised the sensitivity of the system to additional losses through other natural and human inferred causes such as marine erosion, scrub growth and artificial drainage. Undoubtedly drainage improvements and an increase in scrub coverage since the outbreak of myxamotosis in 1954 have contributed to lower ground water levels on the Burrows. Marine erosion of the fore dune ridge and changing beach levels may have also altered the groundwater drainage regime. From the time series plots of seasonally adjusted water table elevation data it was difficult to differentiate between the controls of climate and these factors on the long-term elevation of the water table. The impact on the elevation of the Burrows water table of drainage improvements and scrub encroachment will be investigated further with the use of VMODFLOW in Chapter 7.
Chapter 6
The hydrological characteristics and functioning of the groundwater systems at Northam Burrows and Dawlish Warren
Chapter 6

The hydrological characteristics and functioning of the groundwater systems at Northam Burrows and Dawlish Warren

6.0 Introduction

Chapter 6 describes the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Northam Burrows and Dawlish Warren respectively. The hydrology will be investigated at three scales; firstly considering the general hydrological characteristics of the entire dune system; secondly at a more detailed scale analysing the water table characteristics from cross-sections and flow nets, and thirdly evaluating the degree of spatial variability in the annual cyclical response of selected dipwells.

At both Northam and Dawlish to explain the key hydrological characteristics described at each scale of investigation the influence of site specific physical characteristics including effective precipitation, the underlying geology, saline intrusion, the tide and sediment properties will be considered. Characteristics of these parameters will also be compared with those already described for the larger Braunton dune complex.

Prior to the start of this research (October 1993) groundwater levels were not monitored at Northam or Dawlish (Section 3.2.3b). Therefore, it was not possible to determine whether there has been any long-term change in the elevation of the water, if the systems have been gradually drying out, or if water levels have suddenly fallen as a result of human mismanagement of the groundwater systems. In this chapter trends in weekly water level data (October 1993-April 1996) will be analysed to detect possible factors influencing annual cyclical water table fluctuations. Recommendations put forward in the Northam Burrows management plan (Devon County Council, 1993) for increasing water levels on
the Burrows will also be evaluated (Sections 6.9.1a-6.9.1e). As demonstrated throughout this chapter the scale of the hydrological investigation at both Northam and Dawlish was less detailed than at Braunton.

Part 1 - Northam Burrows

6.1 General hydrological characteristics

At the largest scale of investigation the hydrological characteristics of the entire dune system were considered. The first part of this section relies primarily on field observations since the start of the research in October 1993, combined with anecdotal evidence to briefly describe the general hydrological functioning of the system. The second part of this section describes the seasonal characteristics of the groundwater system from the construction of two dimensional water table contour plots (Section 6.1.2).

Figure 6.1 has been included because the following hydrological description of Northam Burrows consistently refers to sampling sites, specific locations and features within the system.

6.1.1 A hydrological description of Northam Burrows

At Northam, there are a number of key factors which may contribute to a very different hydrological regime than that already described for the Braunton system. The only dune slack at Northam covers an area approximately 40 x 40 m around dipwell 6 (Figure 6.1). In contrast, at Braunton approximately 15% of the 1,350 ha dune system has been mapped as dune slack. The dune slack at Northam contains the water germander (*Teucrium scordium*), which is a particular rarity and protected species (Section 2.7). If the perceived drying out of the Northam system continues then this only area of slack habitat may be lost.
Drainage channel cleared annually by machine up until 1994

Figure 6.1 Sampling sites and the physical characteristics of Northam Burrows.
At Northam the volume of unsaturated sand is considerably less than at Braunton, which may lead to very different water table response characteristics and will be considered further in Section 6.4. Also, in contrast to Braunton the smaller hydrological system at Northam has been extensively altered by human activity. Surface flooding on the coastal plain is controlled by an artificial drainage system (Figure 6.1), installed for the benefit of the golfers and graziers and to the possible detriment of nature conservation. The northern part of the site has been used as a landfill (Figure 6.1) and the construction of the landfill access road has prevented tidal inundation (Section 6.9.1e). The extent of human intervention on this site may therefore lead to very different annual cyclical water table characteristics than those already described for the larger Braunton system.

Additional inputs to the system, which cannot be easily quantified, include tidal waters breaching the pebble ridge and groundwater draining from the surrounding higher land. A domestic supply of water is also used to irrigate the golf course greens and tees during the summer months. Storm drains from the built up areas of Northam and Westward Ho! once drained down onto the Burrows, but with continued residential development they have been diverted.

6.1.2 **Short term hydrological characteristics of the groundwater system; based on seasonal water table contour plots**

The dipwell network at Northam provided the spatial water table elevation data required to construct the SURFER water table contour plots, using the same method as described in Section 4.1.2. Preliminary analysis of the dipwell data identified irregular water table fluctuations at dipwell 11. The data from this well were therefore not used in the interpolation of water table elevations. A problem encountered when constructing the contour plots was that even the most detailed site maps (Ordnance Survey 1:2,500) did not
identify mean sea level, which was required as a datum to represent approximately zero water table elevation (Section 4.1.2). With no indication of mean sea level the most feasible option to create a base level on which to build the contour plots was to assign an estimated water table elevation to the High Water Mark (HWM), which undoubtedly incurred a degree of error, either over or under estimating the elevation of the water table. Despite this possible interpolation error, the contour plots still provided an indication of the hydrological characteristics and functioning of the Northam groundwater system. Contour plots were constructed for February 1995 and September 1995, to compare with the seasonal water table characteristics already described for Braunton Burrows (Section 4.1.2 and Figures 4.3 and 4.4). In this section LTA refers to the period 1972 to 1995. The contour plots (Figures 6.2 and 6.3) illustrate the extreme conditions of the system, with the February 1995 plot following the wettest winter recorded in Britain since 1869 (Marsh and Turton, 1996). The months of October, November and December 1994 and January 1995 received 43% more effective precipitation (418.4 mm) than the LTA. In comparison, the September 1995 plot followed a drought summer with the months of May to August receiving 232% less effective precipitation (-310.6 mm) than the LTA.

The water table contour plots cover all of the dune system north of the main Burrows access road (Figure 6.2). South of the Burrows access road the absence of water level monitoring sites (Figure 6.1) prevented the accurate interpolation of water table elevations.

6.1.2a Interpretation of the contour plots
Both the winter (February 1995) and summer (September 1995) contour plots illustrate a similar radial contour pattern (Figures 6.2 and 6.3). The water table contours run parallel to the seaward boundary curving around Greysand Hill before running parallel to the Skern.
Figure 6.2 Contour plot of the water table at Northam Burrows, February 1995. (Contour elevations are in metres above OD. Cross-sections refer to Figures 6.4-6.6.)
Figure 6.3  Contour plot of the water table at Northam Burrows, September 1995. (Contour elevations are in metres above OD. Cross-sections refer to Figures 6.4-6.6.)
The water table contours therefore follow a similar pattern to those described at Braunton (Section 4.1.2 and Figures 4.2-4.6), forming a groundwater mound.

In February 1995, following the exceptionally wet winter of 1994/1995 the groundwater mound reached a maximum elevation of 5.5 m. The area of localised increased water table elevation in the vicinity of Sandymere was most probably an artefact of the water table interpolation routine (Figure 6.2). As a consequence of the warm and dry conditions that prevailed during the summer of 1995 groundwater drainage by far exceeded inputs to the system and by September 1995 the top of the groundwater mound had decayed by one metre. Therefore, similar to the functioning of the groundwater system at Braunton the contour plots at Northam (Figures 6.2 and 6.3) illustrated the close relationship between effective precipitation and the elevation of the water table.

6.2 Characteristics of the Northam groundwater system from cross-sections and flow nets

Cross-sections and flow nets were derived from the water table contour plots (Figures 6.2 and 6.3) to describe the shape, elevation and gradient of the water table.

6.2.1 Characteristics of the water table from cross-sections

Two cross-sections from east to west were examined (Figures 6.4 and 6.5). The cross-sections were located to identify any spatial variability in the form and seasonal functioning of the groundwater system. A third cross-section was included to evaluate the drainage characteristics northwards from the centre of the groundwater mound.

Graphical representation of the cross sections (Figures 6.4-6.6) incurred a large vertical exaggeration, which will become apparent when describing the hydraulic gradients in
Section 6.2.2. These water table profiles (Figures 6.4-6.6) only give an indication of the shape and functioning of the groundwater system, because of the uncertainty surrounding the exact location of the 0 m water table elevation contour (Section 6.1.2).

The surface topography of Northam Burrows has not been mapped before. Therefore, in order to relate the shape and elevation of the water table at cross-sections A, B and C to the surface terrain, a topographical contour map of Northam was created using spot heights from an EDM survey (Section 3.2.4). These data were then put into SURFER.

6.2.1a Interpretation of the cross-sections

For cross-sections A and B, the winter (February 1995) and summer (September 1995) water table profiles follow the general shape of the surface topography, forming a groundwater mound (Figures 6.4 and 6.5). The water table at cross-section C also closely followed the shape of the surface topography, forming a groundwater wedge, because this cross-section only extended inland for 1,800 m, to the 3.5 m or 4.5 m contour (Figure 6.6).

Figures 6.4-6.6 illustrate how the whole groundwater system fluctuated from winter to summer, emphasising the importance of effective precipitation as a primary source of groundwater recharge. These plots were not accurate enough to describe seasonal water table fluctuations at the extreme margins of the system, because of the uncertainty in assigning an estimated water table elevation to the HWM. However, at more central locations within the groundwater system following the exceptionally wet winter of 1995, the water table was above or within 0.50 m of the ground surface. With a decrease in monthly recharge and an increase in evapotranspiration losses, by September 1995 the water table at these sites was generally in excess of one metre from the ground surface.
Figure 6.4  Cross-section A; the shape and elevation of the water table.  
(Location of cross-section A is shown on Figures 6.2 and 6.3.)

Figure 6.5  Cross-section B; the shape and elevation of the water table.  
(Location of cross-section B is shown on Figures 6.2 and 6.3.)
Seasonal water table fluctuations will be investigated further in Section 6.3 when describing the hydrological characteristics of individual dipwells.

6.2.2 Hydraulic gradients calculated from flow nets

Hydraulic gradients at Northam were calculated from flow lines, inserted at right angles to the water table contours (Figures 6.7 and 6.8). The calculated hydraulic gradients in Tables 6.1 and 6.2 should only be interpreted as probable indicators of the groundwater drainage characteristics, because of the uncertainty surrounding the use of the HWM as a datum (Section 6.1.2). For the same reason the hydraulic gradients at the margins of the system were not considered separately.
Figure 6.7 February 1995 flow net for Northam Burrows. (Contour elevations are in metres above OD. Flow line identification labels refer to Tables 6.1 and 6.2.)
Figure 6.8 September 1995 flow net for Northam Burrows. (Contour elevations are in metres above OD. Flow line identification labels refer to Tables 6.1 and 6.2.)
a) Hydraulic gradients on the seaward side of the groundwater system

Average hydraulic gradients on the seaward side of the groundwater system from the highest water table contour (4.5 m or 5.5 m) to the 1.0 m contour ranged from 1.14 m per 100 m in February 1995 to 0.80 m per 100 m in September 1995 (Table 6.1).

As described for Braunton (Section 4.2.2), the difference between the February 1995 and September 1995 hydraulic gradients emphasised the sensitivity of the system to effective precipitation. In the exceptionally wet winter months leading up to February 1995, greater inputs to the groundwater system increased the elevation of the water table and steepened the hydraulic gradients, thus increasing groundwater drainage and regulating both the shape and elevation of the water table. Throughout the summer months the opposite hydrological processes occurred and drainage losses exceeded effective recharge, causing the water table to fall. In turn this lead to lower hydraulic gradients and reduced further drainage losses from the system (Table 6.1).

On the seaward side of the drainage divide average hydraulic gradients calculated for February 1995 (Table 6.1) were steeper than those measured for the same month at various locations within the Braunton system (Tables 4.2-4.5). In September 1995, with the exception of the hydraulic gradients observed at the extreme margins of the Braunton system, again the average calculated hydraulic gradients at Northam were steeper than those measured at Braunton. The steeper hydraulic gradients at Northam were possibly partially a result of the interpolation plotting routine, but however may also reflect the importance of sediment properties in controlling the hydrological functioning of the groundwater system. An increase in silt and clay fractions for example, would reduce the $K_{sat}$ of the medium and under the principle of Darcy's Law would increase the hydraulic gradient of the water table in order to maintain groundwater flow and regulate both the shape and
Table 6.1  Hydraulic gradients on the seaward side of the groundwater system from the highest water table contour (4.5 m or 5.5 m) to the 1.0 m contour. (Hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 6.7 and 6.8). Flow line identification labels refer to Figures 6.7 and 6.8. LTA refers to 1972-1995.)

<table>
<thead>
<tr>
<th>Location of flowlines (refer to Figures 6.7 and 6.8)</th>
<th>Hydraulic gradients on the seaward side of the groundwater system from the highest water table contour (4.5 m or 5.5 m) to the 1.0 m contour.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feb 95 (Gradients in metres per 100 metres)</td>
</tr>
<tr>
<td>A</td>
<td>0.65</td>
</tr>
<tr>
<td>B</td>
<td>0.75</td>
</tr>
<tr>
<td>C</td>
<td>0.79</td>
</tr>
<tr>
<td>D</td>
<td>0.86</td>
</tr>
<tr>
<td>E</td>
<td>0.90</td>
</tr>
<tr>
<td>F</td>
<td>1.00</td>
</tr>
<tr>
<td>G</td>
<td>1.06</td>
</tr>
<tr>
<td>H</td>
<td>1.13</td>
</tr>
<tr>
<td>I</td>
<td>1.20</td>
</tr>
<tr>
<td>J</td>
<td>1.29</td>
</tr>
<tr>
<td>K</td>
<td>1.39</td>
</tr>
<tr>
<td>L</td>
<td>1.34</td>
</tr>
<tr>
<td>M</td>
<td>1.29</td>
</tr>
<tr>
<td>N</td>
<td>1.29</td>
</tr>
<tr>
<td>O</td>
<td>1.34</td>
</tr>
<tr>
<td>P</td>
<td>1.39</td>
</tr>
<tr>
<td>Q</td>
<td>1.50</td>
</tr>
<tr>
<td>R</td>
<td>1.39</td>
</tr>
<tr>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Antecedent effective precipitation (EP) characteristics
- May-Aug preceding Sept 1995 EP was 232% less than the LTA (310.6 mm)
- Oct-Jan preceding Feb 1995 Braunton received 43% more EP than the LTA (418.4 mm)

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elevation of the water table. A description of the sediment properties at Northam is presented in Section 6.8.

b) **Hydraulic gradients on the Skern side of the groundwater system**

Average hydraulic gradients, draining into the Skern or inland from the highest water table contour (4.5 m or 5.5 m) to the 1.0 m contour ranged from 0.90 m per 100 m in February 1995 to 0.64 m per 100 m in September 1995 (Table 6.2). On both occasions these average hydraulic gradients were less steep than those recorded on the seaward side of the drainage divide (Tables 6.1 and 6.2). Again this may partially be a result of the interpolation plotting routine, however, the depth of the dune sands overlying the basal layer of the groundwater system decrease from west to east (Dartington Amenity Trust, 1970) and therefore during wetter periods the water table intercepts the ground surface, limiting the hydraulic gradients that can be attained.

Again the significant difference between February 1995 and September 1995 hydraulic gradients emphasised the sensitivity of the groundwater system to effective precipitation (Table 6.2).

6.3 **Hydrological characteristics explained from point observations**

At the smallest scale of the nested approach to describing the hydrological characteristics of Northam Burrows water level data from selected dipwells were analysed from October 1993 to April 1996. The aim of this section was to identify any variability in the annual cyclical response of the water table, with respect to geographical location and distance from the centre of the groundwater mound.
Table 6.2 Hydraulic gradients on the Skem and inland side of the hydrological system from the highest water table contour (4.5 m or 5.5 m) to the 1 m contour.

(Hydraulic gradients are calculated in metres and are derived from the flow nets (Figures 6.7 and 6.8). Flow line identification labels refer to Figures 6.7 and 6.9. LTA refers to 1972-1995.)

<table>
<thead>
<tr>
<th>Location of flowlines (refer to Figures 6.7 and 6.8)</th>
<th></th>
<th>Hydraulic gradients on the inland/Skem side of the hydrological system from the highest water table contour (4.5 m or 5.5 m) to the 1.0 m contour.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feb 95 (Gradients in metres per 100 metres)</td>
<td>Sept 1995 (Gradients in metres per 100 metres)</td>
</tr>
<tr>
<td>A1</td>
<td>0.75</td>
<td>0.49</td>
</tr>
<tr>
<td>B1</td>
<td>0.86</td>
<td>0.59</td>
</tr>
<tr>
<td>C1</td>
<td>0.90</td>
<td>0.61</td>
</tr>
<tr>
<td>D1</td>
<td>0.90</td>
<td>0.61</td>
</tr>
<tr>
<td>E1</td>
<td>0.95</td>
<td>0.61</td>
</tr>
<tr>
<td>F1</td>
<td>1.00</td>
<td>0.64</td>
</tr>
<tr>
<td>G1</td>
<td>1.00</td>
<td>0.67</td>
</tr>
<tr>
<td>H1</td>
<td>1.06</td>
<td>0.70</td>
</tr>
<tr>
<td>I1</td>
<td>1.06</td>
<td>0.70</td>
</tr>
<tr>
<td>J1</td>
<td>1.06</td>
<td>0.70</td>
</tr>
<tr>
<td>K1</td>
<td>1.00</td>
<td>0.74</td>
</tr>
<tr>
<td>L1</td>
<td>0.95</td>
<td>0.74</td>
</tr>
<tr>
<td>M1</td>
<td>0.86</td>
<td>0.74</td>
</tr>
<tr>
<td>N1</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>O1</td>
<td>0.67</td>
<td>0.54</td>
</tr>
<tr>
<td>P1</td>
<td>0.67</td>
<td>0.54</td>
</tr>
<tr>
<td>Average</td>
<td>0.90</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Antecedent effective precipitation (EP) characteristics:
- May-Aug preceding Sept 1995 EP was 232% less than the LTA (-310.6 mm)
- Oct-Jan preceding Feb 1995 Braunton received 43% more EP than the LTA (418.4 mm).
Water table data from six dipwells were analysed (coded dipwells 1, 3, 4, 7, 9 and 11 in Figure 6.1). Dipwell 1 was closest to the inland boundary of the system. Dipwells 4, 7 and 9 were less than 300 m from the HWM and dipwell 3 was situated 600 m inland from the HWM. Dipwell 11 was within 200 m of the Skern, on the eastern side of the system.

With the exception of dipwell 11, all the other dipwells appeared to respond similarly on an annual cyclical basis (Figure 6.9a-e). The possible reason for the differing response of dipwell 11 is discussed in the next paragraph. Depending upon effective precipitation characteristics the elevation of the water table began to fall from its winter maximum between late February and April (Figure 6.9a-e). Generally the water table reached a summer time low by August or September and thereafter with an increase in effective recharge began to recover again to a winter maximum.

Between November and March in both 1994 and 1995 the water table at dipwell 1 fluctuated less than 0.30 m (Figure 6.9a). During this same period dipwells 3, 4, 7, 9 and 11 showed significantly greater water table fluctuations (Figure 6.9b-6.9f). The water table at dipwell 1 was possibly being controlled by the drainage ditch network and will be analysed further in Section 6.9c. At dipwells 1 and 7, in consecutive weeks during the winter months, when the water table was at or above the ground surface the water table levelled out (Figure 6.9a and Figure 6.9d). This was the result of the higher pore space in the organic horizon of the vegetated dune sands and the void above the ground surface, which in effect meant that greater inputs to the system were required per unit rise in the elevation of the water table (Shaw, 1994). Water levels in dipwell 11, sited in an area of reclaimed saltmarsh, fluctuated rapidly from week to week and the water table was in excess of 1.40 m from the ground surface throughout the monitoring period (Figure 6.9f).
Figure 6.9 Annual cyclical water table fluctuations for six dipwells on Northam Burrows, from October 1993 to April 1996
a) Dipwell 1 b) Dipwell 3 c) Dipwell 4 d) Dipwell 7 e) Dipwell 9 f) Dipwell 11
(The locations of the dipwells are shown on Figure 6.1.)
The possibility of tidal interference with the hydrological functioning of dipwell 11 will be investigated in Section 6.7.

As the water table fell from its winter maximum through the spring and summer months of both 1994 and 1995, dipwells 1 and 3 demonstrated more rapidly fluctuating weekly water levels (Figure 6.9a and 6.9b) compared with dipwells 4, 7 and 9, which showed a smooth and gradual seasonal adjustment (Figures 6.9c, 6.9d and 6.9e). These differing hydrological characteristics can possibly be explained from an analysis of the sediment properties in the vicinity of each well. An increased content of silt and clay fractions in the region of dipwells 1 and 3 would give a different specific yield compared with a dipwell in a homogenous fine to medium grained sand. Specific yield is defined as the volume of water taken into storage in the column with each unit rise in the water table (Price, 1996). When the water table drops the saturated zone does not drain completely, surface tension and molecular effects cause a thin layer to stay in place around each particle (Todd, 1959). Values of specific yield depend upon grain size, shape, distribution of pores and compaction of the stratum. In an aquifer with a low specific yield, such as a sediment with a high silt and clay content, the water table rises a long way in response to recharge and in the same way falls a long way in response to withdrawal of water from the aquifer (Neuman, 1987). A sediment with a high specific yield generally shows smaller water table fluctuations. Average specific yield values for aeolian sands are 38%, coarse sand 27%, medium sand 28%, fine sand 23%, silt 8% and clay 3% (Johnson, 1967). Differences in specific yield may therefore explain the differing annual cyclical water table characteristics of dipwells 1 and 3, compared with 4, 7 and 9. Variations in specific yield may also explain the more rapid recovery of dipwell 1 from the drought conditions that prevailed during the summer of 1995 (Figure 6.9a).
With the exception of the period between the summer of 1995 and the winter of 1995/1996, seasonal water table fluctuations at Northam were generally in excess of one metre (Table 6.3).

Table 6.3 Maximum fluctuation of the water table between seasons at Northam Burrows. (The locations of the dipwells are shown on Figure 6.1.)

<table>
<thead>
<tr>
<th>Study site and water table monitoring site</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northam Burrows, dipwell 1</td>
<td>1.05 m</td>
</tr>
<tr>
<td>Northam Burrows, dipwell 3</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Northam Burrows, dipwell 4</td>
<td>1.34 m</td>
</tr>
<tr>
<td>Northam Burrows, dipwell 7</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Northam Burrows, dipwell 9</td>
<td>1.07 m</td>
</tr>
<tr>
<td>Northam Burrows, dipwell 11</td>
<td>1.54 m</td>
</tr>
<tr>
<td>Average fluctuation (α)</td>
<td>1.17 m (0.22 m)</td>
</tr>
</tbody>
</table>

As described in Section 4.3, at Braunton water levels central within the groundwater mound fluctuated more than those at the edge of the dune system, which were not only recharged by areal precipitation, but also by groundwater draining from higher elevations within the mound. Within the smaller Northam system distance from the centre of the groundwater mound had no apparent significant effect on annual cyclical water table fluctuations. With the exception of the irregular water table fluctuations recorded at dipwell 11, dipwell 4 which was sited less than 150 m from the HWM fluctuated more than other dipwells on three occasions (Table 6.3). Apart from between the summer of 1995 and the winter of 1995/1996 dipwell 7, which was within 100 m of the HWM (Figure 6.1), demonstrated similar seasonal water table fluctuations to dipwells 1 and 3 which were located at higher elevations within the mounded groundwater system (Figures 6.2 and 6.3). Within the smaller Northam system the effects of distance from the centre of the groundwater mound
were masked by natural factors and the diverse range of human activities controlling the groundwater hydrology.

6.4 The relationship between the elevation of the water table and effective precipitation

As a parallel to Section 4.4 this section aims to evaluate the relationship between the elevation of the water table and discrete periods of effective precipitation at Northam, using Spearman's rank correlation. The relationship between these two variables was investigated for the period December 1993 to December 1995, for each dipwell monitored since the start of the research.

On the basis of the speed of response of the water table to effective precipitation the dipwells can be divided into three distinct groups (Table 6.4).

Dipwells 1 and 2 showed the most rapid response, with the elevation of the water table most closely correlated with effective precipitation from the 0-30 day period. The correlation coefficients were significant at 95 % and explained 80 % of the relationship between the two variables. In the second group, a further eight dipwells were most closely correlated with effective precipitation of the preceding 31-60 day period (Table 6.4). The correlation coefficients were significant at 95 % and explained between 60% and 79 % of the association between the two variables. Although these were the strongest correlations the elevation of the water table in these dipwells was also significantly correlated with antecedent effective precipitation of the 0-30 day period (Table 6.4).
Table 6.4 The relationship between monthly water table elevations and effective precipitation at Northam Burrows (dipwells 1-14), for the period December 1993 to December 1995.

(The locations of the dipwells are shown on Figure 6.1. Shaded boxes indicate the strongest correlations at a 95% significance level. $r_s$ - Spearman's correlation coefficient. $r^2$ - measure of association between the two variables.)

<table>
<thead>
<tr>
<th>Obs. well (and correlation coefficient value required to be significant at 95%)</th>
<th>0-30 days</th>
<th>31-60 days</th>
<th>61-90 days</th>
<th>91-120 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($r_s=0.485$)</td>
<td>0.893 ($r^2=80%$)</td>
<td>0.735</td>
<td>0.484</td>
<td>0.058</td>
</tr>
<tr>
<td>2 ($r_s=0.485$)</td>
<td>0.892 ($r^2=80%$)</td>
<td>0.797</td>
<td>0.594</td>
<td>0.226</td>
</tr>
<tr>
<td>3 ($r_s=0.485$)</td>
<td>0.823</td>
<td>0.890 ($r^2=79%$)</td>
<td>0.659</td>
<td>0.346</td>
</tr>
<tr>
<td>4 ($r_s=0.485$)</td>
<td>0.777</td>
<td>0.856 ($r^2=73%$)</td>
<td>0.795</td>
<td>0.620</td>
</tr>
<tr>
<td>5 ($r_s=0.485$)</td>
<td>0.498</td>
<td>0.802</td>
<td>0.880 ($r^2=77%$)</td>
<td>0.811</td>
</tr>
<tr>
<td>6 ($r_s=0.485$)</td>
<td>0.502</td>
<td>0.723</td>
<td>0.822 ($r^2=68%$)</td>
<td>0.712</td>
</tr>
<tr>
<td>7 ($r_s=0.485$)</td>
<td>0.735</td>
<td>0.886 ($r^2=78%$)</td>
<td>0.869</td>
<td>0.683</td>
</tr>
<tr>
<td>8 ($r_s=0.485$)</td>
<td>0.798</td>
<td>0.863 ($r^2=74%$)</td>
<td>0.790</td>
<td>0.597</td>
</tr>
<tr>
<td>9 ($r_s=0.485$)</td>
<td>0.591</td>
<td>0.752</td>
<td>0.828 ($r^2=69%$)</td>
<td>0.721</td>
</tr>
<tr>
<td>10 ($r_s=0.485$)</td>
<td>0.804</td>
<td>0.839 ($r^2=70%$)</td>
<td>0.591</td>
<td>0.591</td>
</tr>
<tr>
<td>11 ($r_s=0.485$)</td>
<td>0.662</td>
<td>0.777 ($r^2=60%$)</td>
<td>0.458</td>
<td>0.458</td>
</tr>
<tr>
<td>12 ($r_s=0.485$)</td>
<td>0.736</td>
<td>0.891 ($r^2=79%$)</td>
<td>0.642</td>
<td>0.642</td>
</tr>
<tr>
<td>13 ($r_s=0.485$)</td>
<td>0.762</td>
<td>0.877 ($r^2=77%$)</td>
<td>0.528</td>
<td>0.528</td>
</tr>
<tr>
<td>14 ($r_s=0.485$)</td>
<td>0.731</td>
<td>0.838 ($r^2=70%$)</td>
<td>0.628</td>
<td>0.363</td>
</tr>
</tbody>
</table>

The speed of response of the water table to effective precipitation was related to a combination of many possible factors, including position within the groundwater drainage system and variable sediment properties. Site location would determine the lateral input of water and the rate of drainage from the site. Sediment properties such as a variable silt and clay content would affect the hydraulic conductivity and the specific yield. Therefore, the explanation of the differing response times of dipwells in groups 1 and 2 was difficult because of the interaction of all these possible factors.
As described in Section 4.4 the use of MORECS evapotranspiration data may explain some of the variance in the relationship between these two variables. MORECS data provided monthly evapotranspiration rates for short grass, averaged over a 40 x 40 km area. The use of such data may therefore underestimate losses from a coastal dune system with different vegetation coverages.

The final group, consisting of dipwells 5, 6 and 9, took the longest to respond and were most closely correlated with effective precipitation of the preceding 61-90 day period (Table 6.4). The correlation coefficients, significant at 95 %, explained between 68 % and 77 % of the association between the two variables. Although these were the strongest correlations, the relationship between water table elevation and effective precipitation was in fact significant with the 0-30 day period. Dipwell 5 was sited in a dune hollow surrounded by a comparatively greater volume of unsaturated sand, the hydraulic conductivity of which was several orders of magnitude lower than that for saturated sand (Landon, 1984). The thickness of the unsaturated zone may therefore partially explain the slower response of this dipwell. A similar explanation also explained the slower response of dipwell 9. The slower response of dipwell 6 was related to the fact that during the first winter of monitoring the staff at Northam failed to record the height of the water table above ground surface and instead recorded weekly water level measurements as at the ground surface.

The elevation of the water table at Northam generally responded quicker to effective precipitation than at Braunton (Tables 4.10 and 6.4). This was the result of a combination of factors, including both a smaller unsaturated zone and a higher content of silt and clay fractions within the dune sands, which affected the permeability and hence the lateral movement of groundwater through the system.
6.5 The lower geological boundary or impermeable layer of the groundwater system

At Northam the depth and continuity of the lower geological boundary, or impermeable layer of the groundwater system was determined from six boreholes and a hand augered borehole next to dipwell 1 (Figure 3.9). The results from the borehole investigations showed that the dunes and coastal plain were underlain by a continuous silt and clay layer (Table 6.5). This layer extended beneath the pebble ridge and was also occasionally exposed at low tide on the foreshore (Stuart and Hookway, 1954). The silt and clay material was consolidated and in each borehole prevented further penetration of the hydraulic drill. Using the laser diffraction method of analysis (Section 3.3.1), between 76 % and 84 % of the sample consisted of particles less than 62 μm and a maximum of 5 % of the sample consisted of fine pebbles (<3.0 mm) and small fragments of shale weathered from the underlying Pilton Beds. In subsequent groundwater calculations this predominantly silt and clay layer was taken as the lower boundary of the groundwater system. The height of the top of this layer relative to OD increased in elevation in a south easterly direction.

Table 6.5 Characteristics of the basal material from borehole investigations.
(Measurements are in metres above or below OD. Particle size classification according to the scale of Friedman and Sanders (1978). Experimental sites are shown on Figure 3.9.)

<table>
<thead>
<tr>
<th>Drilling rig site</th>
<th>Characteristics of base material</th>
<th>Depth of basal layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silt/clay layer - 78 % &lt; 62 μm.</td>
<td>1.68 m below OD</td>
</tr>
<tr>
<td>2</td>
<td>Silt/clay layer -76 % &lt; 62 μm</td>
<td>0.92 m below OD</td>
</tr>
<tr>
<td>3</td>
<td>Silt/clay layer 84 % &lt; 62 μm</td>
<td>2.45 m below OD</td>
</tr>
<tr>
<td>4</td>
<td>Silt/clay layer 84 % &lt; 62 μm</td>
<td>1.97 m below OD</td>
</tr>
<tr>
<td>5</td>
<td>Silt/clay layer 82% &lt; 62 μm</td>
<td>2.72 m below OD</td>
</tr>
<tr>
<td>6</td>
<td>Silt/clay layer 75 % &lt; 62 μm</td>
<td>2.47 m below OD</td>
</tr>
<tr>
<td>Hand augering next to dipwell 1</td>
<td>Silt/clay layer 83 % &lt;62 μm</td>
<td>1.5 m above OD</td>
</tr>
</tbody>
</table>
Field observations along the course of the Pill, showed that this arterial drainage channel was partially incised into the silty, clay basal layer. Similarly, drainage ditches to the south of the Burrows access road towards Goosey Pool, all of which were less than one metre deep, were also partially incised into a silt and clay sediment. A report by the Dartington Amenity Trust (1970) stated that the depth of the wind blown sand decreased from east to west and in fact at dipwell 1 the silt and clay basal layer was only 2.44 m from the ground surface. The shallow depth of the dune aquifer along the south eastern boundary of the system and the partial incision of the Pill and its tributary ditch network into the basal material will need to be taken into consideration when determining the most effective hydrological management options for raising water levels on the Burrows.

6.6 Saline intrusion

It was important to establish whether saline intrusion would be an increasing problem if the perceived drying out of the dune system continued. A greater saline input to the groundwater system could result in the loss of nationally rare or protected freshwater species, such as the water germander (*Teucrium scordium*) and the sharp rush (*Juncus acutus*) communities.

As described in Section 4.6, the Ghyben-Herzberg theory for saline intrusion stated that salt water intrudes at a depth of about 40 times the fresh water head above mean sea level (Stuyfzand and Bruggeman, 1994). At Northam, considering the elevation of the water table in the most seaward dipwells and the approximate depth of the lower boundary of the groundwater system (Section 6.5), the 40:1 Ghyben-Herzberg ratio was not met. Salt water intrusion was therefore not a problem within the Northam local groundwater system.
6.7 The tidal cycle

Preliminary analysis of weekly water level data identified a rapidly fluctuating water table at dipwell 11 (Figure 6.10). This dipwell, sited in an area of reclaimed salt marsh was possibly being influenced by the tide. From week to week the water table fluctuated by up to one metre. However, dipwell 12 which was less than 100 m from dipwell 11 (Figure 6.1) did not show the same irregular weekly water table fluctuations (Figure 6.10).

Data loggers were set up on dipwells 11 and 12, for 49 hours and 8 hours respectively, to determine the influence of the tide on the elevation of the water table (Section 3.2.5). Throughout the period of monitoring dipwell 11 showed a semi-diurnal water table fluctuation (Figure 6.11), which strongly indicated tidal influence.

Figure 6.10 Weekly water table fluctuations for dipwells 11 and 12, Northam Burrows, from October 1993 to April 1996. (The locations of the dipwells are shown on Figure 6.1).
A study by Serfes (1991) stated that in coastal areas the periodic rise and fall of tide-water stage in the ocean, hydraulically connected streams and tidal marshes, produced sinusoidal groundwater fluctuations in adjacent aquifers. In unconfined aquifers the pressure waves are generated from changes in storage, due to dewatering and resaturation of pores (Erskine, 1991). During the monitoring at Northam the maximum water table elevation occurred between 7 hrs 23 mins and 7 hrs 49 mins after high tide, causing a maximum fluctuation of 0.12 m. The time lag between high tide and maximum water table elevation was a function of the tidal period and amplitude in the water body, the aquifer's transmissivity and storage coefficient, and the distance inland to the water table observation point (Ferris, 1951). As the height of the tide increased through the period of monitoring, towards the fortnightly spring tide, there was a noticeable upward trend in maximum and minimum semi-diurnal water level elevations (Figure 6.11).

Figure 6.11 Short term fluctuations in the elevation of the water table at dipwell 11.
Tidal pressure waves cause groundwater levels and hydraulic gradients to fluctuate continuously (Erskine, 1991). From the water table data collected at dipwell 11 it was more difficult to characterise the annual cyclical functioning of the groundwater system. Each measurement only defines a point in time and not the mean, or net water table fluctuation (Serfes, 1991).

Dipwell 12, although only monitored for a period of 8 hrs did not show the same semi-diurnal water table fluctuations as dipwell 11, even though these dipwells were less than 100 m apart. Groundwater levels at dipwell 12 fluctuated a maximum of 7 mm over the monitoring period. This was the result of a dampening effect, which was described in a study by Erskine (1991) within a sandy coastal aquifer in East Anglia. In this study dampening of the tidal pressure wave had effectively extinguished all tidal fluctuations at 400 m distance inland.

6.8 Physical characteristics of the dune sands

A detailed description of the spatial properties of the dune sands was important in explaining some of the key hydrological characteristics described in Sections 6.1-6.3. Variability in the properties of the dune sands would also need to be taken into account when identifying possible factors influencing annual cyclical water table fluctuations (Section 6.9).

6.8.1 Particle size analysis - variability with depth and within the dune system

Sediment was collected at 0.50 m depths above the water table, at approximately 2.5 m distance of each dipwell within the water table monitoring network (Section 3.2.8). The location of the sampling sites assisted in both identifying any spatial variability in the particle size distribution and in explaining any variability in the $K_{sat}$ measurements to be
described in Section 6.8.2. Research by Bedinger (1961) stated that particle size distribution would have a strong control on the rate of water movement through the medium. Particle size characteristics of the dune sands are summarised in Table 6.6.

A prominent feature of the sediment analysed at Northam was the variability in the silt and clay content (<62 μm), both with depth and spatially within the system (Table 6.6). At a sampling depth of 0.50 m the percentage content of silt and clay fractions ranged from 8% to 34%, as shown on the frequency distribution curves (Figure 6.12). A similar magnitude of variability was also recorded at the 1.0 m and 1.50 m sampling depths (Table 6.6). The comparatively higher silt and clay content measured down through the sediment profiles next to dipwells 1 and 2 (Table 6.6) accounted for the lower $K_{sat}$ values recorded at these sites (Table 6.7).

Analysis of the variability in particle size distribution with depth (Table 6.6) showed that with the exception of sediment sampled next to dipwells 1, 3, 5, 7, and 14, the silt and clay content was greatest in the top sampling layer (0.50 m depth). This reflected the variable texture and density of the aeolian dune sands, which have been laid down in thin layers, just a few millimetres thick, over the past 5,000 to 6,000 years (Comber et al., 1993).

With the exception of the variability in silt and clay fractions (<62 μm), the particle size distribution of the dune sands was uniform both with depth and spatially within the dune system (Table 6.6 and Figure 6.12) and are classified as a medium to fine grained sand (Friedman and Sanders, 1978).
Variability in particle size distribution on Northam Burrows.
(Sampling sites are shown on Figure 6.1. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay-<62μm, FS-fine sand-62μm-250μm, MS-medium sand 250μm-500μm, CS-coarse sand- 500μm-1mm, >1mm-very coarse sand and fine pebbles.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Dipwell 1</th>
<th>Dipwell 2</th>
<th>Dipwell 3</th>
<th>Dipwell 4</th>
<th>Dipwell 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50m</td>
<td>S/C 25.5%</td>
<td>FS 51.0%</td>
<td>MS 21.4%</td>
<td>CS 1.5%</td>
<td>S/C 13.8%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 0.6%</td>
<td>&gt;1mm 3.8%</td>
<td>&gt;1mm 15.0%</td>
<td>S/C 15.5%</td>
<td>S/C 13.4%</td>
</tr>
<tr>
<td>1.00m</td>
<td>S/C 37.0%</td>
<td>FS 50.5%</td>
<td>MS 9.5%</td>
<td>CS -</td>
<td>S/C 18.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 3.0%</td>
<td>&gt;1mm 2.0%</td>
<td>&gt;1mm 10.5%</td>
<td>S/C 18.0%</td>
<td>S/C 15.0%</td>
</tr>
<tr>
<td>1.50m</td>
<td>S/C 19.8%</td>
<td>FS 50.5%</td>
<td>MS 29.5%</td>
<td>CS -</td>
<td>S/C 23.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 0.2%</td>
<td>&gt;1mm 1.0%</td>
<td>&gt;1mm 2.5%</td>
<td>S/C 23.0%</td>
<td>S/C 24.4%</td>
</tr>
<tr>
<td>2.00m</td>
<td>S/C 26.0%</td>
<td>FS 49.5%</td>
<td>MS 23.5%</td>
<td>CS 1.0%</td>
<td>S/C 26.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>S/C 26.0%</td>
<td>S/C 24.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling depth</th>
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<th>Dipwell 7</th>
<th>Dipwell 8</th>
<th>Dipwell 9</th>
<th>Dipwell 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50m</td>
<td>S/C 15.0%</td>
<td>FS 48.2%</td>
<td>MS 35.5%</td>
<td>CS 1.3%</td>
<td>S/C 8.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>S/C 8.0%</td>
<td>S/C 22.6%</td>
</tr>
<tr>
<td>1.00m</td>
<td>S/C 8.0%</td>
<td>FS 53.0%</td>
<td>MS 36.5%</td>
<td>CS 2.0%</td>
<td>S/C 7.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 1.5%</td>
<td>&gt;1mm 1.0%</td>
<td>&gt;1mm 2.0%</td>
<td>S/C 7.0%</td>
<td>S/C 13.5%</td>
</tr>
<tr>
<td>1.50m</td>
<td>S/C 8.2%</td>
<td>FS 58.0%</td>
<td>MS 33.8%</td>
<td>CS -</td>
<td>S/C 3.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td>S/C 3.0%</td>
<td>S/C 1.4%</td>
</tr>
</tbody>
</table>
Table 6.6 cont. Variability in particle size distribution on Northam Burrows.
(Sampling sites are shown on Figure 6.1. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay-<62μm, FS-fine sand-62μm-250μm, MS-medium sand 250μm-500μm, CS-coarse sand-500μm-1mm, >1mm-very coarse sand and fine pebbles.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Dipwell 11</th>
<th>Dipwell 12</th>
<th>Dipwell 13</th>
<th>Dipwell 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 m</td>
<td>S/C 20.0%</td>
<td>S/C 30.5%</td>
<td>S/C 11.3%</td>
<td>S/C 34.0%</td>
</tr>
<tr>
<td></td>
<td>FS 47.5%</td>
<td>FS 52.0%</td>
<td>FS 53.5%</td>
<td>FS 48.5%</td>
</tr>
<tr>
<td></td>
<td>MS 24.4%</td>
<td>MS 15.2%</td>
<td>MS 33.0%</td>
<td>MS 15.0%</td>
</tr>
<tr>
<td></td>
<td>CS 8.1%</td>
<td>CS -</td>
<td>CS 1.0%</td>
<td>CS -</td>
</tr>
<tr>
<td></td>
<td>&gt;1 mm -</td>
<td>&gt;1 mm 2.3%</td>
<td>&gt;1 mm 1.2%</td>
<td>&gt;1 mm 2.5%</td>
</tr>
<tr>
<td>1.00 m</td>
<td>S/C 12.0%</td>
<td>S/C 13.0%</td>
<td>S/C 20.0%</td>
<td>S/C 22.0%</td>
</tr>
<tr>
<td></td>
<td>FS 60.6%</td>
<td>FS 55.5%</td>
<td>FS 52.4%</td>
<td>FS 52.4%</td>
</tr>
<tr>
<td></td>
<td>MS 23.5%</td>
<td>MS 31%</td>
<td>MS 23.6%</td>
<td>MS 23.0%</td>
</tr>
<tr>
<td></td>
<td>CS 3.9%</td>
<td>CS -</td>
<td>CS -</td>
<td>CS 1.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1 mm -</td>
<td>&gt;1 mm 0.5%</td>
<td>&gt;1 mm 4.0%</td>
<td>&gt;1 mm 1.6%</td>
</tr>
<tr>
<td>1.50 m</td>
<td>S/C 15.2%</td>
<td>S/C 14.5%</td>
<td>S/C 20.0%</td>
<td>S/C 22.0%</td>
</tr>
<tr>
<td></td>
<td>FS 56.5%</td>
<td>FS 60.7%</td>
<td>FS 52.4%</td>
<td>FS 52.4%</td>
</tr>
<tr>
<td></td>
<td>MS 27.5%</td>
<td>MS 24.8%</td>
<td>MS 23.6%</td>
<td>MS 23.0%</td>
</tr>
<tr>
<td></td>
<td>CS 0.8%</td>
<td>CS -</td>
<td>CS -</td>
<td>CS 1.0%</td>
</tr>
<tr>
<td></td>
<td>&gt;1 mm -</td>
<td>&gt;1 mm -</td>
<td>&gt;1 mm -</td>
<td>&gt;1 mm -</td>
</tr>
</tbody>
</table>

Figure 6.12  Particle size frequency distribution curves for sediment sampled at the 1.0m depth next to dipwells 1, 3, 5, 6, 10 and 12, on Northam Burrows. (The locations of the dipwells are shown on Figure 6.1.)
6.8.2 $K_{sat}$ below the water table (slug test)

At Northam, AQTESOLV was used to determine $K_{sat}$ from the Bouwer and Rice (1976) solution (Section 4.8.4). The mathematical formulae used in the B-R model have been included in Appendix B.

The slug tests were carried out on piezometers temporarily installed within 3 m of the permanent water level monitoring sites (Figure 6.1). The piezometers were therefore suitably located to identify any spatial variability in $K_{sat}$. The depths of $K_{sat}$ determination are shown in Table 6.7. The properties of saturated sand prevented an evaluation of $K_{sat}$ variability with depth. The slug test results are summarised in Table 6.7.

Table 6.7 $K_{sat}$ results for Northam using the Bouwer and Rice (1976) solution. ($K_{sat}$ measurement sites were within 3 m of the dipwells on Figure 6.1.)

<table>
<thead>
<tr>
<th>Slug test location (Within 3 m of the each dipwell in the monitoring network)</th>
<th>Depth of $K_{sat}$ measurement from the ground surface (metres)</th>
<th>$K_{sat}$ (m d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85-1.15</td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td>0.75-1.05</td>
<td>3.33</td>
</tr>
<tr>
<td>3</td>
<td>1.15-1.45</td>
<td>4.80</td>
</tr>
<tr>
<td>4</td>
<td>1.15-1.45</td>
<td>7.35</td>
</tr>
<tr>
<td>5</td>
<td>1.05-1.35</td>
<td>7.28</td>
</tr>
<tr>
<td>6</td>
<td>1.40-1.70</td>
<td>6.34</td>
</tr>
<tr>
<td>7</td>
<td>0.90-1.20</td>
<td>7.44</td>
</tr>
<tr>
<td>8</td>
<td>1.20-1.50</td>
<td>6.22</td>
</tr>
<tr>
<td>9</td>
<td>1.40-1.70</td>
<td>7.12</td>
</tr>
<tr>
<td>10</td>
<td>1.10-1.40</td>
<td>6.14</td>
</tr>
<tr>
<td>11</td>
<td>2.20-2.50</td>
<td>5.98</td>
</tr>
<tr>
<td>12</td>
<td>1.45-1.75</td>
<td>7.41</td>
</tr>
<tr>
<td>13</td>
<td>1.50-1.80</td>
<td>6.40</td>
</tr>
<tr>
<td>14</td>
<td>1.70-2.00</td>
<td>5.76</td>
</tr>
<tr>
<td>Average $K_{sat}$</td>
<td></td>
<td>6.04 (σ=1.41)</td>
</tr>
</tbody>
</table>

276
$K_{sat}$ ranged from 3.0 m d$^{-1}$ to 7.44 m d$^{-1}$, with an overall mean of 6.04 m d$^{-1}$. For dipwells 1 and 2, $K_{sat}$ values were 49 % (3.0 m d$^{-1}$) and 43 % (3.33 m d$^{-1}$) respectively less than the calculated average for the site. These lower values were a result of an increased percentage content of silt and clay fractions (<62 μm), (Section 6.8.1) and reflected the shallow depth to the silt and clay basal layer of the groundwater system. The lower permeability of the sediment in the area of dipwells 1 and 2 will need to be taken into consideration when discussing the future hydrological management of this part of the system (Section 8.2.2).

The average $K_{sat}$ for sediment sampled at Northam (6.04 m d$^{-1}$) was lower than that measured at Braunton (7.94 m d$^{-1}$) and was also less than values reported in Section 1.5 for various studies on European dune systems, which ranged from 7.5 m d$^{-1}$ to 11.0 m d$^{-1}$ (Beukeboom, 1976; Clarke, 1980; Van Dijk and de Groot, 1987; Bakker and Neinhuis, 1990; Jones, 1993). Also the $K_{sat}$ measurements at Northam showed more variability compared with the fairly uniform values calculated for Braunton (Table 4.15).

6.9 The apparent drying out of Northam Burrows

In 1993 the staff from Northam Burrows Country Park voiced their concerns that water levels within the dune system were falling. The prime concern was that the water table in the Inland Sea was falling, endangering the survival of the nationally rare and protected water germander ($Teucrium scordium$) and sharp rush ($Juncus acutus$) communities. Lower water table elevations were also identified as a possible cause for the reduction in nesting and wintering wildfowl (Corrin, pers. comm.).

Water table elevations have only been monitored at Northam since October 1993 and therefore it was difficult to determine whether any long-term change has occurred, or if
groundwater levels had fallen suddenly as a result of human activity. Water table data from selected dipwells will be used in this section to demonstrate how natural causes and human activity are influencing water levels on Northam Burrows. Also in the most recent management plan for Northam Burrows (Devon County Council, 1993), a number of management options were proposed to encourage tidal inundation and increase water levels on the Burrows. The feasibility and suitability of these proposals will be evaluated in Sections 6.9.1c-6.9.1e.

6.9.1 Possible causes for the drying out of Northam Burrows

Five possible causes for the apparent drying out of the Northam system have been identified and will be evaluated in the following subsections (Sections 6.9.1a-6.9.1e). The possible causes include, changing climatic trends, erosion of the fore dunes and pebble ridge, the drainage ditch network, the installation of tidal flaps on the Pill, and the construction of the landfill access road (Table 1.1).

a) The impact of long-term changing climatic trends on the elevation of the water table

The meteorological data used to describe long-term (1972-1995) climatic trends at Braunton were also used at Northam and a detailed analysis of the data was included in Section 5.2.1. On average from 1972-1995 only 32 % of annual precipitation recharged the groundwater system, the rest was lost through evapotranspiration. With precipitation as the primary source of groundwater recharge a LTA annual effective precipitation total of 273.4 mm emphasised the sensitivity of the Northam system to both changes in effective inputs and additional losses through natural causes, or human activity.

Analysis of the long-term precipitation and effective precipitation data in Section 5.2.1
identified a dry period from 1983-1992. In eight of these years annual effective precipitation was less than the LTA (273.4 mm) and would undoubtedly have lead to a decline in water levels within the system. This sustained dry period may also partially explain why concerns were first expressed early in 1993 that water levels on Northam Burrows were falling. Climate is undoubtedly a key variable controlling the long-term elevation of the water table at Northam, however other factors to be discussed in Sections 6.9.1b to 6.9.1e may also be influencing the long-term hydrological regime.

b) The impact of coastal erosion on the elevation of the water table

A further identified possible cause for the drying out of Northam Burrows was marine erosion. Although erosion was not quantified within this relatively short-term research it was still important to be aware of this natural on going process. Currently the pebble ridge around Greysand Hill is actively being stripped of pebbles and the dune ridge and part of the completed landfill are being eroded. As described in Section 1.4.5 erosion of the seaward margins of the system can affect the groundwater drainage regime and the elevation of the water table.

Between 1864 and 1996 the pebble ridge at Northam retreated landwards by 150 m (Keene, 1997). In effect the retreat of the ridge is gradually reducing the size of the dune system, which in itself may have repercussions on the functioning of the groundwater system. Furthermore, the possible effects of sand and gravel extraction from the Taw-Torridge Estuary (Section 2.4) on sediment transport processes should be considered. At Braunton research by Blackley, et al. (1972) suggested that annual extractions were related to beach erosion between Airy Point and Crow Point (Figure 1.5). However, the authors stated that further detailed experimentation was required to quantify the extent of impact.
c) The impact of the drainage ditch network on the elevation of the water table

Up until 1994 the Pill and a 300 m stretch of drainage ditch along the southern boundary of the system (Figure 6.1) were mechanically dredged each year to remove sediment accumulations and aquatic weed growth. All the other drainage ditches in the network are typically less than 1.5 m wide and 1.0 m deep and some are still cleared on a annual basis by hand (Figure 6.1). However, the majority of drainage ditches within the Great Plain have not been dredged since 1964. From field observations, stretches of many of these ditches are incised into permeable aeolian sands and therefore not only drain surface waters, but also control the elevation of the groundwater table.

Plates 6.1 and 6.2 illustrate how annual mechanical maintenance of the Pill since 1969 has changed the geometry of the channel. Although the impact of annual maintenance is obvious it should be acknowledged that Plate 6.1 was taken during the summer (August 1969), when flows are typically low. In comparison Plate 6.2 was taken in the Autumn (October 1996), when groundwater levels and channel discharge rates are recovering, as effective inputs to the system increase.

Field observations have shown that this channel is partially incised into a silty/clay material (Section 6.5). Therefore, depending on the hydraulic connection between the Pill and the surrounding land, along its entire course through the Burrows, changes in channel geometry will have had varying impacts on the functioning of the groundwater system. Changes to the geometry of the Pill should therefore be taken into consideration when determining the possible contributing causes for the perceived drying out of the system. The impact of deepening the Pill on the elevation of the Burrows water table could be more confidently described through the use of a predictive non-steady state groundwater model.
To evaluate the influence of the drainage ditch network on the elevation of the water table, water level data for dipwells 1-4 (Figure 6.1) were analysed from October 1993 to April 1996. Dipwells 1 and 2 were sited within an area of the system artificially drained by the ditch network, whereas dipwells 3 and 4 were outside the immediate remit of the drainage system. Weekly water table fluctuations were related to precipitation data, as short-term evapotranspiration data required to calculate effective precipitation totals were not available.

In each monitoring year from the beginning of December to the beginning of April, dipwells 1 and 2 (Figure 6.13a) fluctuated less than dipwells 3 and 4 (Figure 6.13b). Also dipwells 1 and 2 showed a dampened response to increased autumn and winter precipitation (Figure 6.13a). The smaller seasonal water table fluctuations recorded at dipwells 1 and 2 possibly demonstrated the efficiency of the drainage ditch network in controlling the elevation of the water table.

October 1994 to January 1995 were exceptionally wet winter months receiving 43% more effective precipitation (418.4 mm) than the LTA (1972-1995). At Braunton the winter of 1994/1995 caused widespread flooding (Section 4.1.1) and in some of the dune slacks flood waters were up to one metre deep. In comparison at Northam in the vicinity of dipwell 1, despite the water table reaching the surface by early November 1994, the efficiency of the drainage ditch network prevented surface flooding (Figure 6.9a). The drainage ditch system has been developed and carefully managed to ensure that the seasonal requirements of the graziers and golfers were met throughout the winter months, but to the detriment of nature conservation interests. The efficiency of the drainage ditch network in managing water table elevations will need to be considered when recommending practical management options for preventing any future possible lowering of the water table on Northam Burrows (Section 8.2.2).
Figure 6.13 The effects of the drainage ditch network on annual cyclical water table fluctuations.

a) Water table fluctuations at dipwells 1 and 2.

b) Water table fluctuations at dipwells 3 and 4.

(Water table data are shown in metres above OD. The locations of the dipwells are shown on Figure 6.1).
d) The impact of the installation and removal of the tidal flaps on the elevation of the water table

The installation of tidal flaps on the Pill at Appledore Bridge in 1975, to prevent tidal inundation, was identified as a possible contributing cause for the perceived drying out of the Northam system. The lack of water table data prior to the installation of the flaps and during their operation has made it impossible to determine exactly how these flaps have influenced the long-term elevation of the water table on Northam Burrows.

In the 1970 management plan for Northam Burrows, the primary goal set out by the governing authorities was to prevent tidal inundation through the installation of tidal flaps (Dartington Amenity Research Trust, 1970). Reduced tidal inundation together with an improved drainage ditch system would enhance the quality of grazing land on the Burrows. In the 1970s therefore, grazing rights set out under the Commons Act 1899 (Dartington Amenity Research Trust, 1970) took priority over nature conservation issues and the system was primarily managed to cater for the needs of both the graziers and golfers.

In 1994, with increasing concerns that Northam Burrows was drying out and the ecology of the site was changing, Devon County Council removed the flaps. The removal of the flaps once again encouraged a tidal input to the system via the Pill and tributary drainage channels. With tides in excess of 5.8 m tidal waters flowed up through the Pill to fill Goosey Pool (Figure 6.1). However, from field observations and according to Corrin (pers. comm.) as soon as the tide receded, all tidal waters drained from the Pill and Goosey Pool within several hours. The main concern of the golfers and graziers was that with tides greater than 5.8 m the Pill would burst its banks and flood the surrounding land. The graziers and golfers were therefore in favour of sluice controlling water levels in the Pill, rather than allowing this tidal channel to function naturally. The effectiveness of this
management option for nature conservation will partially depend upon the hydraulic connection between the Pill and the surrounding land. An analysis of sediment properties in Section 6.8 has already identified a zone of lower $K_{sat}$ to the west of the Pill's course in the vicinity of dipwells 1 and 2.

As described in Section 2.9, Goosey Pool (Figure 6.1) was once a surface water body and a haven for many bird species. However, the pool has gradually been infilled with sediment removed from the Pill (Corrin, pers. comm.). Also up until 1994 the tidal flaps on Appledore Bridge had prevented tidal replenishment of the pool. The latest management plan for the Burrows expressed the desire to deepen the pool and create a perennial surface water body (Devon County Council, 1993). The reinstatement of Goosey Pool is not a scheme to increase water levels on the Burrows, but a hydrological management strategy to increase the bio-diversity and wildlife interests within this part of the system.

e) The impact of the construction of the landfill access road on the elevation of the water table

In 1938 a decision was made to create a landfill close to Appledore Bridge (Dartington Amenity Trust, 1970). Continual tipping of domestic waste created a bank along the eastern boundary of the system, which today is the main access road into the current recycling centre (Figure 6.1). The intention of creating the bank was to afford Northam Burrows a degree of coastal protection, reducing tidal inundation and enhancing the quality of the grazing land. The bank was extended to the former Greysand Lake and saltmarsh area (Figure 6.1), which was also gradually infilled with domestic waste.

Prior to the construction of the landfill and access road, high tides encroached daily upon the northern part of the system and replenished the former Greysand Lake (Plate 6.3). In
contrast to the scene in 1970 and as a consequence of waste disposal activities, the extent of the current Greysand Lake has been substantially reduced (Plate 6.4). The use of Northam Burrows for waste disposal has therefore significantly changed the hydrological functioning of this part of the system and has also resulted in the loss of a diverse range of salt tolerant species (Wolton, pers. comm). Inputs to this part of the groundwater system have been substantially reduced. This area is also hydraulically connected with the Inland Sea (Figures 6.7 and 6.8) and therefore reduced tidal inundation may have contributed to the perceived drying out of this area of slack habitat, which contains the rare water germander (*Teucrium scordium*).

The present Greysand Lake (Figure 6.1) is an ephemeral feature with water levels regulated by an overflow pipe 30 cm in diameter. The overflow pipe removes excess water into the Skern. With tides greater than 5.8 m and when the penstock on the overflow pipe is open, tidal waters add to the extent of this water body. As part of the proposed tidal inundation scheme, Devon County Council plan to lower the elevation of the overflow pipe and replace it with a one metre diameter culvert (Devon County Council, 1993). The overall aim will be to increase tidal inundation, create a perennial water body and raise the elevation of the water table in this part of the system, which in turn will encourage the re-colonisation of salt tolerant species and increase the bio-diversity of the site (Corrin, pers. comm.). The hydrological consequences of replacing the current overflow pipe with a culvert at a lower elevation will be evaluated in the final hydrological management recommendations (Section 8.4.2).
Plate 6.3  Tidal inundation along the north eastern margin of Northam Burrows in the former Greysand Lake area.  
(Photograph taken in 1970 facing north-east, from the current landfill site and Greysand Lake - Figure 2.2.)

Plate 6.4  The extent of the current Greysand Lake, after extensive use of the area as a landfill.  
(Photograph taken February 1996 facing north-east, towards the current Greysand Lake - Figure 2.2.)
Summary

This section has identified the probable factors which have, or continue to influence the elevation of the water table on Northam Burrows. With precipitation as a main input to the groundwater system a LTA (1972-1995) annual effective precipitation total of 273.4 mm emphasised the finely balanced nature of the hydrological system and its sensitivity to reductions in precipitation, or increased evapotranspiration rates. The period of below average annual effective precipitation from 1983 to mid 1992 therefore undoubtedly affected water table elevations on Northam Burrows. Climate appeared to be a main variable controlling the long-term elevation of the water table. From the analysis of observation well data it was also shown how the drainage ditch system was effectively controlling the winter water table elevation. Reduced tidal inundation, changes in the geometry of the Pill and marine erosion have also possibly contributed to changes in the hydrological regime, although no historical data exists to substantiate these hypotheses. With an annual average effective precipitation total of 273.4 mm, additional losses through natural causes or human activity would be detrimental to water table elevations. Having identified the most probable factors which have or continue to influence the hydrology of Northam Burrows Section 8.4.2 will recommend sustainable options for raising water levels, or preventing any future possible lowering of the water table.

Part 2 - Dawlish Warren

6.10 A hydrological description of Dawlish Warren

At the largest scale of investigation the hydrological characteristics of the entire Dawlish Warren system were described from field observations and anecdotal evidence (Section 6.10.1).

Figure 6.14 has been included because the following hydrological description of Dawlish
Warren consistently refers to sampling sites, specific locations and physical features within the system.

At the start of the fieldwork programme in October 1993 the water table monitoring network consisted of six dipwells, increasing to ten by May 1995 (Section 3.2.3a). Restricted access to the golf course prohibited the installation of a dense network of dipwells on this part of the system (Figure 6.14). The water table monitoring sites proved insufficient to create accurate water table contour plots, or flow nets to describe the shape, elevation and gradient of the water table. However, the available dipwell water table data were used to both describe the spatial variability in the annual cyclical response of the groundwater system (Section 6.11) and to identify the possible causes for the perceived changing hydrological regime that were threatening the diversity and composition of the dune habitat flora and fauna (Section 6.17).

6.10.1 General hydrological characteristics

At Dawlish Warren there is no real dune slack habitat. However, part of Greenland Lake, the former tidal inlet between the Inner Warren and the Outer Warren, forms a low lying damp meadow area which characteristically floods in the winter. This area sustains a rich and diverse range of plant communities and is the area most sensitive to long-term changes in the elevation of the water table (Walsh, pers. comm.).

Again compared with Braunton the unsaturated zone at Dawlish Warren is considerably less, which may lead to very different water table response characteristics, as discussed further in Section 6.12.
Figure 6.14  Sampling sites and the physical characteristics of Dawlish Warren.
Approximately half of the Warren is used as a golf course, which is artificially drained, possibly to the detriment of nature conservation interests. The effects of the pump drainage system on the functioning of the groundwater system will be discussed in Section 6.17.1e. As far back as the late 1800s marine erosion of Dawlish Warren spit has been documented (Martin, 1872). Possible changes to the groundwater drainage regime as a result of marine erosion will be described in Section 6.17.1b.

Additional inputs to the Dawlish Warren system include groundwater draining into the system from the adjoining higher lying land and the domestic water supply used to irrigate the greens and tees on the golf course throughout the summer months.

6.11 Hydrological characteristics of the Dawlish dune system explained from point observations

At Dawlish Warren water table data from five dipwells (coded 2, 3, 4, 5 and 6 on Figure 6.14) were analysed to evaluate the degree of variability in the annual cyclical response of the water table. Dipwells 2, 3, 4, 5 and 6 provided the most complete weekly water table elevation records from October 1993 to March 1996. As illustrated on Figure 6.14, dipwell 6 was located on the Warren golf course and within 100 m of the HWM. Dipwells 3 and 4 were sited within Greenland Lake and dipwells 2 and 5 were on the south east face of the Inner Warren dune ridge. Dipwell 5 was the most seaward dipwell, within 75 m of the HWM.

Throughout the monitoring period (October 1993-April 1996) dipwells 2, 3, 4 and 5 demonstrated the same general annual cyclical pattern of water table fluctuations (Figures 6.15a-6.15e), characteristic of the seasonal fluctuations described for both Braunton and Northam (Section 4.3 and 6.3). Irregular water table fluctuations were recorded at dipwell
Figure 6.15  Annual cyclical water table fluctuations for five dipwells on Dawlish Warren from October 1993-April 1996.

a) Dipwell 2  b) Dipwell 3  c) Dipwell 4  d) Dipwell 5  e) Dipwell 6

(The locations of the dipwells are shown on Figure 6.14.)
6. Between October 1992 and April 1996 dipwell 6 fluctuated less than 0.40 m (Figure 6.15e). A more dramatic drop in the elevation of the water table was recorded in May 1995, but recovered by late August to fluctuate less than 0.40 m from September 1995 to April 1996. This sudden drop in the elevation of the water table coincided with the drought summer of 1995 and also the draining of the golf course pond for annual dredging. The water table characteristics at dipwell 6 will be analysed further in relation to sediment properties (Section 6.16) and also when determining the possible effects of the golf course pump drainage system on the elevation of the water table (Section 6.17.1e).

At dipwells 3 and 4 (Figures 6.15b and 6.15c), in consecutive weeks during the winter months when the water table was at the ground surface or within the top organic horizon (0-10 cm depth), the water table fluctuated less from week to week compared with the water table at dipwell 2 (Figure 6.15a). The water table at dipwells 3 and 4 appeared to level out, because of the higher pore space in the organic layer and the void above the ground surface which meant that a greater input to the system was required per unit rise in the elevation of the water table (Shaw, 1994). In comparison the water table at dipwell 2 fluctuated within a sandy medium of a comparatively lower porosity, although the same effect was apparent when water levels in dipwell 2 reached the ground surface for a number of consecutive weeks in February 1995 (Figure 6.15a).

Table 6.8 shows the maximum water table fluctuations between summer and winter seasons, for five dipwells on Dawlish Warren. Without taking into account the irregular water table fluctuations recorded at dipwell 6, the water table at dipwells 2, 3, 4 and 5 fluctuated between 0.68 m and 1.21 m. With the exception of the period between the winter of 1993/1994 and the summer of 1994, water table fluctuations recorded at dipwell 3 were greater than measured at any other dipwell. This well was located at the very edge
of the scrub woodland within Greenland Lake. The possible effects of scrub and tree
growth on the annual cyclical response of dipwell 3 will be investigated further in Section
6.17.1c.

Table 6.8 Maximum seasonal fluctuation of the water table at Dawlish Warren.
(The locations of the dipwells are shown on Figure 6.14.)

<table>
<thead>
<tr>
<th>Study site and dipwell</th>
<th>Maximum fluctuation of the water table between the specified dates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dawlish Warren, dipwell 2</td>
<td>0.95 m</td>
</tr>
<tr>
<td>Dawlish Warren, dipwell 3</td>
<td>0.92 m</td>
</tr>
<tr>
<td>Dawlish Warren, dipwell 4</td>
<td>0.77 m</td>
</tr>
<tr>
<td>Dawlish Warren, dipwell 5</td>
<td>0.83 m</td>
</tr>
<tr>
<td>Dawlish Warren, dipwell 6</td>
<td>0.28 m</td>
</tr>
</tbody>
</table>

From the limited dipwell network on Dawlish Warren it was not possible to evaluate the
effects of location within the groundwater drainage regime on the range of annual cyclical
water table fluctuations.

This section has described the annual cyclical characteristics and functioning of the Dawlish
Warren groundwater system, although evidently further research is required installing
additional dipwells in order to build up a more detailed picture of the shape, elevation and
gradient of the groundwater system. A more comprehensive hydrological description would
also help to determine the best water level management strategy for the system in order to
conserve the diverse wildlife interests. Future potential research at Dawlish Warren is
considered in Section 8.5.
The relationship between effective precipitation and the elevation of the water table

As described in Section 6.4, Spearman's rank correlation was used to evaluate the relationship between the elevation of the water table and discrete periods of antecedent effective precipitation from December 1993 to December 1995.

The results show that the dipwells can be divided into two groups on the basis of water table response to effective precipitation (Table 6.9).

Dipwells 1, 5 and 6 showed the most rapid response, with the elevation of the water table most closely correlated with effective precipitation from the 0-30 day period (Table 6.9). The correlation coefficients were significant at 95% and explained between 67% and 72% of the association between these two variables. The elevation of the water table at dipwells 2, 3, and 4 was most strongly correlated with effective precipitation of the preceding 31-60 day period (Table 6.9). The correlation coefficients significant at 95% explained between 69% and 74% of the variance between the two variables. The reason for the slower response of these wells was not immediately apparent and was probably related to a combination of factors including variable sediment properties and the exact location of the well within the groundwater drainage system, as discussed for the Northam system in Section 6.4. The use of MORECS evapotranspiration data in this exercise, the effects of increased evapotranspiration rates associated with scrub growth and variable sediment properties were possible independent variables influencing the strength of the correlations.
Table 6.9 The relationship between antecedent effective precipitation and monthly water table elevations at Dawlish Warren (dipwell 1-6), for the period December 1993 to December 1995. (For dipwell locations refer to Figure 6.14. Shaded boxes indicate the strongest correlations at a 95% significance level. $r_s$ - Spearman's correlation coefficient. $r^2$ - measure of association between the two variables.)

<table>
<thead>
<tr>
<th>Obs. well (and correlation coefficient value required to be significant at 95%)</th>
<th>0-30 days</th>
<th>30-60 days</th>
<th>60-90 days</th>
<th>90-120 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($r_s=0.645$)</td>
<td>0.821 ($r^2=67%$)</td>
<td>0.736</td>
<td>0.107</td>
<td>-0.111</td>
</tr>
<tr>
<td>2 ($r_s=0.508$)</td>
<td>0.716</td>
<td>0.831 ($r^2=69%$)</td>
<td>0.612</td>
<td>0.394</td>
</tr>
<tr>
<td>3 ($r_s=0.534$)</td>
<td>0.813</td>
<td>0.861 ($r^2=74%$)</td>
<td>0.593</td>
<td>0.309</td>
</tr>
<tr>
<td>4 ($r_s=0.564$)</td>
<td>0.737</td>
<td>0.833 ($r^2=69%$)</td>
<td>0.566</td>
<td>0.240</td>
</tr>
<tr>
<td>5 ($r_s=0.601$)</td>
<td>0.831 ($r^2=69%$)</td>
<td>0.770</td>
<td>0.431</td>
<td>0.178</td>
</tr>
<tr>
<td>6 ($r_s=0.508$)</td>
<td>0.846 ($r^2=72%$)</td>
<td>0.562</td>
<td>0.237</td>
<td>-0.139</td>
</tr>
</tbody>
</table>

At Dawlish, the elevation of the water table generally showed a quicker response to effective precipitation than the Braunton system. The smaller volume of unsaturated dune sands at Dawlish increased the rate of groundwater recharge.

6.13 The lower geological boundary or impermeable layer of the groundwater system

A detailed geological survey of the Warren was not carried out during this research for the reasons discussed in Section 3.2.7. However, research on Dawlish Warren by Kidson (1950) and Durrance (1969;1980) using seismic refraction techniques have quantified the depth to the upper surface of the New Red Sandstone and the extent of the Middle Devensian gravel (Section 2.4: Figures 2.4 and 2.5). However, their studies failed to differentiate between the layers of silt and clay and wind blown sand that overlie the bedrock and gravel (Figure 2.5). The hydrological functioning of the groundwater system will depend upon the permeability, extent and location of the sand, silt and clay. Also without an impermeable lower boundary to the groundwater system, vertical drainage may lead to groundwater being lost to the regional aquifer.
Particle size analysis (Section 6.16.1 and Table 6.10) revealed that a silt and clay layer (74%-86% <62μm) occurred within one metre of the ground surface at dipwells 6A and 7. Furthermore, from the eight exploratory hand augered boreholes on the golf course (Section 3.2.7), at four of these sites (coded Pt4, Pt6, Pt7 and Pt8 on Figure 3.4) a saturated clay layer was reached within 1.5 m of the ground surface. The top of the clay layer occurred close to Ordnance Datum. At the other borehole locations the liquid nature of saturated sand prevented further analysis of the sediment profile. From this investigation it was not possible to determine whether the clay layer occurred within the sand profile or formed a continuous layer on top of the basal geology. A geological review of the Exe Estuary by Durrance (1980) did not describe the shallow depth to the clay layer in this area and only defined the upper surface of the New Red Sandstone, at a maximum depth of 45.7 m below HWMST (Figure 2.4). The shallow depth to a relatively impermeable layer explains why the fairways closest to the estuary flood and have to be intensively drained during the winter months.

The clay layer on the golf course limits the groundwater storage potential and together with the intensive drainage system this part of the system will require careful future management to avoid further changes to the finely balanced hydrological system (Section 6.17e).

6.14 Saline intrusion

At Dawlish Warren geological literature (Kidson, 1950; Durrance 1969; 1980) has failed to differentiate between the sands and clays which overlay the New Red Sandstone (Section 6.13). Depending upon whether a continuous impermeable clay layer overlies the bedrock and at what depth will determine whether saline intrusion is likely to be a problem. Without an impermeable basal layer to the groundwater system, which would prevent saline water entering the local groundwater system, salt water would intrude at a depth of
approximately 80 m below OD (Ghyben-Herzberg principle). This is approximately 40 times the depth of the freshwater head measured in Greenland Lake. Assuming that an impermeable layer does not exist, in an unconfined aquifer every metre the water table is lowered the saltwater interface will rise 40 m (Freeze and Cherry, 1979). Stuyfzand (1993) suggests that the Ghyben-Herzberg principle underestimates the depth to the salt water interface.

6.15 The tidal cycle

Before evaluating the possible factors influencing the long-term elevation of the water table at Dawlish Warren it was essential to evaluate whether the tides were temporarily raising water levels and introducing false trends into the data. Therefore, a dipwell was temporarily installed in the main pond on the Local Nature Reserve and monitored for water table fluctuations over a period of 72 hrs (Section 3.2.6).

Pond water levels were monitored during a predicted high spring tide of 4.2 m above Chart Datum. As described in Section 4.7 changes in barometric pressure and the wind may have changed the predicted height of the high spring tide. During the monitoring period pond water levels periodically fluctuated by 5 mm, which was caused by the wind and birds rippling the water surface of the pond. An overall drop in the pond water level of 10 mm was recorded during monitoring, which was most probably caused by evapotranspiration losses from the pond and the seasonal adjustment of the local water table in response to the summer 1995 heat wave. The staff from Dawlish Warren believe that the pond does fluctuate with some spring tides (Walsh, pers. comm), although no quantitative measurements have been taken. Therefore, when analysing the water table data from the dipwell network care was taken to identify any irregular weekly fluctuations which may be related to tidal pressure and ultimately could lead to misinterpreting the annual cyclical
characteristics of the groundwater system.

6.16 Physical characteristics of the dune sands

The following spatial description of the sediment properties on Dawlish Warren will assist in the explanation of the hydrological characteristics described in Sections 6.11 and 6.12. Sediment properties should also be taken into consideration when identifying possible factors influencing annual cyclical water table characteristics (Section 6.17).

6.16.1 Particle size analysis - variability both with depth and within the dune system

At Dawlish Warren samples were collected for particle size analysis at 0.20 m depth next to dipwells 5, 6, 6a, 7 and 8 (Section 3.2.8 and Figure 6.14). At a more detailed level of analysis samples were collected at 0.20 m sampling depth on a 30 m x 30 m sampling grid across part of Greenland Lake (Section 3.2.8 and Figure 3.10).

Samples from the golf course, within 2.5 m distance of dipwells 6, 6a 7 and 8, showed a significant increase in silt and clay content with depth (Table 6.10 and Figure 6.16). At the 0.80 m sampling depth, next to dipwells 6A and 7, 86 % and 78 % respectively of the sample consisted of silt and clay fractions (<62μm). An increase in silt and clay was also measured at the 0.60 m sampling depth next to dipwell 6 and may partially explain the irregular water table characteristics illustrated in Figure 6.15e. The hydrological functioning of dipwell 6 will be investigated further in Section 6.17.1e. The frequency distribution curves in Figure 6.18 also show some variability in the content of fine sand (62 μm-100 μm). The greater content of silt and clay fractions, and fine sands reduces the permeability of the material and the lowers the hydraulic connection between the golf course and the rest of the system. The sediment sampled at dipwell 5 formed a medium to fine grained sand, with relatively uniform particle size characteristics with depth (Table 6.10). Silt and clay
fractions measured down through the profile at dipwell 5 constituted a maximum of 4.5% of the sample volume.

Table 6.10 Variability in particle size distribution characteristics both with depth and across the sampling field next to dipwells 5, 6, 6A, 7 and 8 on Dawlish Warren. (Sediment was sampled within 2.5 m of the dipwells. Dipwell locations are shown on Figure 6.14. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay (<62μm), FS-fine sand (62μm-250μm), MS-medium sand (250μm-500μm), CS-coarse sand (500μm-1mm), >1mm-very coarse sand and fine pebbles. Shaded boxes indicate saturated conditions and therefore accurate sampling was not possible.)

<table>
<thead>
<tr>
<th>Sampling depth</th>
<th>Dipwell 5</th>
<th>Dipwell 6</th>
<th>Dipwell 6A</th>
<th>Dipwell 7</th>
<th>Dipwell 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20 m</td>
<td>S/C 1.5%</td>
<td>S/C 1.7%</td>
<td>S/C 18.0%</td>
<td>S/C 1.0%</td>
<td>S/C 3.2%</td>
</tr>
<tr>
<td></td>
<td>FS 49.5%</td>
<td>FS 38.0%</td>
<td>FS 15.5%</td>
<td>FA 25.0%</td>
<td>FS 38.5%</td>
</tr>
<tr>
<td></td>
<td>MS 42.5%</td>
<td>MS 48.4%</td>
<td>MS 48.5%</td>
<td>MS 69.0%</td>
<td>MS 55.0%</td>
</tr>
<tr>
<td></td>
<td>CS 5.1%</td>
<td>CS 8.7%</td>
<td>CS 15.8%</td>
<td>CS 5.0%</td>
<td>CS 3.2%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 1.4%</td>
<td>&gt;1mm 3.2%</td>
<td>&gt;1mm 2.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40 m</td>
<td>S/C 2.0%</td>
<td>S/C 3.0%</td>
<td>S/C 10.5%</td>
<td>S/C 3.5%</td>
<td>S/C 6.5%</td>
</tr>
<tr>
<td></td>
<td>FS 47.5%</td>
<td>FS 21.5%</td>
<td>FS 32.4%</td>
<td>FS 48.0%</td>
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<tr>
<td></td>
<td>MS 48.9%</td>
<td>MS 69.8%</td>
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<td>MS 34.3%</td>
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</tr>
<tr>
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<td>CS 1.0%</td>
<td>CS 5.7%</td>
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<td>CS 12.0%</td>
<td>CS 6.5%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 0.6%</td>
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<td>&gt;1mm 2.6%</td>
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</tr>
<tr>
<td>0.60 m</td>
<td>S/C 4.0%</td>
<td>S/C 20.0%</td>
<td>S/C 37.0%</td>
<td>S/C 27.0%</td>
<td>S/C 24.5%</td>
</tr>
<tr>
<td></td>
<td>FS 41.0%</td>
<td>FS 13.5%</td>
<td>FS 37.5%</td>
<td>FS 41.4%</td>
<td>FS 33.4%</td>
</tr>
<tr>
<td></td>
<td>MS 49.6%</td>
<td>MS 55.0%</td>
<td>MS 19.8%</td>
<td>MS 27.5%</td>
<td>MS 39.5%</td>
</tr>
<tr>
<td></td>
<td>CS 3.5%</td>
<td>CS 6.9%</td>
<td>CS 5.7%</td>
<td>CS 2.5%</td>
<td>CS 2.6%</td>
</tr>
<tr>
<td></td>
<td>&gt;1mm 1.9%</td>
<td>&gt;1mm 4.6%</td>
<td>&gt;1mm 1.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80 m</td>
<td>S/C 4.5%</td>
<td>S/C 86.0%</td>
<td>S/C 78.0%</td>
<td>S/C 38.5%</td>
<td>S/C 38.5%</td>
</tr>
<tr>
<td></td>
<td>FS 42.5%</td>
<td>FS 10.5%</td>
<td>FS 16.5%</td>
<td>FS 32.4%</td>
<td>FS 32.4%</td>
</tr>
<tr>
<td></td>
<td>MS 51.5%</td>
<td>MS 2.0%</td>
<td>MS 3.5%</td>
<td>MS 25.0%</td>
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<td>&gt;1mm -</td>
<td>&gt;1mm -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Greenland Lake, silt and clay fractions (<62μm) constituted between 0.2 % and 8.5 % of the sample (Table 6.11). A single higher value of 15.0 % was measured at sampling point 2, at a depth of 1.0 m (Table 6.11). The uniform particle size characteristics both with depth (Table 6.11 and Figures 6.17 and 6.18) and across the sampling grid (Table 6.11 and Figures 6.19 and 6.20) demonstrated that this area has a good hydraulic connection with other parts of the system. Unfortunately, the liquid nature of saturated sand prevented accurate sediment sampling beneath the water table.

As illustrated in Figures 6.16-6.20 and Tables 6.10 and 6.11, with the exception of the variable percentage content of silt and clay fractions (<62μm) and fine sand (62 μm-250

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Figure 6.16 Frequency distribution curves for sediment sampled at 1.0 m depth for and next to dipwells 5, 6, 6A, 7 and 8. (Sediment sampling point 13 is shown on Figure 3.10 and the remaining samples were taken within 2.5 m of each dipwell - Figure 6.14.)
μm) on the golf course, the dune sands at Dawlish exhibit relatively uniform particle size characteristics both with depth and across the sampling field.

Figure 6.17 Frequency distribution curves for sediment sampled at 0.20 m depths, at sampling point 3, within Greenland Lake. (The location of the sampling point is shown on Figure 3.10.)
Table 6.11 | Variability in particle size distribution characteristics both with depth and across the dune system, for points 1-7, Dawlish Warren. (Sampling sites are shown on Figure 3.10. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay-<62μm, FS-fine sand-62μm-250μm, MS-medium sand 250μm-500μm, CS-coarse sand- 500μm-1mm, >1mm-very coarse sand and fine pebbles. Shaded boxes indicate saturated conditions and therefore accurate sampling was not possible.)

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### Table 6.11 cont. Variability in the particle size distribution characteristics both with depth and across the dune system, for points 8-12, Dawlish Warren.

(Sampling sites are shown on Figure 3.10. Particle size classification according to Friedman and Sanders (1978). S/C-silt/clay-<62μm, FS-fine sand-62μm-250μm, MS-medium sand 250μm-500μm, CS-coarse sand-500μm-1mm, >1mm-very coarse sand and fine pebbles. Shaded boxes indicate saturated conditions and therefore accurate sampling was not possible.)

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Figure 6.18 Frequency distribution curves for sediment sampled at 0.20 m depths, at sampling point 6, within Greenland Lake. (The location of the sampling point is shown on Figure 3.10.)

Figure 6.19 Frequency distribution curves for sediment sampled at 1.0 m depth for points 1-6 within Greenland Lake. (Sediment sampling locations are shown on Figure 3.10.)
Figure 6.20  Frequency distribution curves for sediment sampled at 1.0 m depth, for points 7-12 within Greenland Lake.  
(Sediment sampling locations are shown on Figure 3.10.)

6.16.2  \( K_{sat} \) below the water table (slug test)

At Dawlish Warren, slug tests were carried out on five piezometers temporarily installed for the purpose of this experiment, within 3 m of dipwells 1, 2, 3A 5, 6, and 8 (Figure 6.14). The depths of \( K_{sat} \) determination are shown in Table 6.12. These wells were located to emphasise any \( K_{sat} \) variability within the system. The analysis of \( K_{sat} \) with depth was again hindered by the liquid nature of saturated sand.

\( K_{sat} \) values recorded on the golf course (next to dipwells 6 and 8) were lower than values measured in Greenland Lake (next to dipwells 1, 2, 3A 5), (Table 6.12). The lower values on the golf course can be explained by the particle size distribution, with an increase in silt and clay fractions occurring at the depth of \( K_{sat} \) determination (Section 6.16.1). The lower \( K_{sat} \) values recorded on the golf course will influence groundwater movement and the degree of hydraulic connection between the golf course and the rest of the system.
Depending on the hydraulic connection changes to the golf course drainage system, or further scrub growth within Greenland Lake, will have varying effects on the elevation of the water table.

Table 6.12  
\( K_{\text{sat}} \) results for Dawlish Warren using the Bouwer and Rice (1976) solution. (\( K_{\text{sat}} \) measurement sites were within 3 m of the permanent water level monitoring dipwells shown on Figure 6.14.)

<table>
<thead>
<tr>
<th>Slug test location (within 3 m of the listed dipwells)</th>
<th>Depth of ( K_{\text{sat}} ) measurement from the ground surface (metres)</th>
<th>( K_{\text{sat}} ) (m d(^{-1}))</th>
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<td>1</td>
<td>0.85-1.15</td>
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<td>2</td>
<td>0.90-1.20</td>
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<td>0.70-1.00</td>
<td>3.90</td>
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<tr>
<td><strong>Average ( K_{\text{sat}} )</strong></td>
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<td><strong>6.33</strong></td>
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The average \( K_{\text{sat}} \) for Dawlish Warren (6.33 m d\(^{-1}\)) was of a similar order of magnitude to that recorded at both Northam (6.04 m day\(^{-1}\)) and Braunton (7.94 m d\(^{-1}\)). The dune sands at Dawlish are very rapid draining according to the FAO (1963) classification.

6.17 The apparent drying out of Dawlish Warren

At Dawlish Warren the main concern is that as a consequence of the perceived drying out of the system the damp meadow species found within Greenland Lake are declining (Section 2.7).

Water table elevations on Dawlish Warren have only been monitored since the start of this research (October 1993) and therefore it was not possible to determine whether there have been any long-term changes in the elevation of the water table. However, the water table
data collected during this research (October 1993-April 1996) were analysed to determine possible factors controlling annual cyclical water table fluctuations.

6.17.1 Possible causes for the drying out of Dawlish Warren.

At Dawlish Warren five possible causes for the apparent drying out of the dune system were identified and will be evaluated in the following subsections (6.17.1a-6.17.1e). Possible causes included changing climatic trends, coastal erosion of the fore dune ridge, increased evapotranspiration losses from scrub species, the creation of wildlife ponds and the efficient pump drainage system on the golf course (Table 1.1).

a) The impact of long-term changes in precipitation and effective precipitation on the elevation of the water table

When evaluating the possible causes for the apparent drying out of the Dawlish system it was essential to consider long-term climatic trends. Precipitation data from Exmouth meteorological station, less than 1 km to the north east of Dawlish Warren and MORECS monthly evapotranspiration data were analysed for the period 1972 to 1995. This period of meteorological data was comparable to that analysed from RAF Chivenor to describe long-term climatic trends at both Braunton and Northam. Throughout this section LTA will refer to the period 1972 to 1995.

The calculated LTA annual precipitation for Dawlish was 776.3 mm. Figure 6.21 shows that the driest years were 1973 and 1975, when precipitation totals were 26 % (572.0 mm) and 32 % (526.3 mm) respectively less than the calculated LTA. In all the other years between 1972 and 1995 annual precipitation totals were between 14 % less than the LTA and 22 % above the LTA. Annual precipitation totals increased from the mid 1970s to a maximum in 1979 (Figure 6.21), when the site received 21 % more precipitation (941.3
mm) than the LTA. Precipitation totals remained above the LTA until 1983. The most prominent trend in the data (Figure 6.21) was the steady decline in precipitation totals from 1983 to 1992. Between these years annual precipitation totals only exceeded the LTA (776.3 mm) in two years and only by a maximum of 5% (815.1 mm). With precipitation as a primary source of groundwater recharge such fluctuations would have lead to a gradual decline in the elevation of the water table on the Warren. A similar dry spell was also described for Braunton and Northam (Section 5.2.1) and was identified as a major contributing cause for the lower water table elevations recorded on Braunton Burrows from the early 1980s up until 1992. From 1993-1995 inputs to the Dawlish system increased and were between 17% (908.1 mm) and 22% (949.6 mm) above the LTA.

Figure 6.21 Annual precipitation (1972-1995) for Dawlish Warren.
More important to the groundwater investigation at Dawlish Warren was effective precipitation, the amount that actually replenished the groundwater system after evapotranspiration losses. At Dawlish from 1972-1995 on average only 24 % (186.5 mm) of annual precipitation recharged the water table, the rest was lost through evapotranspiration. The evapotranspiration rates used to calculate effective precipitation totals were from monthly MORECS data, which averaged evapotranspiration losses over a 40 x 40 km area and were based primarily on inland measurements for short grass. MORECS data may therefore underestimate evapotranspiration losses from a coastal sand dune environment with areas of scrub woodland. However, the calculated LTA annual effective precipitation total of 186.5 mm emphasised the sensitivity of the hydrological system to annual perturbations in precipitation totals and evapotranspiration rates, or additional losses through natural or human inferred causes. Increased losses from the system would be detrimental to both water table elevations on the Warren and the future conservation of the dune habitat ecology. The LTA annual effective precipitation total also emphasised the significance of the decline in effective precipitation totals from 1983 to 1992 (Figure 6.22). In fact, in 1990 Dawlish Warren received only 4.2 mm of effective precipitation, which was 2.25 % of the LTA. Between 1983 and 1992 effective precipitation only exceeded the LTA (186.5 mm) in 1986 when annual effective precipitation was 19.2 % (222.3 mm) greater than the LTA.
Figure 6.22 Annual effective precipitation (1972-1995) for Dawlish Warren.

Dividing the 24 years of effective precipitation data into two equal sample sizes, from 1972-1983 the average annual effective precipitation total for Dawlish Warren was 210.2 m, but from 1984-1995 this figure fell to an average of 171.9 mm. A similar dryer period through the 1980s and into the early 1990s was also described by the Yeandle Whittaker Partnership (1994) in the water resources review of the Dawlish Sandstone aquifer, using meteorological data from Starcross, 2.5 km to the north east of Dawlish Warren (ST 9720 8210) and Luscombe Castle, 3 km to the south west of Dawlish Warren (ST 9430 7680). Their study however, stressed the need for further detailed analysis of much longer term meteorological data in order to evaluate the significance of this dryer period.

In conclusion the detailed analysis of annual precipitation and effective precipitation data has identified a dryer period from the early 1980s through to the early 1990s. With
precipitation as a primary source of groundwater recharge and with a LTA effective precipitation total of 186.5 mm, consecutive years in the 1980s and early 1990s with below average effective precipitation would undoubtedly have had repercussions on the elevation of the water table on the Warren. Reduced inputs to the system during this period would also explain why concerns were raised in 1993 that the hydrology of the system was changing, to the detriment of the diverse plant communities found on the Warren.

b) The impact of coastal erosion on the elevation of the water table.

Erosion of the fore dune ridge was identified as a possible factor influencing the elevation of the water table on Dawlish Warren. Marine erosion of the dune system can lead to changes in the drainage regime and consequently an overall drop in the elevation of the water table (Section 1.4.5).

The movement and erosion of the spit has been documented in the literature since the late 1800s (Martin, 1872, 1876, 1893; Kidson, 1950, 1964; Hydraulics Research Station, 1963, 1965; Hydraulics Research, 1991; Redfern, 1993 and Sims et al., 1995). Variations in the area of Dawlish Warren spit above MHW have been quantified from Ordnance Survey maps by Sims et al. (1995) (Table 6.13) and the statistics demonstrate that there has been an overall decrease in the area of the spit since 1888.

Table 6.13 Variations in the area of Dawlish Warren above MHW, derived from Ordnance Survey maps.
Source: Sims et al. (1995).

<table>
<thead>
<tr>
<th>Survey Date</th>
<th>Area of Dawlish Warren above MHW (m$^2$ x 10$^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1888</td>
<td>0.84</td>
</tr>
<tr>
<td>1956</td>
<td>0.73</td>
</tr>
<tr>
<td>1968</td>
<td>0.72</td>
</tr>
<tr>
<td>1988</td>
<td>0.67</td>
</tr>
</tbody>
</table>
A GIS study of the Warren by Redfern (1993) stated that although recent breaches of the spit have occurred the site has remained relatively stable since the 1960s. However, field observations throughout the period of this research showed that erosion of the Outer Warren was still a major problem (Plate 6.5). Wave undercutting has also causing widespread slumping of the fore dune ridge (Plate 6.5). Today the spit is protected by groynes, stone filled gabion baskets, concrete revetments and a 400 m length of wave-return sea wall, which is fronted with 35,000 tonnes of armour stone (Sims et al., 1995). Marine erosion of the spit should therefore be taken into consideration when evaluating possible contributing causes for the apparent changing hydrological regime at Dawlish Warren.

A further possible contributing cause for the apparent drying out of the dune system is the increase in bare sand caused by human trampling of the Outer Warren. With dominant south westerly on shore winds the exposed sand is being blown inland and is possibly being deposited into the lower-lying damp meadow area of Greenland Lake (Walsh, pers. comm). In the long-term the accumulation of wind blown sand will gradually raise the elevation of the ground surface and increase the depth to the water table. Within the relatively short span of this research the dynamics and deposition of sand on the Warren were not quantified, but should however be taken into consideration when identifying possible contributing causes for the perceived drying out of Dawlish Warren.
c) **The impact of scrub invasion on the elevation of the water table**

Scrub encroachment (Plate 6.6) was also identified as a possible contributing cause for the perceived changing hydrological regime. As detailed in Section 1.7.1, evapotranspiration losses from shrub and tree species are significantly higher than those recorded from bare sand and grass (Table 1.3), consequently reducing groundwater recharge and contributing to an overall lowering of the water table (Bakker, 1981; Stuyfzand 1993; Van Dijk and Grootjans, 1993).

To evaluate the impact of scrub growth on the elevation of the water table, water level data from three dipwells (coded 3, 3A and 4 on Figure 6.14) were analysed from October 1993 to April 1996. Dipwell 3 was located at the very edge of the encroaching scrub woodland, whereas dipwell 4 was 50 m to the south east in the open meadow of Greenland Lake.
Dipwell 3A was installed in February 1995 in between dipwells 3 and 4, and was within 20 m of the nearest scrub growth.

Plate 6.6 Scrub invasion on Dawlish Warren. (Photograph taken August 1995, from dipwell 5 (Figure 5.14) facing south west.)

Changes in water table fluctuations at these dipwells were compared throughout the period, but land elevation differences (in the order of several centimetres) masked the absolute fluctuations. Therefore, in order to draw attention to the fluctuations relative to the ground surface, it was necessary to correct the water table elevation data to a common datum.

Figure 6.23 shows that during both the summer of 1994 and 1995 the elevation of the water table at dipwell 3, located at the very edge of the scrub woodland, was significantly lower than that recorded at dipwell 4 in the open meadow area. From April 1995, water table elevations measured at dipwell 3A were also higher than those recorded at dipwell 3.
Figure 6.23 Water table fluctuations at dipwells 3, 3A and 4, Dawlish Warren. (Water table data are in metres above OD. The locations of the dipwells are shown on Figure 6.14. Dipwell 3A was only monitored from February 1995 to April 1996).

Furthermore, when analysing annual cyclical water table fluctuations for five dipwells on Dawlish Warren (Section 6.11), the water table at dipwell 3 generally fluctuated in excess of all the other dipwells (Table 6.8). All of these characteristics were perhaps an indication of the influence of scrub growth on the elevation of the water table, with increased evapotranspiration losses associated with the scrub growth at dipwell 3 having a localised effect on the elevation of the water table, which did not extend as far as dipwells 3A or 4. A detailed analysis of the physical properties of the dune sands both with depth (to a maximum of 1.30 m) and across Greenland Lake, revealed a uniform particle size distribution, which would not explain the water table elevation differences between dipwells 3, 3A and 4. To gain a better understanding of the effects of scrub invasion on the elevation of the water table, longer-term water table monitoring is required and additional dipwells should be installed in transects at set distances from the scrub woodland.
Annual effective precipitation rates cited in Section 6.17.1a, based on MORECS monthly evapotranspiration data for grass, would be even less for areas of reedbed, woodland or scrub. Grip (1981) stated that in Swedish experiments, during the summer months, evapotranspiration losses from willow (*Salix ruriminalis*) were up to 40% higher than from grass. As explained in Section 5.2.1 actual annual evapotranpiration losses from the various vegetation units found within each of the dune systems were not available. To obtain such data would require setting up long-term lysimeter studies (Stuyfzand, 1993).

With a LTA (1972-1995) annual total effective precipitation of 186.5 mm additional losses from the system through further scrub encroachment would be detrimental to the already finely balanced hydrological system. Future management of the encroaching scrub will need to be considered when recommending practical management options for raising water levels, or preventing any future possible lowering of the water table on Dawlish Warren (Section 8.4.3).

d) The impact of the wildlife pond on the elevation of the water table

The creation of the wildlife pond to the north east of the interpretation centre (Figure 2.3), was identified as a possible contributing cause for the perceived changing hydrological regime on Dawlish Warren. The main concern expressed by the site warden was that the pond was acting as a sink and draining groundwater from the surrounding aquifer (Walsh, pers. comm.). Although annual evapotranspiration rates from open water are greater than those calculated from bare sand or vegetated sand dunes (Table 1.3), Figure 6.24 shows that throughout the monitoring period water levels in the pond did not fall below those recorded in dipwell 2 (sited less than 10 m from the pond), confirming that the pond was merely incised into the local water table and was not acting as a groundwater sink.
Figure 6.24  The elevation of the water table at dipwell 2 in relation to the pond water level. (Water levels are in metres above OD. The location of dipwell 2 and the pond are shown on Figure 6.14).

From a hydrological management point of view, although the pond was beneficial for habitat diversity, the greater evapotranspiration rates associated with open water would be detrimental to the annual water budget.

e) The impact of the Warren golf course pump drainage system on the elevation of the water table

The Warren golf course is drained by a herring bone drainage system. Most of drainage waters flow into a holding pond at the southern end of the golf course (Figure 2.11). Drainage waters are pumped from the pond into the Exe Estuary and effectively become a net loss from the hydrological system. The efficiency of the pump drainage system has been identified as a possible factor influencing the long-term elevation of the water table on Dawlish Warren.
In contrast to other dipwells on the site, water level data from dipwell 6 demonstrated irregular annual cyclical water table fluctuations (Section 6.11). Dipwell 6 was located within 5 m of both the golf course pond and the main feeder drainage ditch (Figure 6.14). With the exception of May to August 1995, dipwell 6 fluctuated less than 0.40 m throughout the monitoring period (Figure 6.25). The immediate explanation for the minimal water table fluctuations at well 6 was that both the pond and drainage ditch were controlling the elevation of the water table. However, sediment properties and the hydraulic efficiency of dipwell 6 should also be taken into consideration. The sudden drop in the water table recorded between May and August 1995 coincided with the draining of the golf course pond for annual dredging.

On several occasions during the monitoring period dipwell 6 was pumped dry, to break up any skin possibly forming around the well casing, which may restrict groundwater flow into the well (Kruseman and de Ridder, 1977). Analysis of the sediment properties down through the profile of dipwell 6, revealed a uniform particle size distribution from the ground surface to a depth of 0.60 m, where an increase in the silt and clay content occurred and constituted 20 % of the sample volume (Table 6.11). Below this depth the water table prevented accurate sampling, but the auger was penetrated to an overall depth of 1.5 m through a predominantly silty/clay saturated sediment. The increased silt and clay content from a depth of 0.60 m may partially explain the minimal fluctuations of the water table during the summer of 1994, creating a perched water table at this elevation (Figure 6.25). However, if sediment properties were the only factor influencing the water table then annual cyclical fluctuations in excess of 0.40 m would be expected in response to monthly variations in effective precipitation, with the top 0.60 m of the sediment forming a uniform medium to fine grained sand (Table 6.11). This suggested that perhaps the golf course drainage system was also partially controlling the elevation of the water table.
Dipwell 6A was installed in May 1995 within 4 m of dipwell 6 (Figure 6.14). The water table at dipwell 6A (Figure 6.25) fluctuated more than at dipwell 6, but an analysis of the sediment revealed a higher silt and clay content throughout the profile increasing to 86 % at the 0.80 m sampling depth. (Table 6.11). An increase in silt and clay fractions is associated with a lower specific yield value and a greater water table rise in response to recharge and a greater drop in response to groundwater withdrawal, as discussed in Section 6.3. It was therefore difficult to distinguish between the controls of sediment properties and the pump drainage system on the annual cyclical fluctuations of the water table at dipwell 6A.

Water table data from dipwells 7 and 8 (Figure 6.26), both located on the golf course, also showed very different annual cyclical water table characteristics compared with water table
Figure 6.26 Water table fluctuations at dipwells 7 and 8.

(Water table data are in metres above OD. The locations of the dipwells are shown on Figure 6.14. Dipwells 7 and 8 were only monitored from February 1995 to April 1996).

data analysed from dipwells within Greenland Lake (Figures 6.15a-6.15e). At dipwell 7, which was less than one metre from the main drainage channel (Figure 6.14), the elevation of the water table gradually increased from the outset of monitoring in February 1995, through to May 1995 (Figure 6.28), whereas typically water levels on the Warren began to decline from early March in response to lower precipitation totals (Figures 6.15a-6.15e). The possibility of well blockage was eliminated. A feasible explanation for this water table characteristic was that prior to February 1995, during the exceptionally wet winter of 1994/1995, the pump drainage system was used intensively keeping the water level in the pond and main drainage ditch at a minimum to allow maximum drainage efficiency. In effect the drainage system was managing the elevation of the water table in dipwell 7. A more relaxed drainage regime was adopted as weekly precipitation totals dwindled in early
March, allowing the water table at dipwell 7 to equilibrate.

Dipwell 8 was sited 30 m from the main drainage channel (Figure 6.14). Sediment samples taken next to dipwell 8 revealed a uniform particle size distribution with depth (Table 6.11) and silt and clay fractions constituted a maximum of 6.4 % of the sample. The particle size characteristics were similar to those described for the 12 sampling points within Greenland Lake (Section 6.16.2). However, generally on the golf course the sediment contained a greater and more variable silt and clay content (Section 6.16) which would influence groundwater movement within this part of the system. In contrast to the dipwells monitored in Greenland Lake dipwell 8 demonstrated a dampened response to seasonal variations in precipitation and a maximum annual cyclical water table fluctuation of 0.60 m was recorded. Again these water table characteristics may partially be an indication of the golf course drainage regime controlling seasonal water table fluctuations.

This section has highlighted the importance of both variable sediment properties and the artificial drainage system in controlling the annual cyclical range of the water table fluctuations on the golf course. Depending upon the degree of hydraulic connection the golf course artificial drainage system may be influencing the groundwater hydrology across a wider area. Future management of this part of the groundwater system will need to be considered carefully in order to prevent any future possible changes to the groundwater hydrology of the Warren.

f) Summary

Again climate was probably the single most important factor controlling water levels on the Warren. With a LTA annual effective precipitation total of 186.5 mm reductions in
precipitation, or increased evapotranspiration rates associated with scrub growth and open water would be detrimental to the groundwater budget. These figures also emphasised the importance of the decline in effective precipitation totals from the early 1980s through to the early 1990s when effective precipitation totals were consistently below the LTA. Analysis of the dipwell data also showed that the golf course drainage system and scrub encroachment were influencing annual cyclical water table elevations. Additional losses through artificial drainage and scrub growth would reduce effective inputs to the system. It is these factors which can be managed to prevent any future lowering of the water table on Dawlish Warren (Section 8.4.3). Erosion of the fore dune ridge may also be influencing the groundwater drainage regime.

6.18 Conclusion

Chapter 6 was divided into two main parts, evaluating the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Northam Burrows and Dawlish Warren respectively. Hydrological characteristics of each dune system were related to variability in effective precipitation, the geology, saline intrusion, the tide and the physical properties of the dune sands. At each site water level data from the dipwell monitoring network were analysed to detect possible factors controlling annual cyclical water table fluctuations. The hydrology of Northam and Dawlish is summarised in Sections 6.18.1 and 6.18.2. The data presented in this chapter are essential to the final recommendation of hydrological management options (Sections 8.4.2 and 8.4.3) aimed at raising water levels, or preventing any further lowering of the water tables in order to conserve the dune habitat ecology.
6.18.1 Characteristics of Northam Burrows

a) Characteristics of the water table

At Northam the groundwater system was mounded and closely followed the shape of the surface topography. The elevation of the groundwater mound was sensitive to seasonal variations in the distribution of effective precipitation. The flow nets indicated that the hydraulic gradients at Northam were generally marginally steeper than those measured at Braunton. This was possibly related to the greater silt and clay content in the sediment, restricting groundwater movement and hence under the principle of Darcy’s Law increasing the hydraulic gradients in order to move groundwater through the system. At Northam annual cyclical water table fluctuations were generally in excess of one metre. Distance from the centre of the groundwater mound had no significant effect on the range of annual cyclical water table fluctuations.

When investigating the relationship between the elevation of the water table and effective precipitation, the Northam system responded quicker than the Braunton system. This was because at Northam the comparatively smaller unsaturated zone reduced the time taken for precipitation water to reach the water table. At Northam the elevation of the water table was most closely correlated, at a 95% significance level, with effective precipitation of the preceding 0-30 days, or 31-60 days.

b) Depth to bedrock or an impermeable basal layer

Borehole investigations identified a continuous relatively impermeable silty/clay layer beneath Northam Burrows, which was taken as the lower boundary to the groundwater system in groundwater calculations and in the hydrological description of the system.
c) Saline intrusion and the influence of the tide on water table fluctuations

Taking into consideration the depth to the lower boundary to the groundwater system and the height of the water table in the most seaward observation wells, salt water intrusion was not a problem within the local groundwater system at Northam.

A semi-diurnal fluctuation of the water table was recorded at dipwell 11, coinciding with the height of the tide. Water table data from this well were therefore not used to characterise the annual cyclical functioning of the groundwater system.

d) Physical characteristics of the dune sands

A spatial analysis of the sediment properties at Northam revealed a rapid draining, medium to fine grained sand, with an average $K_{sat}$ of 6.04 m d$^{-1}$. The average $K_{sat}$ for Northam was less than the average for Braunton (7.94 m d$^{-1}$) emphasising the importance of the greater silt and clay content in controlling groundwater movement through the system. The lowest measurements of $K_{sat}$ were recorded in the vicinity of the Pill (3.00-3.33 m d$^{-1}$), in a silt and clay rich sediment. Variability in the sediment properties will need to be taken into consideration when recommending practical hydrological management options for increasing water levels on the Burrows (Section 8.4.2).

e) Possible factors influencing the elevation of the water table on Northam Burrows

Climatic trends - on average between 1972 and 1995 only 32 % (273.4 mm) of annual precipitation recharged the groundwater system the rest was lost through the process of evapotranspiration. As precipitation is the main source of groundwater recharge a LTA (1972-1995) annual effective precipitation total of 273.4 mm emphasised the sensitivity of the groundwater system to variability in effective inputs and additional losses through natural, or human inferred causes. These figures also stressed the importance of the decline
in effective precipitation totals from 1983 to mid 1992, when effective precipitation was below the LTA in eight out of ten years. Long-term reductions in effective precipitation was undoubtedly the key factor controlling the hydrological functioning of Northam Burrows.

Marine erosion - erosion of the system around the landfill and the landward retreat of the pebble ridge may be affecting the groundwater drainage regime.

Artificial drainage - analysis of available water table data (October 1993-March 1996) showed that the drainage ditches on the Great Plain were controlling annual cyclical water table elevations and preventing widespread winter flooding to suit the requirements of the graziers and golfers, but possibly to the detriment of nature conservation.

Removal of the tidal flaps from the Pill in 1994 - tidal inputs to the system have increased, but these waters drain as soon as the tide recedes. The effectiveness of sluice controlling the Pill and maintaining constant water levels in the channel in order to raise water levels on the Burrows will depend upon the hydraulic connection of the Pill with the surrounding land.

Construction of the landfill and access road - the disposal of household refuge has substantially reduced tidal inputs to the north eastern part of the system.
6.18.2 Characteristics of Dawlish Warren

a) Annual cyclical water table fluctuations

The water table monitoring network installed on Dawlish Warren proved insufficient to accurately describe the shape, elevation or gradient of the water table. However, the water table data collected during this research were used to describe the spatial and temporal variability in the annual cyclical functioning of the groundwater system. With the exception of the irregular water table characteristics recorded at dipwell 6, annual cyclical fluctuations ranged from 0.68-1.21 m. Human activity was a key factor influencing annual cyclical water table fluctuations within this smaller scale dune system.

The elevation of the water table at Dawlish showed a quicker response to effective precipitation than the larger Braunton system, because of the smaller unsaturated zone. The elevation of the water table was most closely correlated, at a 95 % confidence level, with effective precipitation of the preceding 0-30 days or 31-60 days. The response time was similar to that observed at Northam.

b) Depth to bedrock or an impermeable basal layer

Seismic studies have mapped the depth of the New Red Sandstone beneath Dawlish Warren, but fail to differentiate between the overlying sands, clays and gravels. Therefore it is uncertain whether there is a lower impermeable boundary to the groundwater system, or whether groundwater is being lost through vertical drainage to the regional aquifer. A more detailed geological survey of the Dawlish Warren could be undertaken in future research.

c) Saline intrusion and the influence of the tide on water table fluctuations

The problem of saline intrusion at Dawlish Warren will depend upon whether an
impermeable continuous layer exists above the New Red Sandstone. In the absence of this layer salt water would be found at an approximate depth of 80 m below OD (Ghyben-Herzberg principle). The depth of the salt water, fresh water interface will rise if the perceived drying out of the system continues.

The monitoring of the main pond showed that during a spring tide, of a predicted height of 4.2 m above Chart Datum, tidal pressure did not influence the elevation of the water table.

d) Physical characteristics of the dune sands

With the exception of the $K_{sat}$ values recorded on the golf course the dune sands were very rapid draining, with an average $K_{sat}$ of 6.04 m d$^{-1}$. $K_{sat}$ values on the golf course were considerably less (1.55 m d$^{-1}$ and 3.90 m d$^{-1}$), because of an increased percentage content of silt and clay fractions at the depth of $K_{sat}$ determination. With the exception of the greater and more variable content of silt, clay and fine sands on the golf course the dune sands at Dawlish demonstrated a uniform particle size distribution both with depth and across the sampling field.

e) Possible factors influencing the elevation of the water table on Dawlish Warren

Climate - the analysis of annual precipitation and effective precipitation data identified a dryer period throughout the 1980s and into the early 1990s. In such a finely balanced hydrological system, with a LTA annual effective precipitation total of 186.5 mm, such variations in effective inputs to the groundwater system would undoubtedly have had a significant impact on the elevation of the water table on the Warren.

Marine erosion - erosion of the fore dune ridge is prominent along the entire front of the
spit and has possibly contributed to changes in the groundwater drainage regime from the Warren.

Scrub growth - from late spring and throughout the summer the elevation of the water table was consistently lower at the edge of the scrub woodland, compared with that measured less than 50 m away within Greenland Lake meadow. As a result of the scrub encroachment and associated increased evapotranspiration losses a localised drawdown effect was evident. On average (1972-1995) only 24% of annual precipitation reached the water table (186.5 mm), therefore further losses through increased evapotranspiration rates associated with further scrub growth would be detrimental to water levels on the Warren.

Creation of the wildlife pond - although the pond is good for habitat diversity, the higher evapotranspiration rates associated with open water will have a negative impact on the annual water budget for the area. The pond was not acting as a groundwater sink and was merely incised into the local water table.

Drainage of the golf course - in comparison with other dipwells on the Warren water table data collected on the golf course demonstrated irregular annual cyclical fluctuations. Water table elevations were being influenced by both the golf course pump drainage system and the variable sediment properties found within this part of the system.
Chapter 7
Groundwater modelling
Visual MODFLOW
Chapter 7

Groundwater modelling - Visual MODFLOW

7.0 Introduction

This chapter will begin to focus on the final aim of the research, to recommend sustainable management options aimed at raising water levels, or preventing any further lowering of the water table on Braunton Burrows. This will partially be achieved through the use of Visual MODFLOW (VMODFLOW), developed by Waterloo Hydrogeologic Software (Guiger, 1995). As described in Section 3.4.2a VMODFLOW was selected as the most suitable model for the Braunton groundwater resource management investigation, incorporating the original United States Geological Survey's (USGS) MODFLOW code (McDonald and Harbaugh, 1988) with a fully integrated and graphically controlled pre and post processor.

There are three objectives to the modelling exercise; to determine whether a commercially available model can be calibrated to simulate the scale and complexity of the hydrological functioning of the Braunton groundwater system; to use the model to gain a better understanding of the hydrological functioning of the system and ultimately to develop, and test a set of hydrological management scenarios, to predict the hydro-ecological consequences of altering boundary conditions, or introducing new management practices into the system.

Detailed analysis of the water table data from Braunton Burrows (Section 5.1), identified the following water resource management questions which could not be easily answered with analytical techniques;
• What effect will lowering the overall base elevation of West Boundary Drain have on water levels in the adjoining Braunton Burrows dune system?

• Considering the present hydrology and geometry of West Boundary Drain, what impact will raising water levels in the drain have on the elevation of the Burrows water table?

• What effect will marine erosion of the fore dune ridge have on the elevation of the Burrows water table?

• What long-term effects will further scrub encroachment have on the elevation of the water table within Braunton Burrows?

Chapter 7 will begin by evaluating the various steps in the modelling protocol (Figure 7.1). The modelling protocol will include developing a conceptual model, designing the modelling grid, the calibration process, sensitivity analysis, model validation and finally the use of the calibrated model as a prediction tool to quantify the response of the groundwater system to various hydrological management scenarios. The modelling predictions will be presented and evaluated with regards to their validity and implications for future water level management on Braunton Burrows.
7.1 Grid design and the conceptual model of Braunton Burrows

7.1.1 The modelling domain

Having determined the purpose of the modelling exercise (Section 3.4) the second stage of the modelling protocol was to design the modelling grid and develop a conceptual model of the system. This involved defining the hydrostratigraphic units, sediment characteristics, boundary conditions and inputs, and outputs from the system.

As described by McDonald and Harbaugh (1988), groundwater flow within the aquifer is simulated using the block centred grid, whereby a two dimensional grid is superimposed over the modelling domain. The nodes in the centre of the cells are used to define the elevation of the water table (Figure 7.2). A vertical dimension is then added using layers, which can be confined, unconfined, or a combination of both (McDonald and Harbaugh, 1988; Bradley, 1994; 1996). The vertical dimension of each cell is determined by the top and bottom elevations of each individual layer.
As described by Bradley (1994;1996), cells within each layer are defined as either variable head, constant head or inactive cells. When running VMODFLOW a water table elevation is only calculated for variable head cells, which form the active cells of the modelling domain (Figure 7.2).Inactive cells define areas of the grid which are outside the dimensions of the modelling domain. Therefore, it is possible to model irregular areas using the original rectangular grid (Figure 7.2). Constant head cells are specified during model parameterisation to define boundary cells of known head values (Section 7.1.5). In three dimensional models such as VMODFLOW specified head nodes represent the elevation of the water table.

The active cells of the modelling domain covered approximately 680 ha of dune and marsh
habitat and encompassed the observation well monitoring network (Figure 7.3). The observation wells were important indicators of the degree of model calibration, and were used to compare simulated water table elevations with those previously measured in the field. The spatial distribution of observation wells, within the inherited monitoring network, therefore determined the area of the Burrows which could be modelled and calibrated. The absence of water table monitoring sites to the north of observation well transect 1N-6N, meant that it was not possible to model the northern third of the system, which included Saunton golf course. The boundaries of the active modelling domain are described further in Section 7.1.5.

The observation well calibration points were sited in wet slacks, or on dune turf where the water table was typically less than one metre from the ground surface throughout the year. The ecology of these areas were therefore sensitive to long-term hydrological change and were of primary consideration when analysing the modelling results.

The dimensions of the modelling cells were a function of the expected curvature in the water table, or potentiometric surface, with a finer grid spacing required to define highly curved water table surfaces (Anderson and Woessner, 1992). Also the finer the grid the greater the accuracy of the groundwater flow simulations. Taking into consideration both of these points grid cell dimensions assigned to the entire modelling domain were 50 m x 50 m. The discretisation of the grid was comparable to, or finer than other MODFLOW studies of a similar scale (Table 3.2).
Figure 7.3  The Braunton modelling domain.
7.1.2 Hydrostratigraphic units

With reference to Section 4.8, field experimentation indicated that the stratigraphy of the Braunton system was relatively straightforward. A study of the dune sands demonstrated that they possessed both uniform particle size characteristics and values of $K_{sat}$, resting upon a relatively impermeable silty/clay layer, which formed the lower boundary of the groundwater system. However, initial attempts to accurately simulate the groundwater system and the characteristic water table mound with only two layers, a sand layer 15.0 m thick resting on top of a silt and clay layer 1.0 m thick, proved unsuccessful in steady-state simulations. A comparison of simulated water table elevations with those observed in the field showed that at the centre of the groundwater mound the water table was a maximum of 4.5 m lower than field measurements. This demonstrated that the dune system stratigraphy was spatially more complex than indicated by the somewhat limited spatial analysis of the sediment properties described in Section 4.8.

The final modelling domain was therefore divided into six layers of varying dimensions (Figure 7.4) in order to build up the shape of the dune landscape, to include more spatial variability in $K_{sat}$ and to incorporate the possible effects on the groundwater hydrology of vertical flow between model layers.

The stratigraphic composition of the layers are illustrated in Figure 7.4, taken from cross-section A-B on Figure 7.3. The boreholes described in Section 4.5 revealed a continuous basal layer of compacted silt and clay at an elevation of between -0.96 m below OD and +1.10 m above OD. From the five boreholes it was not possible to calculate the dip of this layer. Therefore, for the purpose of the Braunton groundwater model layer 6 was represented a continuous silt and clay layer extending from 0-1 m above OD (Figure 7.4).
Layer 1 - Aeolian dune sands
Layer 2 - Aeolian dune sands
Layer 3 - Aeolian dune sands, with a transition to marshland along the eastern margin of the system
Layer 4 - Aeolian dune sands, with a transition to marshland along the eastern margin of the system
Layer 5 - Silt, clay and aeolian dune sands (2 m thick)
Layer 6 - Marine basal clay (1 m thick)

Figure 7.4 Stratigraphic composition of model layers-cross sectional profile A-B. (Location of cross-sectional profile A-B is shown on Figure 7.3.)
7.1.3 $K_{sat}$

Initial $K_{sat}$ values for dune sands, assigned to zones within the model layers, were taken from the slug tests results described in Section 4.8.1. VMODFLOW also takes into account anisotropy, differentiated between vertical and horizontal $K_{sat}$, whereas the slug tests measure a combination of both. Aeolian sands are relatively homogenous and are about as isotropic as any deposits occurring in nature (Freeze and Cherry, 1979). In a study by McNamara et al. (1992) vertical anisotropy for sands and gravels was set at a factor of 0.001. In clays horizontal to vertical anisotropy is seldom greater than 10:1 and is usually less than 3:1 (Freeze and Cherry, 1979). A greater horizontal anisotropy represents a greater magnitude of water flux in the horizontal direction. Anisotropy was therefore taken into consideration when assigning $K_{sat}$ values to each layer within the active modelling domain.

An average $K_{sat}$ value of 7.94 m d$^{-1}$ (Table 4.15) was used as an initial value in the parameterisation of the sand layers shown on Figure 7.4. As described in Section 4.8.3, $K_{sat}$ was not measured to the east of the American Road (Figure 7.3). Therefore, little was known about the variability in $K_{sat}$ in this transitional area from dune sands to marshland, except that West Boundary Drain was incised into a silty clay sediment. Values of $K_{sat}$ for this area were therefore estimated, ensuring that the initial values were within the plausible ranges defined by Freeze and Cherry (1979) and Heath (1983), (Table 7.1). Identifying the exact zones within the modelling domain where $K_{sat}$ varied was subjective and a renowned source of error in any model calibration (National Research Council, 1990). From borehole investigations, to determine the depth to bedrock or an impermeable layer, layer 5 (1-3 m above OD) was shown to contain a greater amount of silt and clay fractions (Figure 7.4). Initial values of $K_{sat}$ assigned to layers 5 and 6 were also estimated, with consideration to the plausible ranges for various sediment types quoted by Freeze and Cherry (1979) and Heath (1983), (Table 7.1).
Table 7.1  \(K_{sat}\) values used in the parameterisation of the Braunton Burrows groundwater model.

(\(K_{sat}\) for silt and clay sediments were estimated with reference to the plausible ranges cited by Freeze and Cherry (1979) and Heath (1983). In silt and clay sediments a horizontal anisotropy factor was also incorporated to encourage a greater horizontal flux.)

<table>
<thead>
<tr>
<th>Layer and sediment type</th>
<th>Initial (K_{sat}) values assigned to the model layers (m d(^{-1}))</th>
<th>Final (K_{sat}) values assigned to the calibrated model (m d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Layer 1</strong> Aeolian dune sands</td>
<td>7.94 estimated from the slug tests</td>
<td>1.75-2.10 depending on the zone within the layer</td>
</tr>
<tr>
<td><strong>Layer 2</strong> Aeolian dune sands</td>
<td>7.94 estimated from the slug tests</td>
<td>1.75-2.10 depending on the zone within the layer</td>
</tr>
<tr>
<td><strong>Layer 3</strong> Aeolian dune sands</td>
<td>7.94 estimated from the slug tests</td>
<td>1.75-2.50 depending on the zone within the layer 0.10-0.25 depending on the zone within the layer</td>
</tr>
<tr>
<td>Transitional zone to marshland (silty sand)</td>
<td>(K_{sat}) of silty sand estimated from ranges of values cited in published sources; 10.0 - 10(^{-3}) (Freeze and Cherry, 1979). 10.0 - 10(^{-2}) (Heath, 1983).</td>
<td></td>
</tr>
<tr>
<td><strong>Layer 4</strong> Aeolian dune sands</td>
<td>7.94 estimated from the slug tests</td>
<td>1.75-2.50 depending on the zone within the layer 0.01-0.25 depending on the zone within the layer</td>
</tr>
<tr>
<td>Transitional zone to marshland (silty sand)</td>
<td>(K_{sat}) of silty sand estimated from ranges of values cited in published sources; 10.0-10(^{-3}) (Freeze and Cherry, 1979). 10.0-10(^{-2}) (Heath, 1983).</td>
<td></td>
</tr>
<tr>
<td><strong>Layer 5</strong> Predominantly silt, with some clay and sand particles. Transitional zone to marshland (Silty sediment with some clay particles)</td>
<td>(K_{sat}) of silt estimated from ranges of values cited in published sources; 10(^{-1})-10(^{-5}) (Freeze and Cherry, 1979). 1.0-10(^{-3}) (Heath, 1983).</td>
<td>0.01-0.25 depending on the zone within the layer</td>
</tr>
<tr>
<td><strong>Layer 6</strong> Predominantly clay, with some sand and silt particles. Widely interspersed with small pebbles (2-8 mm diameter).</td>
<td>(K_{sat}) of clay estimated from ranges of values cited in published sources; 10(^{-4})-10(^{-6}) (Freeze and Cherry, 1979). 10(^{-3})-10(^{-7}) (Heath, 1983)</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Some of the Braunton sediment descriptions (Table 7.1) do not fall into any one specific category defined by either Freeze and Cherry (1979), or Heath (1983). The trial and error calibration would help identify zones within the model layers where the initial estimates of $K_{sat}$ values were either too high or too low.

7.1.4 Precipitation and evapotranspiration

Monthly precipitation data were obtained from RAF Chivenor Meteorological Station, via the Environment Agency. Monthly evapotranspiration rates were taken from MORECS data based on short grass. Evapotranspiration rates from different vegetation species found on the Burrows were estimated from the literature (Section 1.6.1) and would therefore possibly incorporate some error into the model calibration. These were the most accurate evapotranspiration rates available for the Burrows.

7.1.5 Boundary conditions

In steady-state simulations the boundary conditions of the modelling domain largely determine the flow pattern (Anderson and Woessner, 1992). Boundary conditions influence transient solutions when the effects of the transient stress reach the boundary. Model boundaries are either physical, such as the presence of an impermeable body of rock or a large surface water body, or hydraulic which includes groundwater divides or streamlines. Modelling problems require at least one specified boundary node head in order to give the model a reference from which to calculate hydraulic heads (Anderson and Woessner, 1992).

At Braunton the eastern margin of the modelling domain was bounded by a physical boundary, West Boundary Drain, which was mathematically represented as a constant head boundary (Figure 7.3). Water levels in West Boundary Drain are penned. The summer penning level is in force from March to October and the winter penning level from October
to March (Slade, pers.comm.). The boundary elevations were adjusted according to the month of simulation. A degree of uncertainty surrounds the exact monthly elevation of water levels in West Boundary Drain prior to the major drainage improvements in 1983. The hydro-metric surveys of West Boundary Drain described in Sections 5.3.2 and 5.3.3 provided the essential data to parameterise the eastern boundary of the model.

The western boundary of the model was also set as a constant head (Figure 7.3). The boundary water table elevations were estimated from water levels measured in the most seaward observation wells and from dune slack elevations, which were taken to represent the approximate elevation of the water table. A degree of uncertainty was therefore incorporated when assigning water table elevations to these boundary nodes. The boundary elevation was adjusted according to the month of simulation. Water level data collected from the most seaward observation wells were the only source of information on monthly water table fluctuations along this boundary. The same technique was also used to assign constant head cells along the southern boundary of the modelling domain (Figure 7.3). Initially the southern boundary was created as a no-flow boundary, but this prevented drainage from the system and kept water levels in the most southerly observation wells too high.

The northern boundary of the modelling domain was mathematically represented as a no-flow boundary, representing the approximate location of the groundwater mound divide (Figures 4.2-4.6). No-flow boundary conditions occur when the flux across the boundary is zero. VMODFLOW assumes a no-flow boundary if not otherwise specified.
7.2 Model calibration

The third step in the modelling protocol was the calibration process. Calibration was accomplished by finding a set of parameters, boundary conditions and stresses which simulated water table elevations and fluxes that were comparable to those measured in the field (Rushton, 1981). Finding this set of values amounts to solving what is known as the inverse problem. The methodology of the trial-and-error calibration process has been summarised in Figure 7.5.

![Diagram of trial-and-error calibration procedure](image)

Figure 7.5 Trial-and-error calibration procedure.

The output from each model run in a trial-and-error calibration should be evaluated both qualitatively and quantitatively, so that a best match between simulated and observed water table elevations can be achieved. To date there is no standard protocol for evaluating the calibration process, although the need for a standard methodology is recognised as an important part of quality assurance in model application (National Research Council, 1990).
The qualitative and quantitative methods used in both the steady-state and transient trial-and-error calibration process, to achieve the best possible solution, are described below.

Simulated water table elevations for each model run were displayed in the VMODFLOW output module as contour maps. These were then compared with SURFER contour plots of observed data, to provide a visual qualitative measure of the similarity between simulated and observed water table elevations. The contour plots gave an idea of the spatial distribution of error in the calibration. However, as described by the National Research Council (1990) with this method of analysis some error may be introduced by the contouring interpolation routine and therefore should not be used as the only proof of calibration.

The VMODFLOW modelling package itself provided powerful analysis tools for evaluating the quality of the fit between computed and observed water table elevations. For each model run a regression analysis was provided, which compared the simulated results to the observed data, at the various calibration points within the model domain. A regression graph was displayed with calibration statistics, including the 'mean error', a correlation coefficient ($r$), and a coefficient of determination ($r^2$), which described the degree of association between the two sets of paired values. After each trial-and-error calibration run, to determine whether the correlation was statistically significant at a 99 % confidence level, the correlation coefficient was compared to a critical table of values provided in Hammond and McCullagh (1975). The calibration residuals at each observation point were also displayed to help identify where further refinements to the model calibration were required.

Even in a quantitative evaluation, the judgement of when the fit between model and reality is good enough is subjective (Anderson and Woessner, 1992; National Research Council, 1990; Dowd, pers, comm). Calibration was dependent upon the trial-and-error adjustment
of parameter values and boundary conditions between sequential model runs, until the quality of fit, explained by the contour plots and the regression output, could not be improved upon. It was important to ensure that the parameter values used in the calibration process were both realistic and within the predetermined ranges of values.

VMODFLOW can simulate both steady-state and time varying hydrological conditions. The MODFLOW code incorporated in the VMODFLOW modelling package simulates three dimensional groundwater flow indirectly by means of a governing differential equation derived from Darcy's Law and thought to represent the physical processes that occur within the system, together with equations that describe heads, or flows along the boundaries of the model (McDonald and Harbaugh, 1988). Vertical and horizontal groundwater flow are calculated from Darcy's Law and the continuity equation, whereby changes in water storage are measured as the difference between inflows and outflows from the system (Bradley, 1994).

7.2.1 Steady-state calibration

Steady-state flow occurs when at any point in a flow field the magnitude and direction of flow velocity are constant with time (Freeze and Cherry, 1979). A steady-state model can be calibrated against any month of the year. In this study the month of November was chosen to represent a typically wet month (Figure 2.4) with low evapotranspiration rates (Figure 2.5). It was also important to select a representative year, in terms of water table elevations measured during the month of November, to ensure that the calibration was realistic and not based upon extreme hydrological events (Anderson and Woessner, 1992). Calculations showed that water table elevations measured at the 23 observation wells in November 1982 were representative of average November measurements taken between 1972 and 1983 (Table 7.2).
Parameterisation of the steady-state model required specifying the boundary conditions, $K_{sat}$, precipitation and evapotranspiration for each node of each layer within the modelling domain. Throughout the remainder of this chapter simulated water table elevations refer to those calculated by the model and observed water table elevations refer to those measured from observation wells in the field.

Table 7.2 Water table elevations within the Braunton system from November 1982 to May 1983 as a percentage difference from the monthly average water table elevations between 1972-1983.

(Water table elevations were measured at all 23 observations wells in the monitoring network - Figure 7.3.)

<table>
<thead>
<tr>
<th>Month</th>
<th>Water table elevations measured at 23 observation wells within the Braunton system from November 1982 to May 1983, expressed as a percentage difference from the monthly average between 1972-1983.</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 1982</td>
<td>6.5 % less than - 7.0 % more than</td>
</tr>
<tr>
<td>December 1982</td>
<td>6.3 % less than - 8.8 % more than</td>
</tr>
<tr>
<td>January 1983</td>
<td>10.0 % less than - 10.0 % more than</td>
</tr>
<tr>
<td>February 1983</td>
<td>2.6 % less than - 7.0 % more than</td>
</tr>
<tr>
<td>March 1983</td>
<td>6.0 % less than - 5.5 % more than</td>
</tr>
<tr>
<td>April 1983</td>
<td>6.0 % less than - 9.0 % more than</td>
</tr>
<tr>
<td>May 1983</td>
<td>4.2 % less than - 6.4 % more than</td>
</tr>
</tbody>
</table>
A uniform precipitation rate must be assigned to the entire modelling domain, but in VMODFLOW, precipitation could only be applied to the top layer of the model and only to active modelling cells. At Braunton the top layer had the most inactive cells (Figure 7.6), because of the necessity to simulate the high dunes. However, there was the option of applying precipitation to the highest active cell in each vertical column of the modelling domain (Figure 7.6). Similarly, evapotranspiration rates could only be applied to active cells in the top layer of the model. Unfortunately VMODFLOW would not accommodate the assignment of evapotranspiration rates in the same way, to the highest active cell in each vertical column, despite the manual stating that it would. The spatial assignment of evapotranspiration rates was partially overcome by specifying an effective precipitation rate (precipitation minus losses from evapotranspiration). However, in the summer months when evapotranspiration losses exceeded precipitation totals, VMODFLOW would not accept negative effective precipitation rates. VMODFLOW's ability to only assign evapotranspiration rates to the uppermost modelling layer was a severe limitation to the length and timing of the groundwater flow simulation period. It should be noted that this preprocessor problem did not affect the steady state, or transient calibration process in any way, but did however, prevent the model from being used to simulate the effects of the theoretical water level management scenarios during the summer months (Section 7.4).

The 23 observation wells in the monitoring network in 1982 and 1983 were used as indicators of the degree of calibration. Although monitoring of observation wells 1N-6N did not begin until mid 1992, these wells were referred to during the model calibration to indicate the possible range of water table elevations along the northern boundary of the active modelling domain.
Precipitation and evapotranspiration rates can only be applied to the top layer (layer 1) of the model and then only to active cells.

However, there was the option of assigning precipitation to the highest active cell in each vertical column, which ensured precipitation was added to the entire modelling domain. The same option in the model would not work when applying evapotranspiration rates.

To overcome this problem an effective precipitation total (precipitation minus evapotranspiration losses) was assigned to the highest active cell in each vertical modelling column, but the model would only accept positive values.

Figure 7.6 Assigning precipitation and evapotranspiration to the top layer of the model.
When comparing simulated and observed water table elevations from the initial November 1982 steady-state simulations it was evident that the system was draining too quickly. The groundwater system was mounded, but water levels at the centre of the mound were up to 4.0 m lower than field measurements. Monthly precipitation totals for RAF Chivenor, supplied by the Environment Agency were known with a high degree of accuracy and were therefore not altered during the trial-and-error calibration process. MORECS data provided the most accurate estimates of actual evapotranspiration losses from the system, and therefore it was again decided not to adjust these values during calibration.

Cross-sections and the analysis of groundwater flow paths helped to determine whether the elevation of the constant head cells along the western and southern boundaries of the modelling domain needed adjusting. The boundary elevations were altered less than 0.10 m during the calibration, so that simulated water table elevations demonstrated a better match with observed water table elevations.

Therefore, the main parameter to be adjusted between sequential runs to improve the calibration and reduce the rate of drainage from the system was $K_{\text{sat}}$, which was a key variable controlling the movement of groundwater through the dune system. In particular greater consideration was given to the assignment of $K_{\text{sat}}$ in both layers 5 and 6, and in the transitional zone from dune sands to marshland, where $K_{\text{sat}}$ values have been estimated from the literature (Section 7.1.3). The final $K_{\text{sat}}$ values used in the model are summarised in Table 7.1. The $K_{\text{sat}}$ values for dune sands were considerably less than values initially derived from the slug tests, but however, were still within the plausible range for medium to fine grained sand quoted by Freeze and Cherry (1979) and Heath (1983). The calibration problems suggested that the physical properties of the dune sand were far more complex than uncovered in the limited spatial analysis of the sediment properties in Section 4.8.
Following the adjustment of $K_{sat}$ values and the boundary elevations along the western and southern margins of the modelling domain, the model was successfully calibrated under steady-state conditions for November 1982. On average the simulated water table elevations was 0.36 m higher than field measurements, based on the observed water table elevation data from 23 observation wells (Figure 7.7 and Table 7.3). The correlation coefficient (0.92) was significant at 99 %, with $r^2$ explaining 84 % of the association between these two variables. However, when attempting to use the steady-state model to simulate the warmer and dryer month of May 1983 and only changing the time varying parameters of precipitation, evapotranspiration and boundary elevations, the model on average underestimated water table elevations within the system (Table 7.3). May 1983 was chosen because water table elevations measured within the 23 observations wells on the Burrows were representative of average water levels measured during the month of May for the monitoring period 1972 to 1983. The model on average underestimated water table elevations by 0.53 m, although the correlation coefficient (0.84) showed that there was still a significant positive relationship (at a 99 % confidence level) between the two paired sets of variables (Figure 7.8 and Table 7.3). The calibration residuals indicated that the greatest errors were being measured towards the centre of the groundwater mound. The most probable explanation was that at the edge of the system the simulated groundwater levels were being controlled by head elevations assigned to the constant head boundary cells. Also water levels at the edge of the dune system were buffered by groundwater draining from higher elevations within the mound, as described in Section 4.3.
Figure 7.7  Steady-state VMODFLOW calibration output for November 1982. (Water table contours are in metres above OD.)
Table 7.3  Simulated and observed water table elevation differences for November 1982 and May 1983, under steady-state calibration conditions. (Water level measurements are in metres. \( r \)-correlation coefficient. \( r^2 \) - measure of association between the two variables.)

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Difference between simulated and observed water table elevations - steady-state conditions (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nov 1982</td>
</tr>
<tr>
<td>1</td>
<td>0.29</td>
</tr>
<tr>
<td>2</td>
<td>0.43</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.42</td>
</tr>
<tr>
<td>6</td>
<td>0.19</td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>0.81</td>
</tr>
<tr>
<td>12</td>
<td>-0.56</td>
</tr>
<tr>
<td>13</td>
<td>-1.00</td>
</tr>
<tr>
<td>14</td>
<td>0.15</td>
</tr>
<tr>
<td>15</td>
<td>2.20</td>
</tr>
<tr>
<td>23</td>
<td>0.42</td>
</tr>
<tr>
<td>25</td>
<td>0.66</td>
</tr>
<tr>
<td>27</td>
<td>0.68</td>
</tr>
<tr>
<td>36</td>
<td>-0.54</td>
</tr>
<tr>
<td>38</td>
<td>-1.34</td>
</tr>
<tr>
<td>40</td>
<td>0.56</td>
</tr>
<tr>
<td>42</td>
<td>0.12</td>
</tr>
<tr>
<td>43</td>
<td>1.24</td>
</tr>
<tr>
<td>55</td>
<td>0.65</td>
</tr>
<tr>
<td>56</td>
<td>0.86</td>
</tr>
<tr>
<td>58</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Descriptive statistics
- Mean
- \( \sigma \)
- \( r \) (sig. at 99%)
- \( r^2 \) (%)

| Precipitation(mm) | 140.6 | 111.5 |
| Et (mm)           | 30.0  | 69.6  |
Figure 7.8  Steady-state VMODFLOW calibration output for May 1983. (Water table contours are in metres above OD.)
The steady-state simulations produced an equilibrium water table profile in response to different stresses and did not take into consideration changes in internal storage, which vary according to the sand, silt and clay content of the material. The annual cyclical water table fluctuations at Braunton demonstrated time varying changes in groundwater storage (Section 4.3). Water was released from storage when the water table fell and was taken into storage during periods of groundwater recharge. Storage was therefore possibly part of the reason why the system could not be accurately calibrated in warmer and dryer months under steady-state conditions.

Generally the application of a steady-state model is justified when water table fluctuations are small in comparison with the total thickness of the aquifer and also the configuration of the water table remains relatively constant (i.e., the high points remain highest and the low points remain lowest), (Freeze and Cherry, 1979; Anderson and Wang, 1982). The greater error in the steady-state calibration results for May 1983 suggested that this assumption did not strictly hold true for the Braunton system and so in an attempt to improve the calibration a transient model was developed.

7.2.2 Transient calibration

Transient flow (unsteady flow or non-steady flow) occurs when at any point in a flow field the magnitude and direction of the flow velocity change with time (Freeze and Cherry, 1979). A transient simulation is divided into stress periods, which are defined as stages where there is the option of changing certain time varying parameters, such as boundary conditions, precipitation, evapotranspiration, and even flow conditions within a river or drain. Each stress period is then divided into time steps and for each time step the water table elevation is calculated. The smaller the time steps the more accurate the representation of the transient changes in the flow field (Anderson and Woessner, 1992).
A transient simulation produces a set of head conditions for each time step within each stress period, whereas steady-state simulations generate only one set of heads for the equilibrium solution (Anderson and Woessner, 1992).

At Braunton the transient calibration began using the initial conditions from the November 1982 calibrated steady-state solution. In the transient simulation of the unconfined Braunton aquifer it was necessary to specify specific yield and specific storage for each active cell of the modelling domain. These parameters describe the capacity of the aquifer to transfer water to and from storage (Price, 1996). As stated by Rushton (1981) storage parameters are not easily, or accurately measured in the field and therefore in many modelling solutions are estimated from plausible ranges cited within the literature. Specific storage values quoted by Domencio (1972) and specific yield values by Johnson (1967), were used to parameterise the transient groundwater model.

In the transient solution the simulation period was discretised into monthly stress periods, from November 1982 to May 1983. Throughout the transient calibration period monthly water table elevations were representative of average monthly elevations measured between 1972 and 1983 (Table 7.2). Each monthly stress period was divided into 15 time steps.

During the transient calibration specific yield and specific storage values were systematically altered within predetermined plausible ranges for sands, silts and clays, in an attempt to reduce the rate of drainage from the system and to improve the calibration during the summer months. $K_{sat}$ values were not adjusted having been extensively altered during the steady-state calibration runs (Section 7.2.1)
Figures 7.9-7.15 and Table 7.4 show that despite using a transient calibration and incorporating storage parameters the model sand dune system was still sensitive to monthly variations in effective precipitation and was still draining far too quickly. For example, in February 1983 when precipitation almost equalled evapotranspiration losses the system began to drain, underestimating the elevation of the water table. The calibration residuals showed that the greatest errors occurred more central within the groundwater mound (Table 7.4), for the same reasons as discussed in Section 7.2.1.

The average water table calibration error from November 1982 to May 1983 ranged from +0.36 m to -0.79 m, with water table elevations increasingly deviating from the mean from February onwards (Table 7.4). For each month of the transient model the correlation coefficients, ranging from 0.94 to 0.88, were significant at a 99 % confidence level and explained between 88 % and 77% of the association between the two sets of paired variables (Table 7.4).

The calibration error was partially related to VMODFLOW being a saturated groundwater flow model and therefore took no account of rates of water movement through the unsaturated zone. The model assumed that during each stress period precipitation instantaneously replenished the groundwater table. However, as described in Section 4.8.5, this is not the case, as the hydraulic conductivity of unsaturated dune sands commonly decreases to 1/100 or 1/1000 of its value at saturation (Landon, 1984). Therefore, the time taken for effective precipitation to reach the water table is a function of the depth of the overlying unsaturated material. Even in months with no effective precipitation antecedent recharge would still percolate through the unsaturated zone to replenish the water table.
Figure 7.9  Transient VMODFLOW calibration output for November 1982
(Water table contours are in metres above OD.)
Figure 7.10 Transient VMODFLOW calibration output for December 1982. (Water table contours are in metres above OD.)
Figure 7.11 Transient VMODFLOW calibration output for January 1983. (Water table contours are in metres above OD.)
Figure 7.12  Transient VMODFLOW calibration output for February 1983. (Water table contours are in metres above OD.)
Figure 7.13  Transient VMODFLOW calibration output for March 1983.
(Water table contours are in metres above OD.)
Figure 7.14  Transient VMODFLOW calibration output for April 1983.
(Water table contours are in metres above OD.)
Figure 7.15 Transient VMODFLOW calibration output for May 1983. (Water table contours are in metres above OD.)
Table 7.4 Simulated and observed water table elevation differences for November 1982 to May 1983, under transient calibration conditions.
(Water level measurements are in metres. r-correlation coefficient. r^2 - measure of association between the two variables.)

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Difference between simulated and observed water table elevations - transient simulations (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.29</td>
</tr>
<tr>
<td>2</td>
<td>0.43</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
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<td>4</td>
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</tr>
<tr>
<td>6</td>
<td>0.19</td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>0.81</td>
</tr>
<tr>
<td>12</td>
<td>-0.56</td>
</tr>
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363
In model calibration a perfect correspondence between field and model water table elevations cannot be expected, because of the need simplify the hydrogeological framework when formulating the conceptual model. Also model input data will rarely characterise all of the scales of variability within a system.

7.3 Sensitivity analysis

In principle the physical parameter values (i.e., permeability, storage, precipitation and evapotranspiration) are measured for every node of the model, but in practice local data or a single 'global' value is used (Bromley and Robinson, 1995). No matter how much data are available model predictions will never be perfect. As described by Anderson and Woessner (1992) it is necessary for the modeller to be aware of the limitations of the derived solution through sensitivity analysis, which will quantify the error in a calibrated model, that arises from uncertainties in the estimate of aquifer parameters, stresses and boundary conditions. A solution can often be found, but is unstable with small changes in the data producing a quite different solution, which renders more uncertainty in the modelling results (Brooks et al., 1994).

During the sensitivity analysis transient calibrated values for $K_{sat}$, storativity, precipitation, evapotranspiration and boundary conditions were changed one parameter at a time. The resulting change in the elevation of the water table from the calibrated transient solution was a measure of the sensitivity of the model to that particular parameter (Anderson and Woessner, 1992). The sensitivity of the model to changes in various parameters was evaluated from November 1982 to January 1983, which were the months best calibrated in the transient model (Table 7.4). The sensitivity analysis results are summarised in Table 7.5, which shows the average difference between water table elevations simulated in the sensitivity test and those previously measured in the transient calibration. These figures
were based upon water level measurements from 23 observation wells within the monitoring network.

\( K_{sat} \) values assigned to layers 4, 5, and 6 (Table 7.1) were increased by 100 % and decreased by 50 % to evaluate the model's sensitivity to this parameter. These percentage changes ensured that the adjusted \( K_{sat} \) values were still within plausible ranges for sand, silt and clay defined by Freeze and Cherry (1979). The sensitivity results were useful in determining which layer must be specified with the greatest accuracy in order to successfully model the flow system (Gillham and Farvolden, 1974). The sensitivity results showed that layer 4 in particular was sensitive to changes in \( K_{sat} \) and a 100 % increase in the parameter value caused the water table on the Burrows to drop on average by between 0.69 m and 0.75 m during the three month sensitivity analysis period. As already discussed in Section 7.2.1, when initially running the steady-state model with \( K_{sat} \) values typical of those measured in the slug test experiments (7.94 m day\(^{-1}\)) the calibration was poor.

Therefore, in subsequent runs \( K_{sat} \) values were significantly lowered (Table 7.1). A 50 % decrease of \( K_{sat} \) values in layer 4 on average caused the water table to rise by between 0.58 m and 0.70 m over the same analysis period. The apparent sensitivity of layer 4 to \( K_{sat} \) emphasised the need for more spatially detailed \( K_{sat} \) data to ensure maximum accuracy in the model predictions. Layers 5 and 6 were less sensitive to changes in \( K_{sat} \) (Table 7.5). This can partially be explained by the fact that although the percentage change in \( K_{sat} \) values were proportionate, the order of magnitude of change was less. The \( K_{sat} \) values of layers 5 and 6 were in the order of centimetres or decimetres per day, whereas the \( K_{sat} \) of layer 4 was in the order of metres per day.

365
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<th>Resulting changes</th>
<th>November 1982</th>
<th>December 1982</th>
<th>January 1983</th>
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<td>Standard deviation**</td>
<td>Average difference*</td>
<td>Standard deviation**</td>
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<td>100 % increase</td>
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<td>Layer 5: Horizontal and vertical hydraulic conductivity</td>
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<td>100 % increase</td>
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<td>0.26</td>
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<td>-0.05</td>
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<tr>
<td>Precipitation</td>
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<td>0.40</td>
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<td>50 % increase</td>
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<tr>
<td>Evapotranspiration rate</td>
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<td>50 % increase</td>
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</tr>
<tr>
<td>Lower the seaward constant head boundary by 0.50 m</td>
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<td>0.30</td>
<td>-0.22</td>
<td>0.29</td>
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Table 7.5 Results of a transient calibration sensitivity analysis.

(*Average difference between simulated water table elevations in the sensitivity test and those simulated in the calibrated model.
**Standard deviation of the differences between simulated water table elevations for the sensitivity test and those simulated for the calibrated model. Measurements are based on water table data from 23 observations wells shown on Figure 7.3).
The model appeared relatively insensitive to a 20% decrease in specific yield values. This percentage change ensured that all adjusted values were still within the plausible ranges for sands, silts and clays according to the classification of Johnson (1967). During the analysis period the maximum effect of adjusting this parameter value was to cause a drop in the elevation of the water of 0.07 m (Table 7.5). Considering the spatial range of water table elevations being simulated (Figures 7.8-7.14), the sensitivity of the model to this parameter was less significant and therefore the accurate assignment of specific yield values were less critical to the final modelling predictions.

Throughout the calibration process the sensitivity of the model to effective inputs has been emphasised. The impact of a 25% decrease and a 50% increase in precipitation totals on the elevation of the water table was evaluated. These adjusted precipitation rates were incorporated into the calculation of monthly effective precipitation rates. Table 7.5 shows that even a 25% decrease in monthly precipitation caused the average elevation of the water table to fall by between 0.50 m and 0.60 m. A 50% increase in areal precipitation resulted in the average elevation of the Burrows water table rising by 0.59 m and 0.68 m between November 1982 and January 1983. The sensitivity of the model to this parameter emphasised the importance of ensuring that accurate monthly precipitation data were available for the site. These results also stress the significance of long-term reductions in precipitation as discussed in Section 5.2.1.

Evapotranspiration rates used in the calculation of effective precipitation totals were perhaps less accurate. The MORECS data provided an averaged evapotranspiration rate for a 40 x 40 km area that encompassed the Braunton Burrows study site. MORECS evapotranspiration rates were also based on losses from short grass. The sensitivity analysis (Table 7.5) showed that a 50% increase in evapotranspiration rates from
November 1982 to February 1983 caused an average drop in the elevation of the water table of between 0.13 m and 0.17 m. The sensitivity of the model to this net loss would have been even greater if simulating summer months when maximum evapotranspiration rates occur. As described in Section 7.1.4, variations in evapotranspiration rates associated with different vegetation species were estimated from the literature. The sensitivity of the model to this parameter emphasised the need for more accurate evapotranspiration data specifically for the Braunton dune system and its various types of vegetation.

The elevation of the water table along the seaward boundary of the modelling domain was estimated from water levels measured in the most seaward observation wells and from slack elevations shown on the Braunton Burrows habitat map. The sensitivity analysis results showed that a 0.50 m drop in the boundary elevation caused water levels, measured at the 23 observation wells, to fall on average by between 0.20 m and 0.23 m during the sensitivity analysis period (Table 7.5). The model's sensitivity to changes in this parameter, as with others described in this section, emphasised a the need for more detailed spatial and temporal data.

7.4 Model validation

Uncertainties associated with the parameterisation of the groundwater model have been identified during model calibration and the sensitivity analysis. The parameter values used in the calibrated model may therefore not accurately represent field water table elevations under a different set of hydrologic stresses, boundary conditions and effective precipitation rates. The next stage in the modelling protocol was therefore model validation. According to Konikow (1978) a model is validated if its accuracy and predictive capability were proven to lie within acceptable limits of error, by tests independent of the calibration data. If the parameters were adjusted during validation the procedure became a second calibration
and another independent data set was required to perform the validation (Anderson and Woessner, 1992). Validation was accomplished when simulated water table elevations were comparable to field observations without changing any parameter values.

Validation of the Braunton model was tested running a transient simulation from October 1976 to April 1977. This period was before any drainage improvements took place on West Boundary Drain, which may have influenced monthly fluctuations of the water table on the Burrows (Section 5.2.5). Only the time varying parameters of precipitation, evapotranspiration and boundary conditions were altered during the model validation simulations. All of the other model parameters remained the same as in the 'best fit' transient solution (Section 7.2.2). The simulated water table elevations were compared with field observation well data and the results have been summarised in Table 7.6.

The transient validation run, from October 1976 to April 1977 (Table 7.7), showed that the average difference between simulated and observed water table elevations, over the validation period, ranged from +0.19 m to -0.53 m (Table 7.7). The greatest difference between simulated and observed water table elevations came in the Spring (March and April 1977), which again was the result of a decrease in monthly precipitation totals and an increase in evapotranspiration losses, emphasising the sensitivity of the model to monthly variations in effective precipitation. Without having to change any other model parameters except for those that vary with time, the average monthly model errors (difference between simulated and observed water table elevations) were of a similar range to those described for the best fit transient calibration solution (Table 7.4). For each month of the transient validation run there was a strong positive correlation between the two variables. The correlation coefficients ranged from 0.58 to 0.91 and were statistically significant at a 99 % confidence level. $r^2$ explained between 33 % and 82 % of the
Table 7.6 Results of the model validation - difference between simulated water table elevations from the validation run and field observation water table data. (Water level measurements are in metres. r-correlation coefficient. \( r^2 \) - measure of association between the two variables. Observation well locations are shown on Figure 7.3.)

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Precipitation (mm)

|                          | 157.2      | 107.6        | 130.0                  | 116.7        |

Et (mm)

|                          | 41.7       | 24.2         | 16.5                   | 18.3         |

370
association between these two sets of paired variables. The successful validation of the model meant that greater confidence could be placed in the modelling predictions presented in Section 7.5.

7.5 The use of the model for future water level management at Braunton Burrows

The final stage in the modelling protocol was the use of the calibrated transient model to predict the response of the groundwater system to various hydrological management scenarios. Three scenarios were investigated;

Scenario A - evaluated the response of the Burrows water table to the deepening of West Boundary Drain by a maximum of one metre.

Scenario B - evaluated the response of the Burrows water table to raising water levels in West Boundary Drain by 0.25 m.

Scenario C - evaluated the response of the Burrows water table to an increase in scrub coverage.

7.5.1 Scenario A

As described in Section 5.3.3, in the summer of 1983 the Internal Drainage Board carried out extensive drainage improvement works on West Boundary Drain and sections of the channel were deepened by almost one metre (Figure 5.26). Also field drainage ditches on the marsh within 5 m of observation well 23 were reinstated. In Section 5.2.5 these drainage improvements works were identified as a probable contributing cause for the lower water table elevations recorded on the Burrows from 1983. No records exist to describe the depth, width, or flow regime of the field drainage ditches immediately after their
reinstatement in 1983 and therefore it was impossible to accurately model this part of the system and confidently interpret the effects that these field drainage ditches would have had on the Burrows groundwater hydrology. However, in scenario A the model was used to evaluate the sensitivity of the Burrows water table to the deepening of West Boundary Drain. The simulation was run for the same period for which the model was initially calibrated, November 1982 to May 1983. In this theoretical scenario West Boundary Drain was deepened in December 1982, by the same amount illustrated on the drainage improvement plans (Figure 5.26). The impact on the Burrows water table of deepening West Boundary Drain was measured as the difference between simulated water table elevations and those recorded in the transient calibration run (Figures 7.9-7.15).

Results

The results from scenario A are summarised in Table 7.7. The modelling predictions indicate that the deepening of West Boundary Drain affected the elevation of the water table across the entire modelling domain. The model indicated that the greatest overall impact was recorded in parts of the system closest to West Boundary Drain and more central within the groundwater mound, including water levels measured at observation wells 1, 2, 3, 4, 6, 23, 36 and 56 (Table 7.7). At these observation wells immediately after the drainage improvements in December 1982 the elevation of the water table fell by between 0.20-0.57 m (Table 7.7). The modelling results indicated that the greatest impact of the drainage improvements occurred in December 1982, along the eastern margin of the system, thereafter the water table began to show a slight recovery in the order of centimetres as groundwater drained from higher elevations in the mound in order to attain a new equilibrium water table elevation between the two systems.
Table 7.7 Results of scenario A - the response of the Braunton dune system water table to deepening West Boundary Drain by a maximum of one metre in its lower sections. (Results are calculated as the difference between scenario A simulated water levels and those simulated for the same period in the transient calibration (Section 7.2.2). Water level measurements are in metres. Observation well locations are shown on Figure 7.3.)

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Difference between simulated and transient calibrated water table elevations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.55</td>
</tr>
<tr>
<td>2</td>
<td>-0.49</td>
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</tr>
<tr>
<td>4</td>
<td>-0.30</td>
</tr>
<tr>
<td>6</td>
<td>-0.20</td>
</tr>
<tr>
<td>7</td>
<td>-0.10</td>
</tr>
<tr>
<td>10</td>
<td>-0.10</td>
</tr>
<tr>
<td>11</td>
<td>-0.07</td>
</tr>
<tr>
<td>12</td>
<td>-0.14</td>
</tr>
<tr>
<td>13</td>
<td>-0.06</td>
</tr>
<tr>
<td>14</td>
<td>-0.06</td>
</tr>
<tr>
<td>15</td>
<td>-0.06</td>
</tr>
<tr>
<td>23</td>
<td>-0.29</td>
</tr>
<tr>
<td>25</td>
<td>-0.12</td>
</tr>
<tr>
<td>27</td>
<td>-0.12</td>
</tr>
<tr>
<td>36</td>
<td>-0.24</td>
</tr>
<tr>
<td>38</td>
<td>-0.16</td>
</tr>
<tr>
<td>40</td>
<td>-0.03</td>
</tr>
<tr>
<td>42</td>
<td>-0.17</td>
</tr>
<tr>
<td>43</td>
<td>-0.06</td>
</tr>
<tr>
<td>55</td>
<td>-0.08</td>
</tr>
<tr>
<td>56</td>
<td>-0.57</td>
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<td>58</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Descriptive statistics:
- **Mean**
- **σ**

<table>
<thead>
<tr>
<th>Precipitation (mm)</th>
<th>Mean</th>
<th>Precipitation (mm)</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
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<td>23.5</td>
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<td></td>
<td>36.1</td>
<td>23.5</td>
<td>36.1</td>
</tr>
<tr>
<td></td>
<td>74.3</td>
<td>23.5</td>
<td>36.1</td>
</tr>
<tr>
<td></td>
<td>111.5</td>
<td>23.5</td>
<td>36.1</td>
</tr>
</tbody>
</table>
It should be stressed that these modelling predictions are not the definitive answer, because as described in Sections 7.2 and 7.3 conceptualization of the modelling domain simplifies the hydrogeological framework. Also input parameters such as $K_{sat}$ were systematically adjusted during the calibration process to more accurately simulate observed water table elevations. The $K_{sat}$ of the sand, silt and clay material in layers 5 and 6, and in the transitional zone from dune sands to marshland were in fact estimated from plausible ranges given by Freeze and Cheery (1979). Although the model was calibrated to the optimum, Anderson and Woessner (1992) state that trial-and-error calibrations do not produce unique solutions and therefore introduce uncertainty into the model results. The modelling predictions should therefore only be taken as an indication of the actual effects such management practices would have on the groundwater hydrology of Braunton Burrows.

For the simulation period December 1982 to May 1983 greatest confidence was given to the December 1982 and January 1983 model solutions. Thereafter, because of the sensitivity of the system to monthly variations in effective precipitation a degree of uncertainty surrounded the accuracy of the model predictions. However, what was apparent from this modelling scenario was that the drainage improvements along the eastern boundary of the system in 1983 would have influenced water levels on the Burrows, contributing to the general overall decline in the elevation of the water table from the early 1980s, as described in Section 5.1.

The model predictions indicated that any future deepening of West Boundary Drain could lead to further lowering of the Burrows water table. West Boundary Drain will therefore need to be carefully managed to prevent any further loss or damage to the dune habitat flora and fauna.
7.5.2 Scenario B

The aim of scenario B was to evaluate the impact on the elevation of the water table on the Burrows of raising water levels in West Boundary Drain by 0.25 m. As described in Section 5.3.3 there was the potential to raise water levels in this drain throughout the year, without causing widespread flooding and the loss of agricultural production.

The transient simulation was run from October 1993 to April 1994, which was ten years after the drainage improvement works had been carried out on West Boundary Drain. In the first model run all parameters were kept the same, simulating the lower ditch elevation and water levels resulting from the 1983 channel improvements. In the second run water levels in West Boundary Drain were raised by 0.25 m from November 1993 through to April 1994. The impact on the elevation of the Burrows water table of raising the ditch water level was therefore measured as the difference between water table elevations simulated in run 1 and those simulated in run 2. The observation well network was revised in June 1992 and so for this scenario water table elevation differences were measured at the 18 observation wells listed in Table 7.8.

Results

The impact on the Burrows water table of raising water levels in West Boundary Drain by 0.25 m is summarised in Table 7.8.
Table 7.8 Results of scenario B - the response of the Braunton dune system water table to raising water levels in West Boundary Drain by 0.25 m. (Results are calculated as the difference between run 1 and run 2 simulated water table elevations. Water level measurements are in metres. Observation well locations are shown on Figure 7.3.)

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Difference between simulated and transient calibrated water table elevations.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.025</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>0.025</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
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<td>0.025</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>36</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>37</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
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<td>0.025</td>
<td>0.025</td>
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<tr>
<td>39</td>
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<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>2N</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>3N</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>4N</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5N</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>6N</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Descriptive statistics:

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.02</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>0.021</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>0.032</td>
</tr>
<tr>
<td></td>
<td>0.039</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>0.041</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>0.041</td>
<td>0.032</td>
</tr>
</tbody>
</table>

| Precipitation (mm) | 74.2 | 163.2 | 131.5 | 100.2 | 94.0 | 67.9 |
| Et (mm)            | 18.6 | 26.9  | 25.8  | 19.5  | 33.0 | 75.6 |
The modelling results indicated that raising water levels in West Boundary Drain by 0.25 m resulted in the Burrows water table rising on average by 0.041 m. The observation wells showing the greatest response were those located closest to the drain, including wells 1, 2, 36, 1N and 2N (Table 7.8). The further the observation well from West Boundary Drain the less effect raising water levels in the drain had on the elevation of the Burrows water table. These modelling results should not be taken as the definitive, because again they are dependent on the accuracy of the adjusted $K_{sat}$ values assigned to the various zones of the modelling domain and in particular the $K_{sat}$ values specified in the transitional zone from dune sands to marshland (Freeze and Cherry, 1979). However, the main conclusion to be drawn from this modelling scenario was that raising water levels in West Boundary Drain was an effective management option for increasing the elevation of the water table on the Burrows, to sustain and enhance the dune habitat flora and fauna.

7.5.3 Scenario C

In the 1992 management plan for Braunton Burrows, English Nature expressed their concerns that scrub was rapidly encroaching upon the dune system and was possibly contributing to lower water table elevations (English Nature, 1992), (Section 5.2.3). In 1990, in the most recent vegetation survey of the Burrows, approximately 8% of the dune habitat was mapped as scrubland (Nature Conservancy Council, 1990). Up until September 1996, when English Nature withdrew National nature Reserve status from the site, scrub growth was mechanically managed. Without controlled management scrub species will continue to encroach.

In this scenario the transient calibrated model was used to evaluate the impact of increasing the scrub coverage shown on the 1990 Braunton Burrows habitat map by 100%, to cover approximately 16% of the dune system. Each scrub cluster mapped on the habitat map
was increased in area by 100%. The model was run for April and May 1983, when temperatures were sufficient to stimulate vegetation growth and the process of evapotranspiration. The limitations of the model in only being able to assign evapotranspiration rates to the upper most layer of the modelling domain (Section 7.2.1), or positive effective precipitation rates to the highest active cell in each vertical column, prevented a longer term simulation into the summer months, where the effects of increased scrub coverage would have been more prominent in the model's predictions. The impact on the elevation of the water table was calculated as the difference between scenario C simulated water table elevations and those previously simulated in the final transient calibration (Figures 7.9-7.15).

Results

The model predictions for Scenario C are summarised in Table 7.9. A 100 % increase in scrub coverage in April and May 1983 caused water table elevations to fall on average by 0.03 m. The standard deviations for April and May 1983 indicated that the water table fluctuated less than 0.02 m from the mean. Higher evapotranspiration losses associated with the increase in scrub coverage affected the water table across the entire modelling domain (Table 7.9), which again emphasised the model's sensitivity to changes in effective inputs and also the hydraulic efficiency of the aquifer. The results from this scenario gave a useful indication of the probable hydrological consequences of stopping to manage scrub growth on the Burrows. In the long-term, the cumulative seasonal impact of increased evapotranspiration rates would be detrimental to an already finely balanced hydrological system (Section 5.2.1) and could result in further changes to the ecological structure of the Burrows.
Table 7.9 Results of scenario C - the effects on the elevation of the Burrows water table of increasing scrub coverage by 100%.
(Results are calculated as the difference between scenario C simulated water levels and those simulated in the transient calibration (Section 7.2.2). Water level measurements are in metres. Observation well locations are shown on Figure 7.3.)

<table>
<thead>
<tr>
<th>Observation well</th>
<th>Difference between simulated and transient calibrated water table elevations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April 1983</td>
</tr>
<tr>
<td>1</td>
<td>-0.03</td>
</tr>
<tr>
<td>2</td>
<td>-0.04</td>
</tr>
<tr>
<td>3</td>
<td>-0.02</td>
</tr>
<tr>
<td>4</td>
<td>-0.03</td>
</tr>
<tr>
<td>6</td>
<td>-0.03</td>
</tr>
<tr>
<td>7</td>
<td>-0.02</td>
</tr>
<tr>
<td>10</td>
<td>-0.04</td>
</tr>
<tr>
<td>11</td>
<td>-0.03</td>
</tr>
<tr>
<td>12</td>
<td>-0.05</td>
</tr>
<tr>
<td>13</td>
<td>-0.04</td>
</tr>
<tr>
<td>14</td>
<td>-0.03</td>
</tr>
<tr>
<td>15</td>
<td>-0.02</td>
</tr>
<tr>
<td>23</td>
<td>-0.05</td>
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<td>25</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>-0.03</td>
</tr>
<tr>
<td>36</td>
<td>-0.02</td>
</tr>
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<td>38</td>
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<td>-0.02</td>
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<tr>
<td>42</td>
<td>-0.02</td>
</tr>
<tr>
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<tr>
<td>55</td>
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<td>56</td>
<td>-0.03</td>
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<tr>
<td>58</td>
<td>-0.02</td>
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<td>Descriptive statistics:</td>
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</tr>
<tr>
<td>Mean</td>
<td>-0.03</td>
</tr>
<tr>
<td>σ</td>
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<tr>
<td>Precipitation (mm)</td>
<td>74.3</td>
</tr>
<tr>
<td>Et (mm)</td>
<td>56.8</td>
</tr>
</tbody>
</table>
7.6 Conclusion

The modelling exercise was a positive attribute to the research. This chapter has shown that it is possible to model the scale and hydrogeology of the Braunton groundwater system with Visual MODFLOW, a commercial groundwater flow modelling package, incorporating the original USGS MODFLOW code. In the process of conceptualising and calibrating the groundwater model, and testing its sensitivity, a further insight into the hydrological functioning of the Braunton groundwater system was gained. The model was also used to test a set of water level management scenarios, to predict the hydro-ecological consequences of altering boundary conditions, or introducing new management practices into the system.

Problems encountered during the initial steady-state calibrations identified a common criticism of modelling in general, the importance of sufficient detail in the field data to ensure maximum accuracy in the model calibration and final hydrological predictions. A lack of spatially detailed $K_{sat}$ data was the greatest problem encountered during the calibration and simulation of the groundwater mound. $K_{sat}$ values in layers 5 and 6 and in the transitional zone to marshland were therefore estimated from plausible ranges defined by Freeze and Cherry (1979) and were extensively altered in subsequent steady-state runs, until simulated water table elevations corresponded more closely with those measured in the field. The model was successfully calibrated for winter conditions, but when attempting to simulate months with lower precipitation rates and greater evapotranspiration losses, the model appeared to drain far too quickly and underestimated water table elevations on the Burrows.

Initially it was thought that using a transient calibration, allowing the groundwater system to gradually re-adjust with time and incorporating storage parameters, would help reduce
the rate of groundwater drainage and improve the calibration. However, even under transient conditions the model was still far too sensitive to monthly variability in effective precipitation and underestimated the elevation of the water table in comparatively drier months. The main problem was that VMODFLOW was a saturated groundwater flow model, which assumed a uniform rate of groundwater recharge. At Braunton there is a large unsaturated zone and therefore rates of groundwater recharge are a function of depth to the water table. VMODFLOW took no account of these varying recharge rates. To more accurately simulate the groundwater domain a combination model would be required, which would simulate water movement in both the saturated and unsaturated zones as a unitary system. The disadvantage of using this type of model, or any model that involved the unsaturated zone, was the introduction of considerable additional complexity and a need for detailed data on the movement of water through the unsaturated zone (Anderson and Woessner, 1992).

A further problem encountered with the model, which limited its usefulness in the Braunton scenario, was the models inability to assign evapotranspiration rates other than to the top layer of the model. At Braunton this was the layer with the smallest dimensions and the most inactive cells. Although this was partially overcome by applying an effective precipitation rate to the highest active cell in each vertical column, the model would not accept negative values typical of the British summer time. This limited the period of simulation.

Despite these initial problems ultimately the model was satisfactorily calibrated to predict the hydro-ecological consequences of three management scenarios. The results from these scenarios would assist in the final recommendation of water level management options for Braunton, aimed at raising water levels and preventing any future possible lowering of the
water table. As a result of the models sensitivity to various parameters, such as $K_{sat}$, precipitation and evapotranspiration, the modelling predictions were only interpreted as probable indicators of the hydro-ecological consequences of introducing or changing hydrological stresses within the system.

In the first modelling scenario the predictions indicated that the deepening of West Boundary Drain would cause a drop in the elevation of the water table across the entire modelling domain. The greatest drop in the elevation of the water table was recorded in observation wells closest to West Boundary Drain. The model predictions emphasised the sensitivity of the Braunton system to changes in the drainage regime along the eastern boundary and therefore identified the need for stringent management of this channel to prevent any future possible lowering of the Burrows water table, which would threaten the dune slack habitat.

Simulating the post 1983 geometry of West Boundary Drain, the second hydrological management scenario evaluated the impact of raising water levels in the ditch by 0.25 m. Observation wells closest to West Boundary Drain showed the greatest water table rise. The maximum average rise in the elevation of the water table recorded during the simulation period was 0.041 m. The modelling results therefore indicated that raising water levels in West Boundary Drain by 0.25 m was an effective management option for raising water levels on the Burrows.

In the final modelling scenario, as a result of increased evapotranspiration losses associated with a 100% increase in scrub coverage, the water table at Braunton fell on average by 0.03 m over a two month simulation period (April and May 1983). The impact would have been even greater if simulating further into the summer season, when typically higher
evapotranspiration rates occur. The possible hydrological consequences of increased scrub growth on the Burrows emphasised the need for controlled management of scrub areas, to avoid any further lowering of the water table and the possible loss, or decline of the dune habitat flora intolerant of long-term hydrological change.
Chapter 8
Management recommendations
8.0 Introduction

Chapter 8 will begin by summarising the most probable factors which are influencing water table elevations on Braunton, Northam and Dawlish, and will evaluate the extent to which human intervention can manage these systems in order to prevent any further loss or damage to the sand dune habitat ecology. The main section of this chapter will be devoted to recommending sustainable water level management options for each of the sites, reflecting upon the spatial and temporal characteristics of the water table elevation data described in Chapter 5 and Sections 6.9, and 6.17. When recommending future water level management options for the Braunton system, consideration will be given to the VMODFLOW modelling predictions.

8.1 Possible factors influencing the elevation of the water table

Although climate was identified as the main factor controlling the long-term elevation of the water table within each dune system, other factors such as artificial drainage, scrub growth and marine erosion were also possibly contributing to increased losses from the groundwater store. Such losses are critical to these finely balanced groundwater systems. At Braunton, Northam and Dawlish although it was not possible to control climatic trends or natural processes, such as groundwater seepage or marine erosion (without major defence schemes), it was possible to manage losses caused by artificial drainage, scrub growth and in some instances tidal inundation. It was therefore these factors that were of paramount importance when recommending the sustainable hydrological management options, aimed at raising water levels, or preventing any future lowering of the water tables (Section 8.2).
8.2 The recommendation of remedial/restorative hydrological management options

When formulating the final hydrological management options for each of the dune systems there are three criteria which need to be taken into consideration;

1. management options for each of the dune systems should reinstate former water levels, or prevent any future lowering of water table elevations, in order to maintain the ecological interests for which these sites are renowned.

2. water levels should be managed to provide for the continued operation of all land users and land uses, although nature conservation must be afforded primary consideration.

3. to ensure that the water level management recommendations are based on scientific principles and that they are sustainable.

The realms of environmental politics dictate that no matter what hydrological management options are recommended, one or more of the land user groups will not be satisfied with the outcome. However, the primary objectives of the proposed hydrological management options for Braunton, Northam and Dawlish are to afford nature conservation the highest priority and to recommend the most sustainable and economically viable solutions.
8.2.1 Future hydrological management of Braunton Burrows

West Boundary Drain

Drainage improvement works carried out on West Boundary Drain and the reinstatement of field drainage ditches on the marshland adjacent to observation well 23 were identified as probable contributing causes for the drop in the elevation of the water table recorded on the Burrows from 1983 (Section 5.2.5). The groundwater modelling predictions indicated that the deepening of West Boundary Drain by a maximum of one metre in the lower sections of the channel would have affected water table elevations across the entire system, although the greatest impact would have been recorded along the eastern margin of the system. The overall conclusion drawn from the modelling was that the dune and marsh systems were hydraulically connected, and therefore the Burrows water table was sensitive to changes in the drainage regime.

The management recommendations for West Boundary Drain are therefore to avoid any further drainage improvement works, which will intentionally or accidentally deepen the channel. To reduce groundwater drainage rates from the Burrows, water levels in the West Boundary Drain should be penned at a higher elevation throughout the year. Under the present management regime the Internal Drainage Board keep water levels in the drain at a minimum throughout the autumn and winter months (October to March) in order to efficiently remove flood waters and prevent widespread flooding of agricultural land. As a consequence, this increases the potential for groundwater drainage from the Burrows. As described in Section 5.3.3, the geometry of the West Boundary Drain and its relative isolation from the rest of the drainage ditch network meant that water levels could be raised throughout the year with the installation of sluice boards and without affected agricultural production on the marsh.
The Environment Agency also surveyed the channel in 1995 and recommended that three sluices should be installed along the length of West Boundary Drain to prevent further lowering of the Burrows water table (Johnston, pers. comm.). These sluices were installed in the summer of 1996 and the Internal Drainage Board have agreed to raise water levels in the drain by 0.25 m from March to October. The next critical stage in the management negotiations will be to raise water levels during the winter penning season, when potential groundwater drainage losses are greatest. Groundwater modelling indicated that raising water levels in West Boundary Drain by 0.25 m was an effective management option to prevent any further lowering of the water table on Braunton Burrows.

Management recommendation: drainage improvement works along the eastern margin of the system should be avoided. English Nature should continue to negotiate with the IDB to raise water levels during the winter penning season (October to March), when potential groundwater drainage losses from the Burrows are greatest.

Scrub encroachment

The encroachment of scrub onto Braunton Burrows was identified as a probable factor influencing the long-term elevation of the water table. With on average (1972-1995) only 32% (273.4 mm) of annual precipitation recharging the water table each year, increased evapotranspiration losses associated with scrub species would further reduce effective groundwater recharge.

Up until September 1996, when English Nature withdrew National Nature Reserve status from Braunton Burrows, the site warden carefully controlled scrub growth to prevent mass encroachment. However, without such management scrub growth will go unchecked, resulting in greater losses from the groundwater system through increased
evapotranspiration rates. A theoretical groundwater modelling scenario (Section 7.5.3) predicted that in a two month simulation period (April and May 1983) a 100% increase in scrub coverage from 8% to 16% would cause the Burrows water table to fall on average by 0.03 m. An even greater impact on the elevation of the water table would have been expected if simulations had extended further into the summer months, when evapotranspiration rates reached a maximum. The possible hydro-ecological consequences of this cumulative annual drop in the elevation of the water table emphasised the need for carefully controlled scrub management.

English Nature withdrew National Nature Reserve status partly because of a disagreement with the landowners over how scrub growth should be managed. On parts of the dune system English Nature wanted to introduce light grazing with cattle and sheep, to reduce the spread of scrub species and to create a short turf in which small delicate plants of nature conservation value could regain the ground they lost with the outbreak of myxomatosis in 1954 (English Nature, 1996). Up until 1996, areas of scrub were mechanically cleared. Without such practical and sustainable management practices scrub will continue to encroach and reduce groundwater recharge. However, because Braunton is a candidate 'Special Area of Conservation' site, English Nature continues to work closely with the MOD and the land owners seeking to secure the favourable management of this site. A detailed management plan is currently being prepared by the MOD, in consultation with English Nature, and will include a detailed management strategy for future scrub control.

**Management recommendation:** mechanical scrub control ideally should be supplemented with light grazing by cattle and sheep, to create a short turf and encourage the growth of delicate small plants of nature conservation value.
Drainage of Saunton Golf Course

The golf course is an integral part of Braunton Burrows and how it is managed hydrologically may affect water levels in other parts of the dune system. The drainage system on Saunton golf course has not been extended since the completion of the 18 hole links course in 1908. Any improvement works to existing drainage ditches should be avoided, because in such a highly permeable sandy medium deepening the ditches to increase discharge rates would also increase potential groundwater drainage, leading to an overall lowering of the water table. With consideration to the seasonal requirements of the golfers the golf course should therefore be managed to prevent widespread surface flooding, but otherwise ditch water levels should be kept high to prevent groundwater drainage and to avoid the flora becoming scorched early into the summer season. With the exception of flood waters, all drainage waters should be retained as far as possible through the installation of sluice boards at appropriate places along the length of the main drainage ditch. English Nature and Saunton Golf Club have come to an agreement to enforce this management recommendation in the near future. To increase the efficiency of the ditches in removing winter flood waters the ditches should be regularly cleared of aquatic weed growth, but care should be taken not to unintentionally alter the geometry of the channel. To help reduce surface flooding caused by compaction slitting machinery should be used to aerate the top 30 cm of the soil and to improve infiltration rates. The effectiveness of this process should be reviewed and the effects on species composition evaluated.

Management recommendation: any further drainage improvements on the golf course should be prevented. Saunton Golf Club have agreed to retain drainage waters, through the installation of sluice boards, helping to maintain higher ditch levels and groundwater drainage. To increase channel efficiency the ditches should be regularly cleared of aquatic weed growth. To help alleviate surface flooding caused by compaction slitting machinery
should be used.

Extraction of sand and gravel from the Taw-Torridge Estuary

A tracer experiment by Blackley et al. (1972) described in Section 5.2.2, showed that there may be a connection between sand and gravel extraction from the Taw-Torridge Estuary and the erosion of the foreshore between Airy Point and Crow Point, Braunton Burrows. Results from this research suggested that sediment was being transported from Airy Point to replenish sand and gravel excavated from near Crow Point. Changes in the level of the foreshore will ultimately affect the groundwater drainage regime from the Burrows. Whilst more detailed research is required to evaluate the exact impact of aggregate extraction, from a management point of view further extractions should be carefully monitored to avoid any unnecessary loss or damage to the foreshore, or dune system. These extractions may also be affecting erosion and deposition processes at Northam Burrows, which is also situated at the mouth of the Taw-Torridge Estuary.

**Management recommendation:** extractions of sand and gravel from the Taw-Torridge Estuary should be monitored carefully to avoid further erosion of beach levels, which in turn may lead to changes in the groundwater drainage regime from the Burrows. Any application for a new extraction licence should be considered carefully.

8.2.2 Future hydrological management of Northam Burrows

The drainage ditch network of the Great Plain

The drainage ditches of the Great Plain (Figure 6.1) were shown to be effective in managing the winter water table elevation to avoid flooding of the coastal plain. Ditch drainage is a net loss from the system, since otherwise these waters would recharge the groundwater system. Higher winter water tables would not only be of maximum benefit to
nature conservation, but would also benefit the graziers, with grass growth continuing later into the summer season.

Therefore the management recommendation, with nature conservation as the primary consideration, would be to fill in the ditches and raise water levels in this part of the system. The bureaucracy surrounding the future management of Northam Burrows as Common Land, means it is unlikely that the Parish Councillors would not allow such drastic changes to the drainage regime. In their opinion increased winter flooding would restrict grazing rights. Therefore, the next best management solution would be to adopt a policy of benign neglect, letting the drainage channels silt up naturally. In fact, many of the drainage ditches on the Great Plain have not been cleared since 1964 (Corrin, pers. comm.). Deepening of these ditches to increase drainage efficiency would also increase the potential for further groundwater drainage and a decline in the elevation of the water table.

Management recommendation: it is recommended that the policy of benign neglect should continue and the drainage ditches of the Great Plain should be allowed to silt up naturally, in order to raise water levels and enhance the habitat ecology.

The Pill

There are two feasible management options for the Pill. Since the removal of the tidal flaps from the Pill in March 1994, the channel has been regularly inundated by tidal waters. These waters drain within several hours of the tide receding. The graziers and golfers are concerned that since the flaps were removed, with spring tides greater than 5.8 m, saline waters have been bursting the banks of the Pill, flooding the surrounding land and scorching the vegetation. A feasible management option would therefore be to sluice
control the Pill at Appledore Bridge (Figure 6.1) and managing water levels in the channel according to the height of the tide and weather conditions. Sluice controlling the Pill and maintaining a constant water level in the channel would have a questionable benefit for nature conservation, because of the poor hydraulic connection between the Pill, which is partially incised into a silty/clay material and the surrounding landscape. The high-technology management option is therefore likely to be costly, labour intensive and of a questionable benefit to nature conservation. Further changes to the geometry of the Pill should be avoided to reduce potential groundwater seepage losses.

The second management option would be to leave the system under its current natural management state, where tidal waters regularly inundate the Pill to fill Goosey Pool and then drain as the tide recedes. This option would be cost effective and would afford nature conservation the maximum benefit under the natural functioning of the channel. Already salt-tolerant species are colonising the banks of the Pill as the system adapts to the increase in saline inundation. Under this management regime, with only minor alterations to the shape of Goosey Pool (Figure 6.1), tidal waters could be retained to create a saline lagoon, increasing habitat diversity and nature conservation interests.

Management recommendation: the status quo policy should continue on the grounds that it is sustainable, cost effective and forms part of the Northam Burrows environmentally sensitive management philosophy. Goosey Pool should be deepened to create a saline lagoon of increased habitat bio-diversity.
Greysand Lake

Before the construction of the landfill access road the eastern side of the Burrows, in the area of the current Greysand Lake and Civic Amenity Centre (Figure 6.1), was regularly inundated by the tide and formed an area of saltmarsh habitat. The construction of the landfill access road severed this link. Photographic evidence suggests that tidal inputs to this part of the system have been substantially reduced. Such changes to the hydrological functioning of the system have probably contributed to the perceived drying out of the dune system. The current management aim is to maintain a perennial saline lagoon through regular tidal inundation, which will also help raise water levels in this part of the system and encourage the colonisation of salt tolerant species. This area is hydrologically connected with the Inland Sea (Section 6.1.2 and Figures 6.2 and 6.3), which supports the declining water germander (*Teucrium scordium*). It is therefore important that the water level management recommendations will not have any detrimental repercussions on water levels in the Inland Sea.

The simplest and most effective management option for increasing tidal inundation, to ensure that Greysand Lake more consistently reaches its maximum current extent, would be to keep the existing outlet pipe and penstock open at all times. This would allow inundation at tides greater than 5.8 m and would also remove excess water when levels became too high. Currently the outlet pipe is only opened on an *ad hoc* basis. With no desires to increase the actual size of the pool, this proposed management option would have no effect on grazing. The management recommendation in the 1993 management plan was to replace the current 0.30 m diameter outlet pipe with a one metre diameter culvert at a lower elevation (Devon County Council, 1993). Without careful water level regulation this could lead to further drainage losses from this part of the system and ultimately could lead to further drainage from the Inland sea.
Careful management will also be required to ensure that the saline pool is regularly flushed particularly in the summer months, because of the unnatural conditions created by the access road. If stagnant water becomes a problem a second pipe and penstock should be installed at a lower elevation to allow regular flushing. This would also allow for more frequent topping up of the pool if required.

*Management recommendation:* it is recommended that the penstock on the existing outlet pipe remains open at all times, so that regular tidal inundation can occur in an attempt to raise water levels and create a perennial saline lagoon of increased nature conservation value. In the second stage of this management option, if stagnant water becomes a problem a second pipe and penstock should be installed at a lower elevation to allow for more regular tidal flushing.

**Inland Sea**

From anecdotal evidence concerns have been expressed that the Inland Sea (Figure 6.1) is drying out, endangering the colonisation of the water germander (*Teucrium scordium*) and the sharp rush (*Juncus acutus*). From field observations it would appear physically and hydrologically impossible to add further water to this part of the system. However, increased tidal inputs to Greysand Lake and a less intensive drainage regime on the Great Plain may lead to a long-term gradual overall rise in the elevation of the water table on Northam Burrows.

The golf course and the graziers are concerned about standing water in this area and would welcome the opportunity to create additional drainage channels to alleviate the problem. Any further drainage in this area would be detrimental to water levels and the colonisation of the hydrologically sensitive water germander (*Teucrium scordium*). The golf course
should therefore be encouraged to continue using their slitting machinery, which aerates the upper 30 cm of the soil and encourages surface water infiltration. The effectiveness of this process should be reviewed, evaluating the effects on species composition.

**Management recommendation:** further drainage in the area should be prevented and the golf course should be encouraged to continue using their slitting machinery to improve infiltration rates. The effectiveness of this management recommendation should be reviewed in the future.

8.2.3 Future hydrological management of Dawlish Warren

**Scrub invasion**

Scrub invasion was identified as a probable contributing factor for the perceived lowering of the water table on the Warren. The annual average (1972-1995) effective precipitation for Dawlish Warren was 186.5 mm, which meant that only 24% of annual precipitation recharged the water table. In such a finely balanced hydrological system increased evapotranspiration losses associated with scrub species would be detrimental to the groundwater system. For the past decade the staff on the Warren have been managing scrub growth in Greenland Lake.

**Management recommendation:** to continue to cut back the scrub growth and avoid further encroachment onto the Warren, which could lead to further lowering of the water table.

**Creation of wildlife ponds on the Local Nature Reserve**

The ponds on the Warren were created in 1983 to enhance habitat diversity in the Local Nature Reserve. During the period of this research the water level in the main pond did not fall below the elevation of the water table measured in surrounding dipwells. The pond was
merely incised into the local water table and was not acting as a groundwater sink. However, from a hydrological management point of view it should be noted that evapotranspiration losses from an open water body are greater than those from bare sand, or vegetated dunes. These additional evapotranspiration losses are therefore detrimental to the finely balanced groundwater system.

**Management recommendation:** to prevent the wildlife pond acting as a groundwater sink the water level in the pond should never fall below water levels in the surrounding dune system. Pond water levels will need to be carefully monitored particularly in the summer months.

**The golf course drainage system**

The golf course pump drainage system was identified to be controlling annual cyclical water table fluctuations on the golf course. In the winter months surface water and groundwater is drained into a holding pond and is then pumped directly out into the Exe Estuary (Figure 6.14) and becomes a net loss from the system.

Future management recommendations for this part of the system, taking into consideration the needs of both nature conservation and the golfers, would be to pump unwanted drainage waters from the golf course holding pond back onto Greenland Lake, the area most threatened by the apparent drying out of the system. In effect, this would result in a change in storage location rather than a net loss from the groundwater system. The feasibility of this management recommendation was discussed both with the golf course and Marcus Hodges, Geological and Environmental Consultants, Exeter, during a site visit. Marcus Hodges Consultants agreed that this was a practical water resource management solution, although a greater understanding of seasonal groundwater flow paths would be essential.
before deciding when and where to pump the drainage waters.

This high-technology management option will be costly. The Warren Golf Club and Teignbridge District Council are currently discussing financial matters.

Future intensification or deepening of the golf course ditch system should be avoided to prevent further groundwater drainage losses and lowering of the water table on the golf course. Within such a small system changes in the elevation of the water table on the golf course may well have repercussions on groundwater levels in another part of the system, although this will depend on the hydraulic connection of the golf course with the rest of the system. Considering the seasonal requirements of the golfers, the ditch should be managed so that surface flood waters are removed, but as far as possible ditch water levels should be kept high to avoid unnecessary groundwater drainage. Water levels within the golf course holding pond should be kept high to avoid the pond acting as a groundwater sink. Further intensification, or deepening of the drainage system should be avoided to prevent any future possible lowering of water table elevations. Surface flooding caused by compaction should be alleviated through the use of slitting machinery, which aerates the soil and increases infiltration rates, rather than intensifying the drainage system. The slitting machinery should not be used on areas of the golf course where the nationally rare Warren crocus (Romulea columnae var. occidentalis) shepherds's cress (Teesdalia nudicaulis) and bulbous meadow grass (Poa infirma) are found.

**Management recommendation:** to pump drainage waters from the golf course holding pond into Greenland Lake, in an attempt to raise water levels in this part of the system. A more detailed analysis of the groundwater hydrology is required before deciding where and when to pump the drainage waters. Further intensification or deepening of the golf course
drainage ditch should be avoided. The golf course should also keep water levels in the pond as high as practically possible to avoid the pond acting as a groundwater sink. To alleviate surface flooding caused by compaction slitting machinery should be used rather than intensifying the drainage system, but areas sustaining nationally rare flora should be avoided.

8.3 An integrated management framework

When evaluating the management problems and conflicts encountered in this study it was clear that the key to successful sand dune management, for nature conservation, was to adopt an integrated management policy. This involves statutory conservation bodies working alongside land owners and users to make them aware of the intrinsic value of the dune habitat, formulating sustainable management strategies which would give priority to nature conservation, but would also take into account the requirements of land owners and user groups. An integrated management framework would also help demonstrate how too much, or too little management can change, or influence the hydrological functioning of a sand dune system and threaten the dune habitat flora and fauna.

8.4 Conclusion

The aim of this chapter was to recommend water level management options for each of the dune systems, which would reinstate former water levels, or prevent any further lowering of the water table, in order to protect and enhance the dune habitat ecology. It was therefore important to ensure that the water level management recommendations were based on scientific principles and were sustainable. Although it was not possible to control factors such as climate, marine erosion or groundwater seepage, it was possible to manage artificial drainage, scrub growth, aggregate extraction, and in some instances tidal inundation. It was therefore these factors that were of primary consideration when
recommending the sustainable water level management options for each dune system, as summarised in Table 8.1. Although primary consideration was given to nature conservation, the requirements of all land users and owners were taken into consideration.

This study has shown that the key to successful sand dune management is an integrated management framework, whereby all land owners and user groups work together to ensure that future development is sustainable.
### Table 8.1 Water level management recommendations for Braunton, Northam and Dawlish

<table>
<thead>
<tr>
<th>Dune system</th>
<th>Factor influencing the hydrological regime.</th>
<th>Management recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Braunton Burrows</strong></td>
<td>West Boundary Drain</td>
<td>Avoid drainage improvement works along eastern margin of the system. Negotiate with the Internal Drainage Board to raise winter water levels in West Boundary Drain.</td>
</tr>
<tr>
<td></td>
<td>Scrub growth</td>
<td>Continue mechanical scrub clearance, supplemented with light grazing.</td>
</tr>
<tr>
<td></td>
<td>Drainage of Saunton golf course</td>
<td>Avoid any drainage improvements. To increase channel efficiency remove aquatic weed growth. Alleviate surface flooding problems caused by compaction with the use of slitting machinery.</td>
</tr>
<tr>
<td></td>
<td>Aggregate extraction</td>
<td>Ensure that any future extractions will not lead to the erosion of the beach, or the dune system.</td>
</tr>
<tr>
<td><strong>Northam Burrows</strong></td>
<td>Drainage ditches of the Great Plain</td>
<td>A policy of benign neglect should continue, allowing the ditches to silt up naturally.</td>
</tr>
<tr>
<td></td>
<td>The Pill</td>
<td>The status quo policy should continue. Goosey Pool should be deepened to create a saline lagoon of increased habitat bio-diversity.</td>
</tr>
<tr>
<td></td>
<td>Greysand Lake</td>
<td>The penstock on the existing outlet should remain open at all times, so that regular tidal inundation can occur. This will create a saline lagoon of increased nature conservation value. If stagnant water becomes a problem a second pipe and penstock should be installed at a lower elevation to allow for more regular tidal flushing.</td>
</tr>
<tr>
<td></td>
<td>Inland Sea</td>
<td>Further drainage should be prevented and slitting machinery should be used to improve infiltration rates.</td>
</tr>
<tr>
<td><strong>Dawlish Warren</strong></td>
<td>Scrub growth</td>
<td>Continue to cut back scrub and avoid further encroachment into Greenland Lake.</td>
</tr>
<tr>
<td></td>
<td>Creation of wildlife ponds</td>
<td>Manage pond water levels to prevent the pond acting as a groundwater sink.</td>
</tr>
<tr>
<td></td>
<td>Golf course drainage system</td>
<td>Pump drainage waters from the golf course holding pond into Greenland Lake to help raise water levels. Avoid further drainage improvements on the golf course and use slitting machinery to avoid surface flooding caused by compaction.</td>
</tr>
</tbody>
</table>
Chapter 9
Conclusion
Chapter 9

Conclusion

9.0 Introduction

The concluding chapter of this thesis has been divided into four main sections. The first section will restate the purpose and importance of this study and will also review the research aims. The second section will compare the hydrology of all three sites, assessing the effects of their size on the hydrological characteristics and functioning of the groundwater systems. Following, will be a section relating to the hydrological management of the Braunton, Northam and Dawlish. This section will describe the probable factors influencing water table elevations and will evaluate the extent to which human intervention can manage the hydrological regime in order to prevent further loss or damage to the sand dune habitat ecology. The recommended water level management options (Chapter 8) will also be evaluated from an unbiased sand dune hydrology point of view, to determine whether the short-term retention of wet dune slacks and wetland areas will be of long-term benefit to the dune system. The general application of the management recommendations for managing other sand dune systems in Great Britain will also be discussed. The final section of this chapter will include a critique of the research and will detail future potential research.

9.1 Background to the research

As discussed in Section 1.0, sand dune systems are important sites for nature conservation (Doody, 1989; Pieters, 1989; Jones, 1993; Stuyfzand, 1993). The ecology for which these sites are often nationally, or internationally renowned are dependent upon the hydrological regime, but except for the Dutch studies it should be acknowledged that sand dune hydrology has not been researched in most European countries. Despite the studies at
Braunton Burrows (Willis et al., 1959a; 1959b), Newborough Warren (Ranwell, 1959; 1972), Ainsdale (Clarke, 1980) and Kenfig (Jones and Etherington, 1989; Jones, 1993), little is understood about the hydrology and water resource management of the 56,300 ha of sand dune habitat around the shores of Great Britain. This identified the need for investigative research to begin to understand how these habitats function hydrologically in order to conserve them from the destruction of human activity, or natural factors. Furthermore, in the 1992 management plan for Braunton Burrows concerns were expressed that in some parts of the system the water table had fallen by one metre since the early 1980s (English Nature, 1992). The changing hydrological regime was identified as the most probable cause for the loss of the fen orchid (*Liparis loeselii*), a decline in the water germander (*Teucrium scordium*) and a reduction in the number of breeding wildfowl. Similar concerns over falling groundwater levels were also voiced by the staff at Northam Burrows and Dawlish Warren.

Taking into consideration the apparent lack of detailed research on the hydrological functioning of British sand dune systems and the need to conserve Devon's three largest dune habitats this thesis therefore aimed to;

1. describe and explain the spatial and temporal hydrological characteristics and functioning of the groundwater systems at Braunton Burrows, Northam Burrows and Dawlish Warren.

2. assess whether these systems were drying out and if so, to determine the most probable causes. At Braunton Burrows this was partially achieved through the use of a hydrological model.
3. recommend sustainable hydrological management options for each dune system, aimed at reinstating former water levels, or preventing any future lowering of the water table.

9.2 **Hydrological characteristics and functioning of the groundwater systems at all three study sites**

To address the first research aim, namely to describe and explain the hydrological characteristics and functioning of the groundwater systems, Braunton Burrows and Northam Burrows were investigated spatially and temporally at three scales;

1. the entire dune system
2. cross-sections and flow nets
3. point observations

The less detailed monitoring network at Dawlish meant that the hydrology could only be examined at the third scale, point observations. At Braunton physical properties of the dune sands were also analysed at an additional scale described as detailed experimental sites, which consisted of a dune and slack unit. Within the smaller systems at Northam and Dawlish properties of the dune sands were analysed next to each dipwell in the monitoring network so that variability in the annual cyclical response of the water table could be related to the physical properties of the dune sands.

9.2.1 **Characteristics of the water table**

At Braunton and Northam analysis of the water table data from the observation well networks showed that the groundwater systems were mounded. Such characteristics were associated with relatively isolated catchments, dependent upon precipitation for groundwater recharge and with percolating waters accumulating over impermeable sub-surface deposits. The margins of the system were the sites of groundwater outflow. As precipitation was the
main input to these systems, the elevation of the water table was very sensitive to seasonal variations in effective precipitation. At Braunton the groundwater mound was asymmetric and the highest water table elevations were recorded closest to the inland boundary of the system. The asymmetric nature of the groundwater mound was possibly related to the lower permeability of the sediment in the transitional zone from dune sands to marshland, which was restricting the inland drainage regime and causing the groundwater to mound along the eastern margin of the system. By contrast, groundwater outflow from the seaward side of the system drained through dune sands of a relatively higher permeability, which in part probably accounted for the lower water table elevations recorded in the seaward dune slacks. In the winter months water table elevations at the centre of the groundwater mound were up to 7 m higher than water table elevations measured at the edge of the dune system. Unfortunately the dipwell network at Dawlish Warren proved insufficient to accurately describe the shape or elevation of the water table and was identified as a potential area for future hydrological research (Section 9.5).

In mounded groundwater systems the volume of water percolating through the system increases from the centre to the margins, since the volume depends upon the size of the catchment area (Willis, et al. 1959a). At Braunton the steepest hydraulic gradients were observed along the seaward margins of the groundwater mound, where there were greater movements of water through the sand. Hydraulic gradients along the seaward margin of the system (between the 0 and 4 m water table contours) ranged from 1.08 m per 100 m in February 1995 to 0.97 m per 100 m in September 1995. At the centre of the groundwater mound, where water levels were maintained at a higher elevation, lower hydraulic gradients were measured. On the seaward side of the drainage system from the centre of the groundwater mound to the 4 m water table contour hydraulic gradients ranged from 0.65 m per 100 m in February 1995 to 0.58 m per 100 m in September 1995. Comparatively steeper
hydraulic gradients were measured on the inland side of the hydrological system, towards the West Boundary Drain, possibly as a result of the lower permeability of the material in the transitional zone from dune sands to marshland. The hydraulic gradients measured by Willis et al. (1959a) in June 1952 were marginally steeper than those calculated for summer and winter months during 1994, 1995 and 1996, which was possibly related to above average precipitation in the spring of 1952, or alternatively may be an indicator of past hydrological conditions within the system. At Northam, on the seaward side of the drainage system, calculated hydraulic gradients were generally marginally steeper than those measured at Braunton, ranging from 1.14m per 100m in February 1995 to 0.80m per 100m in September 1995. These steeper hydraulic gradients were possibly an artefact of the interpolation plotting routine, or alternatively may reflect the importance of the physical properties of the dune sands in controlling the hydrological functioning of the groundwater system. The sediment at Northam contained a greater and more variable content of silt and clay fractions (<62 μm), which lowered rates of $K_{sat}$ and hence hydraulic gradients were steeper in order to maintain the lateral drainage regime.

At all three study sites the water table demonstrated distinct seasonal fluctuations similar to those described for other British sand dune systems (Ranwell, 1959; Willis et al. 1959a; Clarke, 1980). Depending upon effective precipitation characteristics the elevation of the water table began to fall from its winter maximum between late February and April to reach a summer time low by August or September. Thereafter, with an increase in autumn effective precipitation the water table recovered to a winter maximum.

At Braunton annual cyclical water table fluctuations were related to distance from the seaward and inland margins of the system, with water levels at the centre of the groundwater mound fluctuating more than those at the edges. At the edge of the system
the water table was replenished not only by areal recharge, but also by groundwater draining from the centre of the mound. Within the smaller systems of Northam and Dawlish the effects of distance from the centre of the groundwater mound on annual cyclical water table fluctuations were masked by both the level of human activity in the form of artificial drainage systems and unmanaged scrub growth, and by inter-site variability in the physical properties of the dune sands.

9.2.2 The relationship between the elevation of the water table and effective precipitation
When investigating the relationship between the elevation of the water table and effective precipitation, the Braunton system took longer to respond than the smaller systems of Northam and Dawlish. This was related to the greater volume of unsaturated material within the Braunton system, which increased the transit time of water in the vadose zone. At a 95 % confidence level, the elevation of the water table at Braunton was most significantly correlated with effective precipitation of the preceding 91-120 or 121-150 day period. At both Northam and Dawlish with a smaller unsaturated zone the elevation of the water table was most significantly correlated, at a 95 % confidence level, with effective precipitation of the preceding 0-30 or 31-60 day period.

9.2.3 Saline intrusion
At both Braunton and Northam considering the depth to the impermeable basal layer of the groundwater system and the height of the water table above OD in the most seaward observation wells, landward penetration of salt water was considered unlikely. At Dawlish it is not known whether an impermeable basal layer to the groundwater system overlies the parent material. In the absence of this confining layer salt water would intrude into the New Red Sandstone at approximately 80 m below OD, and any further lowering of the water table would lead to further encroachment of saline water.
9.2.4 Physical characteristics of the dune sands

In order to explain any variability in the functioning of the groundwater systems a detailed spatial account of the physical properties of the dune sands at each of the study sites was essential. A spatial analysis of the physical properties of the Braunton dune sands revealed uniform characteristics both with depth and across the sampling field. $K_{\text{sat}}$ values calculated from the slug tests showed that the dune sands were very rapid draining, with an average $K_{\text{sat}}$ of 7.94 m d$^{-1}$. The particle size frequency distribution curves illustrated a medium to fine grained sand, with silt and clay fractions constituting less than 10.1% of the sample. The apparent homogenous nature of the dune sands did not, however, help to explain why the groundwater system mounded along the eastern margin of the system. The most probable explanation was that to the east of the American Road in the transitional zone from dune sands to marshland, where in fact no sampling was undertaken, the texture of the sediment changed, reducing rates of $K_{\text{sat}}$ and restricting the lateral drainage regime. At Braunton the sediment property showing the greatest variability was bulk density, which would affect rates of groundwater recharge. Bulk densities at the 45-50 cm depth ranged from 1.49 g cm$^{-3}$ to 1.59 g cm$^{-3}$.

$K_{\text{sat}}$ values at Northam (mean - 6.04 m d$^{-1}$) and Dawlish (mean - 6.33 m d$^{-1}$) were lower than those measured at Braunton (mean - 7.94 m d$^{-1}$). This was the result of a more variable content of silt, clay and fine sands. Within 300 m of the Pill at Northam and on the golf course at Dawlish $K_{\text{sat}}$ values of between 1.5-3.9 m d$^{-1}$ were calculated from the slug test experiments, and explained why these areas needed to be artificially drained during the winter months. Such inter-site differences in the physical properties of the dune sands and their possible controls on the hydrological functioning of the groundwater system were taken into consideration when firstly determining possible factors influencing annual cyclical water table characteristics and secondly when recommending future water level.
management options aimed at raising water levels, or preventing a further lowering of the water table.

9.2.5 Summary comments

In summary, the findings of this research have provided a detailed comparative description of the hydrological characteristics and functioning of the groundwater systems at Braunton, Northam and Dawlish. This section has shown how the size and geographical setting of the dune system, and the physical properties of the aeolian sands can influence the shape, elevation and seasonal response of the water table. All of these influential factors were taken into consideration when recommending how best to manage the groundwater hydrology of each system to the maximum benefit of nature conservation (Chapter 8).

9.3 Temporal variability in the elevation of the water table and future management

The second aim of this research was to assess whether the three dune systems were drying out and if so to determine the most probable causes. At Braunton spatially representative water table data, collected since 1972, were invaluable in both describing the long-term temporal variability in the elevation of the water table and identifying the probable factors controlling groundwater fluctuations. At both Northam and Dawlish without such historical water table data it was not possible to determine whether groundwater levels were falling, however weekly water table data collected since the start of this research (October 1993) were analysed to identify possible factors influencing annual, or seasonal water table fluctuations.

In simplistic terms the hydrological functioning of each dune system can be viewed as a system of inputs, throughputs and outputs, which ultimately determine the elevation of the water table. At Braunton and Northam between 1972 and 1995 on average only 32% of
annual precipitation recharged the water table, while the rest was lost through evapotranspiration. At Dawlish the figure was even less and between 1972 and 1995 on average only 24 % of precipitation replenished the groundwater store. The LTA (1972-1995) annual effective precipitation total for Braunton and Northam was 273.4 mm and for Dawlish 186.5 mm. As precipitation was the main input to the systems these figures emphasised the finely balanced nature of the groundwater budgets. An analysis of the long-term (1972-1995) water table data from Braunton demonstrated the sensitivity of the system to variability in effective precipitation. Climate was identified as the key variable controlling the long-term elevation of the water table on Braunton and was a major contributing cause for the general decline in the elevation of the water table from 1983 to mid 1992.

The meteorological data used at Braunton were also used to describe long-term climatic trends at Northam Burrows. Undoubtedly therefore, the identified decline in effective precipitation totals from 1983 through to mid 1992 would have had repercussions on the elevation of the water table within Northam Burrows. Similarly a detailed analysis of annual effective precipitation data for Dawlish Warren also identified a marked decline in effective precipitation totals through the 1980s and into the early 1990s. At Dawlish, with a LTA (1972-1995) annual effective precipitation total of 186.5 mm, consecutive years with below average effective precipitation would have lead to a gradual lowering of the water table on the Warren. Reduced inputs to all three systems during this period would also explain why concerns were first raised in 1992/1993 that the systems were drying out to the detriment of nature conservation interests.

With precipitation as the primary source of groundwater recharge to all three dune systems it is important to take into consideration the possible future long-term effects that global
warming and climatic change will have on both water table elevations, and the composition
and diversity of the dune habitat flora and fauna. In south west England, for example, the
combined effects of climatic change and tectonic activity are predicted to cause a relative
sea level rise of 5 mm a\(^{-1}\) between 1990 and 2030 (Comber et al., 1993). In the long-term
this rise in sea level will lead to increased erosion of the dune systems and an overall
change to the groundwater drainage regime. Also according to climate change models,
rising levels of greenhouse gases are likely to raise global surface temperatures by 1.5-
4.5\(^{\circ}\)C over the next 100 years (IPCC, 1995). As a result precipitation is predicted to
increase on average, in middle and high latitude continents (35-55\(^{\circ}\)N), by some 5-10 \% in
the winter months by the year 2030 (IPCC, 1995). This will have a positive impact on
groundwater levels. In the summer months however, it is predicted that evapotranspiration
rates will be higher and precipitation will decrease (IPCC, 1995), having a negative impact
on groundwater budgets. Unfortunately the current generation of climate models still
cannot make the regional forecasts which are required for impact assessments in England.
Predicted higher levels of carbon dioxide in the atmosphere are expected to improve the
efficiency of photosynthesis in plants, which in turn will cause more rapid
evapotranspiration (Information Unit on Climate Change, 1993). Again this will have a
detrimental impact on the groundwater budgets.

Although climate was identified as the main factor controlling the long-term elevation of
the water table at Braunton, Northam and Dawlish, other factors such as scrub growth,
artificial drainage, marine erosion and aggregate extraction were also possibly affecting
annual groundwater budgets. Such losses are critical to these finely balanced systems and
although it is not possible to control climate or marine erosion, caused by sea level rise
(without high technology sea defence schemes), human intervention can control and mange
groundwater losses caused by artificial drainage, scrub growth and aggregate extraction.
Therefore, it was factors such as these that were addressed when recommending the sustainable water level management options for each dune system (Section 8.2). The future management of Braunton, Northam and Dawlish is focused on raising water levels, or preventing any further lowering of water table elevations, in order to conserve the wet dune slacks and wetland areas, which are the sites of greatest ecological value.

Whilst conservation management is often regarded as the maintenance and preservation of a natural landscape, in most cases conservation results in management focused on spatial patterns, thus stabilising a momentary situation (Wanders, 1989). Dune management that tends to keep everything as it is neglects the fact that the natural dune landscape is dynamic and that as a result spatial patterns are changeable. A dynamic approach to dune management takes into account the restoration and, or development of natural processes, rather than the protection of stable structures and patterns (Houston, 1997). At Braunton, Northam and Dawlish it is therefore important to evaluate from an unbiased sand dune hydrology point of view, whether the retention of dune slacks and wetland areas are of long-term benefit to the dune systems.

Sand dune habitat management which encourages dynamism and mobility of the dunes will in the long-term be beneficial to both the groundwater system and the composition and diversity of the dune habitat ecology. Annual evapotranspiration losses from bare dune sand, or sand colonised only by grasses will be considerably less than losses from dune shrub, scrub species and dune woodland (Section 1.6.1), increasing effective inputs to the groundwater system. A more mobile dune system, with blowing sand developing into new dune ridges and dune slacks, will also encourage the early stages of seral succession. At Kenfig research by Jones et al. (1995) has shown that mobility within the dune system is a key component to the long-term conservation, recovery and management of
internationally rare and protected dune slack species such as the fen orchid (*Liparis loeselii*) and petalwort (*Petalophyllum ralfsii*). These species are also in decline at both Braunton and Northam. Within the Kenfig system a significant population increase in the fen orchid (*Liparis loeselii*) has only been observed in those dune slacks which have formed within the last 30 years (Jones *et al.*, 1995).

Under the management regime recommended in this research, the wet dune slacks and areas of wetland can only be retained if the prescribed level of management is sustainable in the long-term. Also evapotranspiration losses from wet dune slacks and areas of wetland are considerably higher than for example from dune turf, or bare sand, reducing annual effective inputs to the groundwater store. These wetland areas also provide ideal site conditions for the continual encroachment of damp loving species such as willow (*Salix repens*). Without intensive scrub management these hydrophilic species will continue to invade, gradually the lowering the elevation of the water table. Consequently lower groundwater levels will probably lead to the loss and decline of internationally rare and protected dune slack species, such as the fen orchid (*Liparis loeselii*) and the water germander (*Teucrium scordium*).

9.4  A management strategy for British sand dune systems

In this research it has been shown that each dune system requires its own specific hydrological management recommendations in order to achieve the common management goal of raising water levels, or preventing any future lowering of the water table, in order to conserve the dune habitat ecology. Inter-site variability in the size of the dune system, geomorphological characteristics and the degree of human intervention with the natural functioning of the groundwater system were the main factors which dictated that each system must be considered individually to ensure that the dune systems were hydrologically...
managed to the maximum benefit of nature conservation.

In considering the hydrological management of just these three very different sand dune systems common management areas were addressed and remedial/restorative options were recommended, including the impact and management of scrub growth and artificial drainage systems. Other factors perceived as influencing the groundwater system, but not so easily managed by human intervention, were long-term changing climatic trends and marine erosion. All of these water resource management issues and feasible remedial solutions should therefore ideally be documented under a 'water level management strategy for sand dune systems', to assist in the conservation of other mismanaged sand dune systems around the shores of Great Britain.

9.5 Critique and future research

Within the scope of this hydrological research problems were encountered which influenced the detail of the hydrological interpretation of each study site and the recommendation of future management options.

At Braunton the long-term water table data were invaluable in confidently describing the hydrological characteristics and functioning of England's largest sand dune system. The data were used to evaluate the temporal variability in the elevation of the water table between 1972-1995. However, at both Northam and Dawlish, with only relatively short-term water table data, collected since the start of this research programme, less detailed hydrological descriptions of the study sites were provided. The lack of historical water table data also made it impossible to determine if these systems were drying out. Management recommendations were therefore made on the strength of two years water table elevation data, anecdotal evidence and field experimentation.
The limited hydrological and geological data available to characterise the groundwater systems at both Northam and Dawlish meant that it was not possible to evaluate whether a commercial groundwater flow model could be successfully applied to simulate the behaviour of the groundwater systems.

A problem at the sites also encountered in the hydro-ecological study at Kenfig (Jones, pers.comm.), was the installation of dipwells and the analysis of sediment properties beneath the water table. The liquid nature of saturated dune sands prohibited a detailed analysis of sediment properties, both with depth and spatially within the sampling field and was therefore a limiting factor in the hydrological description of all three study sites and in the parameterisation and calibration of the Braunton groundwater model.

Although VMODFLOW was successfully used to simulate the hydrological functioning of the groundwater system at Braunton, the modelling exercise identified the need for far more spatially detailed hydrological and geological data. This was a common criticism of modelling in general. In particular more detailed measurements of $K_{sat}$ were required to confidently parameterise both the lower layers of the model and the transitional zone to marshland, along the eastern boundary of the modelling domain. The collection of additional sediment property data and the setting up of experiments to determine actual evapotranspiration losses from the various vegetation types found on the Burrows, would help to improve both the conceptualisation of the system and the resulting calibration.

The extent of the unsaturated zone was also a problem when using a saturated groundwater flow model, as the model took no account of either depth to the water table, or rates of water movement through the unsaturated zone. The model assumed a uniform rate of groundwater recharge, which created problems during calibration. The apparent importance
of the unsaturated zone identified the need for a hydrological model which considered both
the saturated and unsaturated zones as a unitary system. However, such models are less
well developed and tested, and are generally more complex, requiring detailed quantitative
accounts of the physical properties of unsaturated dune sands (National research Council,
1990; Anderson and Woessner, 1992). The study of water movement through the
unsaturated zone would be a detailed research project in itself.

The primary limitation of the model was that the preprocessor attached to VMODFLOW
only allowed evapotranspiration rates to be assigned to active cells in the top model layer.
To simulate the topography of Braunton Burrows the top model layer had the smallest
dimensions and the least active modelling cells. Although this was partially overcome by
assigning an effective precipitation rate to the highest active cell in each vertical modelling
column, the model would only accept positive values. Therefore, it was not possible to
simulate the summer months, when evapotranspiration rates were greater than precipitation
losses. This problem needs to be overcome before developing the Braunton model any
further.

Within this study the potential for future site specific hydrological research has been
identified. At all three study sites the monitoring of water levels should continue on a
regular basis so that the immediate and longer term effectiveness of any hydrological
management strategies, implemented as a result of this research, can be evaluated. Longer
term water level data and a more detailed spatial analysis of the geology and sediment
properties at both Northam and Dawlish would be invaluable in providing a more
comprehensive hydrological description of the functioning of the groundwater systems. At
Dawlish more dipwells need to be added to the existing monitoring network, so that
temporal variability in the shape and elevation of the system can be described with the aid
of contour plots and flow nets.

The additional hydrological and geological data collected at Northam and Dawlish would also be required when evaluating whether the hydrological characteristics and functioning of the groundwater systems could be successfully simulated with the use of an 'off-the-shelf' groundwater flow model. The successful calibration of groundwater models for Northam and Dawlish would help substantiate the long-term effectiveness of the water level management options recommended in this study. At Dawlish a model of the groundwater system would be particularly useful in evaluating the long-term impact of the golf course pump drainage system on water table elevations within the Warren. This cannot easily be achieved with only analytical methods.

The modelling was a positive attribute to the research, demonstrating that it was possible to the model the complex hydrogeology of the Braunton groundwater system with a commercially available groundwater model. However, the use of the groundwater flow model as a predictive management tool in the future conservation of Braunton Burrows could be developed further. When the capability limitations of the model (as already described in this section) have been addressed and additional $K_{sat}$ and evapotranspiration data has been collected, the model could be used to address a wider range of water resource management scenarios. For example the model could be used to evaluate the possible effects that marine erosion and climatic change will have on the long-term functioning of the Braunton groundwater system.

Ultimately this research has provided a unique hydrological description of the functioning and management of three very different sand dune systems. In the wider context of possible future research avenues, the results from this study could be applied to the
management and conservation of other relatively natural sand dune systems in Great Britain, also under the threat of ecological destruction.

9.6 Final conclusions

In summary, as a result of this investigative research far more is understood about the hydrological characteristics and functioning of Devon's three largest sand dune systems. With an improved understanding of the hydrological functioning of these systems it has been possible to identify factors that are influencing water table elevations and to recommend sustainable remedial/restorative hydrological management options, which will help to conserve the dune habitat ecology. This hydrological research has also demonstrated that the key to successful management of sand dune systems for nature conservation is to adopt an integrated management policy, whereby all interest groups work together considering each others needs and formulating sustainable management policies.

In Great Britain and other European countries sand dune systems are under constant threat from human activity and natural factors, such as climatic change. The research described in this thesis therefore provides the applied and theoretical framework to address the water resource management problems encountered within both large and small scale sand dune systems.

Sand dune habitats are extremely fragile and finely balanced hydrological systems, which require sensitive and sustainable management to ensure that they can be enjoyed by future generations.
Appendix A
Sites of Special Scientific Interest citation sheets
Appendix A

Sites of Special Scientific Interest
citation sheets for Braunton Burrows, Northam Burrows
and Dawlish Warren

Braunton Burrows Site of Special Scientific Interest citation sheet

County: Devon  Site Name: Braunton Burrows
District: North Devon

Local Planning Authority: Devon County Council, North Devon District Council

National Grid Ref: SS 430350  Area: 1356.7ha 3352.4ac
Ordnance Survey Sheet: 1:50,000: 180  1:10,000: SS43 NE, NW, SE, SW
Date Notified (Under 1949 Act): 1952 and 1969  Date of Last Revision: 1976
Date Notified (Under 1981 Act): 1986

Other Information: The site is listed in a Nature Conservation Review and is a UNESCO Biosphere Reserve. It lies within the North Devon Area of Outstanding Natural Beauty and, in part, is in a Mineral Consultation Area. The whole of the Site of Special Scientific Interest (SSSI) is a candidate Special Area of Conservation, containing European priority interest habitats.

Description and Reasons for Notification: The dune system of Braunton Burrows, at the mouth of the Taw-Torridge estuary in north Devon, is one of the largest in Britain, being about 5km long and 1.5km wide. Among its lime-rich dunes, up to 30m high, lies an extensive system of slacks, grassland and scrub, inland of a wide sandy foreshore. The site is one of the best areas in the UK for dune grasslands, shifting dunes and dune slacks, which are of European importance. Over 400 flowering plants have been recorded, as well as numerous fungi, lichens, mosses and liverworts and ferns, including many that are nationally rare, or internationally threatened. The Burrows are also of national importance for the study of dune formation and processes.

The foreshore consists mainly of sandy flats, rich in lime from broken seashells, with some intertidal shingle grading to silt in the estuary, in a tidal range of 7m. The strand line supports plants like saltwort (Salsola kali), sea sandwort (Honkenya peploides) and frosted orache (Atriplex laciniata). The fore and mid dunes are classic “yellow” dunes, colonised
and stabilised mainly by marram grass (*Ammophila arenaria*). Several notable plants occur in this habitat including sea stock (*Matthiola sinuata*), sea stork’s-bill (*Erodium maritimum*), sea clover (*Trifolium squamosum*) and sea spurge (*E. paralias*). Inland of these are more stable ‘grey’ dunes, on which the marram is replaced by other grasses, including dune fescue (*Vulpia membranacea*) and the larger of just two populations of clustered club-rush (*Scirpus holoschoenus*) in Britain.

The wet hollows or ‘slack’s between the dunes flood at times of high rainfall, although in recent years they have become drier due to drainage works on the adjoining grazing marshes. They are characterised by creeping willow (*Salix repens*) and support notable plants such as water germander (*Teucrium scordium*), known from only two other sites in Britain, sharp rush (*Juncus acutus*), petalwort (*Petalophyllum ralfsii*), a specially protected liverwort, round-leafed wintergreen (*Pyrola rotundifolia ssp. maritima*), variegated horsetail (*Equisetum variegatum*) and early gentian (*Gentianella anglica*), which is an endemic flower.

Grass swards carry a rich and colourful mixture of grasses, sedges and herbs such as wild thyme (*Thymus praecox*), creeping restharrow (*Ononis repens*), bird’s-foot trefoil (*Lotus corniculatus*), the eyebright (*Euphrasia confusa*) and pyramid orchid (*Anacamptis pyrimalis*). An area of inland shingle is particularly important for lichens, some 60 species having been recorded, including the scrambled egg lichen (*fulgensi fulgens*). Invasion of the dune system by coarse grasses, willow (*Salix*) species, privet (*Ligustrum vulgare*) and bramble (*Rubus fruticosus*) scrub is an increasing problem, following the decline in the rabbit population due to myxomatosis.

The SSSI, with the adjacent Taw-Torridge Estuary SSSI, is a focal point for bird migration routes down the west coast of Britain. The shores of sea and estuary provide important wintering grounds for waterfowl, while the landward parts support a variety of breeding species such as whitethroat (*Sylvia communis*) and stonechat (*Saxicola torquata*) in scrub, skylark (*Alauda arvensis*) and wheatear (*Oenanthe oenanthe*) on grassland, and shelduck (*Tadorna tadorna*) in the dunes. Numerous invertebrates occur including 30 species of terrestrial and freshwater molluscs, among them the endangered and specially protected amber sand-bowl snail (*Catinella arenaria*), known from only two other sites in Britain. Thirty three species of butterfly have been recorded, including large populations of grayling (*Hipparchia semele*), dingy skipper (*Erynnis tages*) and grizzled skipper (*Pyrus malvae*), and the Burrows are one of just two sites in Devon for the small blue butterfly (*Cupido minimus*). The rare beetle (*Nebria complanata*) occurs on the strand line.
Braunton Burrows is a key site for the study of coastal geomorphology. It is one of the three largest sand dune systems on the west coast of Britain and the one least affected by underlying geology and afforestation. It is also important for its diversity of form (including major blowouts), and has the greatest height range of any west coast dune system. In the central part of the Burrows where the highest dunes occur (up to 30m OD), there are three main parallel ridges, separated by slacks and fronted by a line of fore dunes.

The Burrows are among the best documented dune systems in Europe. There is good documentation of post-war changes in dune form, and cartographic records extend to the beginning of the 19th century. Other research studies have been undertaken on their hydrology, on the ecology of several groups of plants and animals, and on the effects of grazing on plant communities.
Northam Burrows Site of Special Scientific Interest citation sheet

County: Devon
District: Torridge
Site Name: Northam Burrows

Status: Site of Special Scientific Interest (SSSI) notified under Section 28 of the Wildlife and Countryside Act 1981 (as amended).

Local Planning Authority: Devon County Council, Torridge District Council

National Grid Ref: SS 445305
Area: 442.5ha 1044.0ac
Ordnance Survey Sheet: 1:50,000: 180 1:10,000: SS 43 SW & SS 42 NW
Date Notified (Under 1949 Act): 1981
Date Notified (Under 1981 Act): 1988

Other Information: Part of the site is listed in the Geological Conservation Review. In the North Devon Area of Outstanding Natural Beauty. Part of the site overlaps with the Taw-Torridge Estuary SSSI.

Description and Reasons for Notification: Northam Burrows is of interest for its wide range of coastal habitats and in particular for the rare and local plants to be found. The site also supports many over-wintering and migratory birds. In addition, the cobble ridge is an important land-form feature.

Situated to the south of the entrance of the Taw-Torridge Estuary, Northam Burrows is a low lying area of gently undulating sand and alluvial deposits. The land dips slightly from north and west to south and east, providing varied drainage conditions. Several pools occur and many narrow ditches criss-cross the area.

The cobble ridge protects the seaward boundaries, behind which lies a system of “yellow” dunes. These are largely dominated by marram (Ammophila arenaria) and, together with other areas of dry grassland, support many species of plants. Red fescue (Festuca rubra) is abundant, with other grasses including sheep’s fescue (Festuca ovina), crested dog’s-tail (Cynosurus cristatus), common whitlow-grass (Erophila verna) and the nationally scarce dune fescue (Vulpia membranacea). Wild pansy (Viola tricolor), viper’s bugloss (Echium vulgare), restharrow (Ononis repens), common bird’s-foot-trefoil (Lotus corniculatus), wild thyme (Thymus praecocis) and lady’s bedstraw (Galium verum) are frequent here. The dunes
also support the rare sea stock (*Matthiola sinuata*) and the nationally scarce bird's-foot Clover (*Trifolium ornithopodioides*) and rock sea-lavender (*Limonium binervosum*).

Where the water table is nearer the surface, wet grassland and dune slack communities occur. These are also herb-rich with species including yellow Iris (*Iris pseudacorus*), bog pimpernel (*Anagallis tenella*), autumn lady's-tresses (*Spiranthes Spiralis*), parsley water-dropwort (*Oenanthe lachanali*), adder's tongue (*Ophioglossum vulgatum*), sedges (*Carex spp.*) and the nationally rare water germander (*Teucrium scordium*).

Large areas of dune grassland and slack are dominated by dense stands of sharp rush (*Juncus acutus*), which has a nationally restricted distribution, and in places forms thickets with hawthorn (*Crataegus monogyna*) and bramble (*Rubus fruticosus*).

Where there is a strong maritime influence a certain degree of salinity supports sea rush (*Juncus maritimus*), grey club-rush (*Schoenoplectus tabernaemontani*) and the nationally scarce brackish water-crowfoot (*Ranunculus baudotii*) in the ditches.

The extensive areas of grassland provide autumn, spring and winter roosting and feedings grounds for many birds, particularly those using the adjacent estuary. Golden plover (*Pluvialis apricaria*), curlew (*Numenium arquata*), wigeon (*Anas penelope*) and brent goose (*Branta bernicla*) occur in over-wintering flocks. The range of habitats present also supports a diverse breeding bird community which includes shelduck (*Tadorna tadorna*), wheatear (*Oenanthe oenanthe*), stonechat (*Saxicola torquata*), whitethroat (*Sylvia communis*), grasshopper warbler (*Locustella naevia*) and sedge warbler (*Acrocephalus schoenobaenus*).

Records to date strongly indicate that the site is also very important for many groups of invertebrates. Species of particular interest include the nationally rare woodlouse (*Armadillidium album*), the nationally scarce Portland moth (*Ochropleura praecos*) and the squashbug (*Arenocoris falleni*).

The cobble ridge is a classic coastal feature noted in particular for the large size of the sediments present. Few spits in Britain are formed of large cobbles at the back of an extensive sandy intertidal zone. Some of the cobble material derives from sources to the south, and sand, gravel and cobbles have moved to the distal end of the spit forming a spatulate feature in the Taw-Torridge Estuary.
Dawlish Warren Site of Special Scientific Interest citation sheet

County: Devon  
Site Name: Dawlish Warren

District: Teignbridge


Local Planning Authority: Devon County Council, Teignbridge District Council

National Grid Ref: SX 985795  
Area: 207.0ha 511.4ac

Ordnance Survey Sheet: 1:50,000: 192  
1:10,000: SX 97 NE, SX 98 SE

Date Notified (Under 1949 Act): 1952  
Date of Last Revision: 1976

Date Notified (Under 1981 Act): 1984

Other Information: Part owned by District Council and part by Devon Trust for Nature Conservation. Proposed site of the Ramsar Convention of wetlands of international importance. Within a statutory Bird Sanctuary (Order No. 901 of 1951) and within the County Structure Plan Nature Conservation Zone.

Description and Reasons for Notification: This site consists of a large sand-spit with adjoining tidal land at the mouth of the Exe Estuary; an area of international importance for several species of wildfowl and wading birds. It is particularly noted for its flora and over-wintering and migratory bird populations.

A wide variety of habitats are present, including saltmarsh, sanddunes, dune grassland and heath, scrub, and freshwater marsh. The flora includes Orchids and several other plants of local distribution, along with many alien and invasive species. Short sward grassland on the warren supports the only mainland British population of the Warren Crocus (Romulaae columnae var. occidentalis). The saltmarsh flora includes eel-grass (Zostera spp.), which is an important food for wigeon (Anas penelope), dark-bellied brent goose (Branta bernicla bernicla) and other species of wildfowl. The estuary also supports nationally important numbers of wintering black-tailed godwit (Limosa Limosa).
Several insects recorded from the Warren have a limited distribution in mainland Britain. These include the sand wasp (*Ammophila sabulosa*), which occurs on undisturbed, exposed sand-faces.

The sand-spit and the estuary which it protects also display features of geological and physiographical interest.
Appendix B
Calculation of $K_{sat}$
Appendix B

Calculation of $K_{sat}$

The Bouwer and Rice (1976) solution for the determination of $K_{sat}$

This section describes the principles behind the Bouwer and Rice (1976) solution used in the computer package AQTESOLV to calculate $K_{sat}$ in an unconfined aquifer (Section 4.8.3). The geometry and symbols used in the following formulae are shown in Figure A1.

![Figure A1](image)

- $y$: change in head (m)
- $D$: saturated thickness (m)
- $H$: depth from water table to the base of well (m)
- $L$: length of screen (m)
- $2r_c$: diameter of well casing (m)
- $2r_w$: radial distance between undisturbed aquifer and centre of well (m)

Figure A1: Geometry and symbols of a partially penetrating, partially perforated well in an unconfined aquifer.

Source: Adapted from Bouwer (1989).
As described by Bouwer and Rice (1976), the rate of flow of ground water into the well, when the water level in the well is a distance \( y \) lower than the static ground-water table around the well, is calculated through a modification of the Theim equation (1906);

\[
Q = 2\pi KL \frac{y}{\ln(R_e/r_w)}
\]

(Equation A1)

\( Q \) volumetric flow into the well (m\(^3\) s\(^{-1}\))

\( K \) hydraulic conductivity of aquifer around well (m\(^3\) s\(^{-1}\))

\( L \) perforated screen length (m)

\( y \) vertical difference between the water level inside the well and the static water table outside (m)

\( R_e \) effective radius over which \( y \) is dissipated (m)

\( r_w \) well radius (m)

Bouwer and Rice (1976) conducted electrical analogue analyses to evaluate \( R_e \) for various system geometries, expressing their results in terms of the dimensionless ratio \( \ln(R_e/r_w) \). An empirical equation was then developed to relate \( R_e \) to the geometry of the system (\( r_w \), \( L \), \( H \) and \( D \)), (Figure A1). In the case of Braunton all the piezometers were only partially penetrating the aquifer and therefore the following equation was applied;

\[
\ln(R_e/r_w) = \left[ \frac{1.1}{\ln(H/r_w)} + \frac{A + B \ln[(D - H)/r_w]}{L/r_w} \right]^{-1}
\]

(Equation A2)

\( R_e \) effective radius over which \( y \) is dissipated (m)

\( r_w \) well radius (m)

\( H \) depth from water table to base of well (m)

\( D \) saturated thickness (m)

\( L \) length of screen (m)
In Equation A2, $A$ and $B$ are dimensionless coefficients that are functions of $L/r_w$ (Figure A2).

In Equation A2, if $\ln \left( \frac{D-H}{r_e} \right)$ is greater than 6, a value of 6 is used for this term. This applies when the saturated thickness is greater than the depth of the piezometer ($H$). AQTESOLV automatically calculates these values from the well geometry data entered.

After the removal of the slug, the rate of rise ($dy/dt$) of the water level in the well can be related to the inflow ($Q$) into the well by the equation;

$$
\frac{dy}{dt} = -\frac{Q}{\pi r_e^2}
$$

(Equation A3).

$\pi r_e^2$ cross-sectional area of the well, where the water level is rising ($m^2$)

Figure A2 The Bouwer and Rice (1976) curves relating coefficients $A$ and $B$ to $L/r_w$.
Source: Adapted from Bouwer (1989).
A combination of Equations A2 and A3 give a description of a radial flow permeameter with inner area $2\pi r_w L$, outer area $2\pi R_e L$ and flow length $R_e - r_w$ (Brown et al. 1995). The final equation for the determination of $K_{sat}$ is therefore:

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right) 1}{2L} \ln \frac{y_o}{y_t}$$

(Equation A4)

$K$ saturated hydraulic conductivity (m s\(^{-1}\))
$r_c$ internal radius of well casing (m)
$R_e$ effective radius over which $y$ is dissipated (m)
$r_w$ well radius (m)
$L$ perforated screen length (m)
$y_o$ water level after the removal of a slug (m)
$y_t$ water level at a specified time (m)

Values for $y_o$ and $y_t$ can be obtained from the water level recovery data stored on the data module. These values are substituted into Equation A4 along with the values calculated for Equation A2, to yield $K_{sat}$.

AQTESOLV performs a non-linear least squares optimisation of $K$ for the given variation in water level with time.
The simplified well permeameter (Talsma and Hallam, 1980).

The principle of this method was described in Section 3.2.6b and illustrated in Figure 3.7. The formula used in the calculation of \( K_{sat} \) was developed by Zanger (1953) and expanded to the following by Bonell et al. (1983):

\[
K = \frac{\ln\left(\frac{h}{r} + \sqrt{\left(\frac{h}{r}\right)^2 - 1}\right) - 1}{2\pi h^2} Q
\]

(Equation A5)

\( K \) is the hydraulic conductivity (cm min\(^{-1}\))
\( h \) is the constant water depth in the auger hole and is measured as the difference between the bottom of the permeameter and the base of auger hole (cm)
\( r \) is the radius of the hole (cm)
\( Q \) is the rate at which water is flowing into the auger hole (cm\(^3\) min\(^{-1}\))

\( Q \) is calculated from;

\[
Q = \frac{\Delta h}{\Delta t} \times SF
\]

(Equation A6)

The scale factor (SF) is the volume of water (cm\(^3\)) between the inner and outer tubes of the permeameter, for each centimetre head of water. For the 2.5 cm radius permeameter used in this study the scale factor is equal to 6.03 cm\(^3\) per centimetre head of water.
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