British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

# Ecohydrological Conditions at Braunton Burrows: activities to date including work supported by BGS Opportunity Funds FY 2011/2012

Groundwater Science Programme

Open Report OR/12/041

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

OPEN REPORT OR/12/041



*Keywords*

Opportunity Funds, coastal dunes, Brauton Burrows.

*Front cover*

Pulling out the continuous sleeved core after drilling down one metre core length.

*Bibliographical reference*

ALLEN D, DARLING W G, JONES M L M, MOUNTFORD O, ROBINS N S, STRAFORD C J AND WALLACE H . 2012. Ecohydrological Conditions at Braunton Burrows: activities to date including work supported by BGS Opportunity Funds FY 2011/2012. *British Geological Survey Open Report*, OR/12/041. 29pp.



Maps and diagrams in this book use topography based on Ordnance Survey mapping.



# Ecohydrological Conditions at Braunton Burrows: activities to date including work supported by BGS Opportunity Funds FY 2011/2012

D Allen[1], W G Darling[1], M L M Jones[2], Mountford O[3], Robins N S[1], Stratford C J[3] and Wallace H[4]

[1]British Geological Survey, Crowmarsh Gifford, Wallingford, OX10 8BB, UK.

[2]Centre for Ecology and Hydrology, Bangor, Gwynedd, LL57 2UW, UK.

[3]Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford, OX10 8BB, UK.

[4]Ecological Surveys (Bangor), Canon Pyon, Hereford, HR4 8PF, UK.

Keyworth, Nottingham British Geological Survey 2012

## BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

*The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.*

*The British Geological Survey is a component body of the Natural Environment Research Council.*

*British Geological Survey offices*


**BGS Central Enquiries Desk**

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

**Environmental Science Centre, Keyworth, Nottingham NG12 5GG**

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

**Murchison House, West Mains Road, Edinburgh EH9 3LA**

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

**Natural History Museum, Cromwell Road, London SW7 5BD**

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

**Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE**

Tel 029 2052 1962 Fax 029 2052 1963

**Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB**

Tel 01491 838800 Fax 01491 692345

**Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF**

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

*Parent Body*

**Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU**

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

# Contents



**FIGURES**

## TABLES



## PLATES

# Summary

Ongoing investigation of the ecohydrological conditions at four west coast dunefields (Ainsdale, Newborough Warren, Whiteford Burrows and Braunton Burrows) has recently been focused at Braunton in North Devon. BGS Opportunity Funds, coupled with the acquisition by CEH of a pneumatic portable auger, has enabled investigation and sampling from cores taken from ‘deep’ boreholes beneath the high dunes at Braunton along the existing Sandy Lane Shore Slack transect. Work has previously focused on the slack floors and the shallow water table beneath them. Analyses of chemistry, stable isotopes, $SF_6$, as well as grain size and falling head permeability will, in due course, enable a better understanding of groundwater provenance in the dune fields and of the recharge processes away from the dune slack floors.

Preliminary results are described. Further data are still awaited and will be incorporated in a future report. A way forward is described which will deliver peer reviewed papers on the deep drilling work at Braunton, a paper on work at Whiteford and detailed investigation funded largely by Natural England and CEH at four new sites. These sites are likely to include two acid coastal dunes on the North Sea Coast, which will contrast with the alkaline sites on the west coast, one in Cumbria and one elsewhere.

# 1 Introduction and background information

Braunton Burrows, a dune system on the North Devon coast, rises to 38 m aOD and covers an area some 5 km by 2 km with the long side adjacent to the coast. The area comprises a series of north to south oriented dunes and slacks shaped by the prevailing on-shore winds. There is a narrow zone of low fore-dunes up to 5 m high adjacent to the beach which are succeeded inland by sand hills up to 15 m high separated by a discontinuous belt of slacks. The succeeding dunes are the highest. Beyond these dunes lies a broad, but poorly defined, belt of lower lying ground with scattered hillocks and many pools, some of which are permanent. Inland again are smaller dunes followed by flat sands with a few scattered small dunes which merge towards cultivated fields on the alluvium. The slacks are mainly dry with ephemeral wet weather pools and these are sensitive to the groundwater elevation (English Nature, 2006; Davy et al. 2010). The water table is domed within the sands, being entirely rain fed, with a maximum elevation of 7 or 8 m aOD in winter beneath the centre of the dome. An idealised cross section of a west coast dune field is shown in Figure 1.

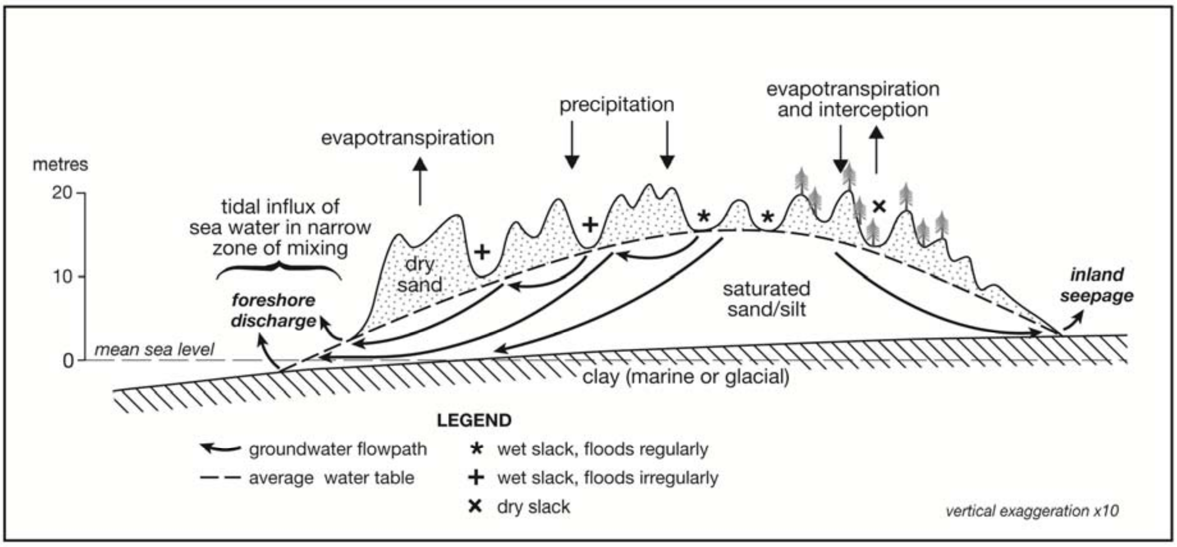


**Figure 1 Idealised conceptual cross section across a coastal dune field.**

Braunton Burrows supports a rainfed groundwater system with a water table that is mounded along an axis near and parallel to the eastern boundary of the Burrows, but trends westward towards the north of the system which is partly covered by golf links. A detailed description of the site was provided by Robins (2007). In summary, annual water level fluctuations in the dune slacks are up to 2 m and they rarely flood in winter. The long term recharge and discharge/abstraction estimate for the Burrows is 478.6 mm. Much of this drains to the foreshore at low tide to the west and towards the West Boundary Drain to the landward side in the east. Deepening of the West Boundary Drain in 1983 affected water levels only in the immediate vicinity of the drain. Some groundwater is intercepted by drainage of fields in the north eastern sector of the dunes. The Golf Club has an abstraction borehole which penetrates the Carboniferous Limestone aquifer which is locally confined by the marine clay beneath the sand. The borehole is used for dry weather sprinkler irrigation over the north end of the Burrows. An integrated hydrology, topography and dune slack vegetation study has been carried out along the main central transect of dipwells to identify the relationship between vegetation communities and depth to the summer water table in the dune slacks. This work has yet to be reported.

## 1.1 HYDROLOGICAL MONITORING

Monitoring of water levels has been ongoing since 1966 and the resulting data set provides a valuable long-term baseline record. Effective rainfall has declined by 5% since the mid 1960s (Figure 2). The 24 month moving average for rainfall at Bideford parallels the dune dipwell hydrographs, reflecting a rainfed system independent of significant outside influences. Since 2001 the water level has fallen although there has been considerable recovery in the last few years. In the long term, groundwater levels may be affected by a number of influences but decline in effective rainfall is the critical influence. Change in land cover is unlikely to be a significant influence on the water table. The historical data set is comprehensive and complements the long record for the Ainsdale National Nature Reserve on the Sefton Coast in Lancashire.

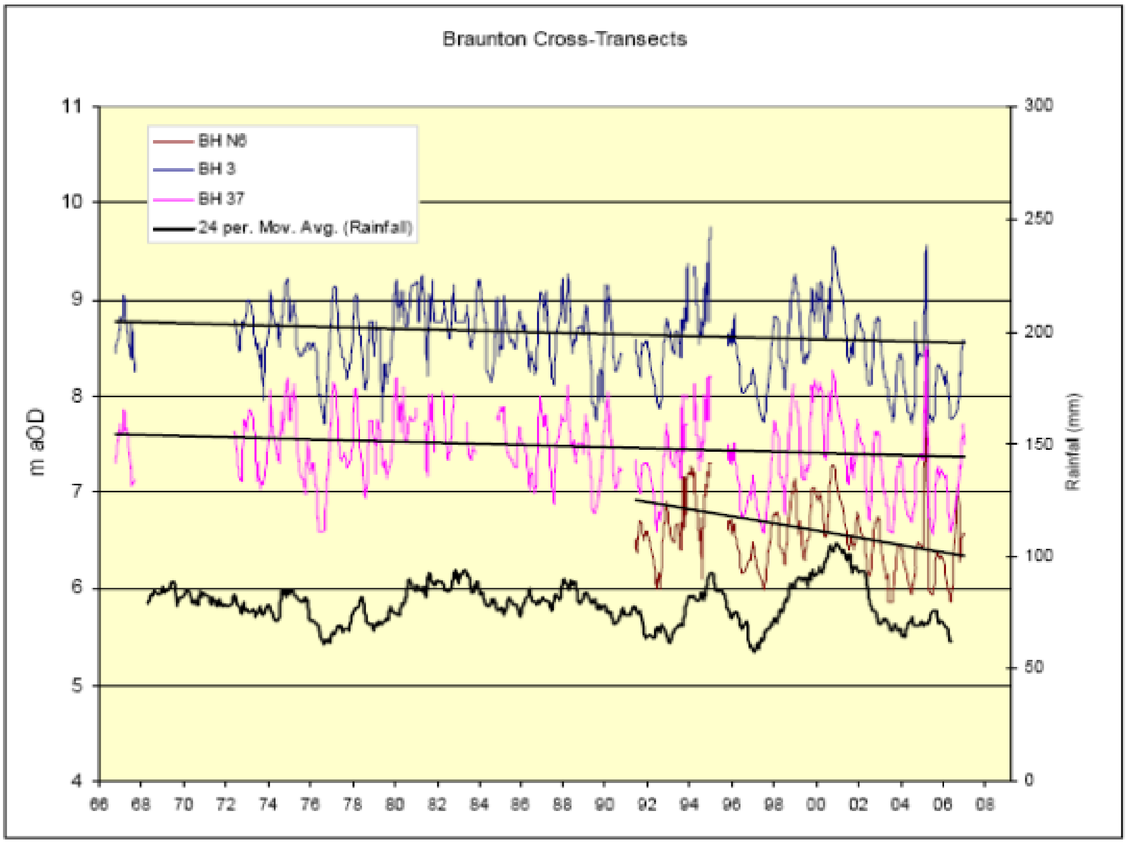


**Figure 2 Typical hydrographs from each of the three transects with 24 month moving average for Bideford rainfall and declining linear trends for each hydrograph.**

### 1.1.1 Existing Dipwell Network

Two transects of dipwells were installed in the 1960s and water levels in the dipwells have been collected at approximately monthly intervals since then (Figure 2). Transect No. 1, along which the new deep dipwells have been installed, runs from the Sandy Lane car park to the west-north-west (Figure 3). Transect Nos. 2 and 3 lie to the south. Having a dataset that covers such a long period is a rarity and enables long-term trends to be identified. Anecdotal reports describe the drying out of the Burrows and the increasingly infrequent flooding of the dune slacks. The recorded changes in groundwater level within the dunes show an overall decline in level of about 0.5 m since 1966 which reflects a reduction in effective rainfall of about 5% over the same period (Figure 2). This decline may be exacerbated by land drainage, coastal erosion of the seaward dune face and increases in evapotranspiration, but these are likely to be modest influences compared to the overall decline in rainfall. Further anecdotal evidence suggests that the beach level, particularly towards the north of Saunton Sands, is dropping, and this may accelerate the recession of the dune face.

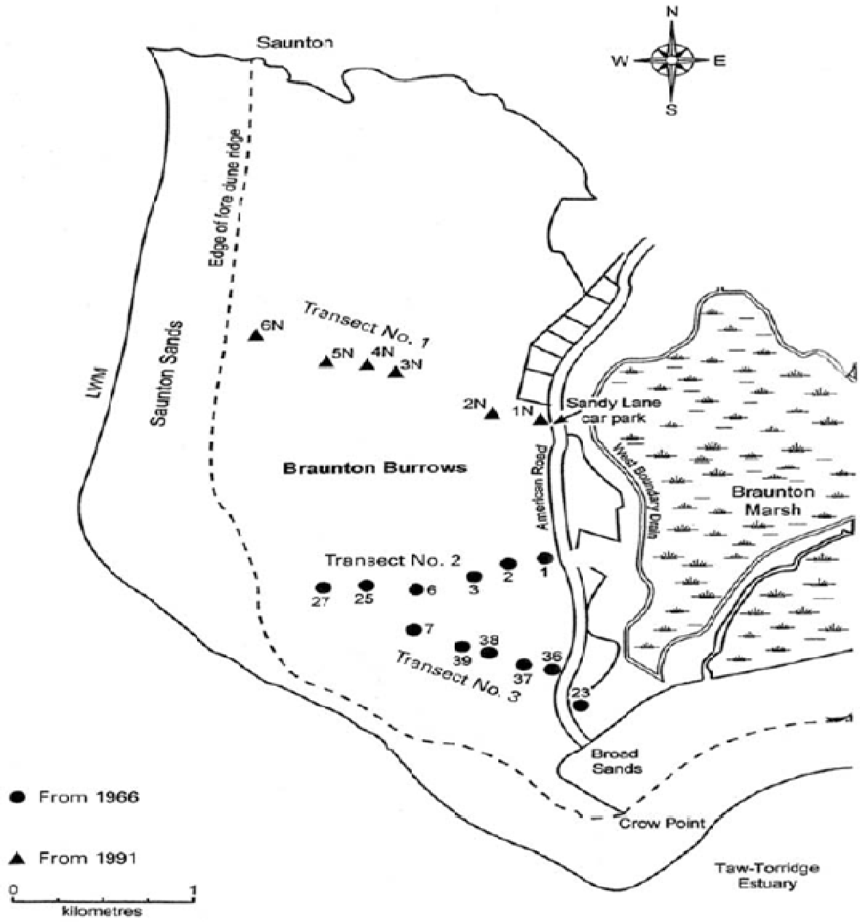


**Figure 3 The older southern transects and the new Transect No. 1.**

In 1992 it was estimated that 12% of the 1350 ha dune system had been inundated by scrub vegetation (Burden, 1998), increased in 2007 to about 20% (Breeds, personal communication). However, 1997 to 2001 rainfall was temporarily increasing year by year, scrub coverage was increasing as well and yet groundwater levels were rising (Figure 4). From 2000 onwards annual rainfall was declining, scrub cover continued to expand and groundwater levels declined. This suggests that it is effective rainfall that is the controlling influence on groundwater levels with a possible minor input from the increased scrub cover. A number of ponds have been developed in the dunes to support wildlife. They act as small groundwater sinks when flooded, but the overall loss of groundwater by open water evaporation is small.

Climate variability may cause a reduction in rainfall input and a marginal increase in actual evaporation (Davy et al., 2010). This will in turn effect a further reduction in groundwater recharge so that the overall water table beneath the Burrows may continue to decline. This could induce further changes in vegetative cover particularly around the dune slacks. However, sea level rise could elevate the base level of the system and inhibit the decline in the water table.

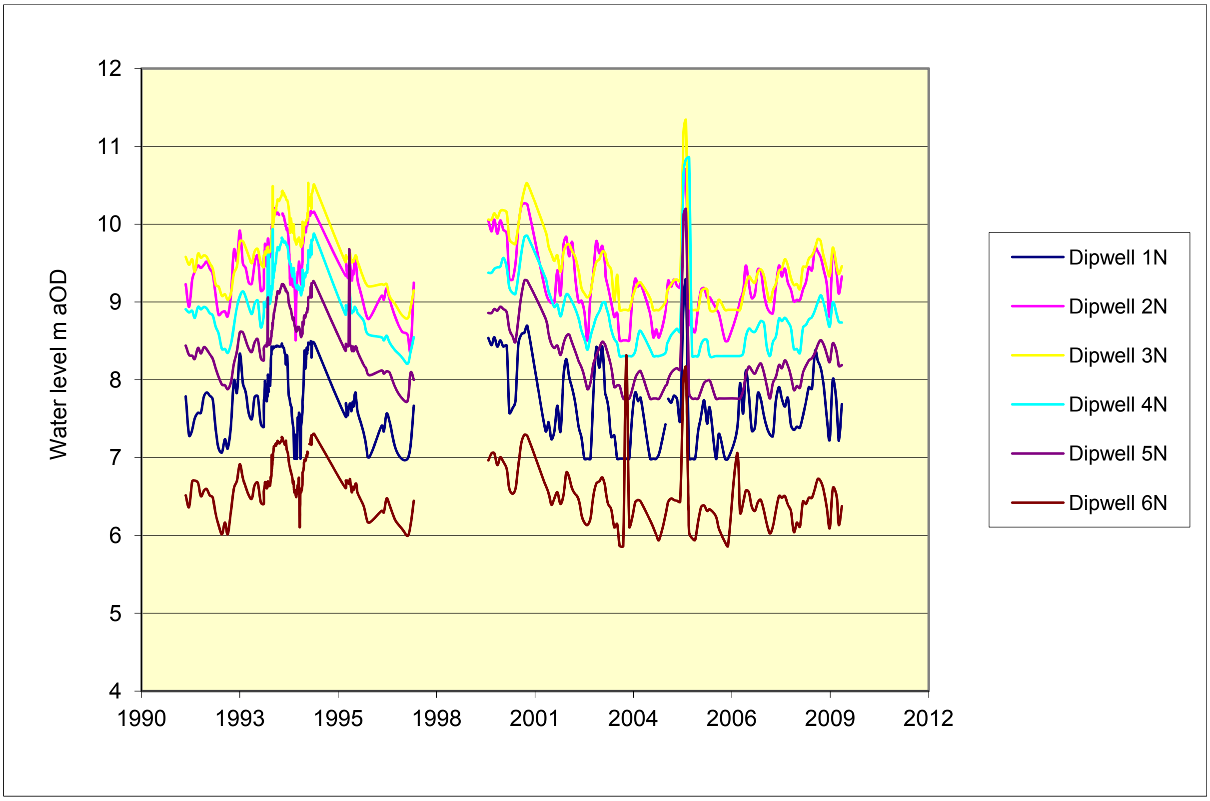


**Figure 4 1991 to 2010 water level data for dipwells on Transect No. 1.**

### 1.1.2 New Shallow Dipwells

In February 2010, three new dipwells were installed at Braunton Burrows. The aim of these was to collect high frequency water level data, which would enable improved hydrological and ecohydrological analysis, including detailed analysis of the water table response to rainfall and calculation of sum exceedence values for improved analysis of vegetation. The dipwells were sighted in three slacks on Transect No. 1(at Dipwell No. 2 in Cotton Slack, Dipwell No. 4 in unnamed slack and Dipwell No. 6 in Beach Head slack – Figure 3) adjacent to, and numbered the same as, existing monthly recorded dipwells so that the high frequency data could be considered in the context of the monthly dipwell record. An automatic water level logger (DIVER™) was installed in each dipwell and set to record water level at half-hourly intervals (Figures 5 to 7). Note that overall amplitude declines slightly towards the constant head effect of the shoreline and that the flashiness of the trace reduces in the same direction. These data have yet to be studied in detail but the correlation between continuous event record and monthly dipwell data is favourable.

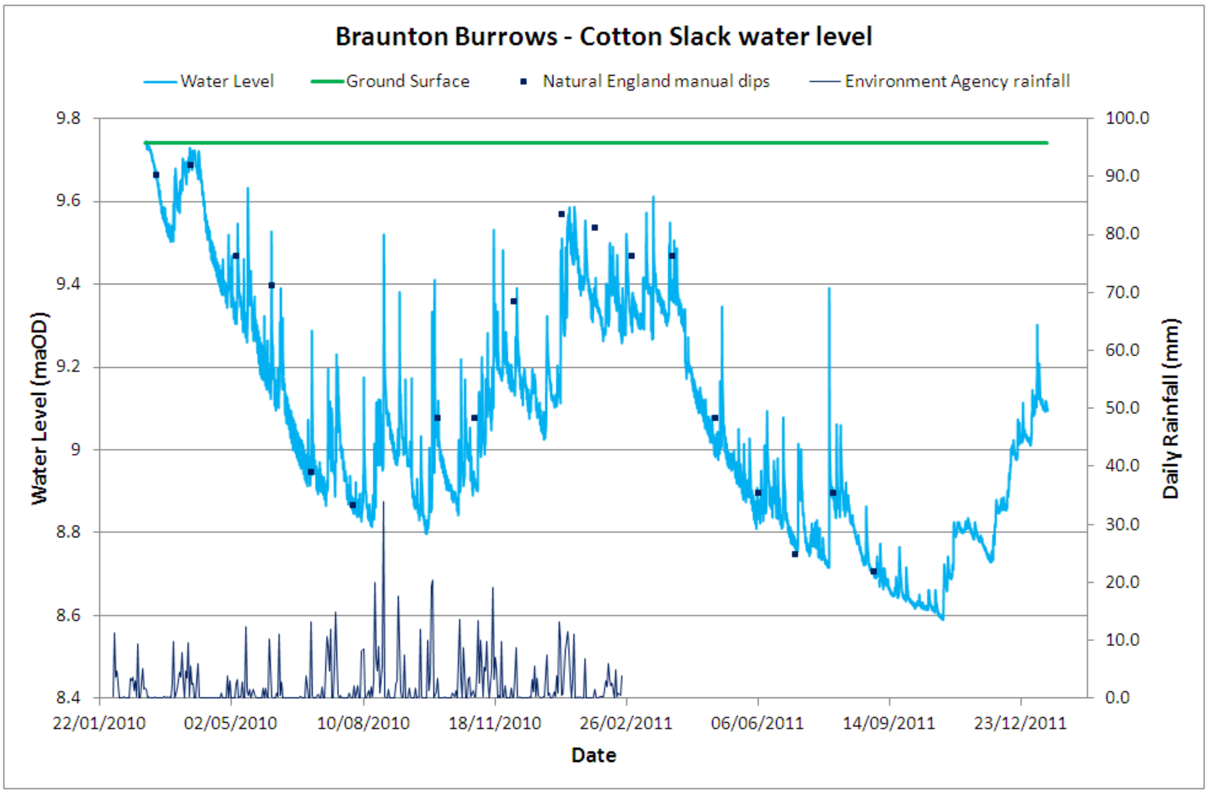


**Figure 5 Continuous water level data, Environment Agency rainfall data, Natural England manual water level data and ground surface level for dipwell CEH 2, in Cotton Slack.**

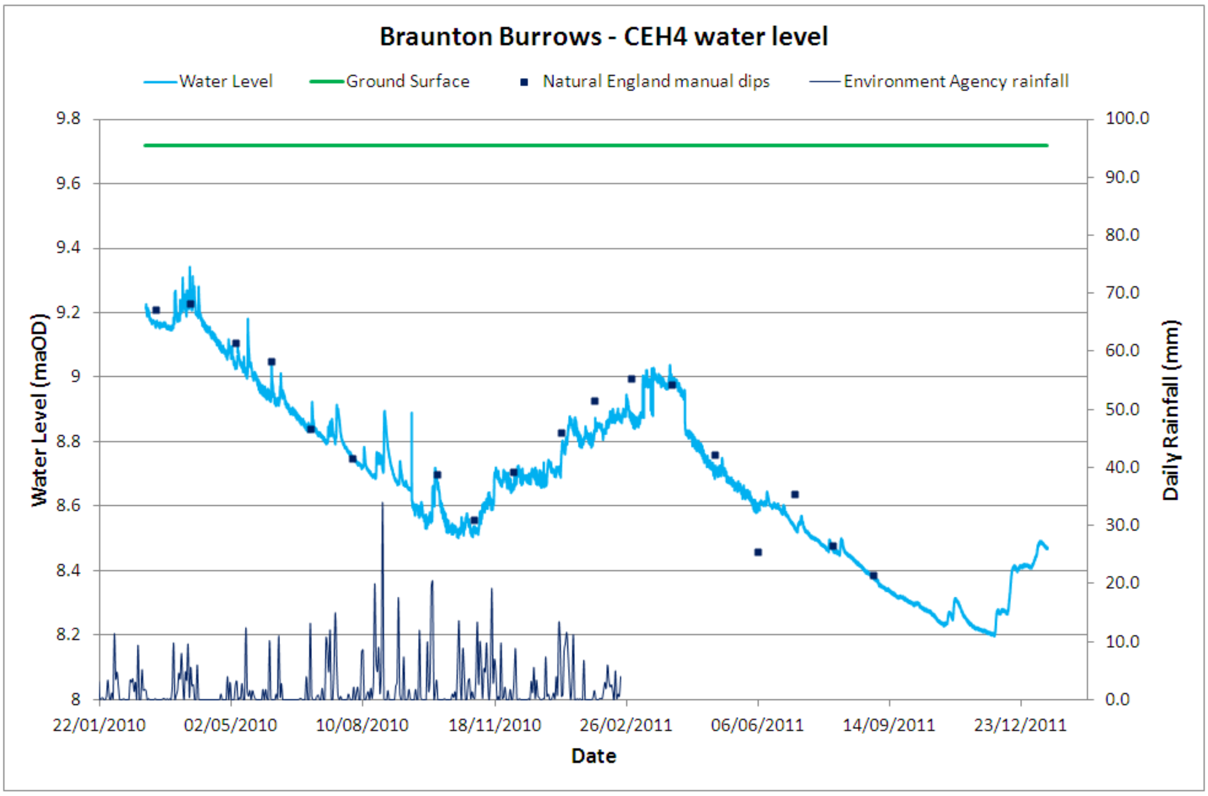


**Figure 6 Continuous water level data, Environment Agency rainfall data, Natural England manual water level data and ground surface level for dipwell CEH 4.**

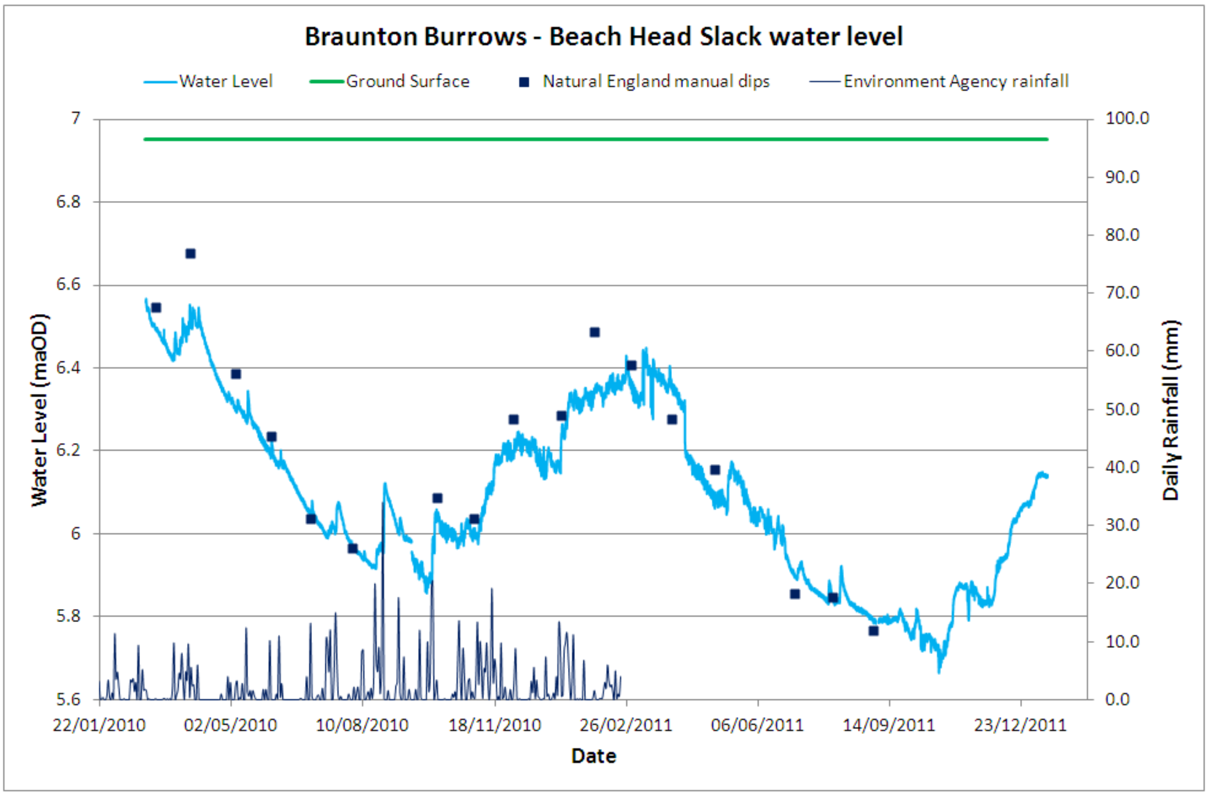


**Figure 7 Continuous water level data, Environment Agency rainfall data, Natural England manual water level data and ground surface level for dipwell CEH 6, Beach Head Slack.**

## 1.2 TOPOGRAPHIC SURVEYS

A detailed topographic survey was carried out on the three slacks including Cotton Slack, and Beach Head Slack, in September 2011 using integrated differential GPS (dGPS) and optical surveying (total station) instruments. Within a single slack, the setup was carried out using dGPS and the subsequent survey was conducted (for the most part) using the total station. This approach gives very high accuracy points within a single slack, for example points measured within a single slack would be expected to have an accuracy of ± 2 mm. It also gives a between slack accuracy of ± 8 mm, which means that we can be confident that a point measured in Beach Head Slack and a point measured in Cotton slack, will be within 16 mm of the true value. Points were recorded around the defining dune ridge and then in closely spaced transects across the slack floor. A simple description of the surface cover (e.g. bare sand, short vegetation, long vegetation, scrub) was assigned to each survey point to enable a surface cover map to be developed. This will assist modelling recharge processes within a slack and help to better define the rainfall interception losses. Topographic features, such as hummocks and small ridges, were picked out as were dipwells, survey markers and quadrat locations.

The survey data were subsequently loaded into ArcMAP and an interpolation routine was carried out in order to produce a surface map (Figure 8, Figure 9 and Figure 10).

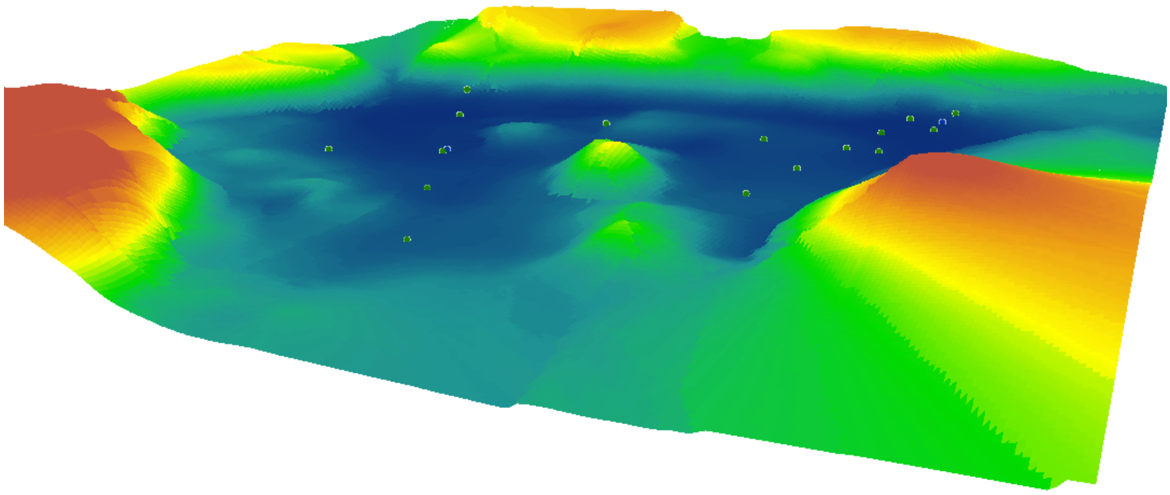

**Figure 8 Surface map of Cotton Slack. Green dots indicate locations of vegetation survey quadrats.**

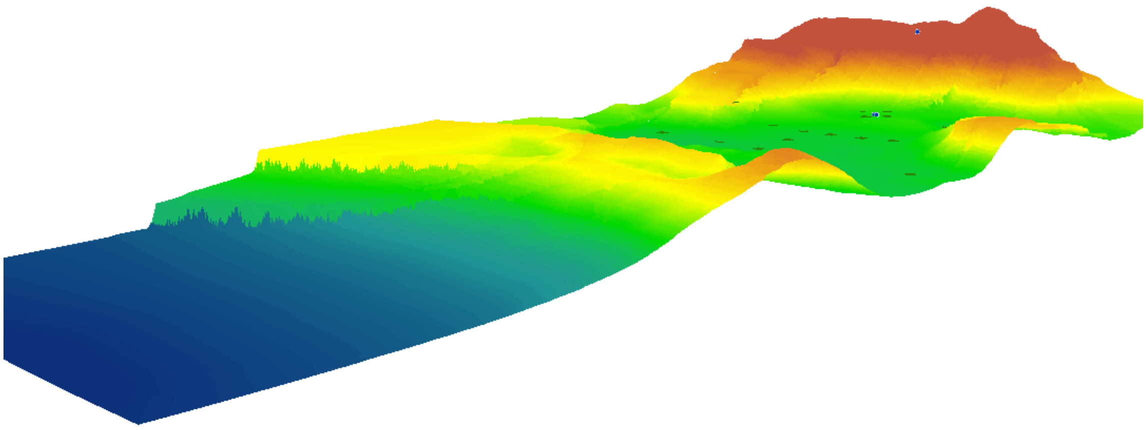

**Figure 9 Surface map of Beach Head Slack. Green dots indicate locations of vegetation survey quadrats.**

## 1.3 VEGETATION SURVEYS

### 1.3.1 Vegetation units.

The National Vegetation Classification (NVC) units are poorly defined (Davy et al., 2010). The species lists from the quadrats are uniformly richer than might be expected: there may be three reasons for this. Firstly the dune slack species are being augmented by dune species indicating that the slacks are drier than they ideally should be. Secondly, the SD14 species are quite common in the SD16 quadrats and *vice versa* since the units are more transitional than in some dune systems (Table 1). Thirdly, the current slack vegetation may be variously influenced by the intensity or otherwise of past scrub management.

The communities are not well dispersed within the slacks, with one slack being predominantly SD16 and the other sites predominantly SD14. Only within Beach Head Slack is there a discernable pattern of communities that may be related to local hydrological variation. It may be that the distribution of individual species may be more instructive in relation to hydrology than that of NVC units on this system.

**Table 1 Distribution of vegetation units**

| | NVC Mean | NVC Range | Braunton Mean | Braunton Range |
|---|---|---|---|---|
| *Salix repens-Campylium stellatum* dune slack. *Festuca rubra* subcommunity (SD14d) | 23 | 12-31 | 29.4 | 19-36 |
| *Salix repens-Holcus lanatus* dune slack. *Prunella vulgaris-Equisetum variagatum* subcommunity (SD16c) | 22 | 14-32 | 28.4 | 20-39 |

### 1.3.2 Bryophytes.

The north end of Cotton Slack is quite rich in bryophites. In contrast, Beach Head Slack has a poor representation of mosses. This is likely to be related to sward height rather than hydrological conditions – the small acrocarpous mosses which predominate tend to be associated with bare patches and/or very low swards.

## 1.4 OPPORTUNITY FUND PROJECT

Work at Braunton Burrows, as at other important west coast dune fields, has focused traditionally on the ecohydrology of the dune slacks with little attention being given to the high dunes (Robins and Jones, 2012). This is because of the difficulty of augering deep dipwells several metres through the vadose zone to the water table beneath the dunes. As a consequence the processes of recharge and the location of the no flux zone are poorly understood.

Two elements were brought together to enable a detailed investigation of the high dunes in autumn 2011. The first was the purchase by CEH of a portable percussion auger system that is capable of recovering core. The second was the successful bid for BGS Opportunity Fund support to undertake detailed analytical work on the recovered sand and water samples.

Five deep dipwells were installed Transect No. 1, each strategically located at or near the brow of a high dune. Three of them penetrated the water table and have been instrumented with continuous water level event recorders. Analytical data are as yet incomplete (April 2012) with groundwater and vadose moisture chemistry data, grain size analysis and falling head permeameter tests outstanding. All other data are described in Section 2. Once the final data sets are available, two peer reviewed papers will be prepared, the first describing the data and focusing on the hydrochemical and isotopic data, the second describing groundwater provenance and recharge processes. It is hoped that a third paper will be prepared that will be led by the ecologists reflecting on the findings and their impact on the ecology of the dune system. The review paper *A review of ecohydrological aspects of sensitive coastal dune slacks on the west coast of England and Wales* is currently in press in *Ecohydrology*.

# 2 Deep core drilling of dry dune hills

In the autumn of 2011 a pilot 'deep' dipwell was augered to a depth of nearly 6 m on a high dune at the eastern end of the Sandy Lane shallow dipwell transect. This proved the concept that a portable percussion auger could drill through the sand and collect near continuous core the length of the hole. The core is delivered within a polythene sleeve and can be sub-sampled by cutting slices through the sleeve. Sub-samples were taken at 10 cm intervals. The open hole stood up during augering with only the upper 30cm or so dry and crumbly. The remainder of the sand was moist and consistently fine-grained to silt grade material. The hole did not reach the water table but was lined with 36 mm diameter plastic pipe and capped top and bottom should access be needed later.

Four additional deep dipwells were augered roughly along the line of the shallow Sandy Lane dipwell transect during an intense campaign in November, this time to depths of just under 8 m. Continuous sampling was achieved in the first four dipwells with partial sampling in the last one nearest the shore. The deep dipwells, from east to west, are numbered D1 to D5 (Table 2). D3, D4 and D5 penetrated the water table, D2, like D1, did not. All were completed with 36 mm diameter pipe slotted over the bottom 2m with a bottom cap and completed at surface with a cap.

**Table 2 Deep augered dipwells**

| Dipwell | Grid ref | Surface elevation (m) | Drilled Depth (m) | SWL (m) 15/2/12 | Notes |
|---|---|---|---|---|---|
| D1 | 2457213544 | 16.14 | 6.00 | Dry | |
| D2 | 2455013542 | 25.20 | 8.62 | Dry | |
| D3 | 2452613561 | 17.03 | 8.62 | 8.38 | |
| D3new | 2452613561 | 17.03 | 9.20 | 8.38 | Troll started 17/1/12 |
| D4 | 2449013568 | 13.09 | 8.62 | 5.93 | Casing removed |
| D4new | 2449013568 | 13.09 | 9.20 | 5.93 | Troll started 15/2/12 |
| D5 | 2447613573 | 11.30 | 8.80 | 5.10 | Sediments risen to depth 5.93 by 17/1/12 |
| D5new | 2447613573 | 11.30 | 9.20 | 5.10 | Troll started 15/2/12 |

The dipwells were revisited in January 2012 in order to pump samples from below the water table for chemistry, $SF_6$ and stable isotopes. However, D3 was too deep to pump. D4 had been damaged with some of the casing pipe removed, and D5 could not be pumped as excessive sand was being drawn. In the event D3, D4 and D5 were re-augered during

February 2012, each to just over 9 m, and lined with 36 mm plain casing with 2 m of slotted pipe at the bottom wrapped in a fine geotextile sock. A bottom cap was also included. The water standing in these three dipwells was sampled on completion, the water table in D3 being too deep for the peristaltic pump to work, while in D4 and D5 discharge water ran clear and well head measurements were taken and samples collected without difficulty.

# 3 Hydrochemical and isotopic analysis of vadose moisture and groundwater

## 3.1 INTRODUCTION

During 2009 and 2010 the groundwater below selected dune slacks at Braunton Burrows, and also at Ainsdale on the Sefton Coast, Kenfig in South Wales and Newborough Warren in Anglesey, were sampled for chemistry and residence time indicators. Further to this in late 2011 five deep piezometers were installed into the high dunes at Braunton Burrows. Core was recovered from three of the dune piezometers (D2, D3 and D4) and moisture content, stable isotopes, and pore water chemistry were determined. In early 2012 groundwater was sampled for stable isotopes, groundwater chemistry and residence time indicators from 2 of the piezometers (D4 and D5). Although the focus of this report is Braunton Burrows, data collected from all sites is presented here in order to provide context. Below is a short discussion of the initial results.

## 3.2 GROUNDWATER CHEMISTRY BELOW DUNE SLACKS

A preliminary investigation of groundwater chemistry in the unconsolidated coastal dune slacks was carried out at Ainsdale, Braunton Burrows, Kenfig, Newborough Warren and Whiteford Burrows during 2009 and 2010. Groundwater samples were taken 1-3 m below dune slacks and dating indicators showed, perhaps surprisingly, that these waters can be up to 20 years old. Groundwater chemistry samples and field measurements illustrate the hydrochemical environment below slack floors. The low apparent transmissivity of the sand and the relatively short, small diameter piezometers used for sampling allowed low-flow sampling using a peristaltic pump. Concern that this would result in inconclusive $SF_6$ tracer samples from the interaction of the sample with the atmosphere due to the low flow rates were unfounded.

As much of the dune systems are above mean sea level there is minimal influx of dense marine water other than beneath the foreshore. The general flow direction is from the higher central dunes towards the land and the shoreline. At low tide, fresh water can be seen to discharge over the underlying impermeable deposits onto the beach and at Whiteford Burrows at an erosion surface cut into the sand (Stratford and Robins, 2009).

The Piper diagram (Figure 10) highlights that the groundwaters are, on the whole, calcium ($Ca^{2+}$) and bicarbonate ($HCO_3^-$) dominated. The pH of the groundwaters and the dominance of $Ca^{2+}$ and $HCO_3^-$ in most of the samples reflect the abundance of calcareous shell fragments in the sands. The dissolution of calcareous material raises the pH from that of rain water to near neutral pH values (Sival et al. 1997). An increasing dominance of chloride ($Cl^-$) and sodium ($Na^+$) were seen in dune slack groundwaters within coniferous woodland and this is thought to result from the effects of evapotranspiration and dry deposition.

The only sample with any significant nitrate was found in a wooded area at Newborough Warren (12204-09) with 2.1 mg/l $NO_3$-N. This sample is oxic with a dissolved oxygen concentration >1 mg/l and low iron and manganese concentrations.

Organic matter reduces the oxygen content in groundwaters, however, upwelling groundwaters also usually have a low dissolved oxygen content and downwelling waters a higher oxygen content. The dissolved oxygen concentration in the groundwaters below the dune slacks are low in most samples producing a reducing environment with subsequent high iron and manganese concentrations. However, some sites have oxidizing conditions with subsequent low Fe and Mn values. Upwelling groundwater is expected to be older but there is no pattern seen as some of the youngest waters are also reducing.


**Plate 1 Percussion auger drill at Braunton Burrows.**

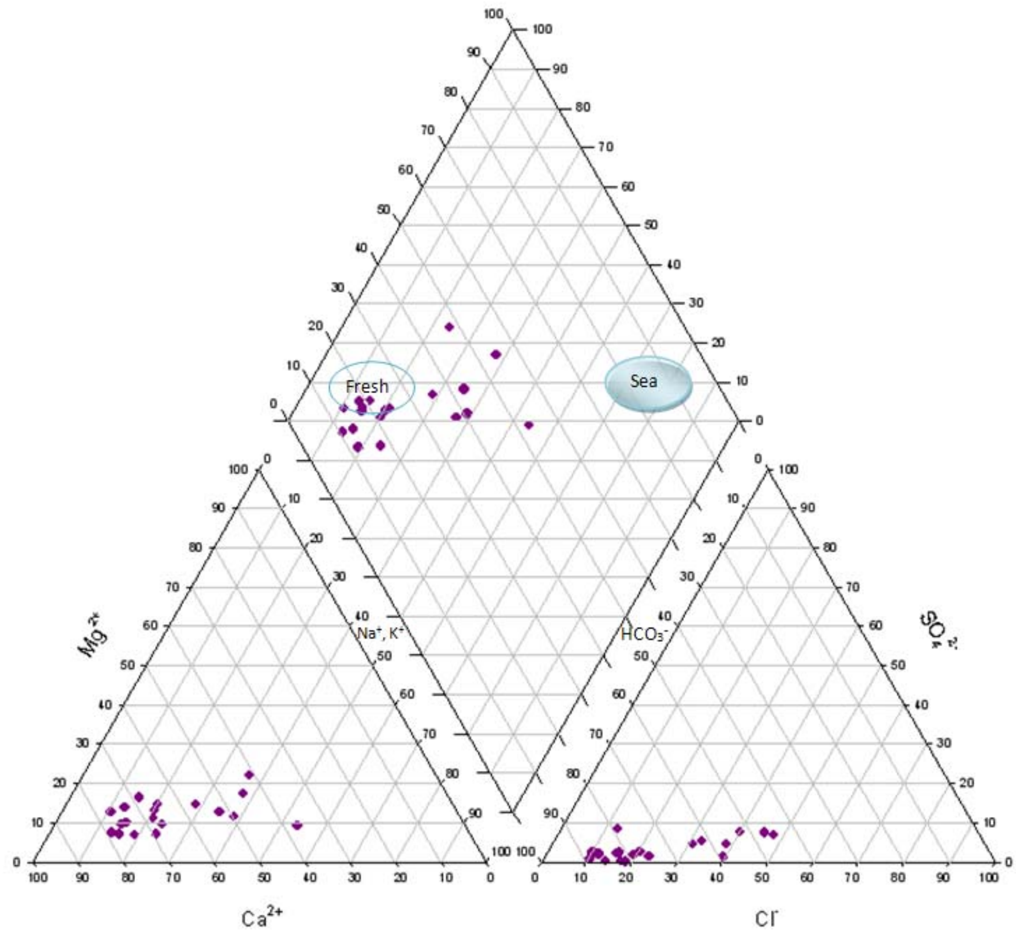


**Figure 10 Piper diagram of dune slack groundwater chemistry. The diagram is annotated to show where seawater and fresh water would plot.**

Year to year variation was illustrated by the repeat sampling twelve months later and analysis of water from two piezometers at Ainsdale. However in the second year the sample was taken from a new dipwell 0.5 m away from the old one to provide improved access for sampling. Both show reducing conditions with high Fe and Mn. The $Cl^-$ concentration doubles over the year from 25 mg/l to 50 mg/l, $SO_4^{2-}$ increases from 0.22 mg/l to 13 mg/l, $HCO_3^{2-}$ decreases from 203 mg/l to 112 mg/l and dissolved organic carbon halves from 8.8 mg/l to 4.4 mg/l. The results for $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$ are within about 25% of each other. However, these two samples (collected within 0.5 m of each other) plot in different places on the Piper plot, one within the main bundle of fresh water samples and the other above this main group with a lower $HCO_3^-$ dominance and higher $Cl^-$ dominance.

## 3.3 RESIDENCE TIME BELOW DUNE SLACKS

Sulphur hexafluoride ($SF_6$) samples were taken as indicators of the age of the groundwaters. Groundwaters up to about 50 years old can be dated using $SF_6$ due to the monitoring of atmospheric trace gases at a number of sites across the globe for about 30 years (Prinn et al. 2000). Gooddy et al. (2006) explains how $SF_6$ concentration can give groundwater ages based on historical atmospheric mixing ratios over the past 50 years for $SF_6$ and its Henry's Law solubility in water. The dissolution of any gas into water is dependent on the temperature of the system. The apparent age of the groundwater is calculated using the Henry's Law constant calculated at the expected recharge temperature. The recharge temperature is generally equivalent to the average annual air temperature and in this case 10$^{o}$C has been used (Gooddy et al. 2006). Groundwaters contain air dissolved due to the equilibrium between rainfall and the atmosphere. During infiltration of rainwater and water level fluctuations, air is entrapped in the porous spaces below the slack floor. Some of this entrapped air will then dissolve into the groundwater and may lead to excess air (EA) in the groundwater (Holocher et al. 2002). This process supplements the equilibrium gas content with the direct, non-equilibrium addition of air, causing dissolved gas contents to rise in inverse proportion to their solubility. Using average ΔNe data from the sand column experiments of Holcher et al. (2002) and a recharge temperature of 10$^{o}$C gave an excess air concentration of 1.5%. This figure was then used to correct the $SF_6$ concentration in the samples and provide recharge dates as seen in Table 3.

**Table 3 Recharge dates for groundwater below dune slacks calculated from $SF_6$ concentration.**

| Sample ID | Site | Eastings | Northings | Sampling Date | $SF_6$ (fmol/l) | Yr of recharge 1.5 ccSTP/L EA ± 2 years |
|---|---|---|---|---|---|---|
| 12204-2 | Whitford Burrows | 244667 | 195483 | 04/08/2009 | 1.36 | 1992 |
| 12204-3 | Whitford Burrows | 244697 | 195505 | 05/08/2009 | 1.19 | 1990 |
| 12204-4 | Whitford Burrows | 244449 | 195495 | 05/08/2009 | 1.72 | 1995 |
| 12204-5 | Whitford Burrows | 244373 | 195210 | 05/08/2009 | 1.29 | 1990 |
| 12204-8 | Newborough Warren | 242420 | 363758 | 11/08/2009 | 1.01 | 1988 |
| 12204-9 | Newborough Warren | 240965 | 364065 | 12/08/2009 | 0.88 | 1987 |
| 12204-10 | Newborough Warren | 240683 | 363759 | 12/08/2009 | 0.71 | 1985 |
| 12204-12 | Ainsdale | 328833 | 409766 | 13/08/2009 | 0.76 | 1985 |
| 12316-1 | Braunton Burrows | 245849 | 135363 | 25/02/2010 | 2.65 | 2004 |
| 12316-2 | Braunton Burrows | 245222 | 135738 | 25/02/2010 | 2.49 | 2003 |
| 12316-3 | Braunton Burrows | 244765 | 135888 | 25/02/2010 | 2.73 | 2005 |
| 12472-1 | Ainsdale | 329330 | 411862 | 18/08/2010 | 3.17 | 2008 |
| 12472-2 | Ainsdale | 329227 | 411711 | 18/08/2010 | 2.76 | 2004 |
| 12472-3 | Ainsdale | 329873 | 411486 | 19/08/2010 | 2.24 | 2000 |
| 12472-4 | Ainsdale | 330036 | 411360 | 19/08/2010 | 2.24 | 2000 |

All groundwater recharge ages are given to ± 2 year accuracy. Water abstracted from the ground is a mixture of waters from all the flow lines reaching the discharge point and hence the recharge ages are a mean age produced from mixing during pumping and normal groundwater flow. The recharge ages of groundwaters pumped from piezometers containing bubbles was not samples due to the possible contamination with air.

Braunton Burrows groundwater from 1-3 m below ground level is approximately the same recharge age of 7 to 5 years with no distinct pattern of distribution. It was also the only site sampled during winter and, therefore, with highest water levels. Two separate sampling campaigns were undertaken at Ainsdale, the first in August 2009 where a recharge age of 24 years was found from a piezometer within the woods (12204-12). A further sampling visit in August 2010 gave much younger dates for groundwaters within the dune system along a transect perpendicular to the foreshore. The two closest to the sea gave recharge ages of 3 to 6 years and the two further inland piezometers gave a recharge age of 10 years. This shows that waters are slightly younger nearer the foreshore than further inland. This implies that the water within the dunes in the forested area was recharged about 20 years before the groundwaters in the more open dune area along the transect, however, this may equally reflect a contaminated sample. A possible cause for the older waters under the forest at Ainsdale is a more stagnant area with less active flow.

The two samples in the forest and the one in the more open dune system at Newborough Warren all gave a similar recharge age of between 21 to 24 years. Similarly the four samples taken in the wooded and more open dune areas at Whiteford Burrows gave a recharge age of 14 to 19 years.

This work shows that groundwater within these dunes systems originated as meteoric water and has been contained within the dune systems for about 20 years in the case of Newborough Warren and Whiteford Burrows.

## 3.4 DEEP DRILLING AT BRAUNTON BURROWS

### 3.4.1 Stable isotope profiles at Braunton

The deep drilling at Braunton Burrows has enabled a variety of profiles to be observed, including stable isotopes in the vadose zone beneath the high dunes (Figure 11).

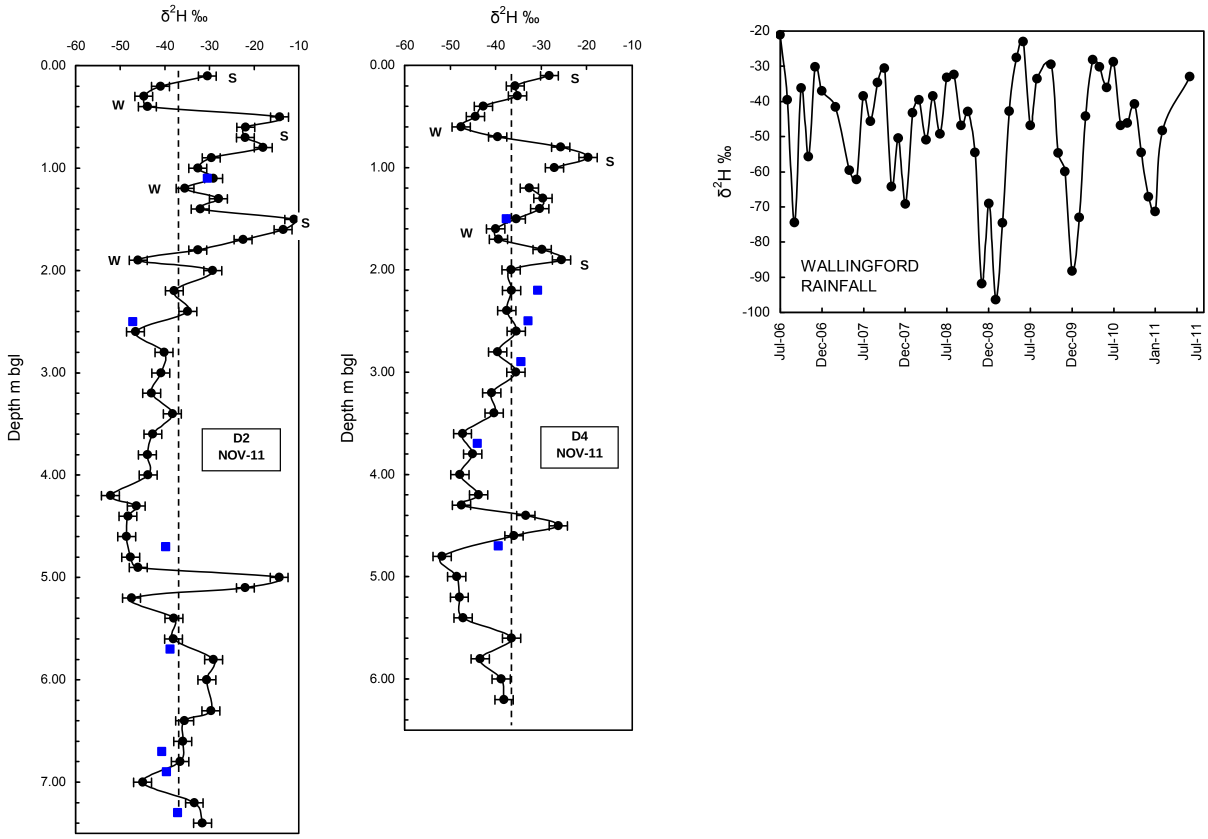


**Figure 11 Profiles of $\delta^2H$ in sand moisture obtained by direct reaction of sand samples from BHs D2 and D4, autumn 2011. Blue datapoints represent analyses of water extracted by centrifuge, showing generally good agreement. Also shown is the rainfall isotope record from Wallingford (nearest rainfall isotope collection station). The dashed vertical line shows the approximate $\delta^2H$ composition of the underlying groundwater**

It is probable that the fluctuations seen in the upper 2 m or so of both profiles are the consequence of seasonal variations in the isotope ratio of rainfall. On this basis it can be estimated that infiltration is occurring at a rate of 0.8–1.0 m per annum. Diffusion will tend to blur the annual cycles at greater depths so the occurrence of spikes in each borehole at around 5 m is surprising. This seems too great a depth for plant roots or animal burrows to have any effect. Possibly they record some unusual local rainfall input, e.g. the heavy summer rainfall in July 2007.

There is little evidence for significant evaporation effects in the profiles. The water samples from D4 were measured for $\delta^{18}O$ in addition to $\delta^2H$, allowing a co-plot to be produced (Figure 12). This shows that while there is a departure from the classic meteoric water slope of 8, there is no approach towards the low slopes of ~2 characteristic of moisture in desert soils undergoing evaporation. Therefore, any losses to evaporation during infiltration appear to be small. However, plant transpiration typically does not cause isotopic fractionation so would not be identifiable by such an approach.

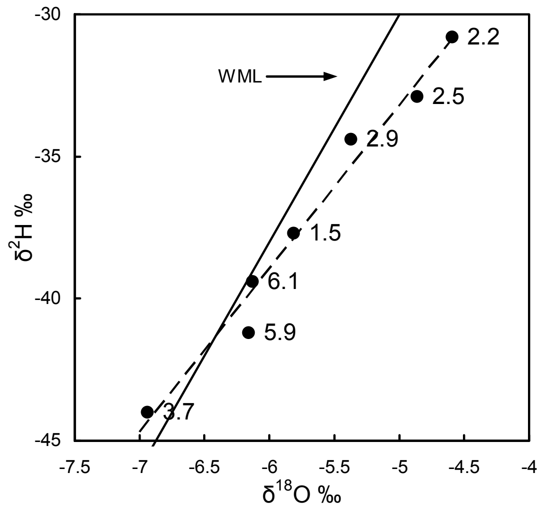


**Figure 12 Isotopic co-plot showing the composition of centrifuged waters from D4 compared to the world meteoric line (WML, the expected ratio in rainfall). sample depths are given in m bgl. the lack of significant deviation from the WML suggests that evaporation has little effect on the infiltrating water.**

### 3.4.2 Pore water chemistry within the dune sands

The core from the deep drilling was recovered and three of the piezometers were sampled in the field. Sub-samples of the core were taken every 10 cm for stable isotopes and then the core was divided into 20 cm lengths which were further divided between moisture content pots and samples for pore water centrifugation. Moisture content was calculated on return. Pore waters were centrifuged from the core materials and standard electrical conductance (SEC) was determined before the samples were sent to the lab for analysis. The laboratory results are still outstanding. Figure 13 is a moisture content and SEC plot with depth for one of these piezometers (D4) and Figure 20 shows conductivity profiles alongside stable isotope data for two of the boreholes..

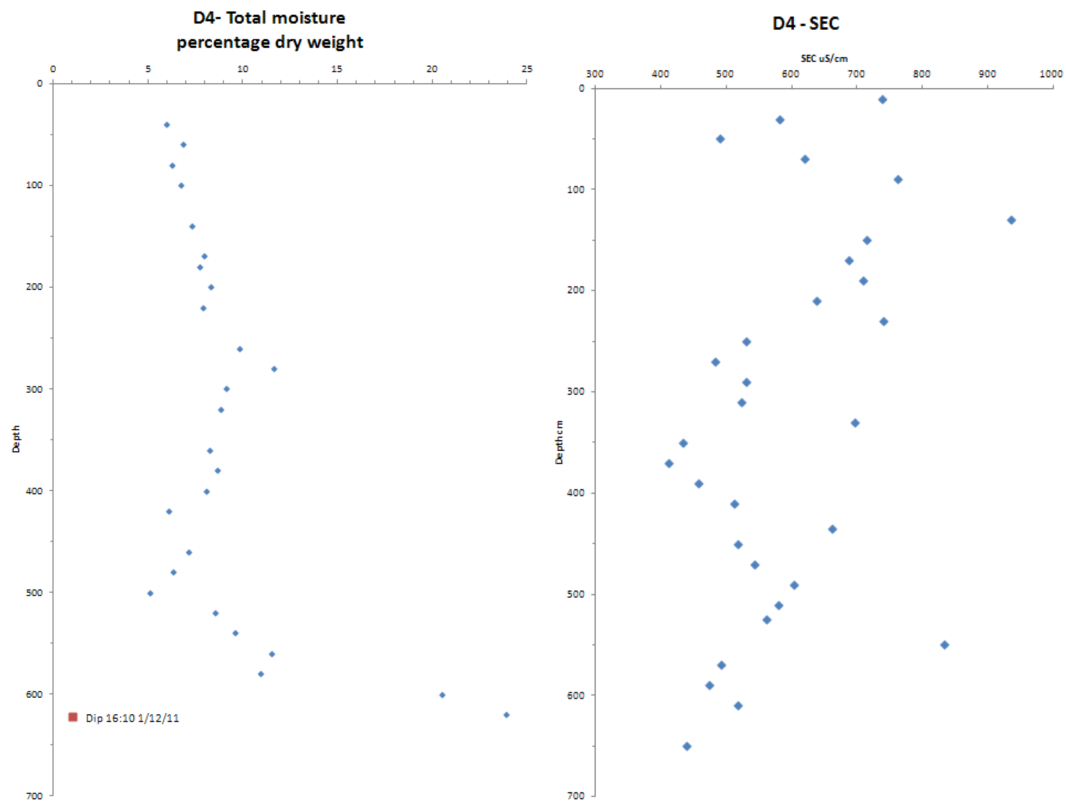


**Figure 13 Total moisture (percentage dry weight) and pore water SEC for piezometer D4. Note: the red square in the left figure indicates the groundwater level in the piezometer after drilling.**

A later visit to Braunton Burrows deepened the piezometers to about 9 m and collected groundwater samples from two of the piezometers (D4 and D5). The results for the full chemical analysis are still outstanding but the results for the residence time indicator are interesting (Figure 14). The residence time indicator ($SF_6$) for the groundwater samples underneath the dune give recharge ages of 13 to 16 years.

**Table 4 Recharge dates for groundwater below dunes calculated from $SF_6$ concentration.**

| BH ID | Site | Eastings | Northings | Sampling Date | $SF_6$ (fmol/l) | Yr of recharge 1.5 ccSTP/L EA ± 2 years |
|---|---|---|---|---|---|---|
| D4 | Braunton Burrows | 24490 | 13568 | 15/02/12 | 1.76 | 1996 |
| D5 | Braunton Burrows | 24476 | 13573 | 15/02/12 | 2.06 | 1999 |

The results from the dune slack groundwater, dune pore water and dune groundwater chemistry can only be used to look at a snapshot in time for the sand dunes. Groundwater chemistry will most probably change during the year as the influence of rainwater infiltration and groundwater flow progress through their annual cycle. Groundwaters below trees were different to those under other vegetation or bare sand. The influence of increased dry deposition can be seen as although most are still $HCO_3^{2-}$ and $Ca^{2+}$ dominated waters the proportion of $Na^{2+}$ and $Cl^-$ are increased.

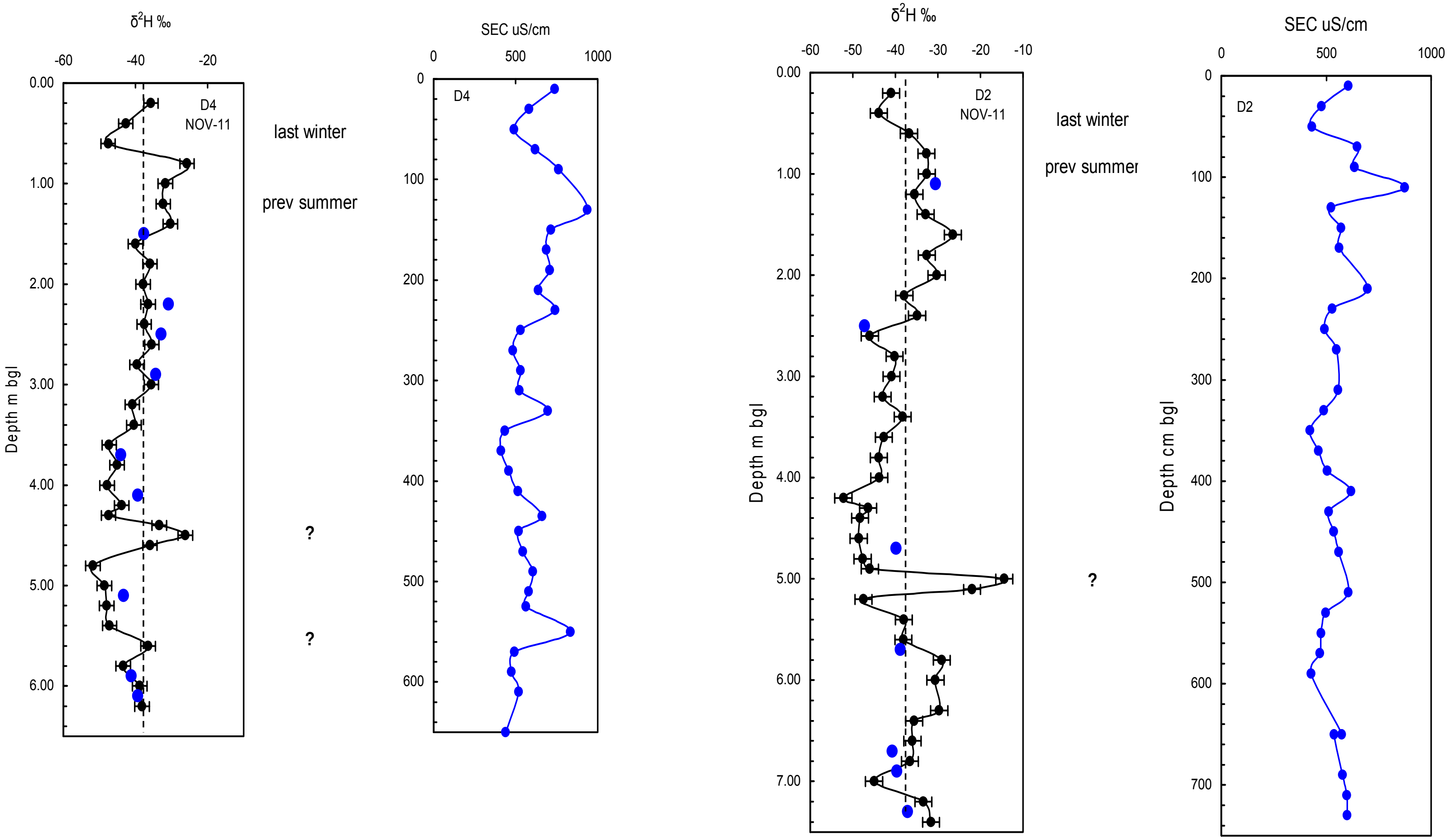


**Figure 14 Example profiles from two of the Braunton Burrows deep boreholes**

# 4 Future activities

Outstanding data from the deep drilling at Braunton will allow preparation of a number of peer reviewed papers. In addition falling head permeameter tests on selected core samples need to be carried out and volumetric sieve analysis also needs to be undertaken.

Significant co-funding has been made available by Natural England through CEH to support investigation of a number of key sites including two supposedly acid sites on the North Sea Coast. Provisional review of these dune fields is listed in the Appendix. This work will progress during FY 2012/2013 to report on the restoration potential at each site. Data gathered may include a variety of techniques that have already been deployed at the four main west coast sites. This work will lead to additional publication opportunities.

A further paper is in preparation describing foreshore erosion, and latterly accretion, along with the development of the primary dune slack, at Whiteford Burrows in Gower.

A key activity underpinning all these activities is gathering the data into a single accessible data resource with metadata which will help access to all the diverse information now held by BGS and CEH.

# 5 References

BURDEN R J 1998. A hydrological investigation of three Devon sand dune systems: Braunton Burrows, Northam Burrows and Dawlish Warren. Unpublished PhD Thesis, University of Plymouth.

DAVY A J, HISCOCK K M, JONES M L M, LOW R., ROBINS, N S and STRATFORD C J 2010. Ecohydrological guidelines for wet dune habitats – Phase 2. Environment Agency Report.

ENGLISH NATURE 2006. Development of eco-hydrological guidelines for dune habitats – phase 1. Technical report. *English Nature* 696.

ROBINS N S. 2007. Conceptual flow model and changes with time at Braunton Burrows coastal dunes. British Geological Survey Commissioned Report, CR/07/072N. 23pp.

ROBINS N S and JONES M L M 2012. Ecohydrological 'Indicators of alteration' - a robust measure of change in dune slacks. *Ecohydrology*. DOI: 10.1002/eco.1264

PRINN R G, WEISS R F, FRASER P J, SIMMONDS P G, CUNNOLD D M, ALYEA F N, O'DOHERTY S, SALAMEH P, MILLER B R, HUANG J, WANG, R H J, HARTLEY D E, HARTH C, STEELE L P, STURROCK G, MIDGLEY P M and MCCULLOCH A 2000. A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE. *Journal of Geophysical Research*, 105, 17751-17792.

HOLOCHER J, PEETERS F, AESCHBACH-HERTIG W, BEYERLE U, HOFER M, BRENNWALD M, KINZELBACH W and KIPFER R 2002. Experimental investigations on the formation of excess air in quasi-saturated porous media. *Geochimica et Cosmochimica Acta*, 66, 4103-4117.

GOODDY D C, DARLING W G, ABESSER C and LAPWORTH D J 2006. Using Chlorofluorocarbons (CFCs) and Sulphur Hexafluoride (SF6) to characterise groundwater movement and residence time in a lowland Chalk catchment. *Journal of Hydrology*, 330, 44-52.

SIVAL F P, GROOTJANS A P, STUYFZAND P J and VERSCHOORE DE LA HOUSSAYE T 1997. Variation in groundwater composition and decalcification depth in a dune slack: effects on basiphilous vegetation. *Journal of Coastal Conservation* 3, 1, 79-86.

# Appendix 1 Review of existing unpublished hydrological and vegetation data for all dune sites in order to refine list of sites for full dune wetland vegetation surveys in 2013.

The CEH/BGS team received a box of reports to consult and copy on the 30th January 2012. The listing below gives the site(s) covered by each report and also a summary indication of the contents in their order within the report/folder. We have tried to bring together the reports that refer to the same site and (within site) have ordered the catalogue by date of survey. Unless stated otherwise, the reports were conducted on behalf of Natural England and/or JNCC (or predecessors). Some other material is loose within folders – such cases are listed but clearly identified. Dates refer to the year of survey rather than the related report where these differ. Apart from the "slack quadrat" totals, note that these early reports use provisional NVC names and numbers that were superseded by the eventual publication in 2000. The community numbers below refer to those listed in the reports and need translation to the published list.

**Braunton Burrows**

1990 [ca 50 pp] as an unbound copy of the 1992 report loose in the box: preamble about survey programme and agencies; methods; site description; standard site recording form; constancy table summarising quadrats (490 quadrats apparently recorded of which 113 were in slacks – types SD14, SD15 and SD16); NVC types recorded; 21 pages of target notes explaining context of individual quadrats etc; species list for whole site; lengthy bibliography

**Lindisfarne**

In 1989 [ca 50+ pp]: methods (supported by a fuller description in Annex 1); general description; vegetation description; site assessment; comments & suggestions; Annex 2 (site recording form); Annex 3 (vegetation types); 17 pages of target notes; Annex 6 containing quadrat data (55 quadrats of which at least 17 were in slacks – types SD15 & SD16) in constancy tables; and detailed vegetation map for site.

**Saltfleetby**

In 1989 [≥ 100 pp] conducted on behalf of National Rivers Authority (Anglian) and covering Saltfleetby-Theddlethorpe Dunes NNR: General description; vegetation description; 7 vegetation maps; vegetation types; ca 40 pages of target notes; and an appendix containing the quadrat data (ca 230 quadrats of which 60 were in slacks – types M22, S6 and S26) in constancy tables and location maps.

In 1990 [20 pp] for Saltfleet Dunes: Methods; general site description; standard site recording form; vegetation types present; constancy table summarising quadrats (15 quadrats recorded – only one in a slack – SD17); 6 pages of target notes explaining context of individual quadrats; detailed vegetation map for site.

**Sandscale**

In 1987 [20 pp] Site Report #2: Methods; vegetation types (NVC and non-NVC); discussion (by habitat); 3 pages of target notes explaining context of individual quadrats; constancy table summarising quadrats (21 quadrats recorded – only 6 in slacks – types SD15, SD16, M23 and M28); detailed vegetation map for site.

### Sefton Coast

As well bound editions of the final reports, there is a folder containing the original MS and figures for all the reports listed below. This should make Xeroxing (if necessary) much easier. With (but not in) the folder there are also loose copies of all the detailed vegetation maps for the nine Divisions of the Sefton Coast.

In 1988/89 [28 pp] 2 copies: Methods; general description (including maps of location, Divisions (see following reports), drift geology and erosion/accretion; vegetation description (NVC types and others); site assessment; protection and management; rarity; diversity; review of existing surveys; bibliography. Note that a revised NVC community listing for the whole coast was tucked (loose) into this introductory report based upon the understanding of NVC types in 1989.

1988 [17 pp] covering Division 1 (Seaforth to Hightown): Methods; general vegetation description (including standard site record, map of main features – site plan); vegetation communities (NVC types); constancy table summarising quadrats (24 quadrats recorded – SD15 only – 1 quadrat); 9 pages of target notes explaining context of individual quadrats; detailed vegetation map for division.

1988/89 [10 pp] covering Division 2 (Altcar Firing ranges): as Division 1 but only 13 quadrats (of which 3 are in slacks – SD15 and SD16) and 3 pages of target notes

1988/89 [16 pp] covering Division 3 (Cabin Hill NNR, Ravenmeols LNR, Lifeboat Road, St Joseph's Hospital and associated land): as Division 1 but 33 quadrats (of which 4 are in slacks – SD15 and SD16) and 9 pages of target notes

1988/89 [14 pp] covering Division 4 (National Trust and associated fields): as Division 1 but 25 quadrats (of which only 1 is in a slack – SD15) and 8 pages of target notes

1988/89 [14 pp] covering Division 5 (Formby Golf Club to Woodvale Airfield): as Division 1 but only 14 quadrats (none in slacks, though SD15 present) and 6 pages of target notes

1988/89 [ca 200 pp] covering Division 6 (Ainsdale Sand Dunes NNR): as Division 1 but 91 quadrats (of which 15 are in slacks – SD15 and SD16), 6 pages of target notes and copies of all 91 quadrat sheets

1988/89 [13 pp] covering Division 7 (Ainsdale LNR and outlying dunes): as Division 1 but only 6 quadrats(of which 4 are in slacks – SD15 and SD16) and 4 pages of target notes

1988/89 [29 pp] covering Division 8 (Birkdale Hills LNR and 3 gold clubs; Royal Birkdale Golf, Hillside Golf Club and Southport & Ainsdale): as Division 1 but 54 quadrats (of which 15 are in slacks – SD15 and SD16) and 19 pages of target notes

1988 [10 pp] covering Division 9 (Southport Dunes & Northern outliers): as Division 1 but without quadrat summary (SD15 & SD16 said to be present) and 6 pages of target notes

### Winterton

In 1989 [43 pp]: Methods (plus detailed annexes); general site description; vegetation description (NVC types); rare species; assessment; standard site recording form; annex of vegetation types; constancy table summarising quadrats (34 quadrats recorded – no SD slacks but 5 mire quadrats – M16e, M23a/b); 17 pages of target notes explaining context of individual quadrats; overall species list for site; detailed vegetation map (2 sheets) for site.

Folder of loose material dated from 1982-1989, and evidently including the raw data-sheets for the 34 quadrats from the final report. Also quite a lot of correspondence, field notebooks and background information on the site.

## SUMMARIES OF EXISTING PUBLISHED GEOLOGICAL AND HYDROLOGICAL DATA FOR ALL DUNE SITES WITH WETLAND.

### Braunton Burrows

Braunton Burrows is a spit dune system near Bideford in North Devon. Braunton Burrows covers an area some 7 km by 2 km with the long side adjacent to the sea coast. The sand overlies a clay horizon, possibly of lacustrine origin, which is situated over raised beach gravels. The area comprises a series of north to south oriented dunes and slacks shaped by the prevailing on-shore winds (Figure 4). It has no significant external influences, other than an apparent long-term decline in rainfall (Davey et al., 2010), and so provides a valuable opportunity to monitor a coastal dune area that is not being affected by anthropogenic or coastal processes.

### Ainsdale Sands

Ainsdale is a 25 km long by 3 km deep hindshore system situated on the Sefton coast between the Mersey and Ribble estuaries (Figure 4). The dune system is impacted by longshore scour which is eroding the dune front and transporting sediment northwards to deposition grounds off Southport and southwards towards the Mersey estuary. Ainsdale Sand Dunes National Nature Reserve is located in the central section of the dunes and has been isolated from anthropogenic development since its establishment in 1965. The site is partly forested. In a typical wet winter, approximately 30% of the slack floors flood to a depth of 0.1 to 0.3 m. The majority of the slacks dry out in summer with the water table falling to around 0.5 m below ground level and only 10% of the slacks remain flooded throughout an average year. These dynamic conditions provide environments for rich assemblages of flora (Jones et al., 2008, JNCC, 2007) and breeding grounds for rare amphibians (Steward, 2001).

### Saltfleetby
(Geology map 104/91)

Hindshore dune system backed by older storm beach sands and low lying land. Up to 300 m wide between Mablethorpe 10 km NW up to Saltfleet Haven. Blown sand rests on salt marsh deposits (silt and clay) over Chalk, with till (chalk rich sandy gravelly clay) inland.

### Winterton
(Geology map 148)

Hindshore dune system in front of low lying land. Blow sand over till in SE part and over sand and gravel coastal barrier complex over till in NW part. Full sequence can be blown sand over sand and gravel of coastal barrier complex over silt and clay over peat over Crag. Up to 800 m wide by 6 km long but continues for further 8 km to NW with a width of between 50 and 100 m. The sand is up to 7 m thick, fine-grained quartz, and is fronted in places by a concrete wall built unto a sand foundation fronted again by sheet piling.

### Seascale
(Geology map 37)

Blown sand area over tidal creek deposits and raised tidal creek deposits with some shoreline material exposed in the blown sand. Extends 6 km NW from Ravenglas and 4 km to SE.

### Sandscale
(Geology map 48)

Compact area of blown sand (2 by 1½ km) over tidal flat deposits backed by raised marine deposits over till.