Protecting the plant communities and rare species of dune wetland systems

Ecohydrological guidelines for wet dune habitats

Wet dunes phase 2

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Ecohydrological guidelines for wet dune habitats

A number of International and European Agreements and Directives have been passed to ensure member states manage and conserve natural resources. These have been translated into UK legislation through a series of Regulations and implementation of these includes conserving UK wetlands.

To ensure wetlands are managed to meet these UK obligations, an understanding of wetland communities and species and their specific and critical ecohydrological requirements needs to be gained. This area of work is still being researched and whilst new information is available a full understanding is yet to be obtained.

Identifying the need for a user-friendly guide containing generic ecohydrological information on the requirements of selected freshwater wetland communities initiated the production of the '*Ecohydrological Guidelines for Lowland Wetland Plant Communities*' (Wheeler *et al.* 2004). These were followed by a series of similar documents covering a wide range of habitats.

Wet dune slacks are wetlands that occur within depressions in coastal dune systems. They usually experience seasonally fluctuating water levels, with amplitudes ranging from dry at considerable sand depth in summer to permanently flooded. They have distinctive biodiversity and high conservation importance, representing European habitat features H2190 'Humid dune slacks' and H2170 'Dunes with *Salix repens* ssp. *argentea*, or Salicion arenariae', listed under Annex I of the European Union Habitats Directive. Additionally wet dunes harbour important dune species, such as Fen Orchid (*Liparis loeselii*), Petalwort (*Petalophyllum ralfsii*) and Natterjack toad (*Bufo calamita*).

English Nature Research Report 696 on the '*Development of eco-hydrological guidelines for dune habitats – Phase 1*' was produced in 2006. Subsequently a number of site-based reports have been produced with additional data. This phase-2 report is one of a new series of guidelines that draws on the additional information and expands on the advice provided in the 2006 publication. This report presents:

- a review of the overall hydrological functioning of humid slacks;
- detailed appraisals and recommendations for the ecohydrology of the British dune slack community types corresponding to Annex I of the EU Habitats Directive (British Plant Community (NVC) types SD13–SD17).

The additional information includes a review of the evidence valid to the establishment of nutrient chemistry guidelines, detailed case studies for important Welsh dunes systems at Kenfig, Morfa Dyffryn and Newborough Warren, and a substantial body of unpublished hydrological data.

The community classification appears to be too subtle and variable to be precisely explained by the five recognised water supply mechanisms. Community type SD16, by far the most abundant and widespread in England and Wales, can develop under wetland water supply mechanisms (WETMEC) dune Type B, C or E; similarly SD15, the next most abundant community can be associated with WETMEC dune Types B, C or D, whereas SD17 is also associated with WETMEC dune Type D. The clearest correspondence is of SD13, characteristic of young, often brackish slacks, with WETMEC dune Type A; the related SD14 may be associated with A, B or C.

More precise eco-hydrological guidelines for wet dune slacks will require long-term monitoring of suitably replicated dipwells, placed strategically at a range of sites within unequivocally identified dune-slack community types. Sites need to be chosen to include the whole range of community types (including rare ones such as SD13), and to reflect different physiographic settings, substrate, climatic conditions and depositional environments. Changes in the communities should be monitored, along with seasonal and long-term changes in water level and water chemistry. Fluctuations in groundwater level in different communities could be best characterised in terms of the probability of exceeding set maxima for winter and summer periods, as well as understanding the magnitude of water table fluctuation and the persistence of wet and dry periods on habitat condition. Such investigations ideally need to be part of larger-scale hydrological investigations of whole dune systems to determine water flow and hydrochemical gradients through the slacks.

Key words: Dune slack, eco-hydrology, hydrological model, management, succession.

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Introduction

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1.1 Objective and scope of the guidelines

1.1.1 Objective

A number of International and European Agreements and Directives has been passed to ensure member states manage and conserve natural resources. These include the Convention on Biodiversity (signed in Rio in 1992), the EC Directive on the Conservation of Natural Habitats and Wild Flora' (the Habitats Directive[8]), the Wild Birds Directive[9], Ramsar[10] and the Water Framework Directive[11].

These have been translated into UK legislation through a series of Regulations. Implementation of these includes conserving UK wetlands.

To ensure wetlands are managed to meet these UK obligations an understanding of wetland communities and species and their specific and critical ecohydrological requirements needs to be gained. This area of work is still being researched, new information is available but a full understanding is yet to be obtained.

Identifying the need for a user-friendly guide containing generic ecohydrological information on the requirements of selected freshwater wetland communities initiated the production of the '*Ecohydrological Guidelines for Lowland Wetland Plant Communities*' (Wheeler *et al.,* 2004). These were followed by a series of similar documents covering a wide range of habitats.

The previous guidelines assisted with:

- carrying out Appropriate Assessments of the effects of Environment Agency permissions and consents required under the Habitats Directive Review of Consents;
- first round of assessment of significant damage to groundwater-dependent terrestrial ecosystems (GWDTE) required for the Water Framework Directive.

This report is one of a new series of guidelines and expands on the advice provided previously for Wet Dune habitats (Davy, A.J, Grootjans, A.P., Hiscock. K. and Petersen, J., 2006).

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[7] All sections and appendices in the report have been written by these authors.

[8] Directive 92/43/EEC, amended by Directive 97/62/EC.

[9] Directive 79/409/EEC.

[10] Convention on Wetlands of International Importance, Ramsar, Iran, 1971.

[11] Directive 2000/60/EC.

1.1.2 Scope of the guidelines

This series of guidelines for lowland wetland freshwater features in England and Wales covers the following range of habitats: wet grassland, fen and mire, swamp and ditch, wet woodland, wet heath, and wet dune slacks.

Box 1 lists the range of plant communities covered by the series, or habitats which have been investigated but which do not have community-specific guidelines. This is jointly prepared by the Environment Agency, Natural England and the Countryside Council for Wales.

Box 1 Communities for which guidelines have been produced to date

Wet grassland[1]

MG4	*Alopecurus pratensis – Sanguisorba officinalis* grassland
MG5	*Cynosurus cristatus – Centaurea nigra* grassland
MG7	*Lolium perenne – Alopecurus pratensis – Festuca pratensis* grassland
MG8	*Cynosurus cristatus – Caltha palustris* grassland
MG9	*Holcus lanatus – Deschampsia cespitosa* grassland
MG13	*Agrostis stolonifera – Alopecurus geniculatus* grassland

Fen and Mire[1 and 5]

M3	*Eriophorum angustifolium* bog pool community
M4	*Carex rostrata – Sphagnum recurvum* mire
M5	*Carex rostrata – Sphagnum squarrosum* mire
M9 (M9-1 and M9-2)	*Carex rostrata – Calliergon cuspidatum* mire or *Acrocladio-Caricetum*
M9 (M9-3)	*Carex diandra – Peucedanum palustre mire (ex. Peucedano-Phragmitetum caricetosum (PPc)*
M10	*Pinguicula vulgaris – Carex dioica* mire
M13	*Schoenus nigricans – Juncus subnodulosus* mire or *Schoeno-Juncetum*
M14	*Schoenus nigricans – Narthecium ossifragum* mire
M18	*Erica tetralix – Sphagnum papillosum raised and blanket* mire
M21	*Narthecium ossifragum – Sphagnum papillosum* valley mire
M22	*Juncus subnodulosus – Cirsium palustre* fen meadow
M24	*Molinia caerulea – Cirsium dissectum* fen meadow or *Cirsio-Molinietum*
M25	*Molinia caerulea – Potentilla erecta* mire
M26	*Molinia caerulea – Crepis paludosa* mire
M29	*Hypericum elodes – Potamogeton polygonifolius* soakway
S1	*Carex elata* sedge swamp
S2	*Cladium mariscus* sedge swamp
S24	*Phragmites australis – Peucedanum palustre* fen
S27	*Carex rostrata – Potentilla palustris* fen or *Potentillo-Caricetum*

Swamp and ditch communities[1]

S4	*Phragmites australis* reedbed
S5	*Glyceria maxima* swamp
A3	*Spirodela polyrhiza – Hydrocharis morsus-ranae* community
A4	*Hydrocharis morsus-ranae – Stratiotes aloides* community
A9	*Potamogeton natans*

Wet woodland[2] (no community guidelines but considered those listed below)

Residual Alluvial Forests
(communities W5, W6 and W7)

W5	*Alnus glutinosa – Carex paniculata* woodland
W6	*Alnus glutinosa – Urtica dioica* woodland
W7	*Alnus glutinosa – Fraxinus excelsior-Lysimachia nemorum* woodland

Box 1 (continued)

Bog woodland
(communities M18, M19, W4)

M18	*Erica tetralix – Sphagnum papillosum* raised and blanket mire
M19	*Calluna vulgaris – Eriophorum vaginatum* blanket mire
W4	*Betula pubescens – Molinia caerulea* woodland

Wet heath[3] (no community guidelines but considered those listed below)

H3	*Ulex minor – Agrostis curtisii* heath (three sub-communities)
H4	*Ulex gallii – Agrostis curtisii* heath (four sub-communities)
H5	*Erica vagans – Schoenus nigricans* heath (two sub-communities)
M14	*Schoenus nigricans – Narthecium ossifragum* mire
M15	*Scirpus cespitosus – Erica tetralix* wet heath (four sub-communities)
M16	*Erica tetralix – Sphagnum compactum* wet heath (four sub-communities)
M21	*Narthecium ossifragum – Sphagnum papillosum* valley mire (sub-communities)

Dune habitats[4] (no community guidelines but considered those listed below) and current report

SD13	*Sagina nodosa – Bryum pseudotriquetrum* dune-slack community
SD14	*Salix repens – Campylium stellatum* dune-slack community
SD15	*Salix repens – Calliergon cuspidatum* dune-slack community
SD16	*Salix repens – Holcus lanatus* dune-slack community
SD17	*Potentilla anserina – Carex nigra* dune-slack community

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[1] Wheeler, B.D., Shaw, S.C., Gowing, D.J.G., Mountford, J.O. and Money, R.P. (2004). *Ecohydrological Guidelines for Lowland Wetland Plant Communities*. Eds. Brooks, A.W., Jose, P.V. and Whiteman, M.I. Environment Agency.

[2] Barsoum, N., Anderson, R., Broadmeadow, S., Bishop, H. and Nisbet, T. (2005). *Eco-hydrological guidelines for wet woodland – Phase I*. English Nature Research Report 619.

[3] Mountford, J.O., Rose, R.J. and Bromley, J. (2005). *Development of eco-hydrological guidelines for wet heaths – Phase 1*. English Nature Research Report 620.

[4] Davy, A.J., Grootjans, A.P., Hiscock. K. and Petersen, J. (2006). *Development of eco-hydrological guidelines for dune habitats – Phase 1*. English Nature Research Report 696.

[5] Wheeler, B.D. and Shaw, S.C. (2010). *Ecohydrological Guidelines for Lowland Wetland Plant Communities. Fens and Mires Update*. Eds. Brooks, A.W. and Whiteman, M.I. Environment Agency.

Wet dunes are wetlands of very restricted area in the UK with distinctive biodiversity and high conservation importance. Box 2 lists those communities that contribute to features designated as being of European importance under the Habitats Directive[12] and found in England and Wales. The area of H2190 (Humid dune slacks) in the UK has been estimated at only 1812 ha and the area of H2170 (Dunes with *Salix repens* ssp. *argentea*, or Salicion arenariae) is even less with an estimated 642 ha (Joint Nature Conservation Committee, 2007), giving a total area wet dune slacks of less than 2500 ha (Figure 1.1). Wet dune slacks also harbour important dune species listed in Annex II or Annex IV of the Directive (see Box 2).

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[12] These European features are identified on Annex 1 of the Habitats Directive.

Box 2 Habitats Directive Annex 1 Wet Dune European Features in England and Wales and Annex II and IV Species

'H2190 Humid dune slacks' (Represented by British Plant Communities (NVC) SD13, SD14, SD15, SD16 and SD17)

***'H2170 Dunes with Salix repens* ssp. *argentea,* or Salicion arenariae'** (Represented by British Plant Community SD16)

Fen Orchid (*Liparis loeselii*)

Petalwort (*Petalophyllum ralfsii*)

Natterjack toad (*Bufo calamita*)

Following the production of the English Nature Research Report 696 on the 'Development of eco-hydrological guidelines for dune habitats – Phase 1' (Davy *et al.*, 2006) a number of site-based reports has now been produced with additional data. In England these cover Braunton Burrows (Robins, 2007), The Sefton Coast (Edmondson *et al.*, 2007) and Winterton Dunes (Coulet, 2007). Other data are available from key dune sites in Wales: Kenfig dunes, Morfa Harlech and Newborough Warren. These studies provide a wider dataset which might be used to validate the conceptual framework for 'how dune slack habitats work' and interim recommendations for ecological target setting produced in Davy *et al.* (2006). In addition the European Commission has established a Natura 2000 model for the management of H2190 Humid dune slacks (Houston, 2008), which takes into account previous experience, best management practice and guidelines developed in different countries or regions.

This update report on wet dune habitats focuses primarily on the hydrological functioning of humid dune slacks and on the ecohydrological requirements of wet dune communities. It is expected that these guidelines, because of their generic nature, will have applicability to wet dune habitats around the coasts of England and Wales where the same communities exist.

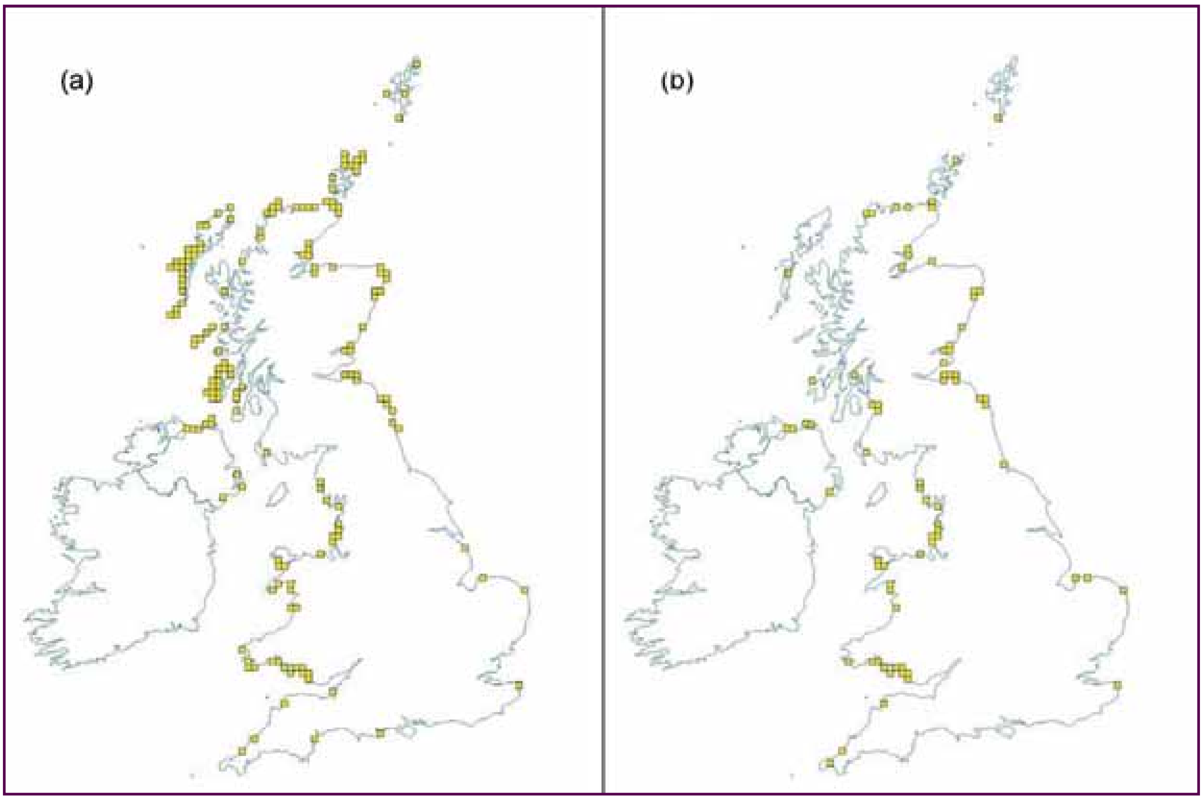
Guidelines have been produced for those communities considered to have sufficient data available at a national level to have scientific credibility. It is important to re-state that the guidelines are *generic* because it is of equal importance to conceptualise how a specific site works hydrologically and by what mechanism(s) the water needs (quality and quantity) of the communities are met.

1.2 Wet dunes context

Coastal dune systems are among the most vulnerable and scarce habitats in Britain. They are essentially successional ecosystems that depend on the availability and mobility of wind-blown sand to maintain a mosaic of inter-related habitats of different ages and elevations. The slacks, or depressions, associated with the dune ridges give rise to a distinctive series of wetlands usually with seasonally varying water levels. The water regime of a slack is determined by the hydrology of the dune system and its location within it. Variations in the level of water tables mean that the sand surface of some slacks may be dry in summer whereas others are permanently flooded. This is a major determinant of their plant and animal communities but hydrochemistry is also important: calcareous dune systems and ground-waters support different communities from acidic ones, salinity may be an influence near the sea, and nutrient enrichment (particularly with nitrogen and phosphorus) has major consequences for community development (Davy *et al.*, 2006).

As a result dune slacks are particularly susceptible to the effects of water abstraction, local afforestation and other changes in land use, atmospheric nitrogen deposition and other forms of pollution; increasingly their hydrology is likely to be threatened by sea-level rise and other potential impacts of climate change, particularly changing patterns of rainfall (Davy *et al.*, 2006). The 2001–2006 Conservation status assessment for the Habitat Directive Annex I habitats, H2190 Humid dune slacks and H2170 Dunes with *Salix repens*, had an overall conclusion of 'Unfavourable: bad and deteriorating' at a UK level for both (Joint Nature Conservation Committee, 2007). 'Recommended actions' in the light of these adverse assessments

Figure 1.1 The distribution of (a) H2190 Humid dune slacks and (b) H2170 Dunes with *Salix repens* ssp. *argentea*, or Salicion arenariae, in the UK



Each yellow square represents a 10 x10-km square of the National Grid and shows the known and/or predicted occurrence of this habitat. Reproduced with permission from Joint Nature Conservation Committee (2007), which provides details of how the maps were derived.

(Joint Nature Conservation Committee, 2009) include research into hydrological conditions of dunes (H2190), research into the dynamics of the habitat and improved access to technical advice (H2170), apart from directly addressing pollution, hydrological change and appropriate land use.

1.3 Use of the guidelines

These updated guidelines provide a generic tool to help conceptualise wetlands and inform assessments of whether vegetation communities associated with European-designated wet dune features should be considered at risk of being out of regime. For example, they may be used for the purposes of impact assessments for new consents under the Habitats Directive or more generally. The guidelines also have a range of potential additional uses:

- Defining criteria against which to assess the potential for significant damage to a GWDTE under WFD and to judge WFD monitoring obligations.
- By Natural England to refine site specific conservation objectives/favourable condition tables for European Habitats Directive sites, and nationally important sites supporting the same communities, by identifying hydrological and environmental features critical for the maintenance (or enhancement) of wetland habitats; by distinguishing these from less critical features.
- Influencing the development and implementation of Water Level Management Plans and preparation of wetland restoration and rehabilitation proposals by providing information on the ecohydrological requirements of specific communities.
- By Natural England, CCW, Wildlife Trusts and other NGOs to manage wet dune sites.
- Water abstraction licensing technical determination reports to assess impacts of new proposals for groundwater and surface water pumping.

Three broad groups of applications can be envisaged. These include status assessment, impact assessment and restoration potential, see Box 3 for more detail.

Box 3 Broad applications for the guidelines

Condition assessment. As part of an audit process, the ecological health of a wetland may need to be assessed. This can either be achieved by direct assessment of ecological objectives, (for example, presence of target species) or by assessment of the factors controlling wetland ecology, such as the hydrological regime. This can help to prioritise action at sites or species/communities most at risk.

Impact assessment. The range of ways in which the water regime of a wetland may be changed includes surface and groundwater abstraction, flow diversion and river channelisation for flood defence. Granting of a licence to undertake a proposed activity, such as an abstraction, may depend upon the level of negative impacts this might cause to a wetland. The level of impact on a wetland can be scored by assessing predicted and actual changes in the hydrological regime in relation to ecohydrological guidelines. Reference should also be made to Acreman and Miller, 2004.

Restoration. In many cases, wetlands have been degraded by changes in the hydrological regime. Restoration is the re-establishment of the structure and function of an ecosystem to a more or less natural condition and this document includes returning the hydrological regime on a wetland to meet a target defined within these guidelines. Whether the target hydrological regime can be met depends upon the degree to which the alteration that caused the degradation can be reversed or mitigation implemented.

1.4 Structure of these guidelines

It is recognised that the conceptual framework and guidelines developed for England and Wales may need to be used in different ways. This is addressed by presenting a brief summary of how the guidelines have been developed (Section 2) and then to review the overall hydrological functioning of humid dune slacks (Section 3). In the subsequent five sections detailed appraisals and recommendations are presented for the ecohydrology of the British dune slack community types corresponding to Annex I of the EU Habitats Directive (British Plant Community types SD13, SD14, SD15, SD16 and SD17; Rodwell, 2000), in the format established for previous wetland eco-hydrological guidelines. Each community guideline is divided into four parts:

- context;
- supply mechanism and conceptual model;
- regimes;
- implications for decision making.

The **Context** section provides information on the **floristic composition**, and distribution of the community. It describes the **landscape situation** and **topography** within which the community is found, the **substratum** with which it is most commonly associated and the zonation and successional patterns and influences on the community.

The **Supply mechanism and conceptual model** section presents information on the main water supply mechanisms to the community and presents a conceptual diagram.

The **Regime** section describes the **water**, **nutrient**, and **management** requirements of the community.

The **Implications for decision making** section helps the user to make key decisions on future option evaluation (that is, for Stage 4 of the Habitats Directive Review of Consents or for Water Framework Directive). This section covers the **vulnerability** and **restorability** of the vegetation community, and identifies key **gaps in scientific knowledge** of the community's ecohydrological requirements.

Section 9 draws together general conclusions, highlights deficiencies in the data and makes recommendations for further work. A series of appendices conclude the report. These include a review of the evidence valid to the establishment of nutrient-chemistry guidelines (Appendix D) and detailed case studies for important Welsh dunes systems at Kenfig, Morfa Dyffryn and Newborough Warren (Appendices E, F and G respectively). The considerable body of unpublished eco-hydrological data for a range of dune systems that have informed both the guidelines and conclusions of this report are available in electronic form.

Section 2

Methodology

Evidence relating to dune systems and their ecohydrology that had become available following the Phase 1 review (Davy *et al.,* 2006) was examined. This took the form of either site-specific reports for English and Welsh dune systems or previously unpublished eco-hydrological data sets relating to these. Figure 2.1 shows a location map for the dune systems considered in this report.

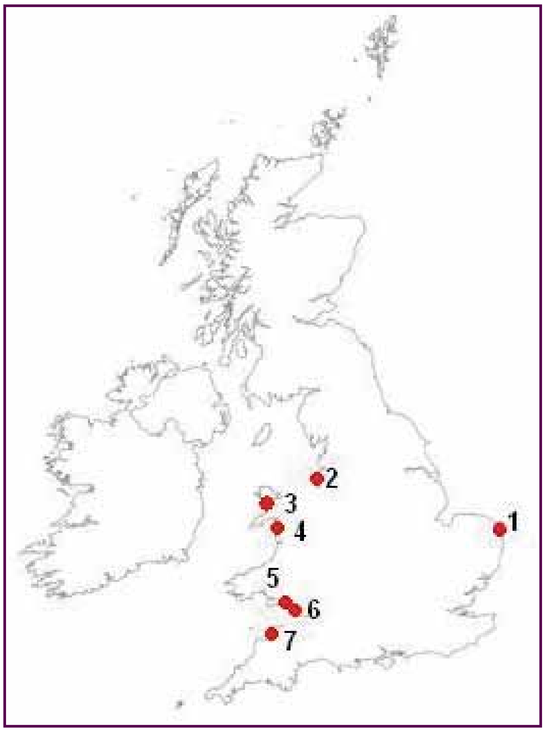
Reports on Braunton Burrows, Devon (Robins, 2007), the Sefton Coast, Lancashire (Edmonson *et al.,* 2007) and Winterton Dunes, Norfolk (Coulet, 2007) in England were considered. Reports on Welsh systems at Kenfig dunes and Merthyr Mawr (South Wales), Morfa Dyffryn National Nature Reserve (West Wales), and Newborough Warren, Anglesey (North Wales) were compiled as part of this study and are presented as Appendices to these guidelines.

Unpublished data were available as series of dipwell measurements at various locations in the dune systems that were more or less closely associated with British Plant Community (NVC) classifications, and these are presented in the electronic appendices. Such data were available for the English systems at Braunton Burrows, the Sefton Coast and Winterton Dunes. The heights of dipwell pipes above the sand surface at Braunton were investigated in order to try and establish groundwater depths. Hydrological data for Welsh sites at Kenfig dunes, Merthyr Mawr, Newborough Warren, Morfa Dyffryn and Morfa Harlech were ground-truthed for British Plant Community type in 2008. The series of dipwell data were summarised and patterns of variation were examined; as far as possible they were related to British Plant Community type. The possibility of applying a frequency of exceedence approach to the ground-water depth data (Martens *et al.*, 2009) in order to characterise the water regimes of different community types was evaluated.

Appendices B and C provide a list with description of the collated reports for Ainsdale, Braunton Burrows, Merthyr Mawr, Newborough, Sefton and Winterton dunes, together with site descriptions, monitoring location details and water level data for Sefton and Ainsdale dune slacks, respectively. A report summarising evidence relating to the establishment of nutrient-chemistry guidelines for sand dune systems was compiled and this is presented in Appendix D.

The information extracted was used first to refine ideas and models relating to the hydrological functioning of wet dune slacks, within their dune systems, and then to inform individual, self-standing eco-hydrological accounts of the relevant plant community types (British Plant Communities (NVC) SD13–17); these include guidelines and recommendations for their hydrological management and are presented in Appendices E–G.

Figure 2.1 Map showing dune slack locations included in this report



1. Winterton; 2. Sefton and Ainsdale; 3. Newborough Warren; 4. Morfa Dyffryn; 5. Kenfig; 6. Merthyr Mawr; 7. Braunton Burrows.

Hydrological functioning of humid dune slacks

3.1 Introduction

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is expected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes. A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

The behaviour of the water table in relation to dune systems is recorded at all the English and Welsh dune systems examined here and it is useful to summarise their hydrogeological functioning in terms of water level variations and gradients.

3.2 Review of hydrology at dune slack sites

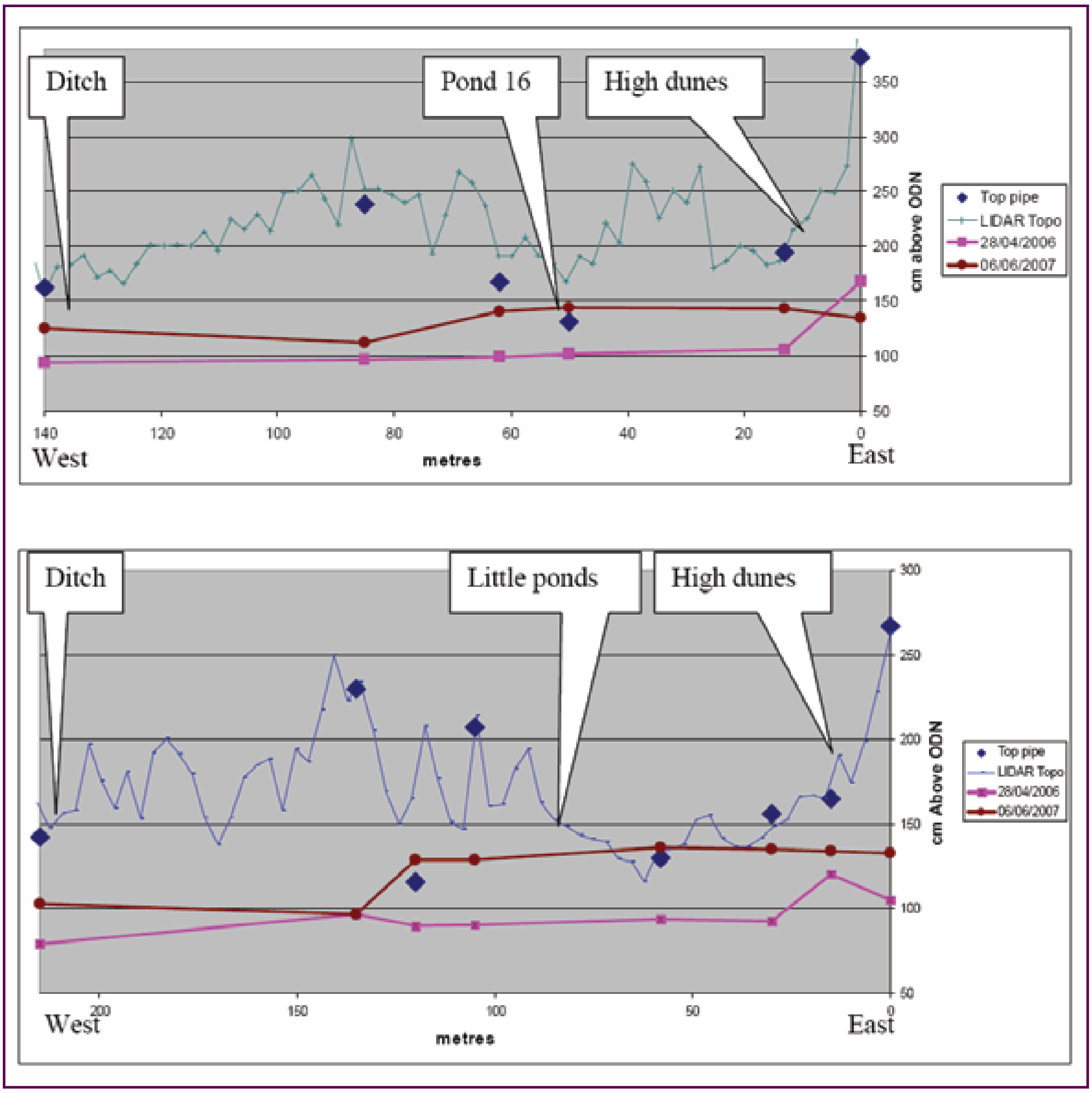
3.2.1 Winterton dunes, Norfolk

From this comparison, guidelines for required water levels to maintain humid dune slacks are identified. At Winterton in Norfolk, a short period of water level monitoring along two transects between spring 2006 and summer 2007 showed a water table fluctuation of 0.5 m (Figure 3.1). Within the area of dune slacks, the water table reached a maximum depth of 0.75 m below ground level, opposite to the condition in the wet summer of 2007 when water levels rose to above ground level in an area of small ponds along one transect. The water table gradient was steepest after the winter rainfall period with high groundwater levels below the dune ridge. During summer 2007, the water levels below the dune ridge remained low with evidence for groundwater draining away from the region of the lower lying ponds (Coulet, 2007).

3.2.2 Braunton Burrows, North Devon

A remarkably long water level record exists for Braunton Burrows on the north Devon coast with monitoring of water levels continuing since 1966. The long-term recharge and discharge/abstraction estimate for the Burrows is 479 mm (Robins, 2007) and the rain-fed groundwater system experiences an annual water level fluctuation of up to 2 m with groundwater mounded beneath the Burrows (Figure 3.2). Effective rainfall has declined by 5% since the mid-1960s and this is observed in the 24-month moving average for rainfall at Bideford and is paralleled by the hydrographs within the dunes that show an overall decline of 0.5 m. Analysis of three transects for the driest and wettest periods on record show that under dry conditions the

Figure 3.1 **Transects showing topographic and groundwater elevations at Winterton Dunes in April 2006 and June 2007 (Transect I top and Transect II below)**



After Coulet (2007).

water table generally lies about 1.5 m below the dune slacks, whereas under wet conditions the water table rises above the dune slacks to create ponding. As each of the monitoring piezometers is located in a slack to minimise auger lengths to the water table, the wet and dry situations indicate an annual water table range of about 1.5 to 2.0 m, from a flooded slack situation, usually about 0.5 m deep, to a water table some 1.5 to 2.0 m below the slack (Robins, 2007).

3.2.3 Sefton dunes

The dune system of the Sefton coastline in North West England near Liverpool is in a dynamic coastal location that is undergoing erosion of up to 4.5 m per year at the southern end and accretion at the northern end. In the 1960s when the Ainsdale National Nature Reserve (NNR) was established, the water table in the dunes was relatively high and many of the dune slacks were flooded perennially. In the early 1970s, the water table fell and many dune slacks dried-up corresponding with a period of low rainfall. Since 1972, water levels have been monitored monthly. Based on the analysis of Clarke and Sanitwong (2007) of 13 monitoring wells, the water table rises from sea level (0.2 m OD) to a maximum of 10.5 m OD at the east side of the dunes with the water table contours running parallel to the coast, except in the southern area where an area of pine trees is associated with water levels that are approximately 0.5 m lower (Figure 3.3). Average groundwater levels at Ainsdale between 1972 and 2002 fluctuated between 6.5 m OD and 7.8 m OD, a range of 1.3 m.

Figure 3.2 (a) **Transects of groundwater level**

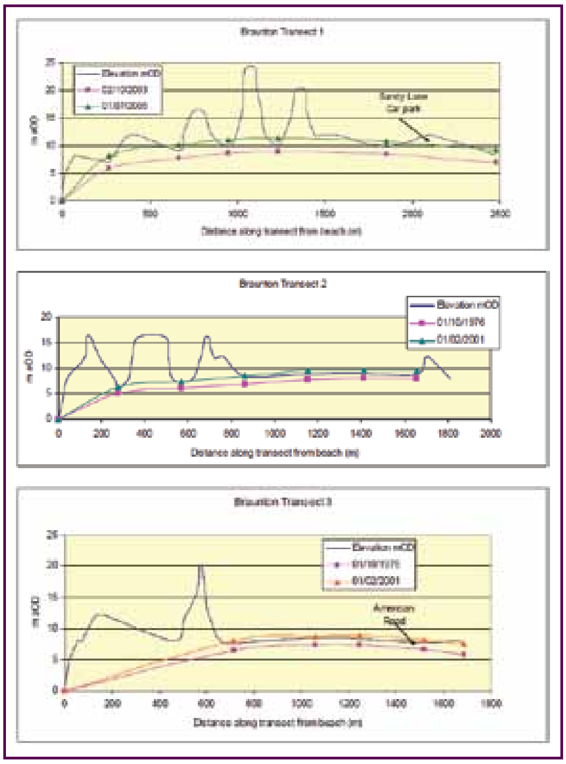
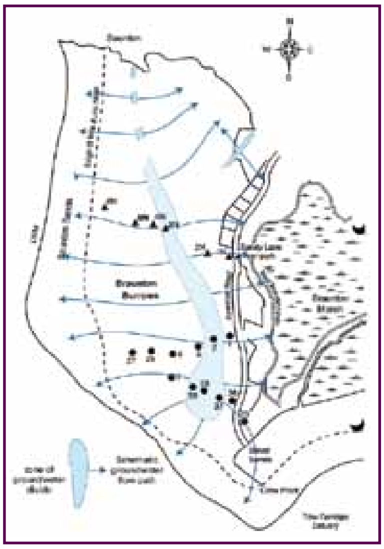


Figure 3.2 (b) **Conceptual groundwater flow model for Braunton Burrows. After Robins (2007)**



Further analysis for the period 1972–2003 for Boreholes 1, 2, 3, 6, 7 and 11 aligned parallel to the coast showed an interquartile range of water table fluctuation of between 0.41 to 0.51 m, except Borehole 7 with a range of 0.25 m. For the wet month of February 1995, the water level elevations in Boreholes 3, 6 and 11 exceeded the ground surface, reaching as high as 0.49 m above ground elevation. In the dry month September 1991, the water level elevations in all the boreholes were below ground surface, descending to a maximum depth of 1.16 m below ground elevation. Reported surface water depths in the slacks at Ainsdale indicate average maximum depths of 0.01–0.15 m. At Borehole 7, adjacent to Slack 65 with its predominant SD15/SD16 habitat, the average maximum depth to the water table is reported to be greater than 0.15 m below the surface water level, with the water table rarely falling below 0.5 m of the surface water level.

Figure 3.3 (a) **Average groundwater levels (m AOD) at Ainsdale 1972–2002**

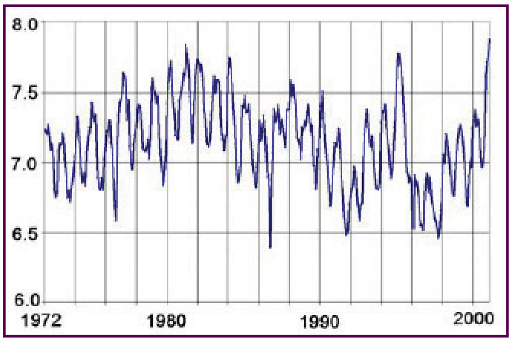
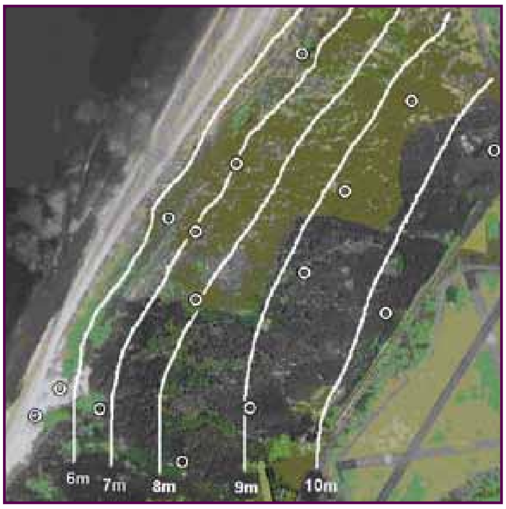


Figure 3.3 (b) **Typical pattern of water table contours. After Clarke and Sanitwong (2007)**

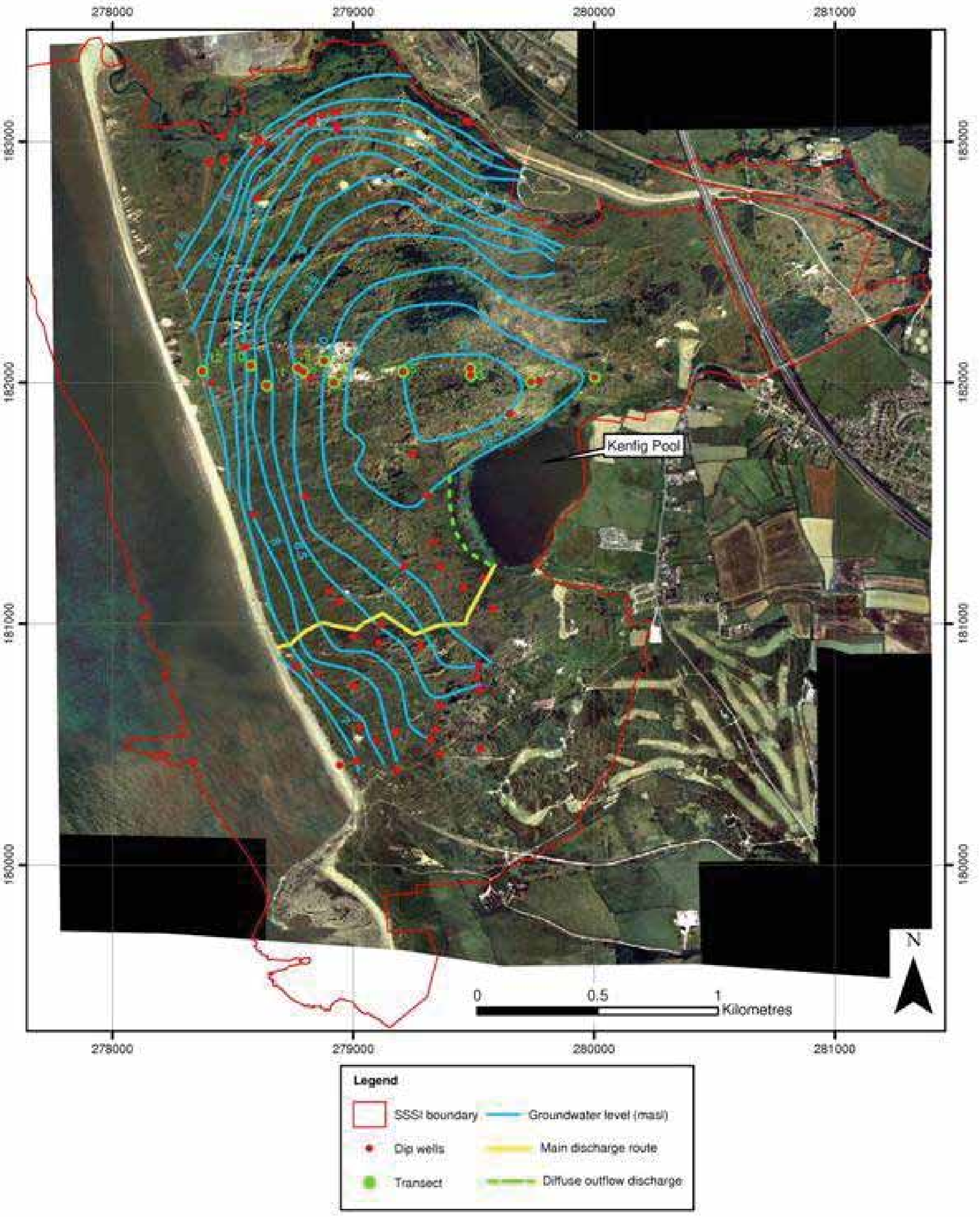


3.2.4 Kenfig, South Wales

At the Kenfig dunes in South Wales it is again seen that the shallow water table controls the inundation of dune slacks and that water levels within the dune slacks and Kenfig Pool are a local expression of a groundwater mound within the dune aquifer. The groundwater mound is centred on a position about 500 m north-west of Kenfig Pool with groundwater flowing quasi-radially away from this mound (Figure 3.4).

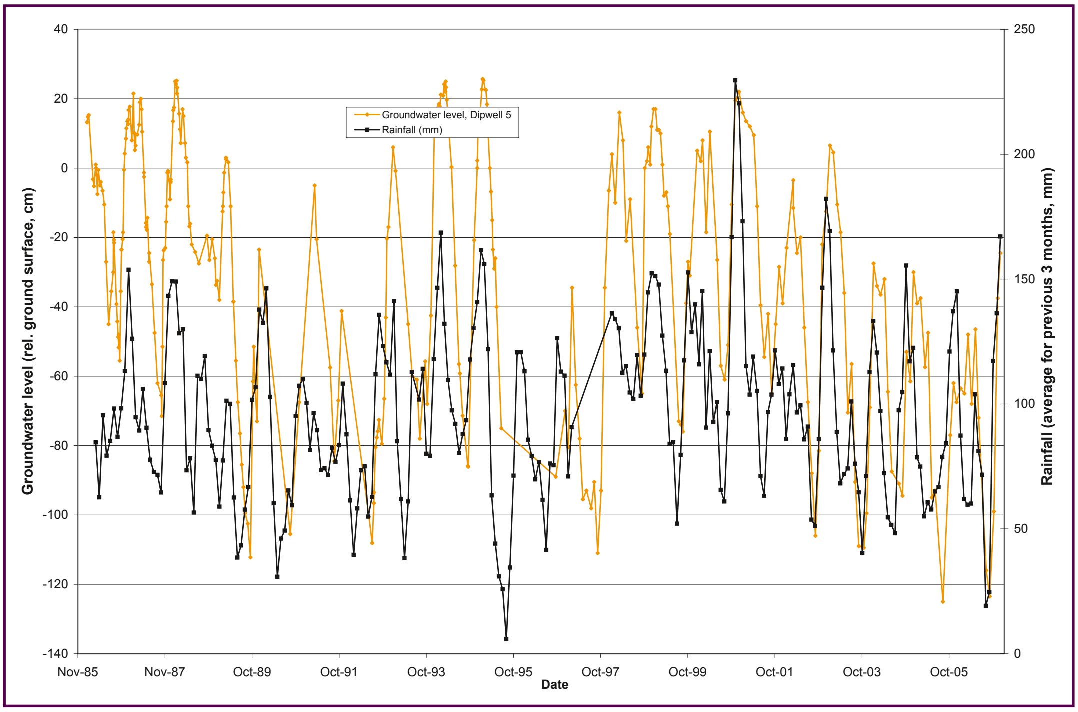
The maximum water level of Kenfig Pool is controlled by diffuse surface water discharges from the western side of the pool, at the southern most point of which a seasonal surface water flow route eventually discharges to the beach via a pipe. As found in other dune systems, the annual cycle of water level fluctuation is in response to the balance of precipitation and evapotranspiration with minimum water level values occurring in late summer or early autumn (August–October) when sub-surface water levels exist.

Figure 3.4 **Annotated aerial photograph of Kenfig Dunes NNR**



From case study of Kenfig Dunes (see Appendix E).

Figure 3.5 Records of long-term water level (Dipwell 5) and rainfall for Kenfig Dunes NNR



From case study of Kenfig Dunes (see Appendix E).

The water table recovers quickly in the autumn and water levels approach or exceed ground surface typically between December and February. Flooding can extend into the spring months but summer flooding is rare and largely restricted to a small suite of slacks characterised by especially low-elevation floors. For a typical water level hydrograph (Dipwell 5 on the main transect), the long-term water level between 1985 and 2005 fluctuated between a minimum of 1.25 m below ground surface and a maximum of 0.2 m above ground surface (Figure 3.5).

Analysis by Jones (1993) of the water level data for the period 1986–89 showed that local hydrological conditions affect the depth of winter flooding, the annual range of water levels and the magnitude of monthly water level fluctuations of the dune slacks. Jones (1993) classified the slacks into six hydrological types, as follows:

Type 1: typified by very shallow winter flooding during which the water table displays a subdued response to rainfall, even during periods of prolonged periods of heavy precipitation.

Type 2: similar to Type 1 but flooding to a greater depth which, for most dipwells, lies between 0.1 and 0.25 m.

Type 3: deep winter flooding and with a capillary fringe above the water table remaining in contact with the soil throughout both 1986 and 1987.

Type 4: extremely deep winter flooding which, for much of the winter, is between 0.6 and 0.8 m with the water table remaining close (always within 0.5 m) to the soil surface even during late summer in 1986 and 1987.

Type 5: exhibits a large annual groundwater range with very marked fluctuations in water level throughout the year, probably affected by the site-specific geomorphological location of slacks.

Type 6: occurs rarely with winter flooding of slacks either absent or for a short duration.

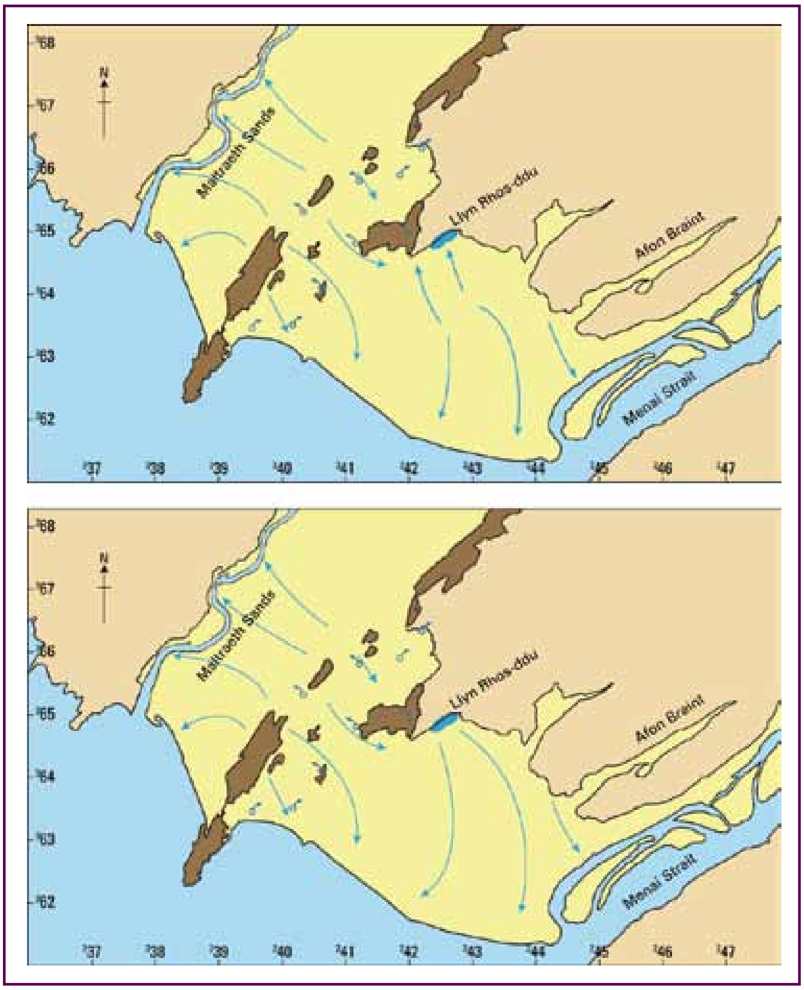
It was also found that all six types of slacks differed with respect to other hydrological characteristics, for example the duration of flooding, mean seasonal water levels and the annual range of water table elevation, implying that variations in the magnitude of each are fairly closely correlated.

3.2.5 Newborough Warren

In south-west Anglesey in North Wales, Newborough Warren comprises a coastal area of late-glacial blown sand dunes over low-permeability glacial till. The bedrock underlying the warren consists of low-permeability Palaeozoic and Precambrian strata. The overlying dunes reach a maximum thickness of 15 m rising to an elevation of over 30 m OD in the vicinity of the rock ridge that traverses the western part of the dunes. The total area of dunes covers about 1,300 ha of which the northern 700 ha is managed pine forest plantation and the southern part left as open dune land. A small lake, Lyn Rhos-ddu, is present on the northern edge of the open warren and receives drainage both from the warren and the higher ground inland. The rock ridge forms a groundwater divide which divides the dunes into two distinct hydrogeological areas. The dune water table elevation fluctuates above the level of Lyn Rhos-ddu which behaves as a near-fixed head hydraulic boundary, feeding the groundwater system in summer but gaining water from the sand aquifer in winter (Figure 3.6).

Again, as elsewhere, the elevation of the water table across the site is determined by a combination of rainfall and evapotranspiration. Ranwell (1959) described widespread flooding of the slacks at Newborough Warren in the wet winter of 1950–51 and an annual water table elevation fluctuation of between 0.7 and 1.0 m. Ranwell (1959) also provided evidence for a rapid recharge-discharge mechanism in the sand aquifer with groundwater responding to single rainfall events plus outflow from the recharged groundwater mound in the interfluve areas between the slacks.

Figure 3.6 Winter (top) and summer (bottom) conceptual flow models for Newborough Warren showing ephemeral springs where bedrock intercepts groundwater flow in the sands

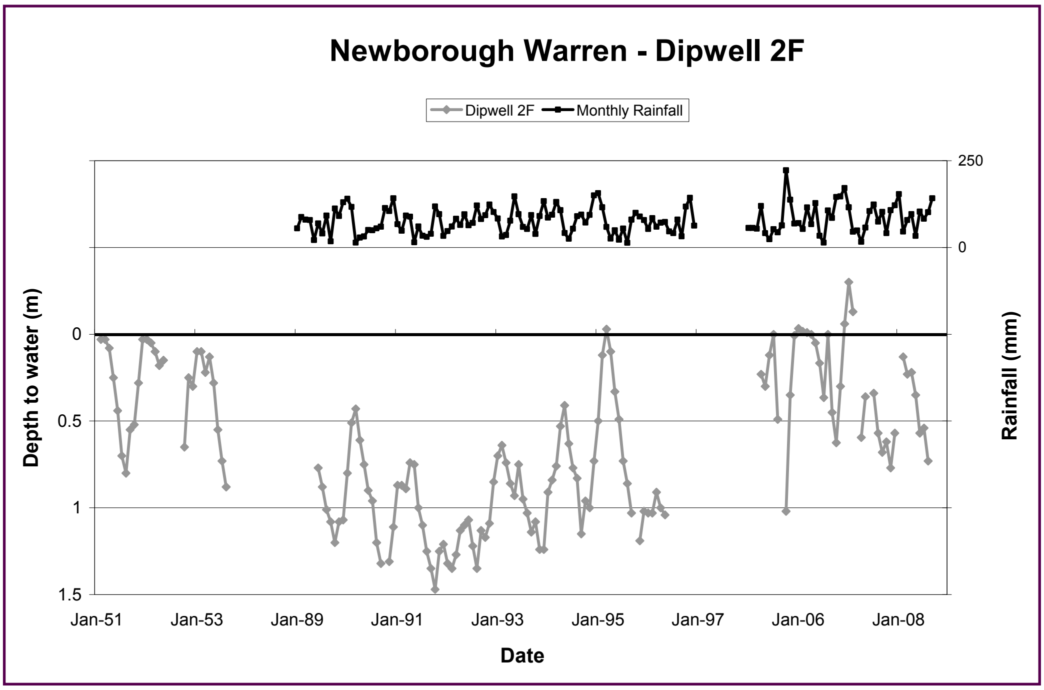


The sand cover is shown in yellow, the rock ridge in brown, and the sea below low water mark in blue, the foreshore being an important part of the groundwater flow system. From case study of Newborough Warren (see Appendix G).

Hydrologically regimes at Newborough Warren appear to have changed over time and, as observed at Braunton Burrows, anecdotal evidence suggests that the dune slacks trended towards a drier phase in the 1970s corresponding to a period of less than long-term average rainfall. Since 2000, annual rainfall has tended to be greater than the long-term average and flooding of some slacks has recurred. A time series of monthly dipwell measurements (Dipwell 2F for Slack A, Site 8) constructed with three sets of data collected by Ranwell (1951–53), the CCW (1989–96) and Hollingham (2005 to present) shows a variation in depth to the water level of +0.3 m OD and -1.5 m OD with the drier period during the late 1980s and early 1990s clearly recorded in the dipwell hydrograph (Figure 3.7). The average annual range of water table elevation measured in the period 1989–95 was 0.75 m (± 1 s.d. of 0.27 m). Data from 2005–06 showed an average winter maximum water table elevation of 0.025 m above the ground surface with an annual range in this period of 0.9 m (± 1 s.d. of 0.13 m). Generally, the summer water table falls to between 1 and 2 m from the ground surface. There is considerable heterogeneity in water table elevation across the site with levels typically 0.2 m greater in the dipwells near the shore and 0.4 m greater in those dipwells away from the forested area. Three distinct annual phases of water table conditions are identified by Ranwell (1959): a high-level phase when there is either dune slack flooding or the water table is close to the surface lasting from November to April; a falling water table between April and August; and recovery of the water table from August to November.

Morfa Dyffryn, together with Morfa Harlech 7 km to the north, located on the central, western coast of Wales is a highly dynamic dune system with a wealth of mobile dunes, bare sand and dune slacks covering an area of 747 ha. The beach and extensive dune system front a cuspate foreland which is about 3 km wide at Llanbedr. Near its southern end the site comprises a narrow, fringing beach of shingle, cobbles and sand on which there are low dunes. Northwards, the dunes are wider and higher attaining heights of 20 m with semi-parabolic ridges enclosing large slacks. The coastal plain which includes Morfa Dyffryn is underlain by Tertiary and Quaternary sediments dominated by silts and clays. Monitoring of the dune-sand water level by the Countryside Council for Wales has continued since 1993. The hydrological regimes defined by the water level data vary appreciably between dipwells, with winter water levels in one set of dipwells generally being 0.2–0.3 m higher relative to the ground surface than in another set. Water level regime descriptors for six dipwells located adjacent to more established

Figure 3.7 Time series of monthly dipwell data for Slack A at Newborough Warren and corresponding rainfall data

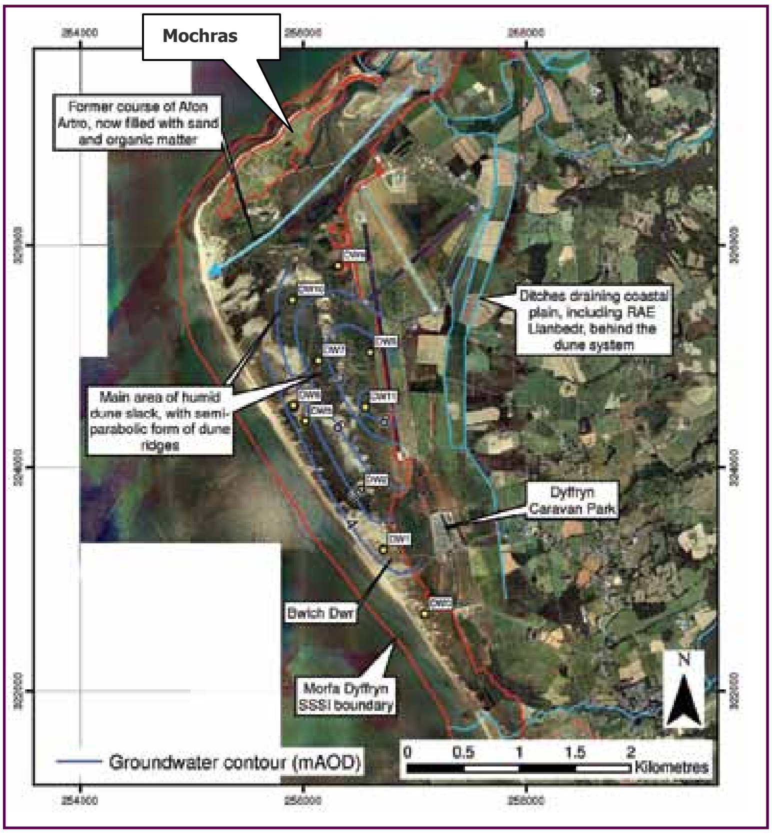


Data collected by: Ranwell (1951–1953); CCW (1989–1996); and Hollingham (2005 to present). Dipwell 2F is situated in Ranwell's Slack A, Site 8. From case study of Newborough Warren (see Appendix G).

dune slacks for the period 1993–2001 show average summer low water levels of between 0.7–1.0 m below ground surface and winter high water levels of between 0.03–0.37 m below ground surface giving an average annual range of between 0.67 and 0.87 m (Figure 3.8). In all dipwells, water levels rose either to ground surface or 0.5 m above ground surface on several occasions in the winters of the early- and late-1990s with evidence for some localised lateral flow and discharge from the dune slacks leading to small-scale differences in water level behaviour. In areas of active dune blowout, damp sand is observed around areas of standing water in a low, flat deflation plain with evidence of a capillary fringe with a maximum thickness of 0.3–0.4 m (Ranwell, 1959). It appears that the composition of dune slack vegetation (predominantly British Plant Community (NVC) SD16, with one wetter slack being SD15) may not be sensitive to differences in hydrological regime of this magnitude, at least in the short term, although detailed differences in vegetation composition between the slacks have not been studied in detail. The coastal plain and estuaries in the vicinity of Morfa Dyffryn have been modified extensively in the past by human intervention, with hydrological consequences, although it is considered that the dynamic nature of the dunes will have limited hydrological impacts on the slacks in maintaining a relatively constant relationship between the ground surface and the water table. The natural dynamism means that slack floors will be re-scoured down to the water table or new slacks will be formed in the wake of migrating dunes.

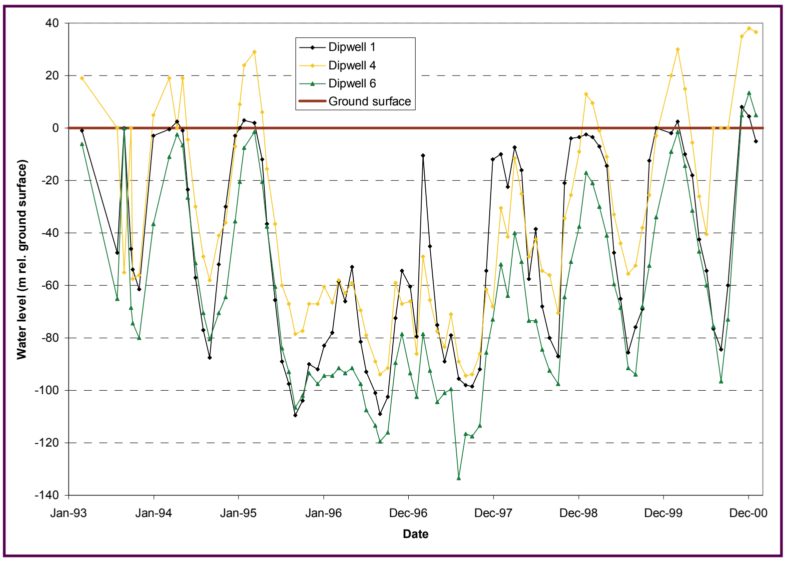
Merthyr Mawr is a large dune system of over 300 ha on the South Wales coast at the eastern end of Swansea Bay (Figure 3.9a). The dune system forms a series of dune ridges and slacks on low-lying ground, as well as perched dunes up the escarpment and on top of the scarp to approximately 1–1.5 km inland (Jones *et al.*, 2005). The dunes border a number of large parallel dune slacks extending roughly eastwards from the sea. Towards the eastern end of the site and also on the escarpment slope and up on to the plateau, the sand reaches a depth of greater than 1 m depth in the low-lying areas between the dunes. The hydrology of the site is complex with a catchment area that includes groundwater input, probably as seepage from the Carboniferous Limestone, streams and wells and ephemeral pools, as well as rainwater inputs. The two main springs are Candlestone Spring to the east of the

Figure 3.8a Annotated aerial photograph



From case study of Morfa Dyffryn (see Appendix F).

Figure 3.8b Water level hydrographs for Dipwells 1, 4 and 6 at Morfa Dyffryn

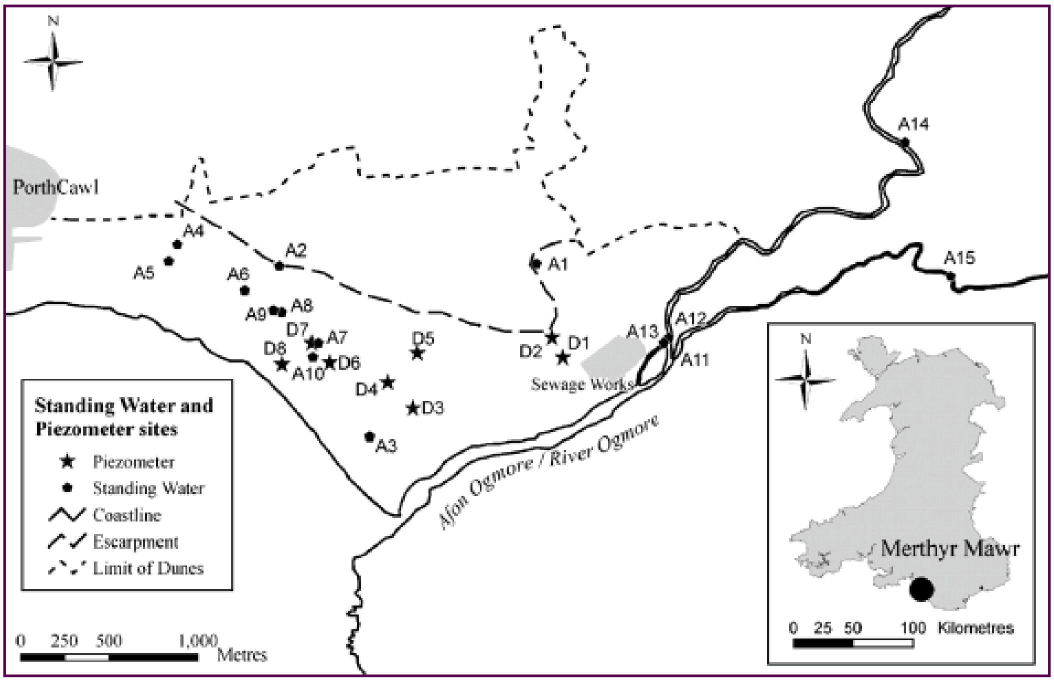


From case study of Morfa Dyffryn (see Appendix F).

site and Burrows Well near the middle of the site at the base of the escarpment. Candlestone Spring flows for much of the year but only flows out into the dunes during the winter, occasionally reaching the sea.

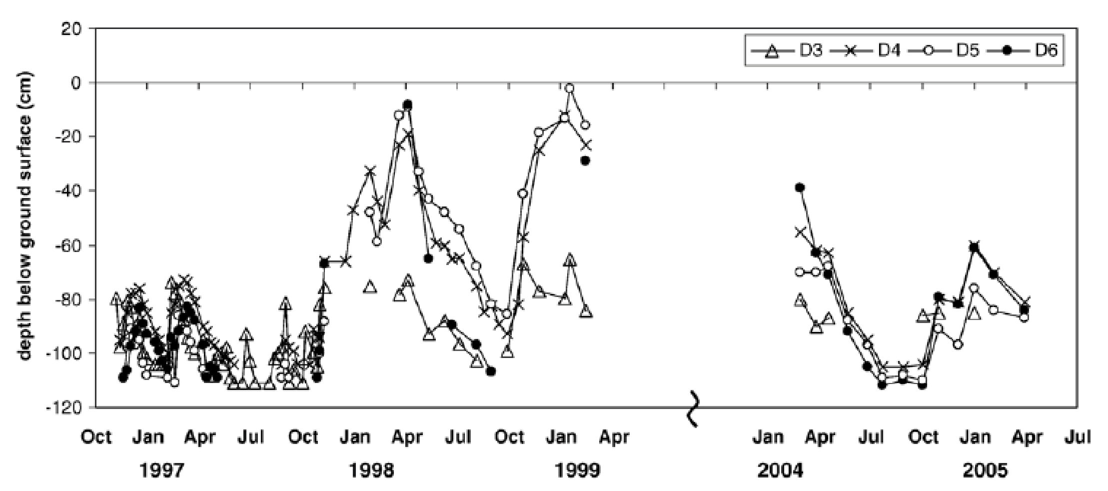
Burrows Well only flows in winter but strongly influences the site by filling a string of hollows and slacks depending on the rate of flow, before seeping into the sand. A major concern for the management of the site is the contamination of the Burrows Well spring with nitrate, possibly from agricultural land on the top of the plateau. The water table responds rapidly to rainfall patterns. A potential problem with the hydrology of the site is the proposed lowering of the water table at a local quarry and possible landfill contamination from another quarry. Water levels measured in Dipwell 4 adjacent to Slack S2 measured at six-hourly intervals between May 2004

Figure 3.9a Map of Merthyr Mawr dune system showing piezometer locations



After Jones *et al.* (2006).

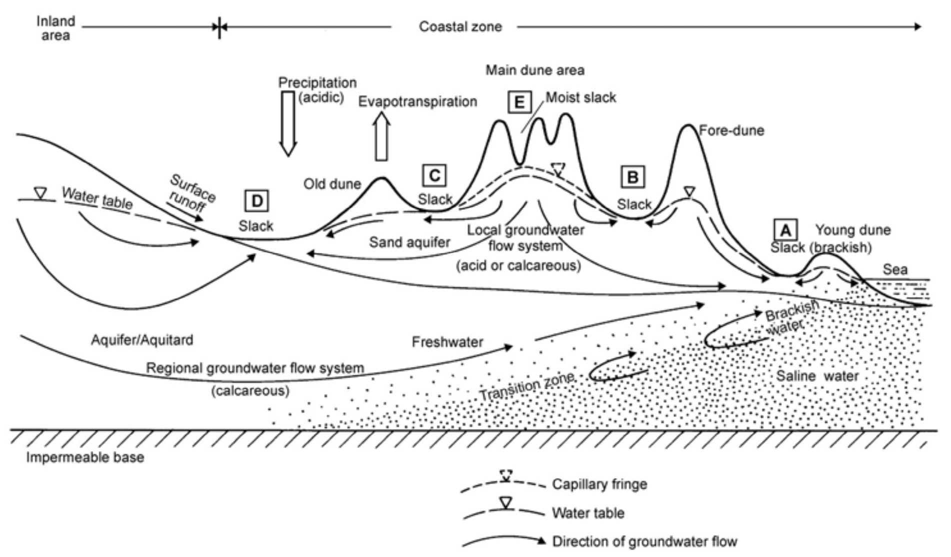
Figure 3.9b Comparison of water levels for piezometers positioned in typical dune slacks



After Jones *et al.* (2006).

and March 2005 vary between a minimum of about 7.5 m OD on several occasions between late August and December 2004 and a maximum of about 9.0 m OD on two occasions in June and October 2004. In general, the amplitude of water level fluctuation during the monitoring period at Dipwell 4 is about 1 m. Longer datasets for the depth of the water table below ground surface for Dipwells D3, D4, D5 and D6, all of which are adjacent to slacks, for the periods November 1996–May 1999 and March–December 2004, show a fluctuation of about 1 m especially in the later part of the record following drier conditions experienced in the mid-1990s. The record for Dipwell D6 shows a greater range of fluctuation of about 1.5 m as a result of lower than expected water levels in 2004 (Figure 3.9b).

Figure 3.10 Conceptual model of hydrological and hydrogeological controls on humid dune slack formation in coastal areas



After Davy *et al.* (2006).

Table 3.1 Water table conditions for defining humid dune slack habitat types

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

3.3 Summary

The examples of the hydrological functioning of dune systems collated in this report prove the conceptual model of the controls on humid dune slack formation presented by Davy *et al.* (2006) (see Figure 3.10). The review of the seven case studies at the locations shown in Figure 2.1 provides insight into the water level fluctuations, both intra- and inter-annually where the data permit. In synthesising the collated information, Table 3.1 compares WETMEC dune Types A–E (after Davy *et al.*, 2006) with the dune habitat British Plant Community type and, for the first time, the water table condition in terms of winter and summer maxima and water table fluctuation. This classification is then the basis of the water level regimes recommended for each of the dune slack community accounts presented in Chapter 4.

The largely qualitative analysis presented here has been constrained by the nature of the available series of dipwell observations which tend to be short, or broken, making comparisons difficult and precluding any meaningful analysis of long-term exceedence statistics. However, approaches to more quantitative methods are found in the literature. For example methods such as frequency of exceedence graphs and water table depth statistics leading to groundwater table classes are not uncommon, although these have their own advantages and disadvantages (Martens *et al.*, 2009). From their experience of the coastal dunes of Belgium, Martens *et al.* (2009) recommend that long time-series of at least eight years are required in order to ascertain different ecohydrological conditions for dune systems. Hence, a number of recommendations for future hydrological monitoring are apparent from this review of the case studies for England and Wales:

1. Dune systems are dynamic and hydrological targets need to consider the totality of a site rather than just focusing on local areas. A holistic approach is required to take account of the changing morphology of a dune system and the succession of dune slack communities.
2. Groundwater level data should be collected with the objective of plotting maps of the water table and the construction of hydrogeological cross-sections. This will require a sustained effort to survey the measurement point and, moreover, the ground elevation at the monitoring location against Ordnance Datum if the depth of the water table, or depth of surface flooding, is to be more accurately recorded. This is especially the case in dune systems where the ground elevation can change in areas of shifting sand. Also, combining groundwater level data with spatial ground elevation data (for example, LIDAR) would enable a depth to water table map and the depth of shallow flooding of dune slacks to be constructed, which could then be systematically compared with ecological survey data.
3. Although groundwater level and surface water level monitoring is currently undertaken with reasonable spatial coverage in dune systems, it is essential that this is maintained for the long term if quantitative analysis and the setting of local water management targets are to be set and defended. The further benefit of continuous long-term data will be the facility to repeat ecological and hydrochemical surveys of dune systems in order to study medium-term trends in water level and ecological conditions, especially if artificial influences such as groundwater abstraction, quarrying and landfill operations are to be identified against baseline conditions.

Section 4

SD13 (*Sagina nodosa – Bryum pseudotriquetrum*) dune-slack community

4.1 Context

The SD13 community is included in the EU Habitats Directive Annex 1 as a dune habitat sensitive to water extraction (European habitat feature 2190 'Humid dune slacks'). Examples of this community are the main British sites for the Annex II species *Petallophyllum ralfsii*, a rare liverwort. The nationally rare species *Equisetum variegatum, Moerckia hibernica* and *Pyrola rotundifolia* also occur in SD13.

4.1.1 Floristic composition

The rather open vegetational mosaic is dominated by patches of low-growing *Salix repens* and short swards of grass-like plants (graminoids), small herbs and bryophytes. The commonest graminoids are *Carex arenaria*, *Juncus articulatus* and *Agrostis stolonifera*, typically accompanied by rosettes of *Leontodon hispidus*, numerous individuals of *Sagina nodosa* and *Centaurium erythraea*. The moss *Bryum pseudotriquetrum* is usually the most prominent of the bryophytes, often accompanied by the liverworts *Aneura pinguis* and *Pellia endiviifolium*. *Petallophyllum ralfsii* is an uncommon addition to this list in one of the variants of the community.

Some 50 species have been recorded within stands of SD13, with a mean of 16 (range 11–26). Species which are particularly characteristic of SD13, and which help separate it from other communities, are listed in Table 4.1. Floristic diversity is enhanced by disturbance associated with fluctuating water level and, sometimes, grazing by rabbits and stock. The ephemerals and less competitive bryophytes become established on damp patches of sand and shell debris as the transient winter flooding recedes.

Rodwell (2000) recognises two sub-communities of SD13: *Poa annua-Moerckia hibernica* sub-community (SD13a); *Holcus lanatus-Festuca rubra* sub-community (SD13b).

Table 4.1 **Species characteristic of SD13**

Characteristic species
Agrostis stolonifera
Aneura pinguis
Anthyllis vulneraria
Blackstonia perfoliata
Bryum pseudotriquetrum
Carex arenaria
Carex flacca
Centaurium erythraea
Epilobium palustre
Equisetum variegatum
Euphrasia officinalis agg.
Festuca rubra
Holcus lanatus
Hydrocotyle vulgaris
Juncus articulatus
Leontodon autumnalis
Leontodon hispidus
Lotus corniculatus
Moerckia hibernica
Pellia endiviifolium
Petalophyllum ralfsii
Pilosella officinarum
Poa annua
Poa pratensis
Prunella vulgaris
Pyrola rotundifolia
Sagina nodosa
Salix repens
Senecio jacobaea

4.1.2 Distribution

This vegetation is very local and has been described from only a very few sites on the coast of Britain. One of the most important sites is at Morfa Dyffryn (West Wales); others have been described at Sefton (England), Lindisfarne (England), Kenfig Warren (South Wales) and Torrs Warren (Scotland). The total area of community in England and Wales has been estimated at 26.5 ha (Davy *et al.*, 2006).

4.1.3 Landscape situation and topography

Stands occur only in coastal dune settings. They typically occupy low-lying, transiently flooded, slacks that receive their water mainly from rainfall and slope run-off and lie between the stabilized dune ridges.

4.1.4 Substratum

The substratum is usually deep, comprising wind-blown, calcareous (shell) sand, with little accumulation of organic matter. Depending on the setting, coastal dune systems may form on a range of bed-rocks that have different permeabilities to water flow, including course sands and gravels, chalk and limestone, and relatively impermeable clays. Saline water typically intrudes below the dune aquifer at the coastal margin.

4.1.5 Zonation and succession

Dune slacks are usually discrete areas, bounded by higher ground, and therefore vegetationally distinct from their surroundings. Typically they are surrounded by the dry grassland communities of the dune ridges. Dune slacks with SD13 are usually found in dune systems that also have a range of other types of dune slack and these all may be components of a single hydrological system. SD13 represents an immature stage in dune-slack succession. It may include early-successional stands where there is new colonization, but stands tend to be maintained in an immature condition by the disturbance resulting from episodes of shallow flooding in winter, followed by drying-out in the summer. The bare, drying sand exposed by receding groundwater levels is repeatedly re-colonized by many of the characteristic species. Removal of biomass and scraping by rabbits, or grazing and trampling by stock, tend to reinforce this cycle.

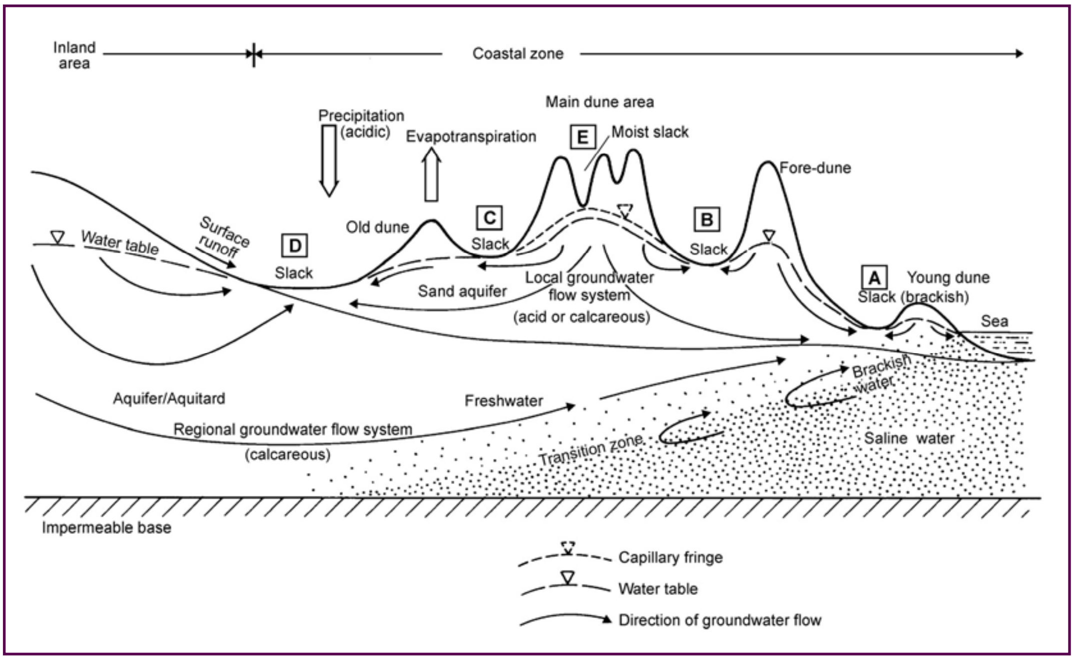
The basins themselves may show internal zonation, as during periodic inundations water is deeper and retained longer in the deeper, central parts, allowing concentric zones of colonization. If the renewal processes are not sufficiently active, particularly if inundation is reduced, SD13 slacks mature and may also accrete wind-blown sand. As they become drier, they may succeed into a *Salix repens-Holcus lanatus* dune-slack community (SD16). Continued invasion can eventually lead to scrub or woodland communities. In contrast, wetter slacks in similar settings with base-rich groundwater normally support the *Salix repens-Campylium stellatum* dune-slack community (SD14). This community is the likely result of maturation associated with wetting of the site, although in the less likely scenario of considerably increased flooding, succession to a *Salix repens – Calliergon cuspidatum* dune slack community is possible.

4.2 Supply mechanism and conceptual model

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is not unexpected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all the dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes.
A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

The hydrological conditions of humid dune slacks are reviewed by Davy *et al.* (2006) who presented a conceptual model (Figure 4.1) of controls on humid dune-slack formation in coastal areas, drawn mainly from examples in The Netherlands. Five dune-slack Types (A to E) are identified and form the basis of the definition of water table conditions shown in Table 4.2 for dune slacks in England and Wales based on a review of relevant case studies. A common feature of dunes systems in England and Wales is a shallow water table controlled by topography. The balance of rainfall input and evapotranspiration losses leads to the development of a groundwater mound in the sand aquifer, mostly aligned to the dune ridge. Another common feature is for an annual cycle of water level fluctuation in response to the distribution of effective rainfall. Minimum water levels occur in late summer or early autumn (August–October) when the water table is found in the dune sands at a level of between 1–2 m below ground surface elevations. The water table is observed to recover in the autumn with water levels approaching or exceeding ground surface elevations, typically between December and February when flooding of dune slacks to a depth of up to 0.15 m or greater is observed. Flooding can extend to the spring months but summer flooding is rare. During dry periods, the thickness of the capillary fringe in reaching the root zone is a further control and benefits those slacks with a low bed elevation, for example in areas of recent dune slack formation close to the sea or within blowouts in the inland dune system. Typical well hydrographs for dune systems reviewed for England and Wales show a relatively consistent pattern in terms of the range of water table fluctuation, often within 0.5–1.5 m. Periods of prolonged drying, as experienced in the 1970s and mid-1990s, and wetter conditions, as experienced in the late 1990s and during the current decade, are recorded in the hydrograph records and are associated with observations of dune habitat decline or succession.

Figure 4.1 Conceptual model of hydrological and hydrogeological controls on humid dune-slack formation in coastal areas



See text for an explanation of dune-slack Types A, B, C, D and E.

Table 4.2 Water table conditions for defining humid dune slack habitat types

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

4.3 Regimes

4.3.1 Water

Water conditions for SD13 are difficult to specify quantitatively, because of the lack of detailed time series data. However, it is usually found in the WETMEC Dune Type A slack and as a very general guide, the range of winter and summer water tables are shown in Table 4.3.

An important consideration in maintaining the vegetation is the annual range of water level. Practically useful eco-hydrological targets may need to be expressed in terms of the frequency, magnitude and duration of deviation from the normal range of the water table. Frequency is probably a key issue, because significant lowering over one annual cycle may entrain irreversible changes. Magnitude and duration of periods outside the normal range still needs to be assessed. Current indications suggest that any lowering of the water table is not desirable.

4.3.2 Nutrients/hydrochemistry

Dune slacks are nutrient-poor habitats in which the characteristic vegetation is maintained by low levels of nutrient input, particularly of nitrogen (N) and phosphorus (P). Generally, N is limiting but in young slacks with calcareous groundwaters, such as SD13, P is likely to be more limiting. At high pH, phosphate may be precipitated with calcium carbonate as a basic calcium phosphate (hydroxyapatite). Increased concentrations of N and P (eutrophication) promote the dominance of more competitive nutrient-demanding species and the loss of diversity and botanical interest. Nutrient limitation is a key factor in maintaining stability in such communities and hence delaying potential successional development. For instance, Willis (1964) found that the addition of N and P to the surface of dunes slacks at Braunton Burrows favoured *Agrostis stolonifera* and other grasses, whereas the addition of only N led to dominance by species of *Carex* (especially *C. flacca*) and *Juncus*. Nutrient enrichment of groundwater would be expected to have similar if slower effects, although direct evidence is lacking. In the virtual absence of data that relate groundwater concentrations to adverse effects, Jones *et al.* (Appendix D) have developed guidelines for acceptable concentrations of total inorganic nitrogen from a review of information on concentrations and possible nutrient sources at UK sand-dune sites (Table 4.4). There is insufficient information to set a reference condition for P.

An annual draw-down of ground-water fed slacks, with drying of the surface in summer, inhibits the development of laminated microbial and algal mats on the sand surface. Such mats otherwise lead to stabilization of the sand surface and N-fixation by their constituent cyanobacteria (reviewed by Davy *et al.*, 2006). Increased nitrogen cycling is associated with successional change.

Base-rich/high-pH groundwater is important for the calcicole plants species that confer much of the botanical interest. Acidification can have complex consequences. Adema *et al.* (2002) found that on the infiltration side of a slack where the topsoil had been decalcified, sulphide concentrations reached toxic levels (30–90 μmol l^{-1}) for many higher plants (Lammerts *et al.*, 1999). At the exfiltration side, no sulphide was detected, although the redox potentials were much lower than in the infiltration site, due to continuous inflow of anaerobic and iron-rich groundwater. The iron-rich groundwater fixed the free sulphide produced by microbial mats to form iron sulphide. At the infiltration side, however, no iron was present and free sulphide could accumulate. These relatively high sulphide concentrations can be tolerated only by wetland species that can oxidize their rhizosphere by radial oxygen release. The sulphide production in the infiltration areas can, however, release phosphates in the iron-depleted topsoil due to binding of sulphides with iron (Lammerts *et al.*, 1999). The infiltration side of such a slack, therefore, is likely to lose its pioneer vegetation.

Table 4.3 Summer and winter water tables for SD13

	Mean
Summer maximum water table (cm bgl)	-50 to -100
Winter maximum water table (cm agl)	2 to 10
Annual range of water table (cm)	50–100

Long-term stability of pioneer vegetation between the exfiltration and central parts of dune-slacks may occur because the pH is buffered, sulphide production is neutralised by iron, and acidification is prevented by discharge of calcareous groundwater. Sival *et al.* (1998) found that, at exfiltration sites of dune-slacks, secondary, *in situ* carbonate deposition occurred in the early stages of dune-slack succession.

Temporal variations in groundwater chemistry may be mainly related to the seasonal event of groundwater recharge. Malcolm & Soulsby (2001) found that the main period of rising groundwater levels in the autumn and winter resulted in a marked dilution of solutes in the aquifer. A period of several weeks appeared to be required for dissolution processes to proceed to equilibrium.

4.3.3 Management

In general SD13 sites are not managed actively, although they may be grazed by rabbits or stock, particularly in summer. Lack of grazing may be detrimental to community stability and species diversity. Recommendations for management of Natura 2000 sites representing H2190 humid dune slacks are provided by Houston (2008).

4.4 Implications for decision making

4.4.1 Vulnerability

SD13 slacks are extremely vulnerable to changes in water supply, its seasonality and its quality. Some of the critical species have practically no tolerance of environmental change. Figure 4.2 indicates the possible floristic impact of changes to the stand environment.

4.4.2 Restorability

The degradation of dune-slack vegetation is likely to result from changes in hydrology, such as lowering of the water table by abstraction, or from eutrophication of the groundwater by pollution and atmospheric deposition of nitrogen.

There is little information on the restoration of slacks in the UK, although work in the somewhat different situation of the Netherlands offers some pointers (Davy *et al.*, 2006). It will rarely be possible to alleviate the problems of a single type of slack without addressing the hydrology/hydrochemistry of the dune system in which it is found, and the other types of slack present.

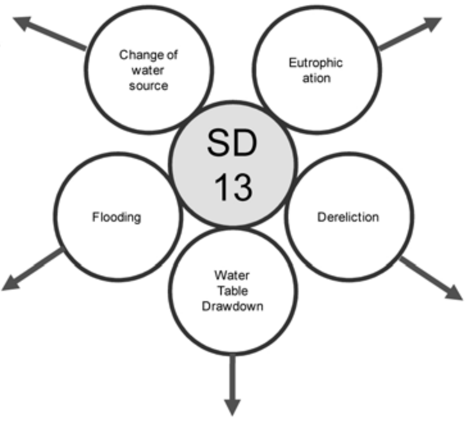
Young slacks, which are rare and highly valued for nature conservation, are inherently threatened by natural succession. New slacks can appear periodically in dynamic dune systems to replace those changed or lost through successional trajectories. Likewise more mature slacks that are lost to woodland or even permanent open water might potentially be replaced locally. Clearly, if dune systems become fixed or lose their supply of blown sand this regenerative capacity is compromised. Therefore measures designed to restore the dune systems as a whole to a dynamic state will tend also to restore the slacks. The loss of sandy foreshore, usually as a result of change in relative sea level, both reduces sand supply and increases erosion by the sea; unless the dune system is able to migrate landward the prospects for restoration are poor. Rising sea levels and the constraints of various kinds of development on the coast will bring this problem into ever sharper focus. Attempts to restore depleted dune water tables (and filter water for re-abstraction) by infiltrating with eutrophic river water have proved disastrous for plant communities. The complex interplay between water supply and chemistry suggests that restorability will be highly site-specific and will require detailed investigation in each case.

As frequently is the case for restoration, success will depend on either a locally persistent seed bank of the desirable species, or their sufficient dispersal from similar habitat nearby. With small areas of rare communities that have experienced long-term changes, artificial reintroductions of key species may be necessary.

Table 4.4 **Guidelines for total inorganic nitrogen (TIN) in dune groundwater**

Status	TIN (mg N L^{-1})
Reference condition	< 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	> 1.0

Figure 4.2 **The possible effects of environmental change on stands of SD13**



Depends on base-rich, calcareous groundwater. Acidification of groundwater would lead to peat accumulation and loss of characteristic calcicoles, and hence botanical interest.

Typically very nutrient-poor. Increased N and P would promote dense growth of grasses, litter accumulation and substantial loss of botanical interest.

Increased flooding may allow succession to SD14 *Salix-Campylium* community, with a shift to species more tolerant of reducing soil conditions. Less likely deep flooding could lead to a *SD15 Salix-Calliergon* community

Accumulation of windblown sand, or cessation of disturbance associated with grazing, may allow succession through SD16 *Salix-Holcus* community, possibly to woodland

Reduction in the amplitude of seasonal water-level fluctuation and decreased winter flooding are both likely to allow succession to a SD16 *Salix-Holcus* community, with greater dominance of *Salix repens*

Restoration measures may include:

- removal of sand-stabilizing features and, in appropriate settings, constraints on the landward migration of dune systems;
- identification and remediation of sources of eutrophic, polluted groundwater; the problem might be cured at source or the polluted water diverted;
- reducing water abstraction and land drainage that is shown to be lowering dune water tables;
- removal of coniferous plantations whose transpirational losses are having a deleterious effect on dune water tables;
- conservation of local surface water in ponds or ditches, for possible reinjection into deeper soil layers;
- sod-cutting or scraping to remove accumulated organic material and re-establish appropriate contact with the water table;
- assuming that appropriate conditions can be reinstated, reintroduction of species of particular interest and importance.

4.4.3 Limitations of these guidelines and gaps in knowledge

The limitations of the information presented here related to SD13 include the following.

- There are currently virtually no data to characterize the temporal water table characteristics of SD13 stands, particularly in contra-distinction from related dune slack types. Time series of dipwell measurements are required to fill this gap. A probabilistic analysis of the duration and frequency of the water levels is more likely to be informative than taking the extreme summer and winter values.
- Hydrochemical data from UK sites are extremely limited and none can be associated with specific adverse effects. Time series analyses of samples from dipwells and slacks are required to fill this gap.
- Insufficient data are available for the establishment of guidelines for groundwater phosphorus concentrations.
- Insufficient data are available for the establishment of separate guidelines for groundwater nitrate and ammonium concentrations.

- Intensive studies on the detailed hydrochemistry of specific slacks are lacking.
- Intensive studies on the ecological requirements of rare and key dune-slack species are lacking.
- More information is needed on appropriate restoration techniques, particularly in UK settings.

Application of the guidelines for total inorganic nitrogen (Table 4.4) is subject to the caveats and recommendations listed below.

- Groundwater (chemistry or water levels) uniformity cannot be assumed under a dune system, or even within the same slack in the case of through-flow slacks.
- Suspected contaminated groundwater needs clarification by (1) ascertaining the water level regime relative to the ground surface and the rooting zone (for example, monitoring dipwells); (2) analysing groundwater for nutrient concentrations, at minimum twice (in summer and a winter), using laboratories that have sufficiently accurate procedures.
- Referring the results to the guidelines. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.
- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.
- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping or grazing will remove nutrients.
- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

SD14 (*Salix repens – Campylium stellatum*) dune-slack community

5.1 Context

The SD14 community is included in the EU Habitats Directive Annex 1 as a dune habitat sensitive to water extraction (European habitat feature 2190 'Humid dune slacks'). It is rich in nationally rare orchid species (*Dactylorhiza praetermissa*, *D. purpurella, Epipactis palustris* and *Liparis loeselii*), and contains other notable rarities, such as *Pyrola rotundifolia*, *Equisetum variegatum* and (occasionally) *Moerckia hibernica*.

5.1.1 Floristic composition

The vegetation canopy is dominated by a more or less closed bushy layer of low-growing *Salix repens*. Beneath is a well-developed carpet of mosses, in which *Campylium stellatum* is generally the most abundant and *Calliergon cuspidatum* is also very common. *Drepanocladus sendtneri, D. lycopodioides* and *Riccardia chamaedryfolia* are less common bryophytes. Within this matrix, a considerable variety of herbaceous vascular plants occurs. Most characteristic of SD14 are *Carex flacca, Equisetum variegatum* (which can be locally dominant) and *Epipactis palustris*, along with more widely distributed dune-slack species such as *Hydrocotyle vulgaris*, *Agrostis stolonifera* and *Mentha aquatica*. Other common species are *Leontodon autumnalis, Ranunculus flammula, Rubus caesius*, and *Juncus articulatus*. Slacks with a stronger maritime influence may contain *Glaux maritima*, *Juncus gerardii* and *J. maritimus*.

More than 110 species have been recorded within stands of SD14, with a mean of 19 (range 8–42) (Rodwell, 2000). Species which are particularly characteristic of SD14, and which help separate it from other communities, are listed in Table 5.1. The relatively high floristic diversity is likely be maintained by the seasonally fluctuating water level, with winter flooding, base-rich conditions and a low nutrient supply.

Rodwell (2000) recognises four sub-communities of SD14: *Carex serotina-Drepanocladus sendtneri* sub-community (SD14a); *Rubus caesius-Galium palustre* sub-community (SD14b); *Bryum pseudotriquetrum-Aneura pinguis* sub-community (SD14c); *Festuca rubra* sub-community (SD14d).

5.1.2 Distribution

This vegetation is very uncommon. It occurs locally on dune systems on the English and Welsh coasts and even more rarely on those in Scotland. The total area of community in England and Wales has been estimated at 136.5 ha (Davy *et al.*, 2006).

5.1.3 Landscape situation and topography

Stands occur only in coastal dune settings. They typically occupy low-lying, seasonally flooded, slacks that receive their water mainly from rainfall and slope run-off and lie between the stabilized dune ridges.

5.1.4 Substratum

The substratum is usually deep, comprising wind-blown, calcareous (shell) sand. Depending on the setting, coastal dune systems may form on a range of bed-rocks that have different permeabilities to water flow, including course sands and gravels, chalk and limestone, and relatively impermeable clays. Saline water typically intrudes below the dune aquifer at the coastal margin.

5.1.5 Zonation and succession

Dune slacks are usually discrete areas, bounded by higher ground, and therefore vegetationally distinct from their surroundings. Typically they are surrounded by the dry grassland communities of the dune ridges and therefore may blend into *Ammophila arenaria-Festuca rubra* semi-fixed dune community (SD7) or *Festuca rubra-Galium verum* fixed dune grassland (SD8) at their margins. Dune slacks with SD14 are

Table 5.1 **Species characteristic of SD14**

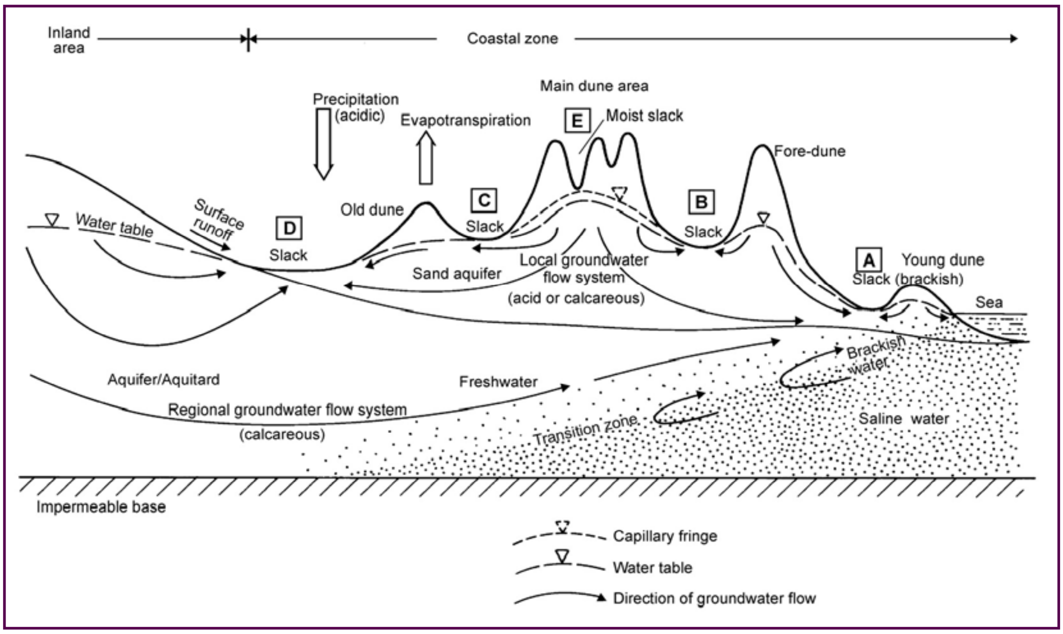
Characteristic species
Agrostis stolonifera
Anagallis tenella
Aneura pinguis
Brachythecium rutabulum
Bryum pseudotriquetrum
Calliergon cuspidatum
Campylium stellatum
Carex arenaria
Carex flacca
Carex nigra
Carex serotina
Cladium mariscus
Dactylorhiza praetermissa
Dactylorhiza purpurella
Drepanocladus lycopodioides
Drepanocladus sendtneri
Eleocharis palustris
Epipactis palustris
Equisetum variegatum
Euphrasia officinalis agg.
Festuca rubra
Galium palustre
Glaux maritima
Holcus lanatus
Hydrocotyle vulgaris
Juncus articulatus
Juncus gerardii
Juncus maritimus
Leontodon autumnalis
Leontodon hispidus
Linum catharticum
Liparis loeselii
Lotus pedunculatus
Mentha aquatica
Moerckia hibernica
Pellia endiviifolium
Phragmites australis
Poa pratensis
Preissia quadrata
Prunella vulgaris
Pulicaria dysenterica
Pyrola rotundifolia
Ranunculus acris
Ranunculus flammula
Ranunculus repens
Riccardia chamaedryfolia
Rubus caesius
Salix repens
Samolus valerandi
Schoenus nigricans
Sonchus arvensis
Trifolium pratense
Trifolium repens

usually found in dune systems that also have a range of other types of dune slack and these all may be components of a single hydrological system. SD14 dune slacks are moderately wet, and deep winter flooding with base-rich water is probably necessary to maintain them. Grazing by rabbits and stock also is probably helpful. The *Bryum pseudotriquetrum-Aneura pinguis* sub-community (SD14c) appears to be the earliest stage within these slacks, which progress to the other sub-types as the canopy of *Salix repens* and tussock-forming herbs develops. Under increasingly wet conditions SD14 may develop from the even rarer *Sagina nodosa-Bryum pseudotriquetrum* dune-slack community (SD13), which is similarly base-rich stage in dune-slack succession. Drying of SD14 slacks could give a transition to the *Salix repens-Holcus lanatus* dune-slack community (SD16) but marked drying allows succession to woodland.

5.2 Supply mechanism and conceptual model

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is not unexpected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all the dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes. A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

Figure 5.1 **Conceptual model of hydrological and hydrogeological controls on humid dune-slack formation in coastal areas**



See text for an explanation of dune-slack Types A, B, C, D and E.

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5.3 Regimes

5.3.1 Water

Water conditions for SD14 are difficult to specify quantitatively, because of the lack of detailed time series data. However, it is usually found in the WETMEC Dune Type A slack and as a very general guide, the range of winter and summer water tables are shown in Table 5.3.

An important consideration in maintaining the vegetation is the annual range of water level. Practically useful eco-hydrological targets may need to be expressed in terms of the frequency, magnitude and duration of deviation from the normal range of the water table. Frequency is probably a key issue, because significant lowering over one annual cycle may entrain irreversible changes. Magnitude and duration of periods outside the normal range still needs to be assessed. Current indications suggest that any lowering of the water table is not desirable.

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Dune slacks are nutrient-poor habitats in which the characteristic vegetation is maintained by low levels of nutrient input, particularly of nitrogen (N) and phosphorus (P). Generally, N is limiting but in slacks with calcareous groundwaters, such as SD14, P is likely to be more limiting. At high pH, phosphate may be precipitated with calcium carbonate as a basic calcium phosphate (hydroxyapatite). Increased concentrations of N and P (eutrophication) promote the dominance of more competitive nutrient-demanding species and the loss of diversity and botanical interest. Nutrient limitation is a key factor in maintaining stability in such communities and hence delaying potential successional development. For instance, Willis (1964) found that the addition of N and P to the surface of dunes slacks at Braunton Burrows favoured *Agrostis stolonifera* and other grasses, whereas the addition of only N led to dominance by species of *Carex* (especially *C. flacca*) and Juncus. Nutrient enrichment of groundwater would be expected to have similar if slower effects, although direct evidence is lacking. In the virtual absence of data that relate groundwater concentrations to adverse effects, Jones *et al.* (Appendix D) have developed guidelines for acceptable concentrations of total inorganic nitrogen from a review of information on concentrations and possible nutrient sources at UK sand-dune sites (Table 5.4). There is insufficient information to set a reference condition for P.

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Table 5.2 Water table conditions for defining humid dune slack habitat types

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

Long-term stability of pioneer vegetation between the exfiltration and central parts of dune-slacks may occur because the pH is buffered, sulphide production is neutralised by iron, and acidification is prevented by discharge of calcareous groundwater. Sival *et al.* (1998) found that at exfiltration sites of dune-slacks secondary, *in situ* carbonate deposition occurred in the early stages of dune-slack succession.

Temporal variations in groundwater chemistry may be mainly related to the seasonal event of groundwater recharge. Malcolm & Soulsby (2001) found that the main period of rising groundwater levels in the autumn and winter resulted in a marked dilution of solutes in the aquifer. A period of several weeks appeared to be required for dissolution processes to proceed to equilibrium.

5.3.3 Management

In general SD14 sites are not managed actively, although they may be grazed by rabbits or stock, particularly in summer. Lack of grazing may be detrimental to community stability and species diversity. Recommendations for management of Natura 2000 sites representing H2190 humid dune slacks are provided by Houston (2008).

5.4 Implications for decision making

5.4.1 Vulnerability

SD14 slacks are extremely vulnerable to changes in water supply, its seasonality and its quality. Experience in The Netherlands indicates that some of the critical species, such as *Liparis loeselii* have practically no tolerance of environmental change. Figure 5.2 indicates the possible floristic impact of changes to the stand environment.

5.4.2 Restorability

The degradation of dune-slack vegetation is likely to result from changes in hydrology, such as lowering of the water table by abstraction, or from eutrophication of the groundwater by pollution and atmospheric deposition of nitrogen. There is little information on the restoration of slacks in the UK, although work in the somewhat different situation of the Netherlands offers some pointers (Davy *et al.*, 2006). It will rarely be possible to alleviate the problems of a single type of slack without addressing the hydrology/hydrochemistry of the dune system in which it is found, and the other types of slack present.

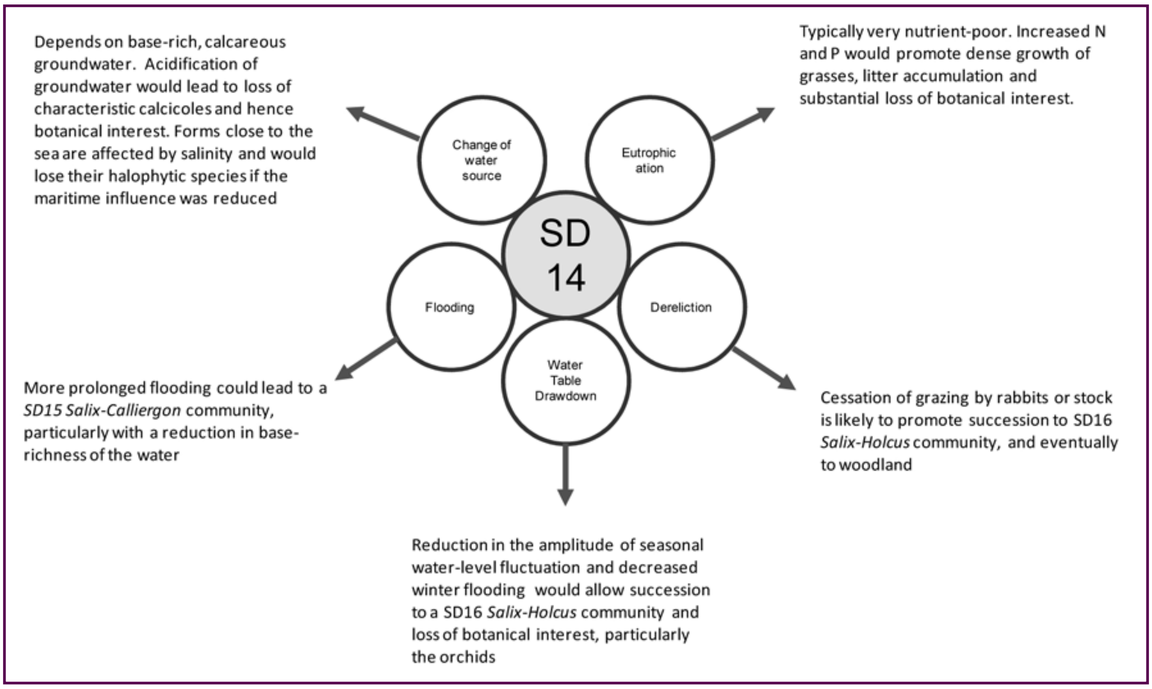
Table 5.3 **Summer and winter water tables for SD14**

	Mean
Summer maximum water table (cm agl)	-50 to -200
Winter maximum water table (cm bgl)	2 to 50
Annual range of water table (cm)	50–100

Table 5.4 **Guidelines for total inorganic nitrogen (TIN) in dune groundwater**

Status	**TIN (mg N L^{-1})**
Reference condition	‹ 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	› 1.0

Figure 5.2 The possible effects of environmental change on stands of SD14



Depends on base-rich, calcareous groundwater. Acidification of groundwater would lead to loss of characteristic calcicoles and hence botanical interest. Forms close to the sea are affected by salinity and would lose their halophytic species if the maritime influence was reduced

Typically very nutrient-poor. Increased N and P would promote dense growth of grasses, litter accumulation and substantial loss of botanical interest.

More prolonged flooding could lead to a *SD15 Salix-Calliergon* community, particularly with a reduction in base-richness of the water

Cessation of grazing by rabbits or stock is likely to promote succession to SD16 *Salix-Holcus* community, and eventually to woodland

Reduction in the amplitude of seasonal water-level fluctuation and decreased winter flooding would allow succession to a SD16 *Salix-Holcus* community and loss of botanical interest, particularly the orchids

Young slacks, which are rare and highly valued for nature conservation, are inherently threatened by natural succession. New slacks can appear periodically in dynamic dune systems to replace those changed or lost through successional trajectories. Likewise more mature slacks that are lost to woodland or even permanent open water might potentially be replaced locally. Clearly, if dune systems become fixed or lose their supply of blown sand this regenerative capacity is compromised. Therefore measures designed to restore the dune systems as a whole to a dynamic state will tend also to restore the slacks. The loss of sandy foreshore, usually as a result of change in relative sea level, both reduces sand supply and increases erosion by the sea; unless the dune system is able to migrate landward the prospects for restoration are poor. Rising sea levels and the constraints of various kinds of development on the coast will bring this problem into ever sharper focus. Attempts to restore depleted dune water tables (and filter water for re-abstraction) by infiltrating with eutrophic river water have proved disastrous for plant communities. The complex interplay between water supply and chemistry suggests that restorability will be highly site-specific and will require detailed investigation in each case.

As frequently is the case for restoration, success will depend on either a locally persistent seed bank of the desirable species, or their sufficient dispersal from similar habitat nearby. With small areas of rare communities that have experienced long-term changes, artificial reintroductions of key species may be necessary.

Restoration measures may include:

- removal of sand-stabilizing features and, in appropriate settings, constraints on the landward migration of dune systems;
- identification and remediation of sources of eutrophic, polluted groundwater; the problem might be cured at source or the polluted water diverted;
- reducing water abstraction and land drainage that is shown to be lowering dune water tables;
- removal of coniferous plantations whose transpirational losses are having a deleterious effect on dune water tables;
- conservation of local surface water in ponds or ditches, for possible reinjection into deeper soil layers;

- sod-cutting or scraping to remove accumulated organic material and re-establish appropriate contact with the water table;
- assuming that appropriate conditions can be reinstated, reintroduction of species of particular interest and importance.

5.4.3 Limitations of these guidelines and gaps in knowledge

The limitations of the information presented here related to SD14 include the following.

- There are currently virtually no data to characterize the temporal water table characteristics of SD14 stands, particularly in contra-distinction from related dune slack types. Time series of dipwell measurements are required to fill this gap. A probabilistic analysis of the duration and frequency of the water levels is more likely to be informative than taking the extreme summer and winter values.
- Hydrochemical data from UK sites are extremely limited and none can be associated with specific adverse effects. Time series analyses of samples from dipwells and slacks are required to fill this gap.
- Insufficient data are available for the establishment of guidelines for groundwater phosphorus concentrations.
- Insufficient data are available for the establishment of separate guidelines for groundwater nitrate and ammonium concentrations.
- Intensive studies on the detailed hydrochemistry of specific slacks are lacking.
- Intensive studies on the ecological requirements of rare and key dune-slack species are lacking.
- More information is needed on appropriate restoration techniques, particularly in UK settings.

Application of the guidelines for total inorganic nitrogen (Table 5.4) is subject to the caveats and recommendations listed below.

- Groundwater (chemistry or water levels) uniformity cannot be assumed under a dune system, or even within the same slack in the case of through-flow slacks.
- Suspected contaminated groundwater needs clarification by (1) ascertaining the water level regime relative to the ground surface and the rooting zone (for example, monitoring dipwells); (2) analysing groundwater for nutrient concentrations, at minimum twice (in summer and a winter), using laboratories that have sufficiently accurate procedures.
- Referring the results to the guidelines. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.
- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.
- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping or grazing will remove nutrients.
- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

Section 6

SD15 (*Salix repens – Calliergon cuspidatum*) dune-slack community

6.1 Context

The SD15 community is included in the EU Habitats Directive Annex 1 as a dune habitat sensitive to water extraction (European habitat feature 2190 'Humid dune slacks'). It can contain the nationally rare species, *Equisetum variegatum*.

6.1.1 Floristic Composition

The vegetation is dominated by *Salix repens* in low-growing shrub layer and *Calliergon cuspidatum* in the bryophyte layer. Other constant species are *Hydrocotyle vulgaris* and *Mentha aquatica*. *Galium palustre*, *Epilobium palustre Equisetum palustre* and *Lotus pedunculatus* are characteristic components, and *Carex flacca, Agrostis stolonifera, Equisetum variegatum* and *Epipactis palustris* are not infrequent. *Festuca, rubra, Poa pratensis* and, locally, the tall herbs *Iris pseudacorus*, *Filipendula ulmaria* and *Phragmites australis* also occur. Rodwell (2000) regards the SD15 vegetation as more akin to poor fen than rich fen.

Some 90 species have been recorded within stands of SD15, with a mean of 14 (range 6–27) (Rodwell, 2000). Species which are particularly characteristic of SD15, and which help separate it from other communities, are listed in Table 6.1. This vegetation is maintained by prolonged flooding with near-neutral ground-water.

Rodwell (2000) recognises four sub-communities of SD15: *Carex nigra* sub-community (SD15a); *Equisetum variegatum* sub-community (SD15b); *Carex flacca-Pulicaria dysenterica* sub-community (SD15c); *Holcus lanatus-Angelica sylvestris* sub-community (SD15d).

Table 6.1 **Species characteristic of SD15**

Characteristic species		
Agrostis stolonifera	*Festuca rubra*	*Phragmites australis*
Angelica sylvestris	*Filipendula ulmaria*	*Poa pratensis*
Calliergon cuspidatum	*Galium palustre*	*Potentilla anserina*
Carex flacca	*Holcus lanatus*	*Pulicaria dysenterica*
Carex nigra	*Hydrocotyle vulgaris*	*Ranunculus flammula*
Cirsium palustre	*Iris pseudacorus*	*Ranunculus repens*
Epilobium palustre	*Juncus acutus*	*Rubus caesius*
Epipactis palustris	*Lotus pedunculatus*	*Salix repens*
Equisetum fluviatile	*Lysimachia vulgaris*	*Scutellaria galericulata*
Equisetum palustre	*Mentha aquatica*	*Succisa pratensis*
Equisetum variegatum	*Molinia caerulea*	*Vicia sativa* ssp. *nigra*
Eupatorium cannabinum	*Oenanthe lachenalii*	

6.1.2 Distribution

This vegetation is widely distributed on dune systems that have slacks, on the coasts of England, Wales and, locally, Scotland. The total area of this community in England and Wales has been estimated at 222.1 ha (Davy *et al.*, 2006).

6.1.3 Landscape situation and topography

Stands occur only in coastal dune settings, usually lying between the stabilized dune ridges. They typically occupy low-lying, wet slacks that receive their water mainly from rainfall and slope run-off, and experience prolonged flooding. The rooting zone is rarely out of contact with the capillary fringe of the water table (Jones, 1992).

6.1.4 Substratum

The substratum is usually deep, comprising wind-blown, sand. Depending on the setting, coastal dune systems may form on a range of bed-rocks that have different permeabilities to water flow, including course sands and gravels, chalk and limestone, and relatively impermeable clays. Saline water typically intrudes below the dune aquifer at the coastal margin.

6.1.5 Zonation and succession

Dune slacks are usually discrete areas, bounded by higher ground, and therefore vegetationally distinct from their surroundings. Typically they are surrounded by the dry grassland communities of the dune ridges and therefore may show transitions to dune grasslands such as *Ammophila arenaria-Festuca rubra* semi-fixed dune community (SD7) or *Festuca rubra-Galium verum* fixed dune grassland (SD8) at their margins. Dune slacks with SD15 are usually found in stabilized dune systems that also usually have a range of other types of dune slack and these all may be components of a single hydrological system.

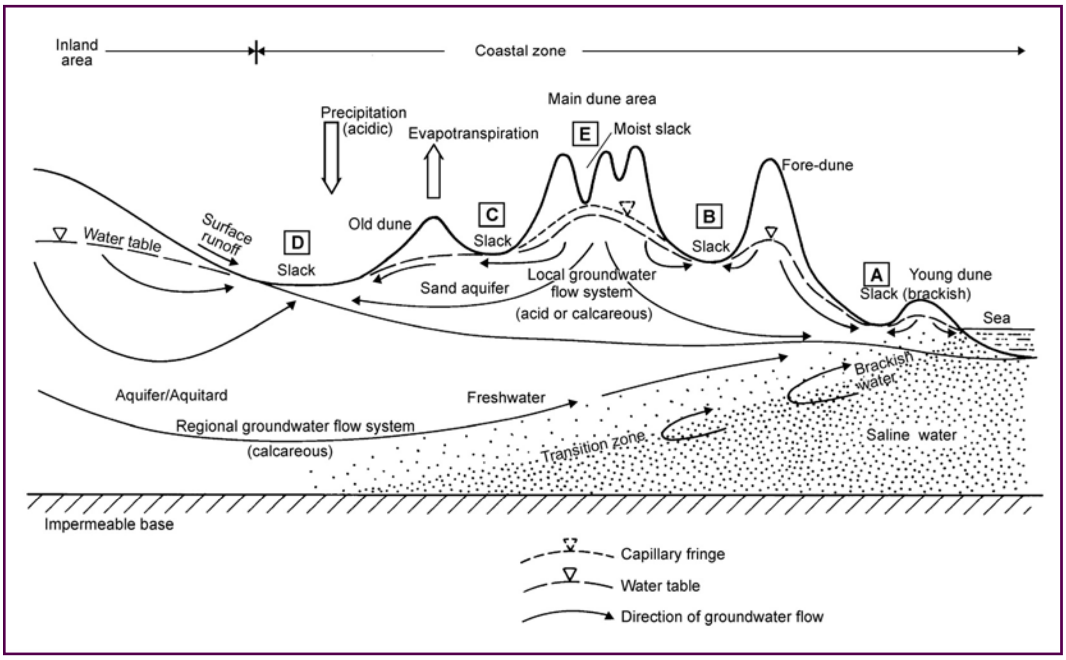
SD15 vegetation itself is normally representative of mature dune slacks that are kept wet by prolonged flooding. Inundation for much or all of the year is important in maintaining the composition and structure of the vegetation. The dense canopy cover of *Salix repens* allows the shade-tolerant moss *Calliergon cuspidatum* to develop a thick, impenetrable mat underneath that further limits the establishment of other species (including shrubs and trees), consistent with the 'inhibition' model of succession (Connell & Slatyer, 1978). Under drier conditions, grazing by rabbits and stock also probably helps to prevent succession to woodland. Drier areas can merge via the *Equisetum variegatum* sub-community into the *Potentilla anserina-Carex nigra* dune-slack community (SD17). Where trees (typically *Salix cinerea, S. caprea* and *Betula pubescens*) do become established, succession progresses to wet woodland (W2 *Salix cinerea-Betula pubescens-Phragmites australis* woodland, or W1 *Salix cinerea-Galium palustre* woodland). In particularly wet slacks, where there are stretches of permanent open water, the *Holcus lanatus-Angelica sylvestris* sub-community may, in contrast, merge in to various types of fen vegetation, such as *Phragmites australis – Eupatorium cannabinum* tall-herb fen (S25), or Eleocharis palustris swamp (S19).

6.2 Supply mechanism and conceptual model

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is not unexpected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all the dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes. A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

The hydrological conditions of humid dune slacks are reviewed by Davy *et al.* (2006) who presented a conceptual model (Figure 6.1) of controls on humid dune-slack formation in coastal areas, drawn mainly from examples in The Netherlands. Five dune-slack Types (A to E) are identified and form the basis of the definition of water table conditions shown in Table 6.2 for dune slacks in England and Wales based on a review of relevant case studies. A common feature of dunes systems in England and Wales is a shallow water table controlled by topography. The balance of rainfall input and evapotranspiration losses leads to the development of a groundwater mound in the sand aquifer, mostly aligned to the dune ridge. Another common feature is for an annual cycle of water level fluctuation in response to the distribution of effective rainfall. Minimum water levels occur in late summer or early autumn (August–October) when the water table is found in the dune sands at a level of between 1–2 m below ground surface elevations. The water table is observed to recover in the autumn with water levels approaching or exceeding ground surface elevations, typically between December and February when flooding of dune slacks to a depth of up to 0.15 m or greater is observed. Flooding can extend to the spring months but summer flooding is rare. During dry periods, the thickness of the capillary fringe in reaching the root zone is a further control and benefits those slacks with a low bed elevation, for example in areas of recent dune slack formation close to the sea or within blowouts in the inland dune system. Typical well hydrographs for dune systems reviewed for England and Wales show a relatively consistent pattern in terms of the range of water table fluctuation, often within 0.5–1.5 m. Periods of prolonged drying, as experienced in the 1970s and mid-1990s, and wetter conditions, as experienced in the late 1990s and during the current decade, are recorded in the hydrograph records and are associated with observations of dune habitat decline or succession.

Figure 6.1 **Conceptual model of hydrological and hydrogeological controls on humid dune-slack formation in coastal areas**



See text for an explanation of dune-slack types A, B, C, D and E.

Table 6.2 **Water table conditions for defining humid dune slack habitat types**

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

6.3 Regimes

Water conditions for SD15 are difficult to specify quantitatively, partly because of the lack of detailed time series data but mainly because it does not correspond closely with a particular dune slack water supply type. It is usually found in the WETMEC Dune-slack Types B, C or D; as a very general guide, the ranges of possible winter and summer water tables are shown in Table 6.3.

6.3.1 Water

Water conditions for SD15 are difficult to specify quantitatively, partly because of the lack of detailed time series data but mainly because it does not correspond closely with a particular dune slack water supply type. It is usually found in the WETMEC Dune-slack Types B, C or D; as a very general guide, the ranges of possible winter and summer water tables are shown in Table 6.3.

An important consideration in maintaining the vegetation is the annual range of water level. Practically useful eco-hydrological targets may need to be expressed in terms of the frequency, magnitude and duration of deviation from the normal range of the water table. Frequency is probably a key issue, because significant lowering over one annual cycle may entrain irreversible changes. Magnitude and duration of periods outside the normal range still needs to be assessed. Current indications suggest that any lowering of the water table is not desirable.

6.3.2 Nutrients/hydrochemistry

Dune slacks are nutrient-poor habitats in which the characteristic vegetation is maintained by low levels of nutrient input, particularly of nitrogen (N) and phosphorus (P). Generally, N is limiting but P concentrations are also low. At relatively high pH, phosphate may be precipitated with calcium carbonate as a basic calcium phosphate (hydroxyapatite). Increased concentrations of N and P (eutrophication) promote the dominance of more competitive nutrient-demanding species and the loss of diversity and botanical interest. Nutrient limitation is a key factor in maintaining stability in such communities and hence delaying potential successional development. For instance, Willis (1964) found that the addition of N and P to the surface of dunes slacks at Braunton Burrows favoured *Agrostis stolonifera* and other grasses, whereas the addition of only N led to dominance by species of *Carex* (especially *C. flacca*) and *Juncus*. Nutrient enrichment of groundwater would be expected to have similar if slower effects, although direct evidence is lacking. In the virtual absence of data that relate groundwater concentrations to adverse effects, Jones *et al.* (Appendix D) have developed guidelines for acceptable concentrations of total inorganic nitrogen from a review of information on concentrations and possible nutrient sources at UK sand-dune sites (Table 6.4). There is insufficient information to set a reference condition for P.

Table 6.3 Summer and winter water tables for SD15

	Mean
Summer maximum water table (cm agl)	-50 to -100
Winter maximum water table (cm bgl)	2 to 10
Annual range of water table (cm)	50–100

Table 6.4 Guidelines for Total Inorganic Nitrogen (TIN) in dune groundwater

Status	TIN (mg N L^{-1})
Reference condition	< 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	> 1.0

An annual draw-down of ground-water fed slacks, with drying of the surface in summer, inhibits the development of laminated microbial and algal mats on the sand surface. Such mats otherwise lead to stabilization of the sand surface and N-fixation by their constituent *cyanobacteria* (reviewed by Davy *et al.*, 2006). Increased nitrogen cycling is associated with successional change.

Base-rich/high-pH groundwater is important for the calcicole plants species that confer much of the botanical interest. Acidification can have complex consequences. Adema *et al.* (2002) found that on the infiltration side of a slack where the topsoil had been decalcified, sulphide concentrations reached toxic levels (30–90 μmol l^{-1}) for many higher plants (Lammerts *et al.*, 1999). At the exfiltration side, no sulphide was detected, although the redox potentials were much lower than in the infiltration site, due to continuous inflow of anaerobic and iron-rich groundwater. The iron-rich groundwater fixed the free sulphide produced by microbial mats to form iron sulphide. At the infiltration side, however, no iron was present and free sulphide could accumulate. These relatively high sulphide concentrations can be tolerated only by wetland species that can oxidize their rhizosphere by radial oxygen release. The sulphide production in the infiltration areas can, however, release phosphates in the iron-depleted topsoil due to binding of sulphides with iron (Lammerts *et al.*, 1999). The infiltration side of such a slack, therefore, is likely to lose its pioneer vegetation.

Long-term stability of pioneer vegetation between the exfiltration and central parts of dune-slacks may occur because the pH is buffered, sulphide production is neutralised by iron, and acidification is prevented by discharge of calcareous groundwater. Sival *et al.* (1998) found that at exfiltration sites of dune-slacks secondary, *in situ* carbonate deposition occurred in the early stages of dune-slack succession.

Temporal variations in groundwater chemistry may be mainly related to the seasonal event of groundwater recharge. Malcolm & Soulsby (2001) found that the main period of rising groundwater levels in the autumn and winter resulted in a marked dilution of solutes in the aquifer. A period of several weeks appeared to be required for dissolution processes to proceed to equilibrium.

6.3.3 Management

In general SD15 sites are not managed actively, although they may be grazed by rabbits or stock, particularly in summer. Lack of grazing may be detrimental to community stability and species diversity. Recommendations for management of Natura 2000 sites representing H2190 humid dune slacks are provided by Houston (2008).

6.4 Implications for decision making

6.4.1 Vulnerability

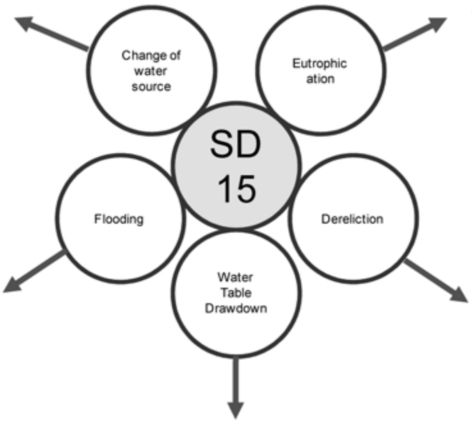
SD15 slacks are extremely vulnerable to changes in water supply, its seasonality and its quality. Some of the critical species have practically no tolerance of environmental change. Figure 6.2 indicates the possible floristic impact of changes to the stand environment.

6.4.2 Restorability

The degradation of dune-slack vegetation is likely to result from changes in hydrology, such as lowering of the water table by abstraction, or from eutrophication of the groundwater by pollution and atmospheric deposition of nitrogen. There is little information on the restoration of slacks in the UK, although work in the somewhat different situation of the Netherlands offers some pointers (Davy *et al.*, 2006). It will rarely be possible to alleviate the problems of a single type of slack without addressing the hydrology/hydrochemistry of the dune system in which it is found, and the other types of slack present.

Young slacks, which are rare and highly valued for nature conservation, are inherently threatened by natural succession. New slacks can appear periodically in dynamic dune systems to replace those changed or lost through successional trajectories. Likewise more mature slacks that are lost to woodland or even permanent open water might potentially be replaced locally. Clearly, if dune systems become fixed or lose their supply of blown sand this regenerative capacity is compromised. Therefore measures designed to restore the dune systems as a whole to a dynamic state will tend also to restore the slacks. The loss of sandy foreshore, usually as a result of change in relative sea level, both reduces sand supply and increases erosion by the sea; unless the dune system is able to migrate landward the prospects for restoration are poor.

Figure 6.2 The Possible Effects of Environmental Change on Stands of SD15



Groundwater circumneutral. Increasingly base-rich waters could increase botanical interest

Typically very nutrient-poor. Increased N and P would promote increased biomass, litter accumulation and substantial loss of botanical interest.

A wet dune slack, flooded for much of the year, with species tolerant of low redox conditions. Further flooding that gave rise to permanent open water would result in development into fen vegetation (e.g. S19 *Eleocharis* swamp or S29 *Phragmites-Eupatorium* tall-herb fen)

Decreased flooding and loss of root contact with the capillary fringe of the water table in summer could allow development of SD17 *Potentilla-Carex* community

At least in drier conditions, reduction in grazing, may assist successional development to woodland. On the other hand, any disruption of the dense canopy of *Salix repens* and the thick *Calliergon cuspidatum* mat is likely to facilitate the establishment of tree and shrub seedlings. The eventual result could be W2 *Salix-Betula-Phragmites* wet woodland or Wi *Salix-Galium* woodland.

Rising sea levels and the constraints of various kinds of development on the coast will bring this problem into ever sharper focus. Attempts to restore depleted dune water tables (and filter water for re-abstraction) by infiltrating with eutrophic river water have proved disastrous for plant communities. The complex interplay between water supply and chemistry suggests that restorability will be highly site-specific and will require detailed investigation in each case.

As frequently is the case for restoration, success will depend on either a locally persistent seed bank of the desirable species, or their sufficient dispersal from similar habitat nearby. With small areas of rare communities that have experienced long-term changes, artificial reintroductions of key spec Restoration measures may include:

- removal of sand-stabilizing features and, in appropriate settings, constraints on the landward migration of dune systems;
- identification and remediation of sources of eutrophic, polluted groundwater; the problem might be cured at source or the polluted water diverted;
- reducing water abstraction and land drainage that is shown to be lowering dune water tables;
- removal of coniferous plantations whose transpirational losses are having a deleterious effect on dune water tables;
- conservation of local surface water in ponds or ditches, for possible reinjection into deeper soil layers;
- sod-cutting or scraping to remove accumulated organic material and re-establish appropriate contact with the water table;
- assuming that appropriate conditions can be reinstated, reintroduction of species of particular interest and importance.

6.4.3 Limitations of these guidelines and gaps in knowledge

The limitations of the information presented here related to SD15 include the following.

- There are currently virtually no data to characterize the temporal water table characteristics of SD15 stands, particularly in contra-distinction from related dune slack types. Time series of dipwell measurements are required to fill this gap. A probabilistic analysis of the duration and frequency of the water levels is more likely to be informative than taking the extreme summer and winter values.

- Hydrochemical data from UK sites are extremely limited and none can be associated with specific adverse effects. Time series analyses of samples from dipwells and slacks are required to fill this gap.
- Insufficient data are available for the establishment of guidelines for groundwater phosphorus concentrations.
- Insufficient data are available for the establishment of separate guidelines for groundwater nitrate and ammonium concentrations.
- Intensive studies on the detailed hydrochemistry of specific slacks are lacking.
- Intensive studies on the ecological requirements of rare and key dune-slack species are lacking.
- More information is needed on appropriate restoration techniques, particularly in UK settings.

Application of the guidelines for total inorganic nitrogen (Table 6.4) is subject to the caveats and recommendations listed below.

- Groundwater (chemistry or water levels) uniformity cannot be assumed under a dune system, or even within the same slack in the case of through-flow slacks.
- Suspected contaminated groundwater needs clarification by (1) ascertaining the water level regime relative to the ground surface and the rooting zone (for example, monitoring dipwells); (2) analysing groundwater for nutrient concentrations, at minimum twice (in summer and a winter), using laboratories that have sufficiently accurate procedures.
- Referring the results to the guidelines. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.
- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.
- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping or grazing will remove nutrients.
- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

SD16 (*Salix repens – Holcus lanatus*) dune-slack community

7.1 Context

The SD16 community is included in the EU Habitats Directive Annex 1 as a dune habitat sensitive to water extraction (European habitat features 2170 'Dunes with *Salix repens* ssp. *argentea*, or Salicion arenariae' and 2190 'Humid dune slacks'). The boundaries between these two habitat types are often diffuse and difficult to define on the ground. The examples selected to represent the former habitat type in the UK sites series are those where creeping willow is usually dominant and forming prominent, low, scrubby growth (sometimes referred to as 'hedgehogs'), usually in and around mature slacks where there has been little or no sand movement recently (Joint Nature Conservation Committee, 2007). The Annex II species Petallophyllum ralfsii, a rare liverwort, can occur rarely in one of the sub-communities, and the nationally rare species *Equisetum variegatum, Moerckia hibernica* and *Pyrola rotundifolia* are found in another sub-community.

7.1.1 Floristic composition

This community is normally dominated by *Salix repens*, which forms a shrubby canopy. It is commonly accompanied by dense growth of the grasses *Holcus lanatus* and *Festuca rubra*. Other grasses, such as *Agrostis stolonifera* and *Poa pratensis* are less prominent, although the sedge Carex flacca is also common. Several dicotyledonous herbs are also common overall, particularly *Lotus corniculatus, Euphrasia officinalis agg., Pilosella officinarum, Senecio jacobaea, Prunella vulgaris, Leontodon autumnalis, Epipactis palustris* and *Ononis repens*. Tree seedlings or saplings (*Betula pubescens, Quercus robur* and *Salix caprea*) are commonly found in one of the sub-communities. Bryophytes are not usually a very significant feature of the vegetation but *Bryum pseudotriqetrum, Calliergon cuspidatum* and *Campylium stellatum* are the most frequent.

Some 90 species have been recorded within stands of SD16, with a mean of 17 (range 6–36). Species which are particularly characteristic of SD16, and which help separate it from other communities, are listed in Table 7.1. Floristic diversity is enhanced by disturbance associated with grazing by rabbits and stock. Unlike wetter slack communities, many of the species are not tolerant of reducing soil conditions.

Rodwell (2000) recognises four sub-communities of SD16: *Ononis repens* sub-community (SD16a); *Rubus caesius* sub-community (SD16b); *Prunella vulgaris-Equisetum variegatum* sub-community (SD16c); *Agrostis stolonifera* sub-community (SD16d).

7.1.2 Distribution

This is the most widespread dune-slack vegetation in Britain, occurring at sites on the coasts of England, Wales and south-east Scotland. It also the most extensive; the total area of community in England and Wales has been estimated at 444.5 ha (Davy *et al.*, 2006). The sites representing H2170 'Dunes with *Salix repens* ssp. *argentea*, or Salicion arenariae' are of only local occurrence on most sites, Sefton Coast being exceptional in supporting a substantial area (Joint Nature Conservation Committee, 2007).

7.1.3 Landscape situation and topography

Stands occur only in coastal dune settings. They typically occupy in low-lying (but rarely flooded), slacks that lay between the stabilized dune ridges.

7.1.4 Substratum

The substratum is usually deep, comprising wind-blown sand, with relatively little accumulation of organic matter. Depending on the setting, coastal dune systems may form on a range of bed-rocks that have different permeabilities to water flow, including course sands and gravels, chalk and limestone, and relatively impermeable clays. Saline water typically intrudes below the dune aquifer at the coastal margin.

Table 7.1 Species characteristic of SD15

Characteristic species		
Agrostis stolonifera	*Fragaria vesca*	*Poa pratensis*
Betula pubescens	*Galium verum*	*Potentilla anserina*
Bryum pseudotriquetrum	*Holcus lanatus*	*Prunella vulgaris*
Calliergon cuspidatum	*Hydrocotyle vulgaris*	*Prunella vulgaris*
Campylium stellatum	*Hypochaeris radicata*	*Pyrola rotundifolia*
Carex arenaria	*Juncus articulatus*	*Quercus robur*
Carex flacca	*Leontodon autumnalis*	*Rubus caesius*
Epipactis palustris	*Leontodon taraxacoides*	*Salix caprea*
Equisetum variegatum	*Lotus corniculatus*	*Salix repens*
Euphrasia officinalis agg.	*Ononis repens*	*Senecio jacobaea*
Festuca rubra	*Pilosella officinarum*	*Trifolium pratense*

7.1.5 Zonation and succession

Dune slacks are usually discrete areas, bounded by higher ground, and therefore vegetationally distinct from their surroundings. Typically they are surrounded by the dry grassland communities of the dune ridges. Hence SD16 can grade into the *Festuca rubra-Galium verum* community of grazed dune ridges (SD8). The basins themselves may show internal zonation, as during periodic fluctuations of the water table, the lower central parts remain moister for longer, allowing concentric zones of colonization. Dune slacks with SD16 are usually found in dune systems that also have a range of other types of dune slack and these all may be components of a single hydrological system. SD16 is a mature, relatively stable stage in dune-slack succession, often representing most of the interdunal areas. It is the dune-slack vegetation least influenced by high water tables and surface flooding. Where topography allows greater surface flooding to occur, a transition to wetter dune slack communities, such as the *Salix repens-Campylium stellatum* dune-slack community (SD14), can occur via the *Agrostis stolonifera* sub-community.

SD16 can develop from the much rarer SD13, particularly if inundation is reduced, or slacks accrete wind-blown sand, to become drier. A reduction in the disturbance resulting from either fluctuations in shallow surface flooding or the cessation of grazing by rabbits and stock can allow rapid successional development. Continued invasion by seedlings of *Betula pubescens, Quercus robur* and *Salix caprea* can eventually lead to scrub or woodland communities.

7.2 Supply mechanism and conceptual model

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is not unexpected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all the dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes. A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

The hydrological conditions of humid dune slacks are reviewed by Davy *et al.* (2006) who presented a conceptual model (Figure 7.1) of controls on humid dune-slack formation in coastal areas, drawn mainly from examples in The Netherlands. Five dune-slack Types (A to E) are identified and form the basis of the definition of water table conditions shown in Table 7.2 for dune slacks in England and Wales based on a review of relevant case studies. A common feature of dunes systems in England and Wales is a shallow water table controlled by topography. The balance of rainfall input and evapotranspiration losses leads to the development of a groundwater mound in the sand aquifer, mostly aligned to the dune ridge. Another common feature is for an annual cycle of water level fluctuation in response to the distribution of effective rainfall. Minimum water levels occur in late summer or early autumn (August–October) when the water table is found in the dune sands at a level of between 1–2 m below ground surface elevations.

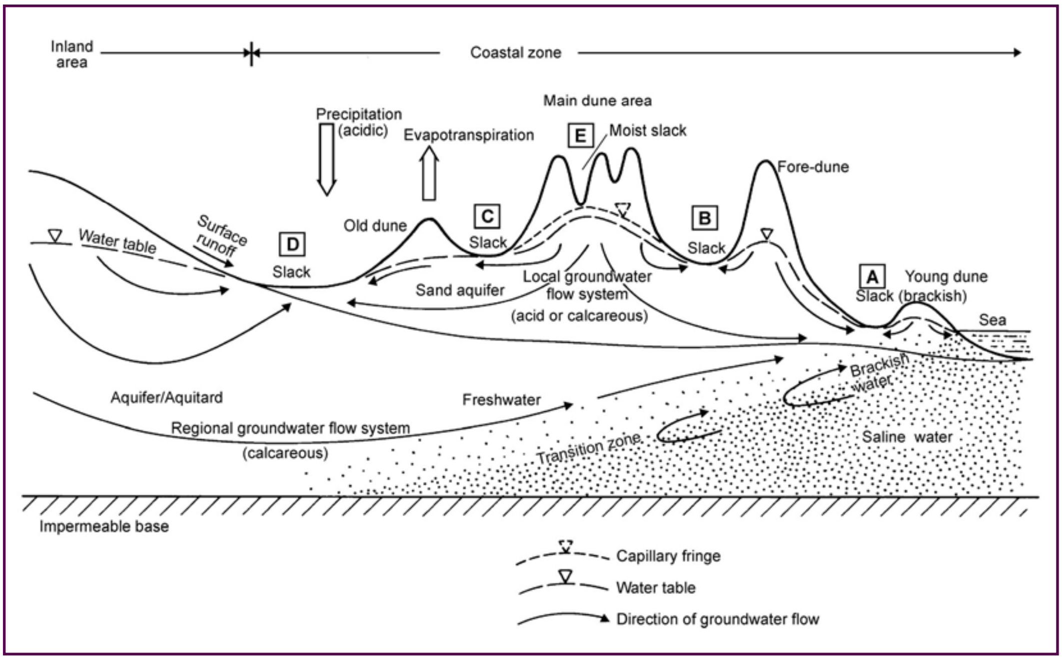
The water table is observed to recover in the autumn with water levels approaching or exceeding ground surface elevations, typically between December Flooding can extend to the spring months but summer flooding is rare. During dry periods, the thickness of the capillary fringe in reaching the root zone is a further control and benefits those slacks with a low bed elevation, for example in areas of recent dune slack formation close to the sea or within blowouts in the inland dune system. Typical well hydrographs for dune systems reviewed for England and Wales show a relatively consistent pattern in terms of the range of water table fluctuation, often within 0.5–1.5 m. Periods of prolonged drying, as experienced in the 1970s and mid-1990s, and wetter conditions, as experienced in the late 1990s and during the current decade, are recorded in the hydrograph records and are associated with observations of dune habitat decline or succession.

7.3 Regimes

7.3.1 Water

Water conditions for SD16 are difficult to specify quantitatively, partly because of the lack of detailed time series data but mainly because it does not correspond closely with a particular dune slack water supply type. It is usually found in the WETMEC Dune-slack Types B, C or E; as a very general guide, the ranges of possible winter and summer water tables are shown in Table 7.3.

Figure 7.1 Conceptual model of hydrological and hydrogeological controls on humid dune-slack formation in coastal areas



See text for an explanation of dune-slack Types A, B, C, D and E.

Table 7.2 Water table conditions for defining humid dune slack habitat types

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

An important consideration in maintaining the vegetation is the annual range of water level. Transient winter flooding and dry conditions in summer, when roots may be out of contact with the capillary fringe of the water table are characteristic. Practically useful eco-hydrological targets may need to be expressed in terms of the frequency, magnitude and duration of deviation from the normal range of the water table. Frequency is probably a key issue, because significant lowering over one annual cycle may entrain irreversible changes. Magnitude and duration of periods outside the normal range still needs to be assessed. Current indications suggest that any lowering of the water table is not desirable.

7.3.2 Nutrients/hydrochemistry

Dune slacks are nutrient-poor habitats in which the characteristic vegetation is maintained by low levels of nutrient input, particularly of nitrogen (N) and phosphorus (P). Generally, N is limiting but P concentrations are also low. At relatively high pH, phosphate may be precipitated with calcium carbonate as a basic calcium phosphate (hydroxyapatite). Increased concentrations of N and P (eutrophication) promote the dominance of more competitive nutrient-demanding species and the loss of diversity and botanical interest. Nutrient limitation is a key factor in maintaining stability in such communities and hence delaying potential successional development. For instance, Willis (1964) found that the addition of N and P to the surface of dunes slacks at Braunton Burrows favoured *Agrostis stolonifera* and other grasses, whereas the addition of only N led to dominance by species of *Carex* (especially *C. flacca*) and *Juncus*. Nutrient enrichment of groundwater would be expected to have similar if slower effects, although direct evidence is lacking. In the virtual absence of data that relate groundwater concentrations to adverse effects, Jones *et al.* (Appendix D) have developed guidelines for acceptable concentrations of total inorganic nitrogen from a review of information on concentrations and possible nutrient sources at UK sand-dune sites (Table 7.4). There is insufficient information to set a reference condition for P.

An annual draw-down of ground-water fed slacks, with drying of the surface in summer, inhibits the development of laminated microbial and algal mats on the sand surface. Such mats otherwise lead to stabilization of the sand surface and N-fixation by their constituent cyanobacteria (reviewed by Davy *et al.*, 2006). Increased nitrogen cycling is associated with successional change.

Table 7.3 **Summer and winter water tables for SD16**

	Mean
Summer maximum water table (cm agl)	-50 to -200
Winter maximum water table (cm bgl)	0 to 20
Annual range of water table (cm)	50–200

Table 7.4 **Guidelines for Total Inorganic Nitrogen (TIN) in dune groundwater**

Status	**TIN (mg N L^{-1})**
Reference condition	< 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	> 1.0

Base-rich/high-pH groundwater is important for the calcicole plants species that confer much of the botanical interest. Acidification can have complex consequences. Adema *et al.* (2002) found that on the infiltration side of a slack where the topsoil had been decalcified, sulphide concentrations reached toxic levels (30–90 µmol l^{-1}) for many higher plants (Lammerts *et al.*, 1999). At the exfiltration side, no sulphide was detected, although the redox potentials were much lower than in the infiltration site, due to continuous inflow of anaerobic and iron-rich groundwater. The iron-rich groundwater fixed the free sulphide produced by microbial mats to form iron sulphide. At the infiltration side, however, no iron was present and free sulphide could accumulate. These relatively high sulphide concentrations can be tolerated only by wetland species that can oxidize their rhizosphere by radial oxygen release. The sulphide production in the infiltration areas can, however, release phosphates in the iron-depleted topsoil due to binding of sulphides with iron (Lammerts *et al.*, 1999). The infiltration side of such a slack, therefore, is likely to lose its pioneer vegetation.

Long-term stability of pioneer vegetation between the exfiltration and central parts of dune-slacks may occur because the pH is buffered, sulphide production is neutralised by iron, and acidification is prevented by discharge of calcareous groundwater. Sival *et al.* (1998) found that at exfiltration sites of dune-slacks secondary, *in situ* carbonate deposition occurred in the early stages of dune-slack succession.

Temporal variations in groundwater chemistry may be mainly related to the seasonal event of groundwater recharge. Malcolm & Soulsby (2001) found that the main period of rising groundwater levels in the autumn and winter resulted in a marked dilution of solutes in the aquifer. A period of several weeks appeared to be required for dissolution processes to proceed to equilibrium.

7.3.3 Management

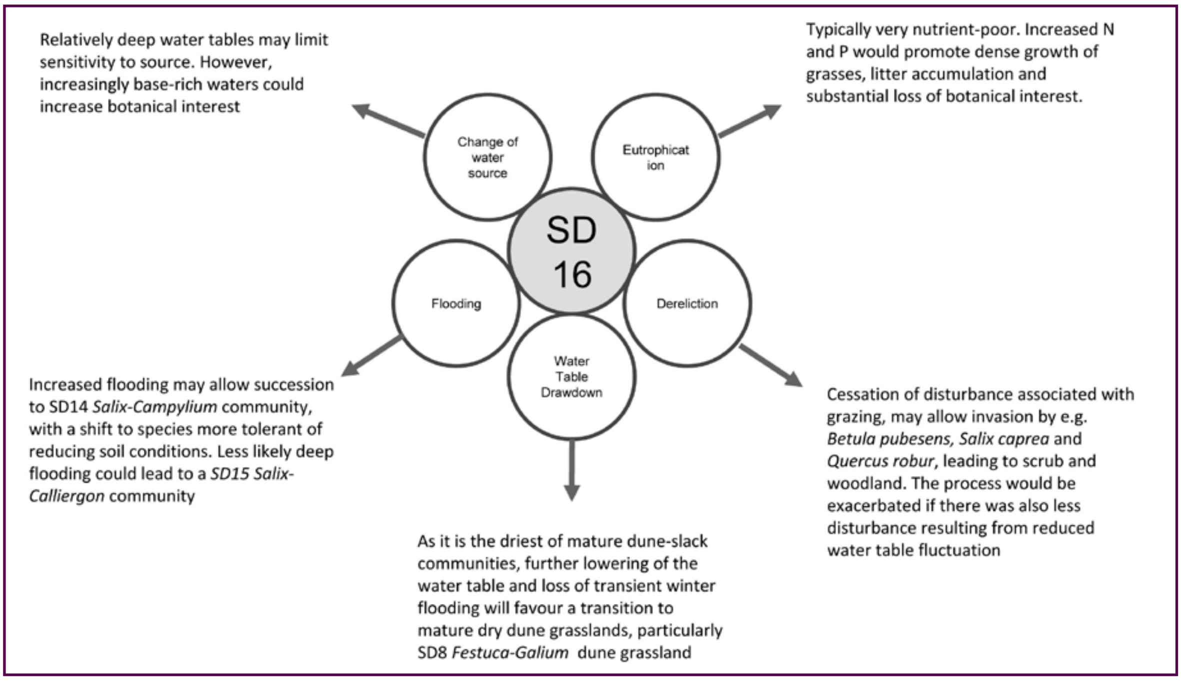
In general SD16 sites are not managed actively, although they may be grazed by rabbits or stock, particularly in summer. Lack of grazing may be detrimental to community stability and species diversity. Recommendations for management of Natura 2000 sites representing H2190 humid dune slacks are provided by Houston (2008).

7.4 Implications for decision making

7.4.1 Vulnerability

SD16 slacks are extremely vulnerable to changes in water supply, its seasonality and its quality. Some of the critical species have practically no tolerance of environmental change. Figure 7.2 indicates the possible floristic impact of changes to the stand environment.

Figure 7.2 The Possible Effects of Environmental Change on Stands of SD16



Relatively deep water tables may limit sensitivity to source. However, increasingly base-rich waters could increase botanical interest

Typically very nutrient-poor. Increased N and P would promote dense growth of grasses, litter accumulation and substantial loss of botanical interest.

Increased flooding may allow succession to SD14 *Salix-Campylium* community, with a shift to species more tolerant of reducing soil conditions. Less likely deep flooding could lead to a *SD15 Salix-Calliergon* community

Cessation of disturbance associated with grazing, may allow invasion by e.g. *Betula pubesens, Salix caprea* and *Quercus robur*, leading to scrub and woodland. The process would be exacerbated if there was also less disturbance resulting from reduced water table fluctuation

As it is the driest of mature dune-slack communities, further lowering of the water table and loss of transient winter flooding will favour a transition to mature dry dune grasslands, particularly SD8 *Festuca-Galium* dune grassland

7.4.2 Restorability

The degradation of dune-slack vegetation is likely to result from changes in hydrology, such as lowering of the water table by abstraction, or from eutrophication of the groundwater by pollution and atmospheric deposition of nitrogen. There is little information on the restoration of slacks in the UK, although work in the somewhat different situation of the Netherlands offers some pointers (Davy *et al.*, 2006). It will rarely be possible to alleviate the problems of a single type of slack without addressing the hydrology/hydrochemistry of the dune system in which it is found, and the other types of slack present.

Young slacks, which are rare and highly valued for nature conservation, are inherently threatened by natural succession. New slacks can appear periodically in dynamic dune systems to replace those changed or lost through successional trajectories. Likewise more mature slacks that are lost to woodland or even permanent open water might potentially be replaced locally. Clearly, if dune systems become fixed or lose their supply of blown sand this regenerative capacity is compromised. Therefore measures designed to restore the dune systems as a whole to a dynamic state will tend also to restore the slacks.

The loss of sandy foreshore, usually as a result of change in relative sea level, both reduces sand supply and increases erosion by the sea; unless the dune system is able to migrate landward the prospects for restoration are poor. Rising sea levels and the constraints of various kinds of development on the coast will bring this problem into ever sharper focus. Attempts to restore depleted dune water tables (and filter water for re-abstraction) by infiltrating with eutrophic river water have proved disastrous for plant communities. The complex interplay between water supply and chemistry suggests that restorability will be highly site-specific and will require detailed investigation in each case.

As frequently is the case for restoration, success will depend on either a locally persistent seed bank of the desirable species, or their sufficient dispersal from similar habitat nearby. With small areas of rare communities that have experienced long-term changes, artificial reintroductions of key species may be necessary.

Restoration measures may include:

- removal of sand-stabilizing features and, in appropriate settings, constraints on the landward migration of dune systems;
- identification and remediation of sources of eutrophic, polluted groundwater; the problem might be cured at source or the polluted water diverted;
- reducing water abstraction and land drainage that is shown to be lowering dune water tables;
- removal of coniferous plantations whose transpirational losses are having a deleterious effect on dune water tables;
- conservation of local surface water in ponds or ditches, for possible reinjection into deeper soil layers;
- sod-cutting or scraping to remove accumulated organic material and re-establish appropriate contact with the water table;
- assuming that appropriate conditions can be reinstated, reintroduction of species of particular interest and importance.

7.4.3 Limitations of these guidelines and gaps in knowledge

The limitations of the information presented here related to SD16 include the following.

- There are currently virtually no data to characterize the temporal water table characteristics of SD16 stands, particularly in contra-distinction from related dune slack types. Time series of dipwell measurements are required to fill this gap. A probabilistic analysis of the duration and frequency of the water levels is more likely to be informative than taking the extreme summer and winter values.
- Hydrochemical data from UK sites are extremely limited and none can be associated with specific adverse effects. Time series analyses of samples from dipwells and slacks are required to fill this gap.
- Insufficient data are available for the establishment of guidelines for groundwater phosphorus concentrations.

- Insufficient data are available for the establishment of separate guidelines for groundwater nitrate and ammonium concentrations.
- Intensive studies on the detailed hydrochemistry of specific slacks are lacking.
- Intensive studies on the ecological requirements of rare and key dune-slack species are lacking.
- More information is needed on appropriate restoration techniques, particularly in UK settings.

Application of the guidelines for total inorganic nitrogen (Table 7.4) is subject to the caveats and recommendations listed below.

- Groundwater (chemistry or water levels) uniformity cannot be assumed under a dune system, or even within the same slack in the case of through-flow slacks.
- Suspected contaminated groundwater needs clarification by (1) ascertaining the water level regime relative to the ground surface and the rooting zone (for example, monitoring dipwells); (2) analysing groundwater for nutrient concentrations, at minimum twice (in summer and a winter), using laboratories that have sufficiently accurate procedures.
- Referring the results to the guidelines. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.
- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.
- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping or grazing will remove nutrients.
- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

SD17 (*Potentilla anserina – Carex nigra*) dune-slack community

8.1 Context

The SD17 community is included in the EU Habitats Directive Annex 1 as a dune habitat sensitive to water extraction (European habitat feature 2190 'Humid dune slacks').

8.1.1 Floristic composition

The vegetation is dominated by various combinations of grass-like plants (graminoids) and low-growing herbs. Many species may occur but the most distinctive combination is *Agrostis stolonifera*, *Carex nigra* and *Potentilla anserina* and any, or all, of these can be very abundant. Other common components are *Festuca rubra*, *Holcus lanatus* and *Juncus articulatus*. In addition, *Ranunculus repens, Trifolium repens, Cardamine pratensis, Equisetum palustre* and *Euphrasia officinalis agg.* are also frequently seen. Taller facies of the vegetation can be characterised by *Iris pseudacorus* and *Angelica sylvestris*. More maritime, salt-influenced forms of the community may have *Elymus repens*, *Triglochin maritimum* and *Carex disticha*. As in many other types of dune slack, *Calliergon cuspidatum* is generally the most abundant bryophyte; *Plagiomnium rostratum, Brachythecium rutabulum* and *Eurhynchium praelongum* are much less abundant mosses.

Table 8.1 **Species characteristic of SD17**

Characteristic species
Agrostis stolonifera
Angelica sylvestris
Anthoxanthum odoratum
Bellis perennis
Brachythecium rutabulum
Calliergon cuspidatum
Caltha palustris
Cardamine pratensis
Carex arenaria
Carex disticha
Carex flacca
Carex nigra
Carex panicea
Cerastium fontanum
Cynosurus cristatus
Dactylorhiza fuchsii
Eleocharis palustris
Elymus repens
Epilobium palustre
Equisetum fluviatile
Equisetum palustre
Equisetum variegatum
Euphrasia officinalis agg.
Eurhynchium praelongum
Festuca rubra
Galium palustre
Glaux maritima
Holcus lanatus
Hydrocotyle vulgaris
Iris pseudacorus
Juncus articulatus
Lathyrus pratensis
Leontodon autumnalis
Lotus corniculatus
Mentha aquatica
Parnassia palustris
Pedicularis palustris
Plagiomnium rostratum
Plantago lanceolata
Plantago maritima
Poa trivialis
Potentilla anserina
Prunella vulgaris
Ranunculus flammula
Ranunculus repens
Rubus caesius
Rumex acetosa
Rumex crispus
Sagina procumbens
Salix repens
Taraxacum officinalis agg.
Triglochin maritimum
Vicia cracca

Rodwell (2000) recognises four sub-communities of SD17: *Festuca rubra-Ranunculus repens* sub-community (SD17a); *Carex flacca* sub-community (SD17b); *Caltha paustris* sub-community (SD17c); *Hydrocotyle vulgaris-Ranunculus flammula* sub-community (SD17d).

Nearly 90 species have been recorded within stands of SD17, with a mean of 15 (range 5–39) (Rodwell, 2000). Species which are particularly characteristic of SD17, and which help separate it from other communities, are listed in Table 8.1. This vegetation is maintained by wet conditions, usually accompanied by periodic flooding with base-rich ground-water.

8.1.2 Distribution

This vegetation is widely distributed in Britain on dune systems that have slacks, particularly in wetter climate of the north, where is the most common vegetation of dune slacks and moist depressions in machair. The total area of this community in England and Wales has been estimated at 146.4 ha (Davy *et al.*, 2006).

8.1.3 Landscape situation and topography

Stands occur only in coastal dune settings, usually lying between the stabilized dune ridges. They typically occupy low-lying, wet slacks that receive their water mainly from rainfall and slope run-off, and experience seasonal fluctuations in the water table that result in winter flooding.

8.1.4 Substratum

The substratum is usually deep, comprising wind-blown, sand. Depending on the setting, coastal dune systems may form on a range of bed-rocks that have different permeabilities to water flow, including course sands and gravels, chalk and limestone, and relatively impermeable clays. Saline water typically intrudes below the dune aquifer at the coastal margin.

8.1.5 Zonation and succession

Dune slacks are usually discrete areas, bounded by higher ground, and therefore vegetationally distinct from their surroundings. Typically they are surrounded by the dry grassland communities of the dune ridges and therefore SD17 slacks may show sharp transitions into *Festuca rubra – Galium verum* fixed dune grassland (SD8) at their margins, where there is a change of slope ground and water level. However, in the gentle depressions of the machair of north-west Scotland, where this vegetation is particularly common, the transition may be more gradual: the *Carex flacca* sub-community of SD17 blending into the *Prunella vulgaris* sub-community of SD8. Where SD17 gives way to continuously flooded vegetation, also usually in Scotland, the *Hydrocotyle vulgaris* sub-community may from a continuum with swamp or mire communities, typically *Eleocharis palustris* swamp (S19) or *Phragmites australis* swamp and reed-bed (S4) (Dargie, 1993). In the wetter, less base-rich slacks of northern Britain, accumulation of organic matter can lead to peat-based *Scirpus cespitosus-Erica tetralix* (M15) or *Erica tetralix-Sphagnum compactum* (M16) wet heaths, sometimes as a mosaic with SD17.

Dune slacks with SD17 are usually found in dune systems that also have a range of other types of dune slack and these all may be components of a single hydrological system. SD17 dune slacks are a relatively mature stage of dune slack vegetation; although they are generally wet, succession is probably inhibited by the seasonally fluctuating water table, and moderately deep winter flooding with more or less base-rich water. Grazing by stock is a feature of machair and this probably retards or prevents invasion by scrub and trees, at least in the less-wet parts.

8.2 Supply mechanism and conceptual model

The hydrogeological functioning of humid dune slacks requires that ponds are wet for certain periods of the year since habitat quality is reduced if such ephemeral ponds are flooded for too long. A common feature of dune slacks is their dependence on shallow groundwater conditions which maintain moist soils in the summer as well as periodic inundation in the winter and spring. Given the topographic range of dune systems, it is not unexpected that water levels within dune slacks are a local expression of the water table developed within a dune sand aquifer. Examples of topographic control on the water table elevation are seen in all the dune systems containing dune slack communities. Additional controls on dune water levels include the impact of tree planting, golf course development and dewatering operations, such as required for land drainage and quarrying, in affecting groundwater recharge and discharge regimes.

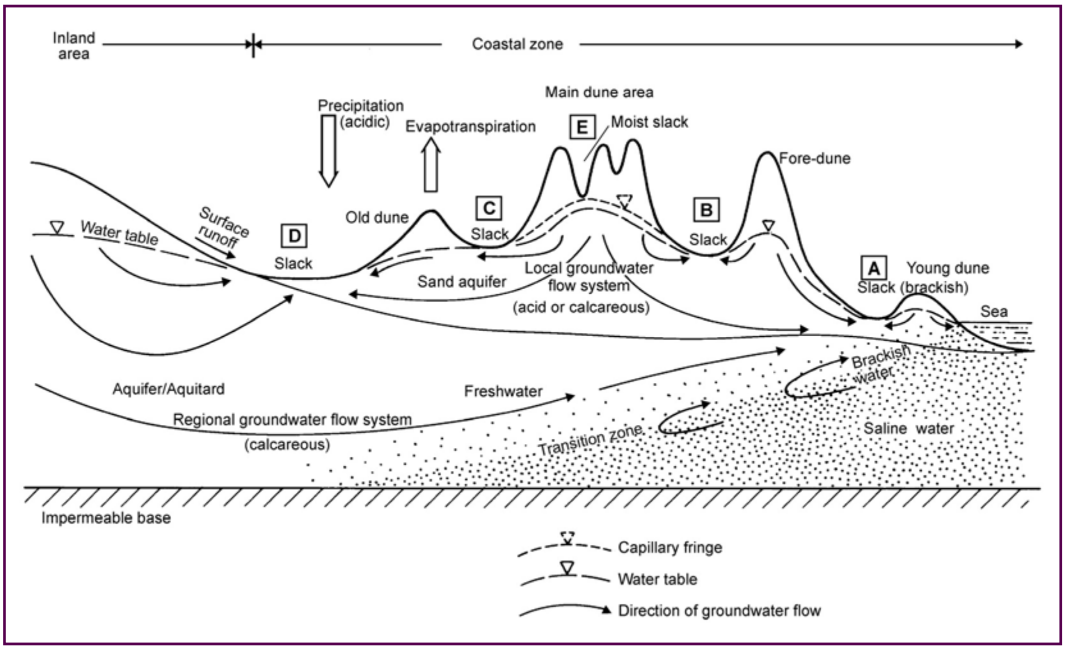
A further influence is coastal erosion and sea-level rise in changing the hydraulic gradient between an inland dune area and the sea. However, the primary control on water levels in a dune sand aquifer is the balance of precipitation and evapotranspiration leading to rain-fed, freshwater recharge. Even single rainfall events can lead to a rise in water level. In some cases, long-term variation in seasonal and annual rainfall over several years can cause long periods of drought or flooding that can have lasting impacts on humid dune slacks.

The hydrological conditions of humid dune slacks are reviewed by Davy *et al.* (2006) who presented a conceptual model (Figure 8.1) of controls on humid dune-slack formation in coastal areas, drawn mainly from examples in The Netherlands. Five dune-slack Types (A to E) are identified and form the basis of the definition of water table conditions shown in Table 8.2 for dune slacks in England and Wales based on a review of relevant case studies. A common feature of dunes systems in England and Wales is a shallow water table controlled by topography. The balance of rainfall input and evapotranspiration losses leads to the development of a groundwater mound in the sand aquifer, mostly aligned to the dune ridge.

Another common feature is for an annual cycle of water level fluctuation in response to the distribution of effective rainfall. Minimum water levels occur in late summer or early autumn (August–October) when the water table is found in the dune sands at a level of between 1–2 m below ground surface elevations.

The water table is observed to recover in the autumn with water levels approaching or exceeding ground surface elevations, typically between December and February when flooding of dune slacks to a depth of up to 0.15 m or greater is observed. Flooding can extend to the spring months but summer flooding is rare. During dry periods, the thickness of the capillary fringe in reaching the root zone is a further control and benefits those slacks with a low bed elevation, for example in areas of recent dune slack formation close to the sea or within blowouts in the inland dune system. Typical well hydrographs for dune systems reviewed for England and Wales show a relatively consistent pattern in terms of the range of water table fluctuation, often within 0.5–1.5 m. Periods of prolonged drying, as experienced in the 1970s and mid-1990s, and wetter conditions, as experienced in the late 1990s and during the current decade, are recorded in the hydrograph records and are associated with observations of dune habitat decline or succession.

Figure 8.1 Conceptual model of hydrological and hydrogeological controls on humid dune-slack formation in coastal areas



See text for an explanation of dune-slack Types A, B, C, D and E.

Table 8.2 Water table conditions for defining humid dune slack habitat types

WETMEC dune type[1]	Dune slack	Dune habitat British Plant Community (NVC) type	Water Table Condition[2]	Comments
A	Young dune slack (brackish)	SD13 & 14	Winter[3] maximum: 2 to 10 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 100 cm	Young stages of habitat development found at coastal fringe. SD14 tolerant of brackish conditions.
B	Rain-fed dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	Common hydrological condition for dune slacks with appearance of SD14, 15 & 16.
C	Rain-fed flow-through dune slack	SD14, 15 & 16	Winter[3] maximum: 2 to 20 cm Summer[4] maximum: -50 to -200 cm Water table fluctuation: 50 to 150 cm	SD15 dominant since tolerant of flow-through system water chemistry.
D	Boundary slack (semi-aquatic)	SD15 & 17	Winter[3] maximum: 5 to 50 cm Summer[4] maximum: -50 to -100 cm Water table fluctuation: 50 to 150 cm	SD15 tolerant of prolonged flooding and near-neutral pH. SD17 found in mature, low-lying areas, for example, shelly machair.
E	Moist dune slack	SD16	Winter[3] maximum: 0 to 5 cm Summer[4] maximum: -100 to 200 cm Water table fluctuation: 100 to 200 cm	Tolerant of dry conditions and preference for aerobic conditions.

[1] WETMEC (Wetland Water Supply Mechanism) dune types after Davy *et al.* (2006).

[2] Water level elevations given with respect to depth in centimetres below ground level (cm bgl). A positive number indicates a water level above ground surface, a negative number a level below ground surface.

[3] Winter maximum water levels are normally recorded during the period of water level recovery between November and April.

[4] Summer maximum water levels are normally recorded during the baseflow recession period between May and October.

8.3 Regimes

8.3.1 Water

Water conditions for SD17 are difficult to specify quantitatively, because of the lack of detailed time series data. However, it is typically found in the WETMEC Dune Type D slack and as a very general guide, the range of winter and summer water tables are shown in Table 8.3.

An important consideration in maintaining the vegetation is the annual range of water level. Practically useful eco-hydrological targets may need to be expressed in terms of the frequency, magnitude and duration of deviation from the normal range of the water table. Frequency is probably a key issue, because significant lowering over one annual cycle may entrain irreversible changes. Magnitude and duration of periods outside the normal range still needs to be assessed. Current indications suggest that any lowering of the water table is not desirable.

8.3.2 Nutrients/hydrochemistry

Dune slacks are nutrient-poor habitats in which the characteristic vegetation is maintained by low levels of nutrient input, particularly of nitrogen (N) and phosphorus (P). Generally, N is limiting but in young slacks with calcareous groundwaters P is likely to be more limiting. At high pH, phosphate may be precipitated with calcium carbonate as a basic calcium phosphate (hydroxyapatite). Increased concentrations of N and P (eutrophication) promote the dominance of more competitive nutrient-demanding species and the loss of diversity and botanical interest. Nutrient limitation is a key factor in maintaining stability in such communities and hence delaying potential successional development. For instance, Willis (1964) found that the addition of N and P to the surface of dunes slacks at Braunton Burrows favoured *Agrostis stolonifera* and other grasses, whereas the addition of only N led to dominance by species of *Carex* (especially *C. flacca*) and *Juncus*. Nutrient enrichment of groundwater would be expected to have similar if slower effects, although direct evidence is lacking. In the virtual absence of data that relate groundwater concentrations to adverse effects, Jones *et al.* (Appendix D) have developed guidelines for acceptable concentrations of total inorganic nitrogen from a review of information on concentrations and possible nutrient sources at UK sand-dune sites (Table 8.4). There is insufficient information to set a reference condition for P.

An annual draw-down of ground-water fed slacks, with drying of the surface in summer, inhibits the development of laminated microbial and algal mats on the sand surface. Such mats otherwise lead to stabilization of the sand surface and N-fixation by their constituent cyanobacteria (reviewed by Davy *et al.*, 2006). Increased nitrogen cycling is associated with successional change.

Base-rich/high-pH groundwater is important for the calcicole plants species that confer much of the botanical interest. Acidification can have complex consequences. Adema *et al.* (2002) found that on the infiltration side of a slack where the topsoil had been decalcified, sulphide concentrations reached toxic levels (30–90 μmol l^{-1}) for many higher plants (Lammerts *et al.*, 1999). At the exfiltration side, no sulphide was detected, although the redox potentials were much lower than in the infiltration site, due to continuous inflow of anaerobic and iron-rich groundwater. The iron-rich groundwater fixed the free sulphide produced by microbial mats to form iron sulphide. At the infiltration side, however, no iron was present and free sulphide could accumulate. These relatively high sulphide concentrations can be tolerated only by wetland species that can oxidize their rhizosphere by radial oxygen release. The sulphide production in the infiltration areas can, however, release phosphates in the iron-depleted topsoil due

Table 8.3 Summer and winter water tables for SD17

	Mean
Summer maximum water table (cm agl)	-50 to -100
Winter maximum water table (cm bgl)	5 to 50
Annual range of water table (cm)	50–100

to binding of sulphides with iron (Lammerts *et al.*, 1999). The infiltration side of such a slack, therefore, is likely to lose its pioneer vegetation.

Long-term stability of pioneer vegetation between the exfiltration and central parts of dune-slacks may occur because the pH is buffered, sulphide production is neutralised by iron, and acidification is prevented by discharge of calcareous groundwater. Sival *et al.* (1998) found that at exfiltration sites of dune-slacks secondary, *in situ* carbonate deposition occurred in the early stages of dune-slack succession.

Temporal variations in groundwater chemistry may be mainly related to the seasonal event of groundwater recharge. Malcolm & Soulsby (2001) found that the main period of rising groundwater levels in the autumn and winter resulted in a marked dilution of solutes in the aquifer. A period of several weeks appeared to be required for dissolution processes to proceed to equilibrium.

8.3.3 Management

In general SD17 sites are not managed actively, although they may be grazed by rabbits or stock, particularly in summer. Lack of grazing may be detrimental to community stability and species diversity. Recommendations for management of Natura 2000 sites representing H2190 humid dune slacks are provided by Houston (2008).

8.4 Implications for decision making

8.4.1 Vulnerability

SD17 slacks are extremely vulnerable to changes in water supply, its seasonality and its quality. Some of the critical species have practically no tolerance of environmental change. Figure 8.2 indicates the possible floristic impact of changes to the stand environment.

8.4.2 Restorability

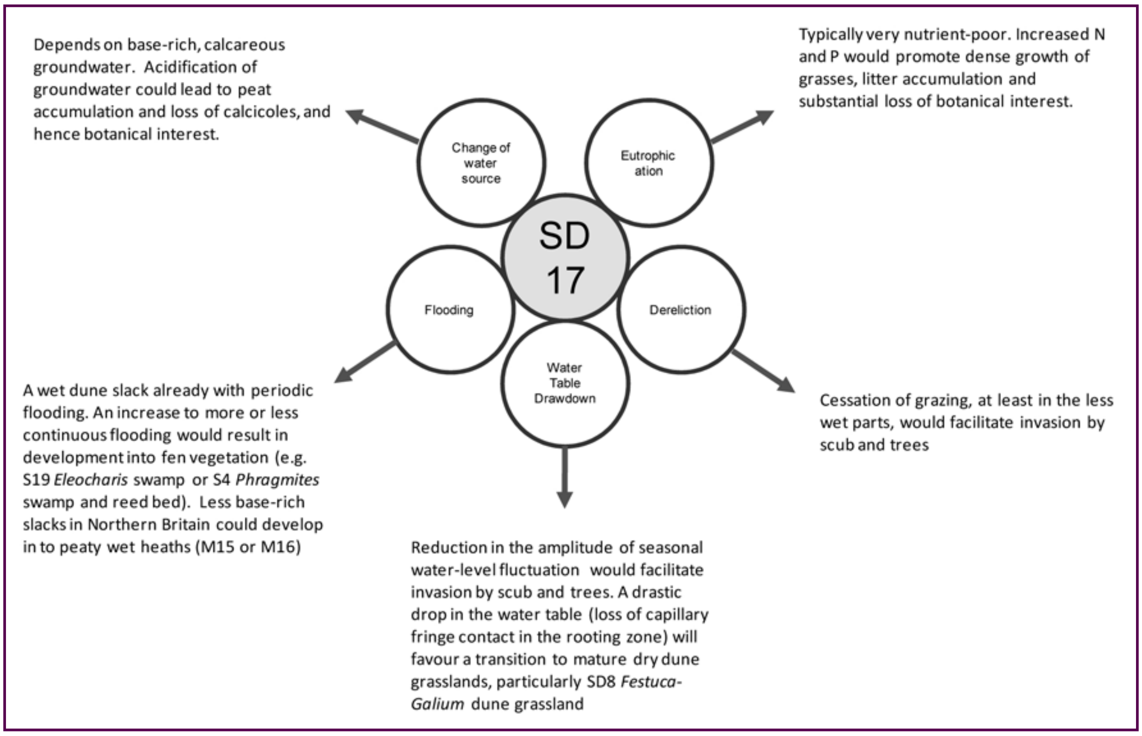
The degradation of dune-slack vegetation is likely to result from changes in hydrology, such as lowering of the water table by abstraction, or from eutrophication of the groundwater by pollution and atmospheric deposition of nitrogen. There is little information on the restoration of slacks in the UK, although work in the somewhat different situation of the Netherlands offers some pointers (Davy *et al.*, 2006). It will rarely be possible to alleviate the problems of a single type of slack without addressing the hydrology/hydrochemistry of the dune system in which it is found, and the other types of slack present.

Young slacks, which are rare and highly valued for nature conservation, are inherently threatened by natural succession. New slacks can appear periodically in dynamic dune systems to replace those changed or lost through successional trajectories. Likewise more mature slacks that are lost to woodland or even permanent open water might potentially be replaced locally. Clearly, if dune systems become fixed or lose their supply of blown sand this regenerative capacity is compromised. Therefore measures designed to restore the dune systems as a whole to a dynamic state will tend also to restore the slacks. The loss of sandy foreshore, usually as a result of change in relative sea level, both reduces sand supply and increases erosion by the sea; unless the dune system is able to migrate landward the prospects for restoration are poor. Rising sea levels and the constraints of various kinds of development on the coast will bring this problem into ever sharper focus. Attempts to restore depleted dune water tables (and filter water for re-abstraction) by infiltrating with eutrophic river water have proved disastrous for plant communities. The complex interplay between water supply and chemistry suggests that restorability will be highly site-specific and will require detailed investigation in each case.

Table 8.4 **Guidelines for Total Inorganic Nitrogen (TIN) in dune groundwater**

Status	TIN (mg N L^{-1})
Reference condition	< 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	> 1.0

Figure 8.2 The possible effects of environmental change on stands of SD17



Depends on base-rich, calcareous groundwater. Acidification of groundwater could lead to peat accumulation and loss of calcicoles, and hence botanical interest.

Typically very nutrient-poor. Increased N and P would promote dense growth of grasses, litter accumulation and substantial loss of botanical interest.

A wet dune slack already with periodic flooding. An increase to more or less continuous flooding would result in development into fen vegetation (e.g. S19 *Eleocharis* swamp or S4 *Phragmites* swamp and reed bed). Less base-rich slacks in Northern Britain could develop in to peaty wet heaths (M15 or M16)

Cessation of grazing, at least in the less wet parts, would facilitate invasion by scub and trees

Reduction in the amplitude of seasonal water-level fluctuation would facilitate invasion by scub and trees. A drastic drop in the water table (loss of capillary fringe contact in the rooting zone) will favour a transition to mature dry dune grasslands, particularly SD8 *Festuca-Galium* dune grassland

As frequently is the case for restoration, success will depend on either a locally persistent seed bank of the desirable species, or their sufficient dispersal from similar habitat nearby. With small areas of rare communities that have experienced long-term changes, artificial reintroductions of key species may be necessary.

Restoration measures may include:

- removal of sand-stabilizing features and, in appropriate settings, constraints on the landward migration of dune systems;
- identification and remediation of sources of eutrophic, polluted groundwater; the problem might be cured at source or the polluted water diverted;
- reducing water abstraction and land drainage that is shown to be lowering dune water tables;
- removal of coniferous plantations whose transpirational losses are having a deleterious effect on dune water tables;
- conservation of local surface water in ponds or ditches, for possible reinjection into deeper soil layers;
- sod-cutting or scraping to remove accumulated organic material and re-establish appropriate contact with the water table;
- assuming that appropriate conditions can be reinstated, reintroduction of species of particular interest and importance.

8.4.3 Limitations of these guidelines and gaps in knowledge

The limitations of the information presented here related to SD17 include the following.

- There are currently virtually no data to characterize the temporal water table characteristics of SD17 stands, particularly in contra-distinction from related dune slack types. Time series of dipwell measurements are required to fill this gap. A probabilistic analysis of the duration and frequency of the water levels is more likely to be informative than taking the extreme summer and winter values.
- Hydrochemical data from UK sites are extremely limited and none can be associated with specific adverse effects. Time series analyses of samples from dipwells and slacks are required to fill this gap.

- Insufficient data are available for the establishment of guidelines for groundwater phosphorus concentrations.
- Insufficient data are available for the establishment of separate guidelines for groundwater nitrate and ammonium concentrations.
- Intensive studies on the detailed hydrochemistry of specific slacks are lacking.
- Intensive studies on the ecological requirements of rare and key dune-slack species are lacking.

More information is needed on appropriate restoration techniques, particularly in UK settings. Application of the guidelines for total inorganic nitrogen (Table 8.4) is subject to the caveats and recommendations listed below.

- Groundwater (chemistry or water levels) uniformity cannot be assumed under a dune system, or even within the same slack in the case of through-flow slacks.
- Suspected contaminated groundwater needs clarification by (1) ascertaining the water level regime relative to the ground surface and the rooting zone (for example, monitoring dipwells); (2) analysing groundwater for nutrient concentrations, at minimum twice (in summer and a winter), using laboratories that have sufficiently accurate procedures.
- Referring the results to the guidelines. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.
- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.
- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping or grazing will remove nutrients.
- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

Section 9

Discussion and conclusions

The rationale underlying this work was to link ecological and hydrological classifications of wet dune slacks. The ecological classification used for purposes of conservation management, the comprehensive typification of British plant communities (NVC) (Rodwell, 2000), recognises six main communities (SD13–17), which collectively correspond with the designations H2190 Humid dune slacks and H2170 Dunes with *Salix repens* of Annex I of the European Union Habitats directive. This is based largely on plant species composition, which in turn is considerably influenced by water levels, water chemistry, climate and successional development of communities. A typology for dune-slack water supply mechanisms (WETMECS) was derived in Phase 1 of this study and recognises five distinct situations (A–E), depending largely on elevation, proximity to the sea and physiographic setting (Davy *et al.*, 2006).

The analysis presented here suggests that in general the community classification appears to be too subtle and variable to be precisely explained by the water supply mechanisms. Community type SD16, by far the most abundant and widespread in England and Wales (Davy *et al.*, 2006) can develop under water supply mechanisms B, C or E; similarly SD15, the next most abundant community can be associated with WETMECs B, C or D, whereas SD17 is also associated with D. The clearest correspondence is of SD13, characteristic of young, often brackish slacks, with WETMEC A; SD 14 is often in similar situations but it can probably also develop under WETMECs B and C, as examples occur at Newborough Warren that are 1 km from the sea and are over 60 years old (Jones, Sowerby and Rhind, in press).

There are several possible reasons for the rather weak correspondences. Foremost, is the quantitative evidence base relating water levels to community types. Although we have examined many dipwell data from a range of sites, it is often not possible to assign dipwells with confidence to a particular plant community type and, where this is possible, community types tend to show great spatial and temporal variation in their water regimes. Also, series of dipwell observations tend to be short, or broken, making comparisons difficult and precluding the analysis of long-term exceedence statistics. Other problems arise from the community classification itself. Dune slacks are components of a functioning dune system that are inter-related spatially, not least by water flow, as well as temporally by succession. Consequently, they do not fit neatly into a phytosociological classification system: there are intermediate communities, ecotones and geographical variations, giving rise to ambiguity of classification.

A single dune slack may include areas allocated to several different plant communities, and an area classified as a particular community may be reclassified as a different one a few years later without the necessity for a change in water regime. In contrast to the complexity of these communities, the recent functional wetland typology for Scotland (SNIFFER, 2009) includes a single category for all dune slacks. Finally, it must be acknowledged that the five water supply mechanisms that can be recognised are essentially based on combinations of hydrological flow patterns and currently may not take enough account of either water chemistry or water depth. Water depth and its seasonal variation are probably the most important drivers of vegetation type; it seems likely that a particular water-supply mechanism can generate a range of water-depth environments, depending on other site-specific factors.

There are two main outputs in this report: (1) an integrated overview of hydrological mechanisms and functioning in the wet slacks of UK dune systems; and (2) individual, self-standing accounts of the six dune-slack community types with recommendations for their management. The former provides a conceptual framework, based on examination of information from many of the important dune systems in England and Wales, that integrates and informs the latter. The conceptual framework itself provides a basis for evaluating eco-hydrological guidelines for wet slacks in general and could provide guidance in the absence of plant community analyses. The independent, individual-community accounts are intended to provide interim guidelines in the standard format (Wheeler *et al.*, 2004), with information as specific as is possible currently. Because they are independent, they inevitably include much re-iterated material, both among accounts and also from the conceptual framework and case studies. In the first case, this is because there is much in common among the British Plant Communities, as outlined previously; in the second case it is because the reviews and case studies have been important in informing the comprehensive individual accounts of the plant community types.

The problems in marrying ecological and hydrological information at higher resolution highlight the gaps in current knowledge. More precise eco-hydrological guidelines for the management of wet dune slacks will require substantial additional field investigation:

- Long-term monitoring of suitably replicated dipwells, placed strategically at a range of sites within unequivocally identified dune-slack community types.
- Sites should be chosen to include the whole range of community types (including rare ones such as SD13), and to reflect different physiographic settings, substrate, climatic conditions and depositional environments.
- Changes in the communities should be monitored, along with seasonal and long-term changes in water level and water chemistry.
- Fluctuations in groundwater level in different communities could be best characterised in terms of the probability of exceeding set maxima for winter and summer periods, as well as understanding the magnitude of water table fluctuation and the persistence of wet and dry periods on habitat condition.
- Such investigations ideally need to be part of larger-scale hydrological investigations of whole dune systems to determine water flow and hydrochemical gradients through the slacks.
- The results of these studies should be integrated to assess likely impacts of climate change, particularly resulting from sea-level rise and changing patterns of rainfall, on the eco-hydrology of wet dune systems.

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Appendix A

Species names

Flowering plants (excluding grasses, sedges and rushes)

Anagallis tenella	Bog Pimpernel
Angelica sylvestris	Wild Angelica
Anthyllis vulneraria	Kidney Vetch
Bellis perennis	Daisy
Betula pubescens	Downy Birch
Blackstonia perfoliata	Yellow-wort
Caltha palustris	Marsh-marigold
Cardamine pratensis	Cuckooflower
Centaurium erythraea	Common Centaury
Cerastium fontanum	Common Mouse-ear
Cirsium palustre	Marsh Thistle
Dactylorhiza fuchsii	Common spotted-orchid
Dactylorhiza praetermissa	Southern Marsh-orchid
Dactylorhiza purpurella	Northern Marsh-orchid
Epilobium palustre	Marsh Willowherb
Epipactis palustris	Marsh Helleborine
Eupatorium cannabinum	Hemp Agrimony
Euphrasia officinalis agg.	Eyebright
Filipendula ulmaria	Meadowsweet
Fragaria vesca	Wild Stawberry
Galium palustre	Common Marsh-bedstraw
Galium verum	Lady's Bedstraw
Glaux maritima	Sea-milkwort
Hydrocotyle vulgaris	Marsh Pennywort
Hypochaeris radicata	Cat's-ear
Iris pseudacorus	Yellow Iris
Lathyrus pratensis	Meadow Vetchling
Leontodon autumnalis	Autumn Hawkbit
Leontodon hispidus	Rough Hawkbit
Leontodon taraxacoides (=saxatilis)	Lesser Hawkbit
Linum catharticum	Fairy Flax
Liparis loeselii	Fen Orchid
Lotus corniculatus	Common Bird's-foot-trefoil
Lotus pedunculatus	Greater Bird's-foot-trefoil
Lysimachia vulgaris	Yellow Loosestrife
Mentha aquatica	Water Mint
Oenanthe lachenalii	Parsley Water-dropwort
Ononis repens	Common Restharrow
Parnassia palustris	Grass of Parnassus
Pilosella officinarum	Mouse-ear Hawkweed
Plantago lanceolata	Ribwort Plantain
Plantago maritima	Sea Plantain
Potentilla anserina	Silverweed
Prunella vulgaris	Sefheal
Pulicaria dysenterica	Common Fleabane
Pyrola rotundifolia	Round-leaved Wintergreen
Quercus robur	Pedunculate Oak
Ranunculus acris	Meadow Buttercup
Ranunculus flammula	Lesser Spearwort
Ranunculus repens	Creeping Buttercup
Rubus caesius	Dewberry
Rumex acetosa	Common Sorrell
Rumex crispus	Curled Dock
Sagina nodosa	Knotted Pearlwort
Sagina procumbens	Procumbent Pearlwort
Salix caprea	Goat Willow
Salix repens	Creeping Willow
Samolus valerandi	Brookweed
Scutellaria galericulata	Skullcap
Senecio jacobaea	Common Ragwort
Sonchus arvensis	Perennial Sow-thistle
Succisa pratensis	Devil's-bit Scabious
Taraxacum officinalis agg.	Dandelion
Trifolium pratense	Red Clover
Trifolium repens	White Clover
Triglochin maritimum	Sea Arrow-grass
Vicia cracca	Tufted Vetch
Vicia sativa	Common Vetch

Grasses, sedges and rushes

Agrostis stolonifera	Creeping Bent
Anthoxanthum odoratum	Sweet Vernal-grass
Carex arenaria	Sand Sedge
Carex disticha	Brown Sedge
Carex flacca	Glaucous Sedge
Carex nigra	Common Sedge
Carex panicea	Carnation Sedge
Carex serotina (= viridula)	Yellow-sedge
Cladium mariscus	Great Fen-sedge
Cynosurus cristatus	Crested Dog's-tail
Eleocharis palustris	Common Spike-rush
Elymus repens	Common Couch
Festuca rubra	Red Fescue
Holcus lanatus	Yorkshire Fog
Juncus acutus	Sharp Rush
Juncus articulatus	Jointed Rush
Juncus gerardii	Saltmarsh Rush
Juncus maritimus	Sea Rush
Molinia caerulea	Purple Moor-grass
Phragmites australis	Common Reed
Poa annua	Annual Meadow-grass
Poa pratensis	Smooth Meadow-grass
Poa trivialis	Rough Meadow-grass
Schoenus nigricans	Black Bog-rush

Mosses and liverworts

Aneura pinguis
Brachythecium rutabulum
Bryum pseudotriquetrum
Calliergon cuspidatum
Campylium stellatum
Drepanocladus lycopodioides
Drepanocladus sendtneri
Eurhynchium praelongum
Moerckia hibernica
Pellia endiviifolium
Petalophyllum ralfsii
Plagiomnium rostratum
Preissia quadrata
Riccardia chamaedryfolia

Horsetails

Equisetum fluviatile	Water Horsetail
Equisetum palustre	Marsh Horsetail
Equisetum variegatum	Variegated Horsetail

Appendix B

Available reports for main dune systems considered

The CD can be requested via the electronic publications catalogue.

Folder	File name	Type of information	Dates covered	Quality
Ainsdale	Clarke_and_Sanitwong_Na_Ayutthaya ICCD07 final.pdf	Report – Probabilistic assessment of Future coastal groundwater levels in a dune system in England (Ainsdale)	1970–2000 considered	
	drp dipwells FOR USE IN GRAPHS.xls	Raw Data – Dune restoration project – borehole readings (cm bdp) from 13 BHs	1991–1993 & 2001–2002	
	Sefton borehole data 7nov02 AK.xls	Graphed data – of the above groundwater levels for all 13 of the boreholes	1991–2003	
		Raw data – Water level data for 15 different boreholes on Sefton coast*	1999–2002 (for each)	*Measurement units are unclear
	AinsdaleNNR DailyRain 1972-2003.xls	Raw Data – daily rainfall data (mm/day) for Ainsdale NNR	1972–2003	
	Atkins Long-term Well Analysis 3feb04 RSW1.xls	Raw data – Water levels (m AOD) for 55 different boreholes	Various: Most 1972–1997 or 1999–2003	Some data missing
	CR_07_072N Braunton Burrows conceptual flow model nsr.pdf	Graphed data – water level (m AOD) against time for boreholes within certain habitats for example, coniferous forest	1990–2004	Some data missing
		BGS report – Conceptual flow model and changes with time at Braunton Burrows	Published: 2007	
	Finalappendix E	Graphs – Water level trends at Ainsdale NNR boreholes 1–14 and a-y (m AOD)	1991–2003	
	ESFinal7_04.pdf	Report – EIA of options for management of seaward areas at Ainsdale NNR	Published: 2004	
Braunton	ALL_DATA.xls	Raw data (from the BGS report) – water level readings for 44 boreholes, and in some cases this is relative to the known datum elevation	1966–2007 But many BHs abandoned in 1991	Some data missing

Folder	File name	Type of information	Dates covered	Quality
	BH3 Monthly WL analysis.xls	Graphed data – Monthly summary of the average depth to the water level, seasonal changes in water table, also graph comparing wet and dry years for BH 3 at Braunton Burrows	Average of 1972–1997	
	Graphs_to_OD.xls	Data – water levels with respect to OD for 19 BHs in the study area	1966–2007 (some 1991–2007)	Some data missing
		Plus raw rainfall data (monthly average)	1966–2006	Some data missing
		Graphs – Of the above groundwater level data (m AOD) for three transects and – Cross section along transect, with rainfall and water level lines plotted	1966–2008	
	CR_07_072N Braunton Burrows conceptual flow model nsr	Report (BGS) – Conceptual flow model and changes with time at Braunton Burrows coastal dunes. Hydrographs, WL monitoring, cross sections, rainfall analysis and conceptual flow model are included	1966–2004	
Merthyr Mawr	Merthyr Mawr Final report v3	Report – Determining a nitrogen budget for the dune system. Includes analysis of groundwater/rainfall, also surface water chemistry, vegetation, nutrient budgets	Published: 2005	
Newborough	Srtatford et al. Newborough Review Final Report	Report – A review of hydrological reports for Newborough Warren (CEH/BGS). Water levels and a move away from wet slack species is the focus of this review	Published: 2006	
Sefton	In ‘Documents’ folder: Dune wetlands of the Sefton coast Part one.doc	Report – Analysis of current information on the Sefton coastal dunes	Published: 2007	
	Dune wetlands of the Sefton Coast Part 2 Refs.doc	Reference list – all sources and references from phases 1&2 inc. those from the above spreadsheet.		
	Sefton Dune Wetlands Spreadsheet.xls (2 tabs):	Table – shows available information/records from previous work on this system – many vegetation studies	Various studies between 1983 and 2004	

Folder	File name		Type of information	Dates covered	Quality
		Sefton coast research partnership meeting	Report – Sefton Coast Partnership; research meeting ’06. Various reports on current sand dune slack research at Sefton (including Ainsdale), including hydrology and eco-hydrology guidelines	Published: 2007	
	In ‘Sefton – ZIP – BH log’ folder:	SD 31/41, 31/42, 31/43, 31/44, 31/45 AND 31/46	Borehole description sheets – These are EA boreholes in Ainsdale NNR, Sefton. Data available to accompany boreholes SD 31/42 and SD 31/43 (a.k.a Ainsdale BHs K and L)	Surveyed in 2006	
		Slack Outline Map.DAT/.ID/.MAP/.TAB	Map – Base map with spreadsheet info added		
		Un-numbered slacks.DAT/.ID/.MAP/.TAB	Map – Slacks without numbers		
		Converted GIS Files	GIS files – The above files but converted into a ArcMap format from another GIS programme		
	In ‘Maps’ folder:	Borehole & Piezometer Locations.DAT/.ID.MAP/.TAB	Data – Coordinates for BH and piezometer locations		
Winterton	wintertondata-file.xls (2 tabs):		Data – Groundwater levels (cm above OD) for several dips/data loggers along two permanent transects at Winterton	Feb–June 2006	
			Data – Water Quality results for 39 samples- taken from 16 surface water ponds and along both transects in study area	Samples all taken on one day–21st May 2007	No long-term trend
	Coulet Winterton report.pdf		Report – Managing Winterton Dunes for Natterjack Toads	Summer 2007	
	Maps showing transects and ponds.doc		Map – Showing the location of the ponds, slacks, transects and boreholes referred to in the data and the results	From 2007 report (above)	

Site descriptions and data for Sefton and Ainsdale dune slacks

1. Birkdale Sandhills LNR Frontal Dunes: Slack 40

This is an example of a slack that has recently formed (1970s) but undergoes very little management. It is actually a complex of small primary slacks. According to the definitions of Ranwell (1972) this is a wet slack.

During the 1988 NVC Vegetation Survey the slack was mapped as comprising type SD15. Edmonson *et al.* (2007) noted that there may have been an area of SD18 dune scrub around slack 40a, but the precision of the map does not allow a clear conclusion. By 2003/2004 most slacks remain characterised as SD15 vegetation. However, one is now mapped as SD16 and another is supposedly an ‘unformed SD/MG mix’. The only recorded management is scrub clearance, which took place in 2003.

2. Birkdale Sandhills LNR Frontal Dunes: Slack 48

The slack can be defined as a young, mature wet slack. The 1988 NVC survey indicated the slack was already considered modified by the succession to scrub and invasion by alien species, despite its relatively young age. Therefore, management has been much more intense than in slack 40. Management has been in the form of annual mowing from 1996 and grazing in 1995 and 1999. By the 2003/04 NVC survey, areas of SD16 and SD17d were recorded. Accordingly, Edmonson *et al.* (2007) point to this as evidence that suggests a change to a later successional character. Community change away from young, base-rich conditions

3. Birkdale Sandhills LNR: Slack 11

This slack is described as large, mature and complex, is located in a very stable area of the Sandhills, and has significant areas of scrub in and around it (Edmonson *et al.*, 2007). The authors also go on to comment that in both the 1988 and 2003/04 NVC surveys a spatial vegetation pattern was identified; predominantly the open area is SD16b vegetation at the eastern, landward end and SD15 at the seaward end. Previous work has shown that the presence of the coastal road just to the west of this slack may impede flow through to the coast, causing the water to back up at this end of the slack. There is also a scrape which is mapped as a swamp community. Edmonson *et al.* (2007) commented that the high water table is assumed to have prevented scrub encroachment in the remaining open areas, but that SD16d indicates a drying slack.

4. Birkdale Sandhills LNR: Slack 18

Like slack 11 (above) this slack is described as large, mature and complex and is also located in the very stable area of the Birkdale Sandhills just landward of the coastal road. Significant areas of swamp community occupy the seaward end of this slack, surrounded largely by SD15. The wet character at this end has largely persisted between 1988 and 2003/4 (Edmonson *et al.*, 2007). At the landward end a community of SD15d with a significant area of scrub has also persisted as the major NVC type from 1988–2003/4.

There are significant areas of scrub/woodland in and around the slack which threaten its open character. Scrub removal was carried out in the 1980s; however there has been no recent management through removal or grazing. Therefore, Edmonson *et al.* (2007) stated that it can be assumed scrub encroachment is inhibited by the very wet conditions in some parts of this slack.

As above, the presence of the coastal road to one side of this slack has been said to be significant to the local water regime (Edmonson *et al.* 2007). This is confirmed by aerial photos during flood events, which shows water being held back from its normal seaward flow path due to the road.

Smith (1986) recorded the average maximum water depth to be 1–15 cm of surface water. Smith (1986) also recorded a high density of Natterjacks and three rare plant species present. Later, Skelcher (2006) recorded no Natterjacks breeding at this site.

5. Royal Birkdale Golf Course: Slack J (2nd green)

This young, small slack is located in stable dunes and scrub on Birkdale golf course.

In the 1988 NVC survey this slack is classified as a dry slack and is mapped as a mosaic of SD16b with other communities including mesotrophic grassland.

A permanent quadrat was established here in 1998 (Butcher *et al.*, 1999–2002), and is recorded as being SD16b. Four other quadrats were: SD14 to SD16 transition, SD15, SD15b and SD16 to MG9. Butcher *et al.* (2000) also reported that mowing maintains much of the slack vegetation.

The 2003/4 NVC records only a small amount of slack vegetation; SD16 and mesotrophic grassland mosaic. Thomas *et al.* (2004) later classified the vegetation in the permanent quadrat as SD14d, previously recorded by Butcher *et al.* (1999–2002) as being SD16b. Edmonson *et al.* (2007) commented that SD14d is more typical of sites with a wider water table fluctuation than this.

Changes in NVC are recorded in the permanent quadrat over time:

- 1998: SD16b.
- 1999: SD16 (‘fair’ matches to SD16b and SD15d).
- 2000: SD15D–SD16 (equally poor matches to both).
- 2001: SD15d.
- 2002: SD15d.
- 2004: SD14d.

Water table fluctuation is small; it never drops below 0.3 m below the surface. Edmonson *et al.* (2007) pointed out that both the wetted period and the water table level have declined during the past decade. Previous studies report a drying trend, but with the persistence of some wet slack species.

There have also been detailed studies of the bryophytes at this site.

6. Massams Slack (covers Ainsdale Sand Dunes NNR Slacks 2 and 3)

This is a large primary dune slack which dates back to around 1900 when an area of beach along the Sefton coast was artificially enclosed. The slacks are located in the frontal dune area on an eroding section of coastline and are now at a fairly advanced state of encroachment by a sand sheet.

In the 1960s Massams slack was characterised by wet slack species. Robinson (1971) noted that these conditions were most likely prevailing due to an outflowing drainage ditch being blocked at this time. By 1970 the same author found evidence of a drying trend in conditions in the slacks (Robinson, 1971). However, in 1974 Edmonson (1974) found a large number of new species, most of which are wet slack species.

Smith (1978) recorded the average maximum water table depth. In slack 2 it is at the ground surface, in slack 3 it is 1–15 cm above the ground level. Smith (1978) also recorded Natterjacks breeding in both pools. A later survey (Skelcher, 2006) recorded breeding only in one end of slack 3, and at very low density.

By the 1988 NVC survey much of slack two had been invaded by the sand sheet. A scrape is mapped as open water; the remainder classified as a mix of SD15, SD16 and semi-fixed dune surrounded by scrub. In 2003/4 encroachment had continued; dune scrub and 'woodland' area have increased, and a small area of SD16b remains (NVC survey).

In 1988 slack three was largely classified as a 'dry slack' with small areas of SD18b and SD15/16 mix. Management has been carried out in this slack: Re-profiling in 1989/91 and shrub clearance in 2002 and 2005. By the 2003/4 NVC survey the entire southern end had been lost to sand, the north end of the slack is now classified as being made up of 'swamp', dune scrub and a small remaining patch of SD15.

7. Ainsdale Sand Dunes NNR: Slack 48

This is a large, mature, secondary slack located in the dunes at Ainsdale. Again the blocking of a seaward drain in 1960 affected the hydrological regime at this site; subsequently Robinson (1960) recorded an increase in wet slack species, and the disappearance of dry slack species. Edmonson (1974) also recorded species typical of early wet-slack succession. There was little early management, but rabbit exclosures were added in 1974.

In 1978 the average maximum water table was recorded at being at surface level in the slack. Three major vegetation patches dominated in 1988, from seaward to landward: SD15d; SD15b and SD16; SD15d and SD16 (NVC survey). Conifer felling was carried out in the adjacent dune restoration project in 1992; this would suggest subsequent changes in the water regime (recovery) and then the vegetation composition in this slack.

The 2003/4 NVC survey classified the slack as mainly SD15a mixed with some SD16b to the seaward and northward sides, in mosaic with dune vegetation. Also, one small patch of SD15a as well as some SD16 mixed with S19 (swamp) is mapped.

Note. Slack outline inaccuracies (see case studies in Sefton coast report).

8. Ainsdale Sand Dunes NNR: Slack 65

This slack in Ainsdale sand dunes is medium-sized and believed to be a complex of both primary (the seaward end) and secondary (the landward end) dune slacks in origin.

Smith (1978) stated that this slack is the most ecologically valuable on the entire Sefton Coast and the landward end has been found to be particularly species rich (1988 NVC survey). The landward end includes a monitoring well and two scrapes that have undergone re-profiling, and are now classified as open water. Significant areas of scrub were cleared in 1990 although some patches around the landward edge remain.

Vegetation was predominantly a mix of SD15 and SD16 during both NVC surveys (1988 and 2003/4). This slack has been reported to fit with Type C of Davy *et al.* (2006) due to it being a large seaward slack, with surface water flow. Groundwater flow infiltrates on the up-gradient slack edge and flows out of the down-gradient edge, and once water has reached the surface, it flows to the seaward end of this slack. The water table fluctuates between about 50 cm below the surface, to an average maximum of over 15 cm of surface flooding.

9. Ainsdale NNR: Slack 100

This slack is described as being a medium-sized, damp, secondary dune slack, likely originating from around 1898 (O'Garra, 1976).

The 1988 NVC survey mapped the slack as SD16, with a mix of SD15/SD16 mix to the seaward end. A large area of scrub extends landward from the slack. Mowing occurred in the 1980s and 1990s and sheep grazing from 1991.

Scrub clearance was carried out in 2003/2004 on the landward edge of the slack. By the 2003/4 NVC survey the slack is classified as a mix of SD16 and SD17; it is linked on the landward side to slack 111 by a patch of SD16 and SD7, where the scrub used to be.

The slack is said to be most like Type B from the classification of Davy *et al.* (2006) because it is believed to be fed by precipitation to the dune system, with groundwater flowing into the slack and water lost to evapotranspiration. Average maximum water table depth has been recorded at about 1–15 cm of surface flooding (Smith, 1978). The nearest well is in a connected slack to the landward side of slack 100.

Stack location/ description	Slack No.	Borehole/ piezometer No. area (ha)	Area (ha)	Age/when formed?	Management	1998 NVC vegetation survey	2003/4 NVC vegetation	Important species?	Other
Birkdale Sandhill LNR a small complex of slacks: 40/40a/b/c/d Primary/mature/frontal dune slacks with v. little mgmt	40		0.05	Recent – 1970s	2003: Scrub clearance	40 and 40b considered to be continuous): SD15 40a: possibly SD18, but hard to see on map 40c and 40d: not considered separate from dune that surrounds them	40: SD15 40a:an ‘unformed MG/SD mix’ 40b: SD16 40c:not mapped 40d: SD15	Skelcher (2006) records no Natterjack breeding site in this slack	Birkdale Sandhill LNR a small complex of slacks: 40/40a/b/c/d. Primary/mature/frontal dune slacks with v. little mgmt.
Birkdale Sandhill NNR Mature slack, frontal dunes, v. close to dune front	48	Boreholes K and L are landward of this site	0.06	Recent (mid 1970s)	1996-onwards: mowing (much succession to scrub and alien invasion had occurred by 1988 NVC despite being a young slack)	Incipient SD15 – scrub transition	75%: SD15 15%: SD16 10%: SD17d SD15 remains dominant but appearance of SD 17 suggesting successional change in comm	Skelcher (2006) This is a breeding site for Natterjacks in small numbers (13 spawn strings and tens of maturing toadlets)	

Stack location/ description	Slack No.	Borehole/ piezometer No. area (ha)	Area (ha)	Age/when formed?	Management	1998 NVC vegetation survey	2003/4 NVC vegetation	Important species?	Other
Birkdale Sandhill NNR Large/mature/ complex dune slack w/significant scrub in & around it	11	Coastward, are EA boreholes K and L. Landward is Hillside 4	2.22	Scrape excavated in 1976		Slack area underestimated: surrounded by dense bands of shrub. Plus SD18 found inside slack area Remaining open area: SD15 (some diagnosed to SD15a) Also, SD16 at Eastern end	Large area on perimeter classed as woodland. Small area of SD18 (dune scrub) inside slack Remaining open area: SD16b, small area of SD15 on seaward side	Skelcher (2006) records no Natterjack breeding site in this slack	Smith (1978) records average max. water table at c.1–15 cm of surface water
Birkdale Sandhill NNR Large mature complex wet-slack -stable and senescent area of NNR	18	Coastward, are EA boreholes K and L. Landward: EA bh M and Hillside 4	2.25	Formed from bomb craters and a 1976 scrape	Scrub removal: 184/85 and 1987	SD15 and SD16 on seaward edge SD15a mainly on the landward side with more SD16b around the edges Significant area of scrub is mapped: mostly SD18	A large area of S7 (swamp) occurs in slack. Plus area of S20 on the seaward side Landward of swampy area: mosaic of SD15d with M27 (mire), and small area of SD15a Landward edge: largely SD15a, but within a mosaic with SM17d and SD16 At seaward end there is a small patch of woodland, then stand of SM18 (salt marsh comm)	Skelcher (2006) records no Natterjack breeding site in this slack	Smith (1978) records average max. water table at c.1–15 cm of surface water

Stack location/ description	Slack No.	Borehole/ piezometer No. area (ha)	Area (ha)	Age/when formed?	Management	1998 NVC vegetation survey	2003/4 NVC vegetation	Important species?	Other
Royal Birkdale Golf course Slack J (2nd green) Young, wet slacks Drying trend reported, but some wet slack spp. are persisting	J	J	0.32 (measured from GIS base not survey)	Visible in 1945 aerial photos	Regular mowing and cutting to control willow growth	Dry slack. Mapped as SD16b with MG1 grassland. Much more work done by Butcher *et al.* 1999–2002…5 quadrats: 1) SD16 to SD14 transition 2) SD15 3) SD15d 4) SD16 to MG9 5) SD16b 6) Thomas *et al.* (2004) IDs quadrat J (estab'ed by Butler) as SD14d	Only small area of vegetation is recorded: Large part in centre is just slack and mesotrophic grassland (that is, no NVC type) Outer fringe is mesotrophic grassland and SD16 mosaic	Not surveyed for Natterjacks	Small fluctuations in water table, never below 0.3 m below surface. But wetted period and water table level declined over monitoring period
Massam Slacks (includes Ainsdale NNR slacks 1&2 Large primary dune slack Currently being encroached by invading sand	Ainsdale 1 & 2	Boreholes 1, 2 and 3	2.13 (slack 2)	1900s (detailed study from 1952 onwards – Blanchard)	Slack 3: Shrub Clearance – 2002 and 2005 Reprofiling – 1989:filled in, 1991:3N reprofiled	Slack 2: area not covered by sand is a mix of SD15, SD16 and semi fixed dune. Some areas of scrub surround Slack 3: major part mapped as 'dry slack', then SD18b north of that, and further still a SD15/16 mix	Slack 2: further encroachment by sand. SD18 to east and west, also area of SD16b remains, but clearly drier than previous years. Small patch of woodland also Slack 3: south overwhelmed by sand, area of undefined 'swamp' and at the northern end SD15 remnant	Very few Natterjacks in northern end of slack 3, no adults observed	

Stack location/ description	Slack No.	Borehole/ piezometer No. area (ha)	Area (ha)	Age/when formed?	Management	1998 NVC vegetation survey	2003/4 NVC vegetation	Important species?	Other
Ainsdale sand dunes NNR	48	Closest is well 6	1.01		Grazing: rabbit exclosures 1974 Scrub Clearance: 1992 phase 1 conifer clearance is adjacent to this slack.	Three mains areas, going seaward to landward: SD15d SD15b/SD15d SD15d/SD16	Main area: SD15a/SD16b mixture Seaward and N edges: SD16b Central area of SD15a and adjacent patch of SD16/S19 mix	Not survey, believed to be unsuitable habitat	N.B. Slack outline inaccuracies, see case study report
Ainsdale sand dunes NNR (C)	65	Well 7	2.19		Grazing: rabbit exclosures since 1945, sheep grazed from 1991 Scrub clearance: adjacent scrub in 1990s Re-profiling: 1992 part in-filled	Seaward end: SD16/SD15d mix with two large areas of open water (1976 scrapes) Landward is mix of SD15d and SD16 NE corner: some scrub N end: patch of SD18b	Main area: SD15/SD16, still with two areas of open water Small patch of SD16d with woodland on northern edge	Low density, no adults/ recruitment observed, some spawn	
Ainsdale sand dunes NNR (B)	100	Well 11 is landward	0.31		Mowing: 1980s/1990s Grazing: sheep form 1991	Main central area: SD16 and SD17. Seaward: Mix of SD15d to SD16 transition and SD15d. Large belt of scrub extends form slack	Main area: SD16 and SD17, with a circular area of SD16d in the centre Landward extension: SD16D/SD7 semi fixed dune – links to slack 111	Not surveyed for Natterjacks	Average max water table ca. 1–15 cm of surface water

Borehole identifier	Location	Associated slacks	***Is borehole datum related to ground level?***	**Previous mention of surface water level in/around borehole/**	Dominant NVC type	**Is there a previous or suggested classification?**	**Surface water levels (calculated from new date)**
Slack?	Dominant NVC Type	Is There a Previous or Suggested Classification?	Surface Water Levels (calculated from new date)	No, but there is details in reports about drying out etc. see case study details	???	N	?
K – Birkdale golf course (SD31/58)	Birkdale Golf Course	#48 @ Birkdale Sandhills LNR	N	N	15 (16/17)	N	?
L – Birkdale golf course (SD31/59)	Birkdale Golf Course	#48 @ Birkdale Sandhills LNR	N	N	15 (16/17)	N	?
K -EA (SD31/42) SD 3025 1335	Ainsdale	#11 @ Birkdale Sandhills LNR Also, #18	Elevation of BH = 8.081 m OD Measured from: GL	Slack 11: 1–15 cm is average max. of surface water Slack 18: 1–15 cm is the average max. of surface water. (Unique vegetation pattern – see case study details)		N	Mean: -163 cm Max: -158 cm Min: -169 cm
L -EA (SD31/43) SD 3028 1333	Ainsdale	#11 @ Birkdale Sandhills LNR Also, #18	Elevation of BH = 8.718 m OD Measured from: GL			N	Mean: -205 cm Max: -198 cm Min: -212 cm
K -EA (SD31/42) SD 3025 1335	Ainsdale	#11 @ Birkdale Sandhills LNR Also, #18	Elevation of BH = 8.081 m OD Measured from: GL	Slack 11: 1–15 cm is average max. of surface water Slack 18: 1–15 cm is the average max. of surface water. (Unique vegetation pattern – see case study details)		N	Mean: -163 cm Max: -158 cm Min: -169 cm

Borehole identifier	Location	Associated slacks	***Is borehole datum related to ground level?***	**Previous mention of surface water level in/around borehole/**	Dominant NVC type	**Is there a previous or suggested classification?**	**Surface water levels (calculated from new date)**
BH 1 – from Ainsdale long-term data set	Ainsdale	Massam slack – slack 2	5.23 m OD (presumed)	Massams slack 2: max water depth = ground surface Massams slack 3: average max water table = 1–15 cm of surface water		N	Mean: -61 cm Max: 15 cm Min: -123 cm
BH 2 – from Ainsdale long-term data set	Ainsdale	Massam slack – slack 3	5.26 m OD (presumed)	Max water depth = 1–15 cm of surface water		N	Mean: -31 cm Max: 44 cm Min: -86 cm
BH 3 – from Ainsdale long-term data set	Ainsdale		5.63 m OD (presumed)			N	Mean: -30 cm Max: 34 cm Min: -89 cm
Well 6 – from Ainsdale long-term data set	Ainsdale Sand dunes NNR	#48 @ Ainsdale Dunes NNR	7.48 m OD (presumed)	Average maximum water table = at surface level (refer to case studies)		N	Mean: -44 cm Max: 48 cm Min: -117 cm
Well 11 – from Ainsdale long-term data set	Ainsdale NNR	#100 @ Ainsdale Dunes	Ground level is 9.54 m OD (surveyed)	c. 1–15 cm of surface water (max)		Davy *et al.* Type B (ref: c/studies) NB: Well no. 11 is in a connected slack to #100	Mean: -38 cm Max: 49 cm Min: -121 cm

Summary of annual groundwater level data for Ainsdale boreholes

Well no.	**BH1**			**BH2**			**BH3**			**BH6**		
	Dip	**GL**	**Water level**	**Dip**	**GL**	**Water level**	**Dip**	**GL**	**Water level**	**Dip**	**GL**	**Water level**
Mean	4.62	5.23	0.61	4.95	5.26	0.31	5.33	5.63	0.30	7.04	7.48	0.44
SD	0.32			0.29			0.28			0.34		
Maximum	5.38	5.23	-0.15	5.70	5.26	-0.44	5.97	5.63	-0.34	7.97	7.48	-0.48
Minimum	4.00	5.23	1.23	4.40	5.26	0.86	4.75	5.63	0.89	6.32	7.48	1.17
Upper quartile	4.38	5.23	0.85	4.72	5.26	0.54	5.11	5.63	0.52	6.80	7.48	0.68
Low quartile	4.87	5.23	0.36	5.14	5.26	0.12	5.52	5.63	0.11	7.27	7.48	0.21
Interquartile range	0.49			0.42			0.41			0.47		

Well no.	**BH7**			**BH11**			**K (EA)**			**L (EA)**		
	Dip	**GL**	**Water level**	**Dip**	**GL**	**Water level**	**Dip**	**GL**	**Water level**	**Dip**	**GL**	**Water level**
Mean	7.19	7.31	0.12	9.19	9.54	0.38	6.46	8.08	1.63	6.67	8.72	2.05
SD	0.20			0.37			0.04			0.04		
Maximum	7.63	7.31	-0.32	10.03	9.54	-0.49	6.51	8.08	1.58	6.74	8.72	1.98
Minimum	6.50	7.31	0.82	8.33	9.54	1.21	6.39	8.08	1.69	6.60	8.72	2.12
Upper quartile	7.08	7.31	0.24	8.93	9.54	0.62	6.42	8.08	1.66	6.63	8.72	2.08
Low quartile	7.33	7.31	-0.02	9.44	9.54	0.10	6.49	8.08	1.59	6.71	8.72	2.01
Interquartile range	0.25			0.51			0.06			0.07		

All measurements in metres; a positive Water level indicates depth of water above ground level, a negative number indicates depth of water below ground level;
GL is measurement datum height above ground level.

Summary of winter and summer groundwater level data for Ainsdale boreholes

Datum (m AOD) **5.23** **5.26** **5.63** **7.48** **7.31** **9.54**

1972–2003 (Note: some data missing)

Winter	**Oct–March**																	
	BH1			**BH2**			**BH3**			**BH6**			**BH7**			**BH11**		
	Dip	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**
Mean	4.68	5.23	0.55	5.00	5.26	0.26	5.38	5.63	0.25	7.08	7.48	0.40	7.22	7.31	0.09	9.22	9.54	0.32
SD	0.32			0.27			0.28			0.35						0.38		
Maximum	5.30	5.23	-0.07	5.54	5.26	-0.28	5.97	5.63	-0.34	7.97	7.48		7.63	7.31	-0.32	10.03	9.54	-0.49
Minimum	4.05	5.23	1.18	4.47	5.26	0.79	4.79	5.63	0.84	6.32	7.48	1.17	6.59	7.31	0.72	8.33	9.54	1.21
Upper quartile	4.43	5.23	0.80	4.82	5.26	0.44	5.18	5.63	0.45	6.82	7.48	0.66	7.18	7.31	0.13	8.93	9.54	0.61
Low quartile	4.96	5.23	0.28	5.21	5.26	0.05	5.59	5.63	0.04	7.32	7.48	0.16	7.34	7.31	-0.03	9.49	9.54	0.05
Interquartile range	0.52			0.38			0.41			0.50			0.15			0.56		

Summer	**April–Sept**																	
	BH1			**BH2**			**BH3**			**BH6**			**BH7**			**BH11**		
	Dip	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**	**Dip**	**GL**	**WL**
Mean	4.57	5.23	-0.66	4.89	5.26	-0.37	5.28	5.63	0.35	7.01	7.48	0.47	7.15	7.31	0.16	9.16	9.54	0.38
SD	0.31			0.30			0.26			0.32			0.22			0.36		
Maximum	5.38	5.23	0.15	5.70	5.26	0.44	5.94	5.63	-0.31	7.88	7.48		7.59	7.31	-0.28	10.00	9.54	-0.46
Minimum	4.00	5.23	-1.23	4.40	5.26	-0.86	4.75	5.63	0.89	6.36	7.48	1.13	6.50	7.31	0.82	8.39	9.54	1.15
Upper quartile	4.33	5.23	-0.90	4.65	5.26	-0.61	5.07	5.63	0.56	6.78	7.48	0.70	7.02	7.31	0.30	8.92	9.54	0.63
Low quartile	4.76	5.23	-0.47	5.06	5.26	-0.20	5.45	5.63	0.18	7.24	7.48	0.24	7.32	7.31	-0.01	9.41	9.54	0.13
Interquartile range	0.43			0.41			0.38			0.47			0.31			0.49		

All measurements in metres; a positive Water level indicates depth of water above ground level, a negative number indicates depth of water below ground level; GL is measurement datum height above ground level.

Datum (m AOD)
2001–2003

Winter	**8.081** **Oct–March**			**8.718**		
	K (EA)			**L (EA)**		
	Dip	**GL**	**WL**	**Dip**	**GL**	**WL**
Mean	6.47	8.08	1.62	6.68	8.72	2.04
SD	0.04			0.04		
Max	6.51	8.08	1.58	6.74	8.72	1.98
Min	6.39	8.08	1.69	6.60	8.72	2.12
Upper quartile	6.44	8.08	1.64	6.66	8.72	2.06
Low quartile	6.50	8.08	1.58	6.72	8.72	2.00
Interquartile range	0.06			0.06		

Summer	**8.081** **April–Sept**			**8.718**		
	K (EA)			**L (EA)**		
	Dip	**GL**	**WL**	**Dip**	**GL**	**WL**
Mean	6.45	8.08	1.64	6.66	8.72	2.06
SD	0.04			0.04		
Max	6.49	8.08	1.59	6.71	8.72	2.01
Min	6.40	8.08	1.68	6.60	8.72	2.11
Upper quartile	6.41	8.08	1.67	6.62	8.72	2.10
Low quartile	6.48	8.08	1.60	6.70	8.72	2.02
Interquartile range	0.07			0.08		

Establishment of nutrient-chemistry guidelines

Background

Dune slacks are an oligotrophic (nutrient-poor) habitat in which the species assemblages are adapted to low levels of nutrient input (Grootjans *et al.*, 1996; Jones & Etherington, 1992; Sival, 1996). Research on calcareous dune slacks in the Netherlands suggests that the limiting nutrient is primarily nitrogen (N), but in some cases, the youngest dune slacks may be nitrogen and phosphorus (P) co-limited, shifting to nitrogen (N) limitation as soil development starts to occur (Lammerts & Grootjans, 1997; Lammerts *et al.*, 1999). Studies in the UK suggest that P is more limiting than N in the younger slacks (Willis, 1963). Elevated nutrient levels in groundwater may therefore alleviate N or P limitation and alter species composition and soil development in dune slacks where the rooting zone is in contact with groundwater.

Sources of nutrients are many and varied, but can be classed into four broad categories: atmospheric deposition, fertilisers, animal wastes, and industrial wastes. These enter groundwater primarily via leaching through soils, or as surface run-off or direct discharge into water bodies such as lakes and streams which subsequently feed the groundwater. Contaminated water impacts dune slacks as exogenous groundwater flowing into or under a dune system, or from pollution sources within or nearby the dune system.

Evidence of eutrophication in dune slacks

The practice of filtering river water through dune sand as a purification process in the Netherlands led to marked changes in nutrient levels in dune slacks. Long-term changes attributed to this process and to abstraction of groundwater include an increase in nitrophiles such as *Urtica dioica* and a decline in the base-loving (high pH) species of conservation interest (van Dijk, 1989). Lowering of the water table also promotes acidification by preventing the re-buffering of surface soil layers by calcareous-rich groundwater in winter. Such evidence suggests major potential impacts, but the combined effects of high nutrient inputs, water table lowering and acidification can not be separated in this case. Experiments with nutrient additions to dune slacks, including Willis (1963) and those reviewed in Lammerts & Grootjans (1997), show that nitrogen increases dominance of graminoids such as *Agrostis stolonifera, Calamagrostis epigejos*, and *Juncus* and *Carex* species, with some decline in forb species. However, most experiments used high doses of N applied to surface soils, or in mesocosms, and are of limited relevance for determining effects of nutrient enrichment from groundwater. Empirical evidence of the effects of nutrient enrichment on dune slack soils and vegetation is lacking and remains a knowledge gap, particularly with respect to nutrient inputs from groundwater.

Defining acceptable N concentrations

Most of the evidence discussed above relates to sources of nutrients other than groundwater, or is not solely attributable to groundwater. There is little published or anecdotal evidence which can be used to set acceptable levels of nutrient enrichment in groundwater based on observations of adverse impact. Therefore, the approach taken here is to use available data on nutrient concentrations, together with information on possible pollution sources, to define a ‘reference condition’ and possible deviations from that. There are insufficient data from which to define a reference condition for phosphorus, so the guidelines focus on nitrogen.

Assessment of acceptable N concentrations uses total inorganic nitrogen (TIN) since both nitrate and ammonium can contribute to the readily available N load. Ammonium concentrations can be locally important depending on the pollution source. For example, at St Fergus dunes in Scotland ammonium from a sea-bird roost constitutes the majority of TIN (Malcolm & Soulsby, 2001). Dissolved organic nitrogen (DON) is proportionally a large component of total N (> 75 %) in unpolluted groundwater (Jones *et al.*, 2005), but overall concentrations are generally low and it is less readily taken up by plants or bound in soil than inorganic nitrogen.

Figure D1 shows TIN concentrations plotted against chloride for data from 12 sand dune sites in England, Wales and Scotland, listed in Table D1. East and south coast sites with lower rainfall tend to have higher chloride concentrations, and this gives an indication of the extent to which N concentrations may be higher on the East coast as they are less diluted by rainfall compared with west coast sites. Dipwells with known or suspected contamination (for example, from springs, bird roosts or adjacent to other pollution sources) are given different symbols; none were affected by saline incursion.

Figure D1a shows the full range of TIN concentrations recorded, with the highest concentrations typical of lowland agricultural streams (Casey *et al.*, 1989). Figure D1b shows the same data but with greater resolution in the lower part of the scale. These data show that the groundwater sampled in most dipwells has a TIN concentration < 0.20 mg N L^{-1}, while the lowest concentration at a dipwell known or suspected to be contaminated from an identifiable source is just over 0.40 mg N L^{-1}. However, Stuyfzand (1993) analysing 'fossil' groundwater in the Netherlands suggests a pre-1910 concentration of 0.67 mg N L^{-1}. It is not clear why 'fossil' groundwater concentrations in the Netherlands should be so much higher than clean sites in the UK, although nitrogen fixation by the shrub *Hippophae rhamnoides* (sea buckthorn) may be a source.

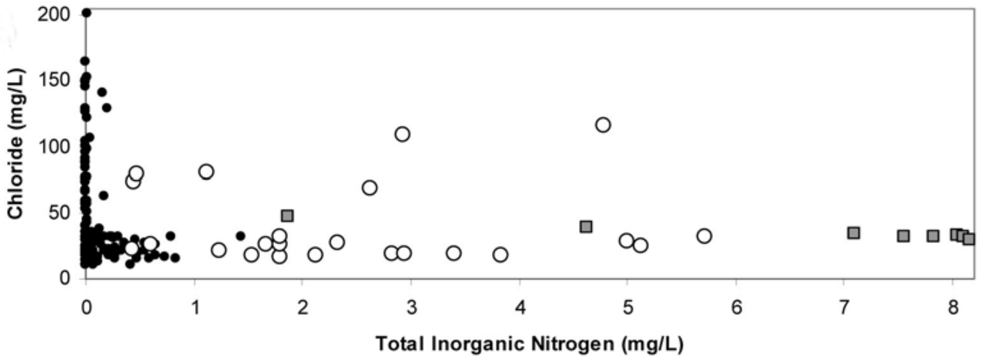
Table D1 gives a breakdown of the data by site and data source. While east coast sites are less well represented, it appears that they also show a reference condition of TIN concentrations < 0.20 mg N L^{-1}. With the exception of the two longer studies, most data were collected in summer when N leaching is lowest due to biological uptake of N. N. However the limited available evidence suggests there is little seasonal variation in nutrient concentrations in uncontaminated dipwells (Jones *et al.*, 2005). The table shows that some relatively unimpacted sites such as Newborough, Harlech and. Merthyr Mawr have a subset of dipwells showing slightly elevated TIN concentrations. In some cases this is attributable to a pollution source but not in others. The local scale heterogeneity that can occur highlights the need for slack-specific water chemistry determination and guards against assumptions that groundwater bodies beneath dune systems are uniform for example, (Jones *et al.*, 2006; Malcolm & Soulsby, 2001).

Suggested limits for TIN concentrations

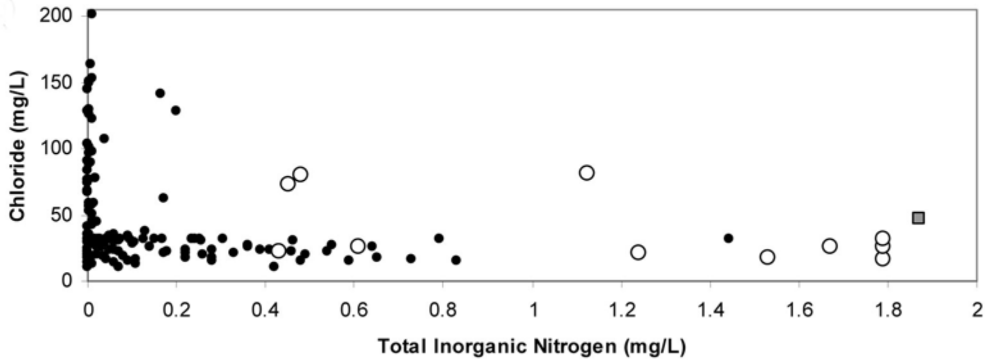
Dipwells at relatively unimpacted UK dune systems suggest a 'reference condition' of TIN concentrations < 0.20 mg N L^{-1}. Therefore, on the basis of deviation from a UK reference condition, and on data from contaminated dipwells, it is suggested that dune groundwater concentrations > 0.20 mg N L^{-1} are unusual, concentrations > 0.40 mg N L^{-1} may indicate contamination, and concentrations > 1.0 mg N L^{-1} indicate likely contamination and merit concern. It should be stressed that these recommendations are not made on the basis of adverse impact, since little or no data are currently available from the UK to guide such recommendations. It should also be noted in the context of setting up monitoring procedures that these concentrations are close to or below the detection limits for many routine water chemistry analyses by commercial companies.

Figure D1 Total inorganic nitrogen (TIN) concentrations in dune groundwater plotted against chloride concentrations

Data from 12 sites in England, Wales and Scotland, listed in Table D1



The same graph re-scaled giving greater resolution below 2 mg N L^{-1}



Coulet, 2007; Jones *et al.*, 2002a; Jones *et al.*, 2005; Malcolm & Soulsby, 2001; Mills, 2006.
Black squares are dipwells presumed to be uncontaminated, open circles are suspected contaminated, and grey squares are known to be contaminated.

Table D1 Mean and range (Min – Max) of total inorganic N (TIN) concentrations (mg N L^{-1}) at UK sand dune sites

Data Source		N	TIN Mean	(Min – Max)
	One off surveys			
(Jones *et al.*, 2002a)	Newborough	4	0.28	(0.03 – 0.79)
	Harlech	3	0.52	(0.03 – 1.44)
	Pembrey	2	0.06	(0.05 – 0.06)
	Kenfig	3	0.19	(0.03 – 0.31)
	Merthyr Mawr	3	0.04	(0.02 – 0.07)
	Ainsdale	3	0.04	(0.02 – 0.05)
	Studland	1	0.10	
	Great Yarmouth[1]	1	5.71	
	Winterton	1	0.17	
	Seaton	2	0.20	(0.15 – 0.24)
	Bamburgh	2	0.07	(0.01 – 0.13)
	Short duration or spatial studies			
(Mills, 2006)	Newborough[2]	7 wells, monthly (x 3)	0.29	(0.00 – 0.73)
(Coulet, 2007)	Winterton[2]	37 wells (x 1)	0.04	(0.00 – 0.46)
	Longer term studies (~1 year)			
(Jones *et al.*, 2005)	Merthyr Mawr (uncontaminated)	3 wells, monthly (x 13)	0.06	(0.00 – 0.55)
	Merthyr Mawr (suspected or known contaminated) [3]	5 wells, monthly (x 13)	2.56	(0.05 – 8.15)
(Malcolm & Soulsby, 2001)	St Fergus[4]	6 wells, monthly (x 12)	2.07	(0.45 – 4.78)

N = number of separate sampling points/dipwells.

[1] Adjacent to caravan park.
[2] Nitrate only.
[3] Adjacent to contaminated springs or sewage works.
[4] Adjacent to gas terminals and winter loch used as bird roost.

Factors affecting the risk of eutrophication

Exposure to exogenous groundwater sources in different dune system types

The potential for exposure to external sources of nutrients depends partly on the type of dune system. Hydrologically isolated systems such as Ainsdale (Edmondson *et al.*, 2007) and Braunton (Willis, 1959) are predominantly affected by atmospheric inputs, while bay dunes and other systems showing full or partial connectivity to inland groundwater have a much greater potential for exposure. East coast dune systems are generally narrow and aligned close to the shore due to their orientation relative to the prevailing winds. These types will have greater connectivity with groundwater from inland and increased exposure to polluted groundwater. Within the slack typology of Davy *et al.* (2006), the greatest exposure is in type E on the inland edge of a dune system, where half of the 'catchment' is non-dune habitat. While, the majority of UK dune slacks probably fall into types B and E where rainfall infiltrating the dunes is the primary influence, modified versions of type E may occur where the slack is contained within a dune system but exposed to groundwater from inland.

Local scale heterogeneity

Considerable within site heterogeneity in groundwater chemistry can occur, both in redox conditions and buffering capacity (Sival & Grootjans, 1996; Sival *et al.*, 1997) and in geochemistry including nutrient concentrations (Bakker & Nienhuis, 1990; Jones *et al.*, 2006). This can be caused by buried organic layers, patchiness in the calcareous materials available for weathering, patterns of groundwater flow in flow-through slacks, and complex groundwater sources (Jones *et al.*, 2006; Malcolm & Soulsby, 2001; Sival & Grootjans, 1996; Stuyfzand, 1993, 1999). Therefore, one or more slacks on a site may be exposed to contaminated groundwater, while others on the same site remain unaffected.

Nutrient inputs within the context of the whole nutrient budget

When considering the potential impact of a nutrient, it is necessary to look at the whole nutrient budget. Net inputs of P from other sources such as atmospheric deposition are low, similarly losses of P are low, although both P (and N) inputs from roosting water birds may cause local enrichment (Malcolm & Soulsby, 2001; Ranwell, 1959). Input and output pathways for N are more critical. Atmospheric deposition can provide a major input of N to dune systems, particularly on the east coast of the UK, downwind of both industrial and agricultural sources of N, where sites are likely to receive inputs in the range of 10–25 kg N ha^{-1} yr^{-1} (Jones *et al.*, 2002b). On many of the south-west facing dune systems on the western coasts of the UK, background N deposition is relatively low, and detailed measurements show that both Newborough Warren and Merthyr Mawr receive atmospheric inputs in the order of 10–11 kg N ha^{-1} yr^{-1} (Jones *et al.*, 2005; Jones *et al.*, 2008). This is comparatively low for much of England and Wales. However, even these levels of deposition bring N inputs within the lower end of the critical load range of 10–25 kg N ha^{-1} yr^{-1} defined for dune slacks (Achermann & Bobbink, 2003). Biological N fixation can also be a major input. In very young slacks, microbial mats are a source of N (Stal *et al.*, 1994). In established dunes, the N-fixing and often invasive shrub Hippophae rhamnoides can fix large quantities of N, up to 170 kg N ha^{-1} yr^{-1} (Stewart & Pearson, 1967). When leached, this N can also affect groundwater chemistry (Stuyfzand, 1993). Therefore, within the context of inputs from atmospheric deposition or biological fixation, additional inputs of N from groundwater may be sufficient to cause critical load exceedence.

The main loss pathways of N in dune slacks are leaching (measured at 3.4–4.4 kg N ha^{-1} yr^{-1} in a relatively unpolluted system. Jones *et al.*, 2005), and N2O emissions from de-nitrification, likely to be no more than 1–2 kg N ha^{-1} yr^{-1}, based on measurements in riparian buffer zones adjoining agricultural land. Denitrification is likely to be greatest in slacks where surface soils undergo frequent wetting and drying cycles, that is, where water levels are near the surface rather than slacks experiencing prolonged inundation. Adema *et al.* (2005) also show that denitrification is much higher around the rooting zone of plants with radial oxygen loss in early successional slacks. Mowing, with off-site removal of cuttings has been tried in a few sites for example, Kenfig and Braunton and in the Netherlands (Sival and Grootjans, 1996). It can be a major loss pathway, but is not common practice. Grazing may mediate some adverse effects by reducing dominance of nitrophiles, but is not a loss pathway as it does not remove nutrients from the system. Furthermore, some stock, such as ponies, may preferentially dung around watering areas, including slacks.

Loss terms may be important in evaluating site-specific exposure to elevated N, however they are not considered separately in the critical load calculations. They are implicit in the empirical observations of damage response at specified levels of N inputs.

Nutrient type and timing of exposure

The form of nutrients in groundwater is an important risk factor governing exposure. Phosphorus is readily bound to exchange sites on clay particles and organic matter, so contact of groundwater with slack soils may lead to adsorption of phosphorus. The availability of phosphorus compounds is pH dependent, being most available between pH 5 and 7, and less available outside that range, bound to iron and aluminium hydrous oxides below pH 5, and bound in calcium complexes above pH 7 (Brady & Weil, 1999). Like phosphorus, ammonium is readily bound to exchange sites in the soil. Both these nutrients therefore will remain in the soil and available for plant and microbial uptake later in the growing season. Nitrate, by contrast, is only weakly bound to exchange sites and is therefore highly mobile in soil. Nitrate will only be available for uptake by plant roots while the groundwater is within the rooting zone, which usually occurs in winter outside the main growing season. The nitrate is rapidly leached from the soil profile when the water table drops. Therefore, when considering nutrient impacts, both the type of nutrients and the timing of exposure may be important risk factors. To suggest a hierarchy of risk, ammonium and phosphorus are potentially a problem at any time of year due to retention within slack soils, while nitrate is primarily a problem where groundwater reaches the rooting zone during the growing season, and is most likely to have adverse impact in the wetter slacks where there is longer contact of groundwater with the rooting zone.

Summary

In summary, many factors influence the potential for adverse impacts caused by elevated nutrient levels in dune groundwater. These include: Age of the slack, which determines which nutrient is most limiting; The form of nutrient, which affects whether enrichment is temporary or has longer lasting effects; The timing of exposure relative to the growing season; The quantity of enrichment, in combination with other nutrient sources at the site, including atmospheric deposition; Site management such as mowing which may mitigate some effects of nutrient enrichment. Suggested guidelines for total inorganic nitrogen concentrations are given in Table D2 below, based on deviation from a reference condition. There are insufficient data from which to define a reference P concentration.

Table D2 Guidelines for total inorganic nitrogen (TIN) concentrations in dune groundwater

Status	TIN (mg N L $^{-1}$)
Reference condition	‹ 0.20
Possible contamination	0.20–0.40
Likely contamination and cause for concern	› 1.0

Recommendations for use of these guidelines

- Do not assume that groundwater (chemistry or water levels) is uniform under a dune system, or even within the same slack in the case of through-flow slacks.

- Where it is suspected that contaminated groundwater is affecting a slack, the following actions may help clarify the situation:

    - Establish a dipwell with regular monitoring or a datalogger to ascertain the water level regime relative to the ground surface and the rooting zone.

    - Get groundwater samples analysed for nutrient concentrations. Take both a summer and a winter sample, and ideally more often; nutrient concentrations may differ through the year. Use laboratories that have sufficiently accurate procedures and low detection limits to measure the low concentrations which may occur for ammonium and nitrate.

- Compare the results with the concentrations describing reference condition in Table D2 above. If they suggest contamination is likely, and the water level regime is such that the water table is in contact with the rooting zone then further action may be required.

- It may be possible to narrow down potential pollution sources; boron is often used as an indicator of sewage pollution; stable isotopes can also be used as tracers. Seek specialist advice.

- Local-scale management intervention may be possible, depending on the nature of the contamination. For example, long-term mowing or turf stripping will remove nutrients. Grazing may also be an option.

- Consider the slack within the context of the whole dune system. Small-scale enrichment may not be an issue, providing the impact is limited and stable.

Case study 1: Kenfig dunes and Merthyr Mawr, South Wales

Site description and management issues

Introduction

Kenfig Dunes National Nature Reserve (NNR) and Merthyr Mawr Warren form part of the larger Kenfig Special Area of Conservation (SAC), based on the presence of a series of habitats and species features listed under Annexes I and II of the EU Habitats and Species Directive. Kenfig is located around 5 km north-west of Porthcawl, on the eastern shoreline of Swansea Bay (Figure E1), while Merthyr Mawr lies immediately east of Porthcawl. Hydrological aspects of the case study focus on Kenfig, while nutrient chemistry aspects focus primarily on Merthyr Mawr.

Figure E1 Location of Kenfig dunes NNR

Figure E2 Slack No. 9 (after Jones, 1993), Kenfig Dunes NNR, September 2008

Water levels within the slacks were universally much higher than average for late summer as a result of above-average rainfall during summer 2008.

The humid dune slacks feature is a particularly important component at Kenfig and is represented by extensive and high quality examples (for example, Figure E2). It is strongly dependent on the shallow groundwater regime which maintains moist soils in the summer as well as periodic winter and spring inundation. The humid dune slacks also support formerly extensive but now declining populations of the two qualifying Annex II species represented at the site, the liverwort 'petalwort' *Petalophyllum ralfsii* and fen orchid *Liparis loeselii* (CCW, 2008).

Water level and basic climate monitoring at the site were initiated in the mid-1980s and continues to the present day. Interpretation of the results of this monitoring, along with wider hydrologically-related information, means that the hydrological regime is one of the better understood relative to other dune systems in England and Wales.

Environmental setting, Kenfig Dunes NNR

Kenfig NNR stretches 3 km north–south and 2–3 km east–west. The site represents the core part of a large hindshore-type dune system characterised by a dominantly west-east trending series of dune ridges and secondary (parabolic) dune slacks (Figure E3). Eighteen major parabolic slack complexes can be recognized, ranging from minor elements less than 100 m in length to larger forms which extend from the landward slope of the foredune ridge to the eastern boundary of the reserve.

Kenfig Pool, the largest (24 Ha) freshwater lake in South Wales, is located in the central, eastern part of the site. It is an expression of the dune system water table, is between 2 and 3 m deep, and its level fluctuates seasonally by c. 0.3 m.

The solid and drift geology underlying the site is complex. The general sequence from depth is:

- Carboniferous Limestones and Grits (major aquifer);
- Triassic Mudstones (aquitard);
- Glacial Till (aquitard);
- Glaciofluvial Sand and Gravels (minor aquifer);
- Estuarine Clays and Alluvium (organic-rich clays and silts with beds of peat)(aquitard);
- Blown Dune Sands (minor aquifer); ranging from 0 m to at least 5 m thick.

Investigations and monitoring

For his doctoral research Dr Peter Jones examined the phytosociology of dune slack communities at Kenfig, and the influence of hydrology upon composition and structure of the vegetation. During this project an intensive shallow groundwater monitoring network comprising over 100 shallow (c. 1 m) dipwells (Figure E3) was established across the site.

The west-east orientation of the dune ridges and elongate dune slack systems meant that a significant proportion of the dipwells were arranged in west-east transects. One of these, usually referred to as the 'main transect' (Figure E3), was chosen for monitoring on a more regular basis than the remainder of the network. It is fairly closely aligned to grid line easting 820 and passes from east to west through some of the best examples of dune slack habitat. The selection of the transect for more regular monitoring was made on the basis of the following criteria:

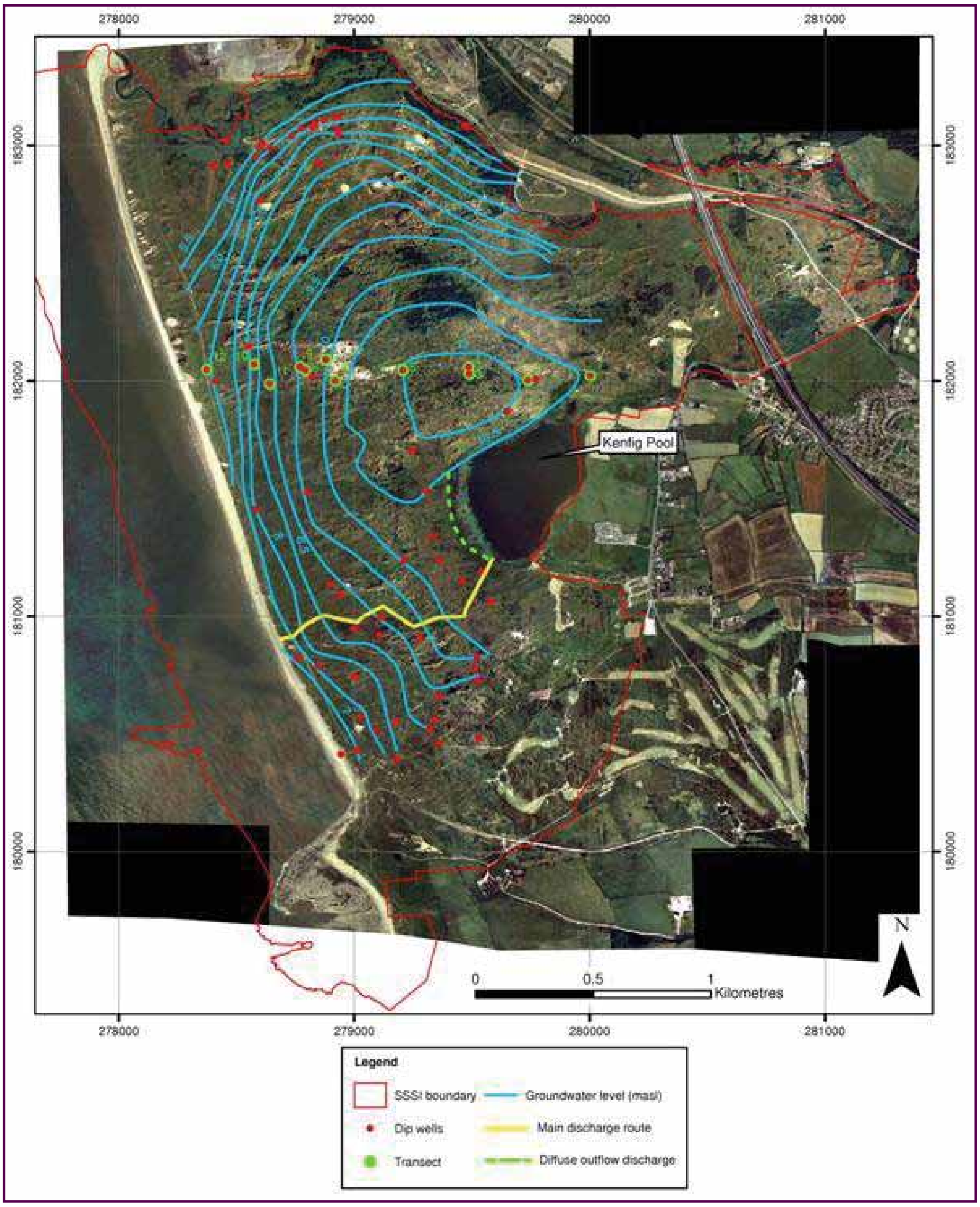
1. It passes through the groundwater dome of the superficial dune system aquifer (Jones, 1993 and Figure E3) and thus for monitoring purposes is suitable for assessing the seasonal and longer term dynamics of the dome in relation to climate and other factors.

2. It is coincident with the line of widest lateral development of the perennial unconfined aquifer of the lower dunes, where sand extends vertically some distance beneath the water table.

3. The route of the transect is relatively accessible, clear-cut and easily walked, which aids monitoring and surveying.

The transect initially (1986) comprised eight dipwells. More dipwells were gradually added, partly as a means of providing a degree of back-up between adjacent sites to cover losses due to vandalism, and also to track the gradual easterly development of young dune slacks in an active area of dune evolution at the seaward, western end of the transect as slack floors gradually stabilised. The transect currently comprises 12 dipwells.

Figure E3 Annotated aerial photograph of Kenfig Dunes NNR



Water levels along the transect have been monitored at varying frequencies (rarely less than monthly) since 1986, and the resulting dataset represents an extremely valuable resource in both site-specific and generic habitat-type contexts.

Investigations and monitoring in support of an assessment of possible hydrogeological impacts of large-scale dewatering of Cornelly Quarry (and associated quarries) (3 km east-south-east of Kenfig Dunes) supplied additional information about the groundwater system at and around the site from 2002 (see, for example, ESI, 2003). A number of observation boreholes were installed both within the site, and between the site and the quarry, to provide information for the impact assessment and to facilitate enhanced groundwater monitoring.

Rainfall has been measured continuously at the site since 2002, through a succession of different rain gauges in various positions.

Hydrology, Kenfig Dunes NNR

Hydrology, site scale

Contouring of dipwell water levels (Figure E3) shows that water levels within the dune slacks are local expressions of a groundwater mound (or dome) within the dune sand aquifer, as is Kenfig Pool. This groundwater mound is centred on a position around 500 m north-west of Kenfig Pool, and groundwater flows quasi-radially from this position within the dune sands.

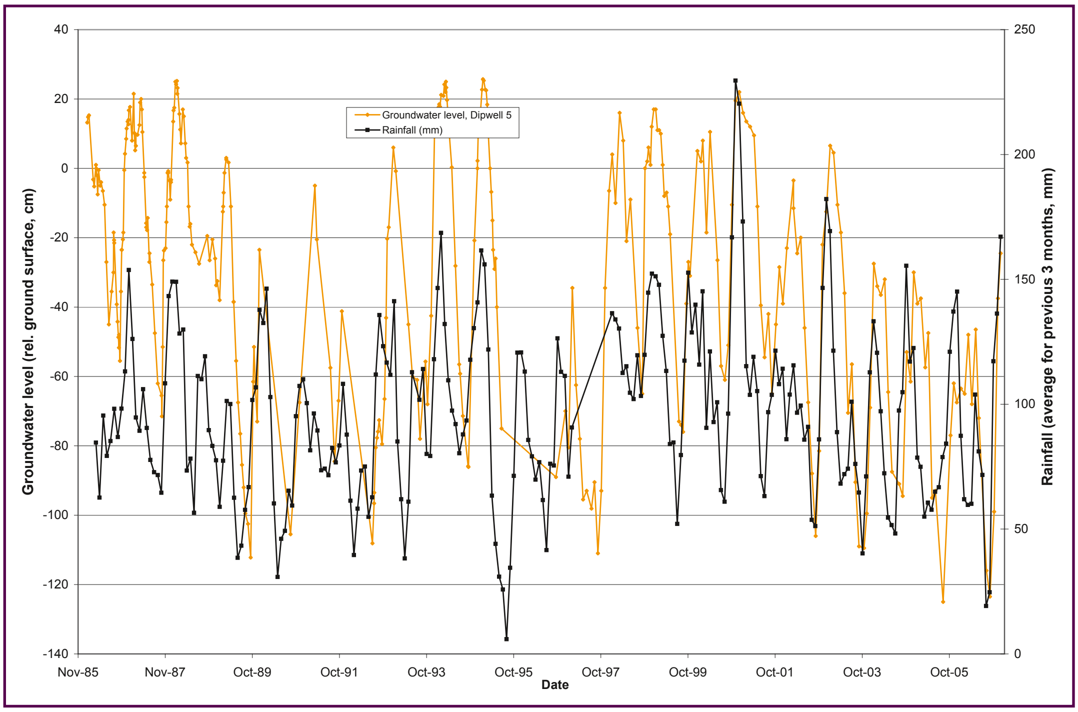
The dome of the dune sand groundwater mound is asymmetric in two respects: 1) the highest point lies east of the mid-point of the main transect, and 2) the dome dips more sharply and ultimately to a lower base level to the west than to the east (Figure E3). Both of these features are presumably related at least in part to the physiographic context of the dune system, namely that it is backed by higher-lying ground to the east, from which there is a surface water and/or groundwater supply. This contrasts with the classic strongly dome-shaped profile described by Willis (1959) for the Braunton Burrows (North Devon) system, which instead occupies an estuarine margin location backed by low-lying coastal grazing marsh.

From the available data, it appears that the amplitude of annual water level fluctuation is not related to proximity to Kenfig Pool, and therefore that the pool does not exert the ‘damping’ influence on water level fluctuations which might be expected.

An upper maximum water level is imposed on Kenfig Pool by overflow in the form of diffuse surface water discharges from the western side of the pool (Figure E3). The southernmost of these marks the start of a seasonal surface water flow route which eventually discharges to the beach via a pipe.

The dune sand aquifer is most probably hydraulically separated from the underlying Glaciofluvial Sand and Gravel aquifer over the majority of the site by a layer of Estuarine Clays. It therefore represents a largely independent system with the dominant water source being direct rainfall. To the north-east of Kenfig Pool however, the Glaciofluvial Sand and Gravel aquifer appears to be hydraulically connected both to the dune sands and the underlying solid geology (Carboniferous and Triassic formations). The role of this connection in terms of groundwater flows between the dune sands, the Glaciofluvial Sands and Gravels and the underlying Carboniferous and Triassic formations is currently uncertain (ESI, 2003).

Figure E4 **Long-term water level (Dipwell 5) & rainfall records, Kenfig Dunes NNR**



The Kenfig dune field continues east and eventually upslope of the groundwater mound towards the minor road between Pyle and Porthcawl, but in these areas the sands are much thinner and therefore the groundwater is transient and discontinuous.

Hydrology, dune slack scale

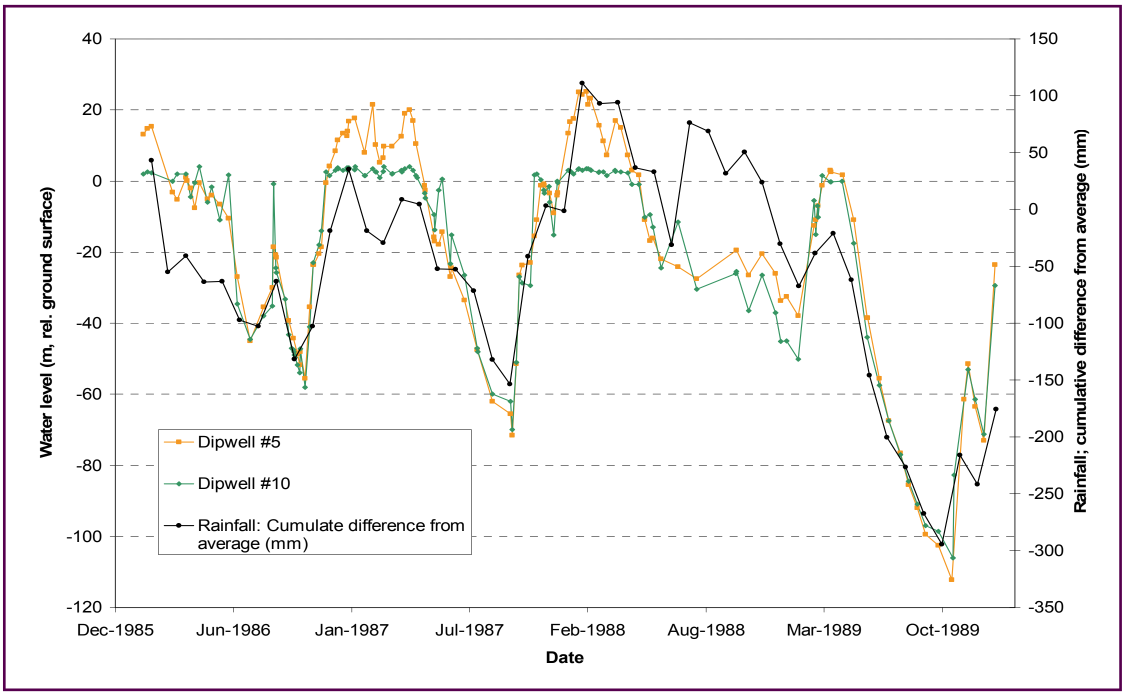
Figure E4 is a typical water level hydrograph for the dune slacks (for Dipwell 5 on the main transect) for the entire period of record. The water levels exhibit the expected annual cycle as a result of changes in the amount of precipitation and evapotranspiration. Water level minima usually occur in late summer or early autumn (August–October), and for most sites they represent substantially sub-surface water levels. Autumnal recharge, coupled with a decline in evapotranspiration, results in a usually fairly rapid rise in water table level and water levels approach or exceed ground surface typically between December and February. Flooding can extend well into the spring months and is sometimes marked by a mid-spring (April) maximum, but water levels are usually into the declining phase by May. Summer-time flooding is rare and largely confined to a small suite of slacks characterised by especially deep floors.

Figure E4 also includes, for each month, the average rainfall during that month and the preceding two months; it shows that there is a clear link between rainfall and groundwater levels.

Whilst the overall seasonal response of water levels in the various dune slacks is similar, there are some differences in detailed behaviour relating to local hydrological controls. Figure E5 shows higher frequency water level data (1986–89) for Dipwells 5 and 10. The hydrograph for Dipwell 5 is typical for the site, as discussed above. The hydrograph for Dipwell 10 differs in that the water level seems to be controlled at an upper maximum of around 4 cm above ground level. This level is maintained for lengthy periods which are expressed on the hydrograph as water level plateaus, and the behaviour is caused by surface water discharge from the dune slack in which the dipwell is located into an adjacent, lower, dune slack.

Through analysis of the water level data for 1986–89, Jones (1993) noted that the depth of winter flooding, the annual range of water levels, and the magnitude of monthly water level fluctuations vary considerably between slacks.

Figure E5 **Water level records, 1986–89, Dipwells 5 and 10, Kenfig Dunes NNR**



Slacks were referred to six hydrological types, as follows:

- **Type 1**; typified by very shallow winter flooding. During flooding the water table displays a subdued response to rainfall, with even prolonged periods of heavy rain only resulting in a relatively small change in the depth of flooding.
- **Type 2**; similar to Type 1, but floods to a greater depth. Depth of flooding for most dipwells lies between 10 and 25 cm.
- **Type 3**; deep winter flooding, and capillary fringe of the water table remained in contact with the soil throughout both 1986 and 1987.
- **Type 4**; extremely deep winter flooding – between 60 and 80 cm for much of the winter. Water table remained close to the surface even during late summer in 1986 and 1987 and, whilst water levels do fall to lower levels during dry summers, for practical purposes Type 4 slacks can be placed within Ranwell's (1972) semi-aquatic group of slacks where the water table always lies within 0.5 m of the soil surface.
- **Type 5**; exhibit a large annual groundwater range, and very marked fluctuations in level occur throughout the year. Very variable hydrological character, probably owing to the site-specific geomorphological location of slacks referable to this type.
- **Type 6**; occur rarely, winter flooding either absent or for a short duration.

It was found that all six groups also differed with respect to other key hydrological attributes, namely the duration of flooding, mean seasonal water levels and the annual range of water table elevation, implying that variations in the magnitude of each are fairly closely correlated. Figure E5 also includes a plot of monthly cumulative difference from average (January 1986 to December 1987) rainfall. The close relationship between this line and the water levels again demonstrates that rainfall is an important determinant of groundwater level.

Ecohydrology

Through characterisation and analysis of vegetation communities, hydrological regimes and hydrochemistry, Jones (1993) developed a slack classification system for Kenfig, based on the system proposed by Ranwell (1972), as follows:

- **Semiaquatic habitat**. Kenfig Hydrological Type 4 (see above). Water table only rarely falls more than 50 cm below the soil surface. Soils remain in contact with the water table throughout years with a normal distribution of rainfall, and may remain at field capacity for much of the summer period. Deep (up to 1.5 m) and prolonged flooding is typical.
- Soil redox potentials (at 5 cm depth) usually less than 50 mV throughout summer, with soils usually becoming reducing (-50 mV) during June and July.
- No clear NVC equivalent identified.
- **Wet slack habitat A**. Kenfig Hydrological Type 3. Water table rarely falls more than 1 m beneath the soil surface, and soils will remain in capillary contact throughout the summer months in years with normal rainfall. Winter flooding ranges from 0.1 m to 0.8 m in depth, usually extending into May.
- Soil redox potentials are usually less than 100 mV throughout the summer, and become reducing during June and July.
- NVC types SD 15 *Salix repens – Calliergon cuspidatum* and SD 17 *Potentilla anserine – Carex nigra* communities.
- **Wet slack habitat B**. Kenfig Hydrological Type 2. Water table rarely falls more than 1.3 m beneath soil surface, but soils usually do pass out of capillary contact with the water table during late summer. Winter flooding ranges from 0.05 to 0.2 m, and rarely extends into the early summer months.
- Soil redox potentials may range between 200 and 100 mV throughout the summer period.
- NVC types SD 14 *Salix repens – Campylium stellatum* community in young slacks and SD 15 *Salix repens – Calliergon cuspidatum* in older sites.

- SD 13 probably occurs within this slack type, based on descriptions from Rodwell (2000).
- **Wet slack habitat C**. Kenfig Hydrological Type 1. Similar to wet slack habitat B, but winter flooding is limited to less than 0.15 m depth, and is strictly regulated by surface water flow. The centre of parabolic slack complexes fall within this category.
- NVC types SD 14c *Salix repens – Campylium stellatum* community, *Bryum pseudotriquetrum-Aneura pinguis* sub-community.
- **Dry slack habitat A**. Kenfig Hydrological Type 6. Water table typically ranges between 0.2 and 1.4 m below ground surface, with flooding being rare and of short duration. Soils may fall out of capillary contact with the water table at any time from March onwards, and usually remain out of contact throughout the period of vegetative growth.
- Soil redox potentials never fall below 200 mV.
- NVC types SD 16 *Salix repens-Holcus lanatus* community.
- **Dry slack habitat B**. Not represented at Kenfig.

Factors affecting the hydrology, Kenfig Dunes NNR

The primary control on groundwater levels within the dune sand aquifer is climate, that is, rainfall and evapotranspiration, with some local geomorphological controls, as identified above.

Coastal erosion will gradually reduce the width of the dune system and initially could be expected to result in steeper water table gradients to seaward, particularly in the aftermath of any significant erosion events. Over time, the water table will re-equilibrate at a new lower level, suggesting that the seaward-most slacks at least are likely to become drier.

The potential impact on the hydrology of the site of proposed deeper quarrying and dewatering of Cornelly Quarry (and associated quarries) has been assessed by Tarmac Western Ltd (ESI, 2003). The main pathway for impact transmission is the Carboniferous Limestone, in which the quarries are established, which extends under Kenfig Dunes, as noted above. The assessment was necessarily complex, and its results were somewhat uncertain, both because of the potentially karstic nature of the Carboniferous Limestone and because of the uncertain hydraulic connection between the Carboniferous Limestone and the dune sand aquifer.

Factors affecting nutrient chemistry, focusing on Merthyr Mawr

The second large dune system within the same Special Area of Conservation (SAC), Merthyr Mawr, lies a few km to the south east of Kenfig Dunes. The groundwater nutrient chemistry was intensively studied at Merthyr Mawr over a period of a year (Jones *et al.,* 2005, 2006). Merthyr Mawr is also a hind-shore system but is backed by a faulted carboniferous limestone escarpment, from which two springs emerge, as well as diffuse groundwater seepage: Burrows Well is a sporadic spring, usually dry in summer but with very high flow in winter which flows out along a weakly defined channel, overflowing into two or three slacks, depending on flow volume. It is heavily contaminated with nitrate (NO_3-N concentrations up to 8 mg N L^{-1}).

Candlestone Spring flows for most of the year, at varying flow but only appears to be contaminated with nitrate at times of high flow. There are two other potential sources of nitrate at the site. The Pen Y Bont sewage treatment works lies on the eastern edge of the dunes, beside the River Ogwen, and takes sewage from Porthcawl which lies to the west of the dune system, via a pipe buried under the frontal dunes then north beneath the eastern part of the dune complex. The other potential source is the N-fixing shrub sea buckthorn (*Hippophae rhamnoides*) which, by the 1990s, had developed into extensive thickets across the site. Much of the *Hippophae* has now been cleared under a maintenance programme, but some stands remain and some are being retained as bird cover and for control of access. This combination of on-site and external potential pollution sources, together with a complex hydrological system feeding the groundwater under the dunes means that some slacks are exposed to contaminated groundwater for at least part of the year, while others remain relatively pristine. However, the effects of groundwater chemistry on the vegetation and soils have not been studied at Merthyr Mawr.

The groundwater nutrient chemistry at Kenfig is relatively unknown. A single survey in 2001 showed that total inorganic nitrogen (TIN) concentrations ranged from 0.03–0.31 mg N L^{-1}, and are therefore relatively clean (see main report section on groundwater chemistry).

Summary

The humid dune slacks feature at Kenfig is extensive, of high quality and of international importance. Water level and basic climate monitoring at the site was initiated in the mid-1980s and continues to the present day; the hydrological regime is one of the better understood relative to other dune systems in England and Wales, and the site is very important in terms of eco-hydrological studies on dune slack habitats.

Water levels within the dune slacks are a local expression of a groundwater mound developed within the dune sand aquifer. The groundwater mound is mainly rainfall-fed, although it is asymmetric, reflecting the supply of water from the landward, eastward side of the site into the dune system.

Based on their hydrological regimes, characterised by, for example, depth of winter flooding and amplitude of annual water level fluctuation, the dune slacks have been allocated to one of six hydrological types. These hydrological types map successfully to slack habitat types as characterised by NVC types, demonstrating that for this site at least a characteristic hydrological regime can be identified for single or grouped NVC types.

During the current project, local surveying was carried out to establish the difference in elevation between dipwell locations and the bases of adjacent slacks. Water level data were quality-assured and processed, and values for parameters which summarise the hydrological regimes were contributed to the national-scale dataset.

Case study highlights

- Water level and NVC data from Kenfig and Merthyr Mawr were used in the development of water level guidelines for dune slacks.
- Water chemistry data from Merthyr Mawr, and a few samples from Kenfig were used in the development of the nutrient chemistry guidelines for dune slacks.
- A 20+ year continuous monthly hydrological record exists for Kenfig Dunes.
- A detailed ecohydrological slack classification was developed for Kenfig by Peter Jones in the early 1990s, based partly on Ranwell's earlier classification (1959).

Key issues are:

- There is potential for lowering of water levels at Kenfig, due to lowering of the Cornelly Quarry.
- Eutrophication of winter seasonal springs and of groundwater occurs at Merthyr Mawr, but the impact on vegetation and soils has not been studied.

Case study 2: Morfa Dyffryn National Nature Reserve, West Wales

Site description and management issues

Background

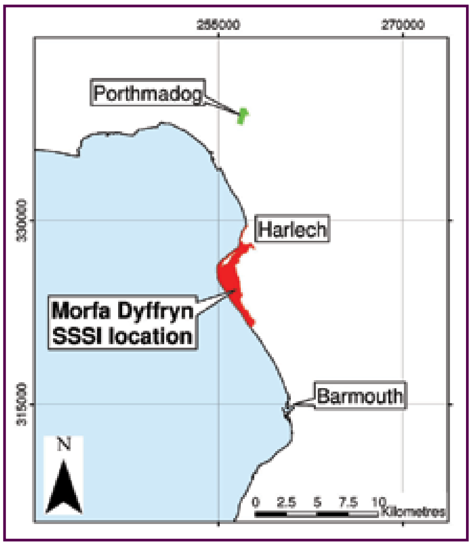
Morfa Dyffryn National Nature Reserve (NNR) along with Morfa Harlech, 7 km to the north form part of the 'Morfa Harlech a Morfa Dyffryn' Special Area of Conservation (SAC). Morfa Dyffryn is located on the central, western coast of Wales between Llanenddwyn (SH 580230) to the south and Llandanwg (SH 570285) to the north (Figure F1). Morfa Dyffryn is designated as a Special Area for Conservation (SAC) because of the presence of habitats listed under Annex 1 of the Conservation (Natural Habitats, &c.) Regulations 1994. These include Humid Dune Slacks (2170) and Dune Slacks with *Salix repens spp. argentea* (Salicion arenariae). Morfa Dyffryn was first notified as a Site of Special Scientific Interest in 1953.

Morfa Dyffryn is a highly dynamic dune system, with a wealth of mobile dune, bare sand and dune slacks. Marram grass mobile dune vegetation is extensively developed, both on the foredunes and the high dune ridges inland, and a range of scarce and rare plants is also represented on the slightly more stable and less exposed dunes inland.

The dune slack features at the site support nationally rare liverworts, including the Annex 2 listed *Petalophyllum ralfsii* and *Bryum mosses*, along with a range of rare orchids, helleborines and many other plants.

Morfa Dyffryn was first described from a geomorphological viewpoint by Lewis *et al.*(1938), but has received little attention in terms of environmental monitoring, characterisation or research since then. An important exception to this is the monitoring of dune sand water levels undertaken by the Countryside Council for Wales (CCW) since 1993.

Figure F1 Location of Morfa Dyffryn



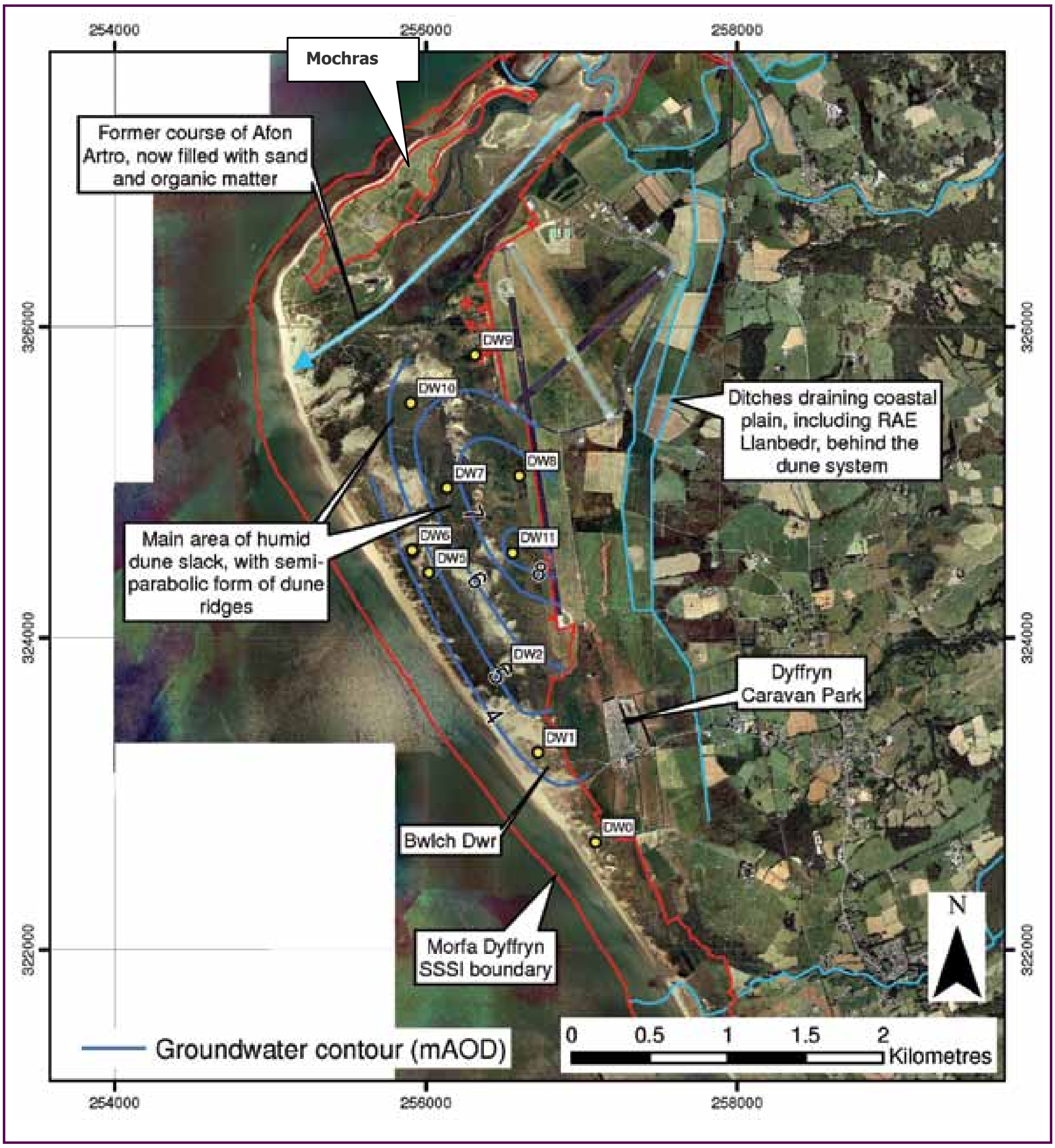
Environmental setting

The Morfa Dyffryn site has an area of 747.2ha. The beach and extensive dune system front a cuspate foreland (May, 2003), which is about 3 km wide at Llanbedr (Figure F2). Near its southern end the site comprises a narrow, fringing beach of shingle, cobbles and sand upon which there are low dunes. Northwards, the dunes are wider and higher, enclosing large slacks.

The coastal plain and estuaries in the vicinity of Morfa Dyffryn have been modified extensively by man in the past:

- In 1819 the Afon Artro was diverted to flow to the north of the morainic hill of Mochras (Figure F2), the latter formerly being an offshore island. By 1830, the northward longshore drift of sand, and accumulation of organic matter, had closed the former channel of the Artro, joining Mochras to the mainland.
- The construction of RAE Llanbedr (Figure F2) in the 1940s destroyed a large area of inland dune and salt marsh between the existing dunes and the break of slope at the base of the Rhinog mountain range.

Figure F2 **Morfa Dyffryn: Aerial photograph of the site with annotations**



Morfa Dyffryn is unusual amongst most English and Welsh sand dune sites as it is geomorphologically active, with extensive areas of bare sand and migrating dunes. The active dunes attain heights of 20 m, with semi-parabolic ridges enclosing large areas of slack habitat (Figures F2 and F3). Once dunes attain a critical height (Ranwell, 1972), they tend to migrate inland and blowouts become dominant. This behaviour causes problems with management of some aspects of the site, for example maintenance of an open drainage channel (Bwlch Dwr; Figure F2) through the dunes which removes water from the Dyffryn Caravan Park; migration of a large dune across this channel results in the need for regular drain re-excavation.

There is an extensive area of secondary dune slacks at Morfa Dyffryn which lies immediately landward of the foredune ridges. The slacks exhibit a wide range of successional development, and implied age; from mature, densely vegetated slacks through to sparsely vegetated embryonic slacks. A good example of the latter is located at the northern end of the site, close to Mochras, where the dunes are noted to be particularly active. At this point a large and active dune blowout has left a low flat deflation plain, enclosed by dune ridges, as shown in Figure F4. The fringe of damp sand around the area of standing water, maintained by the capillary rise above the water table which achieves a maximum height of 30–40 cm (Ranwell, 1959), can also be seen in Figure F4.

Figure F3 **Extensive dune slacks between tall parabolic dune ridges, Morfa Dyffryn**

The coastal plain which includes Morfa Dyffryn is underlain by Tertiary and Quaternary sediments dominated by silts and clays. The dune sands overlie these predominantly lowly permeable deposits. The eastern edge of the coastal plain is coincident with the north-south oriented Mochras fault, which throws up resistant Cambrian Harlech Grits which form the Rhinog mountain range immediately to the east.

Investigations and monitoring

Monitoring of water levels within the dune slacks within the site has been undertaken by CCW, and latterly by the Snowdonia National Park Authority. An initial series of six shallow (c. 2 m deep) (Figure F2) dipwells were installed in 1993, within or adjacent to dune slacks, along a south-east to north-west transect which follows the central axis of the dune system. Water levels were measured at roughly monthly frequency until 2001, when they were halted because of health and safety concerns over lone working. The data have been used to develop the ecohydrological guideline values reported elsewhere in this volume. A further four dipwells were installed (one at either end of the existing transect and two on RAE Llanbedr) during 2004.

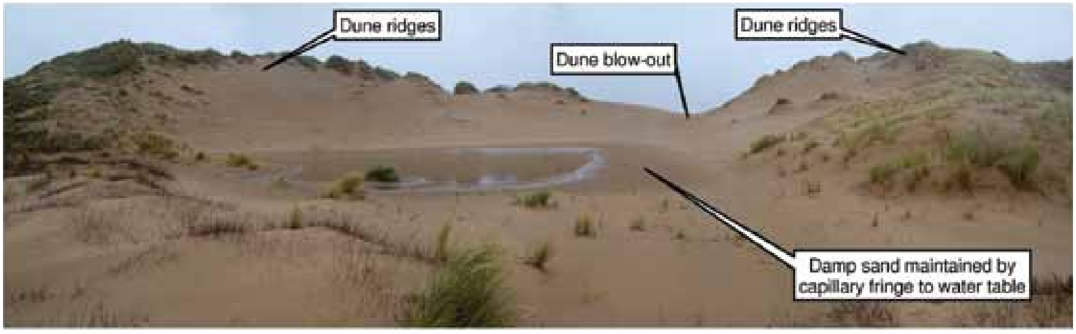
An investigation into the effects of the Environment Agency Wales-maintained drains on the hydrology of the site was ongoing at the time of writing. Actions had included the installation of two further dipwells (2008) and development of a scoping study hydrological conceptual model for the site.

Hydrology

Hydrology, site scale

The water level data suggest that there is a groundwater mound associated with the dune system, although there are currently insufficient control points (that is, dipwells) to ‘close’ this mound to the eastern side (Figure F2). It is also interesting to note that the mound is centred immediately to the east of, rather than in the centre of, the dune system. The water levels are lowered within the airfield by an extensive drainage system, and it might be expected that this would shift the centre of the groundwater mound within the dune to the west, but this is not the case. There is a westward hydraulic gradient through the whole of the central dune system, with water levels along the eastern edge of the central dune system being around 4 m higher than those along the western, seaward margin of the site.

Figure F4 **Embryonic dune slack at the northern end of the Morfa Dyffryn site, 2008**



Dune slack water level monitoring

Table F1 gives summary water level regime descriptors for the six original dipwells at Morfa Dyffryn for the period 1993 to 2001, and Figure F5 is a composite hydrograph showing the water level records for these dipwells. Of interest are:

- the average winter high water level for all six dipwells is below the ground surface. Reference to the full dataset shows that this average level is influenced significantly by the drier conditions during the mid-1990s. Water levels in dipwells 2, 4 and 5 regularly rose above the ground surface (by up to 50 cm) during the winters of the early- and late-1990s (for example, Dipwell 4, see Figure F5). The water levels in dipwells 1, 3 and 6 rose to the ground surface at the same times;
- the average annual range of water levels varies by 20 cm between the dipwells. This range is likely to be related to the positions of the dipwells within the wider dune system; it does not appear to be related to the average water level in relation to the ground surface;
- the dipwells can be divided into two classes in terms of water level regime, with average water levels in dipwells 2, 4 and 5 being 20–30 cm higher (relative to the ground surface) than those in dipwells 3 and 6. It is likely that the dune slacks in which dipwells 2, 4 and 5 are located were created by sand scour during a period of relatively low water levels, and those in which dipwells 3 and 6 are located were created during a period of relatively high water levels;
- the vegetation local to the dipwells is dominantly NVC SD16. SD15 is present at dipwell 2, one of the wetter slacks, which fits the wetter hydrological regime for this vegetation type. However, it is unclear why the other wetter slacks containing dipwells 4 and 5 are closer in character to SD16 rather than SD15;
- small-scale differences in water level behaviour can be identified in Figure F5; for example water levels in Dipwell 1 only rise to around the ground surface, whereupon they are likely to be controlled by lateral flow and discharge from the local dune slack.

It is worth noting that the sand dune system is active, and new slacks are being created continuously. The existing dipwells are located in the more established slacks and, as such, the vegetation assemblages and water level regimes in the youngest slacks are poorly represented; installation of further dipwells is planned to address this limitation in the network.

Figure F5 Water level hydrographs for Dipwells 1, 4 and 6, Morfa Dyffryn

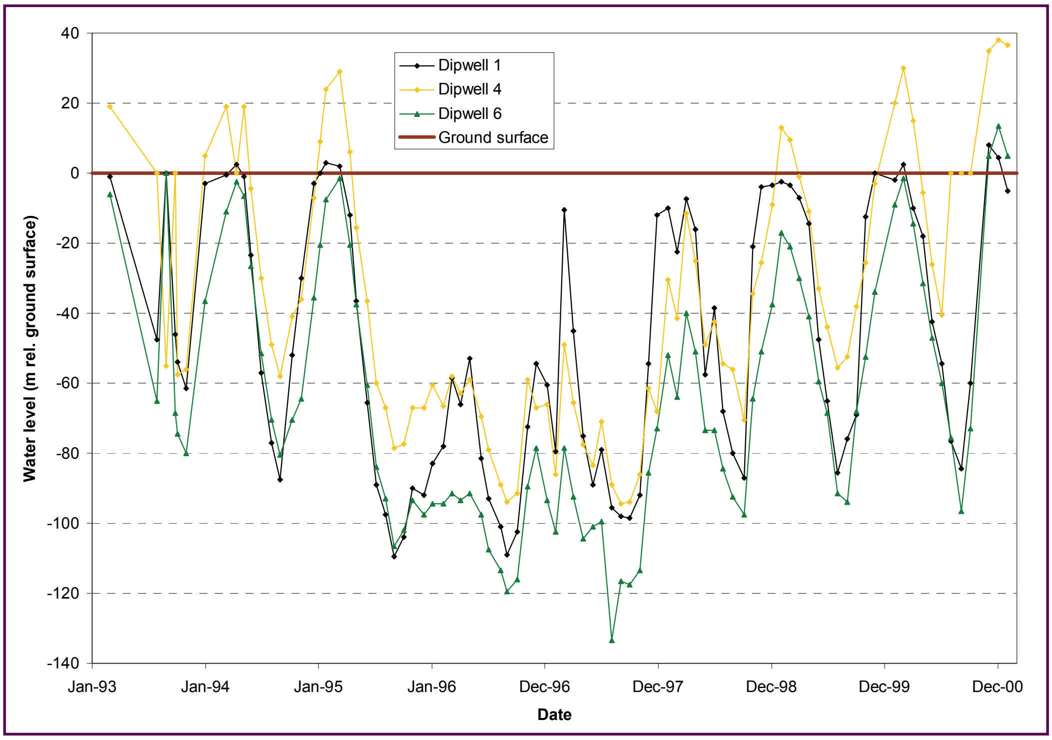


Table F1 **Water level regime descriptors (1993–2001) for dipwells at Morfa Dyffryn**

Dipwell	Average summer low*	Average winter high*	Average annual range (cm)	VNC type local to Dipwell
1	-94.5	-7.7	86.8	SD16
2	-80.8	-5.3	75.5	SD15
3	-104	-36.9	67.1	SD16
4	-70.2	-3.2	67.0	SD16
5	-77.8	-3.5	74.3	SD16
6	-104	-29.6	74.4	SD16

* cm above ground surface, that is, negative values indicate sub-surface water levels.

Factors affecting the hydrology

The dune slacks at the site are referred to hydrological types B and C (Davy *et al.*, 2006), and these are noted to be highly sensitive to hydrological change. The coastal plain and estuaries in the vicinity of Morfa Dyffryn have been modified extensively by man in the past, and these modifications have had hydrological consequences.

Historical changes

The re-direction of the Afon Artro to the north of Mochras (1819) resulted in relatively rapid filling of its former channel along the northern margin of the Morfa Dyffryn dune field with sediments and organic matter. The net effect of this change would have been to raise peripheral groundwater levels in this area, most probably resulting in a related rise in dune water levels in this vicinity. It would be very difficult to estimate the magnitude of this change with any confidence.

The area of coastal plain between the dune field and the foot of the western slope of the Rhinog mountain range has been extensively drained for agriculture and other uses. Figure F2 shows an extensive system of surface water drains running through this area, discharging mainly into the Arfon Artro to the north. A separate area to the south, encompassing a caravan park complex, is drained by an open channel (Bwlch Dwr) driven directly through the dunes. Surface water is also managed within RAE Llanbedr by an extensive series of drains.

One effect of the extensive drainage of the coastal plain inland of the dune complex is to lower the groundwater levels immediately to the east of the dune complex which support the groundwater mound within the dunes. In turn, this will most probably lower groundwater levels within the dunes, and therefore alter the water level regime within the dune slacks. Again, however, it would be difficult to estimate the magnitude of this change with any confidence.

Effects of morphological change

The site is currently the most mobile dune system in Wales. By analogy with other sites[13] such as Newborough, Merthyr Mawr and Kenfig, the dunes at Morfa Dyffryn were probably much more mobile in the 1950s than today. Therefore, many of the hydrological changes described above pre-date this period and most slacks will have developed under the new hydrological regimes. The most recent hydrological change is probably the ditch draining the caravan park, and this may be having some local impact on water tables.

Since the site is highly dynamic, and the slacks exhibit a wide range of successional development, there are relatively few worries about direct hydrological impacts. The site currently appears to be functioning as a healthy active dune system, in which context relatively minor changes in water level are not necessarily a threat because the natural dynamism means slack floors will be re-scoured down to the water table or new embryo slacks will be formed in the wake of

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[13] Based on aerial photographs and published literature.

migrating dunes. Nutrient enrichment may also be of less concern, as long as the dynamic nature of the site is maintained. This is because older enriched soils may become buried by advancing dunes, and because enough new early successional habitats are created to compensate for the enhanced successional and soil development which may result from nutrient enrichment of the older habitats (Jones *et al.* 2002a, 2002b, 2008; Plassmann, 2008).

Summary

Morfa Dyffryn is the most dynamic dune system in Wales, with a wealth of mobile dune, bare sand and dune slacks. Its dune slack habitats are of international importance, particularly as the dynamic nature of the site represents something close to the natural condition for dune slack creation and evolution. Despite the site's importance, it has received little recent attention in terms of monitoring and research, except for monitoring of water levels in a suite of shallow dipwells.

The dune slacks at Morfa Dyffryn exhibit a wide range of successional development, and implied age; from mature, densely vegetated slacks through to sparsely vegetated embryonic slacks.

The conceptual understanding of the dune sand groundwater system is somewhat uncertain. The dunes appear to support a groundwater mound, but it is centred to the east of the central area, between the central dunes and Lanbedr RAE airfield.

The hydrological regimes defined by the water level data vary appreciably between dipwells, with water levels in one set of dipwells generally being 20–30 cm higher relative to the ground surface than in another set. Vegetation local to the dipwells is predominantly NVC SD16, with one wetter slack being SD15, with the implication that the composition of dune slack vegetation may not be sensitive to differences in hydrological regime of this magnitude, at least in the short term. However, longer term shifts in vegetation community or changes in the abundance of component species can not be ruled out.

The coastal plain and estuaries in the vicinity of Morfa Dyffryn have been modified extensively by man in the past, with hydrological consequences. However, it is thought that the dynamic nature of the dunes will have limited the hydrological impacts on the dune slacks, primarily because the elevation of the ground surface will have evolved such that the relationship between the ground surface and the water table would remain fairly constant.

Case study highlights

- Water level and NVC data from Morfa Dyffryn and Morfa Harlech were used in the development of water level guidelines for dune slacks.
- Limited water chemistry data from Morfa Harlech was used in the development of the nutrient chemistry guidelines for dune slacks.
- Morfa Dyffryn is one of the most dynamic dune systems in England and Wales, with a large area of dune slacks of varying age, with new embryonic slacks being formed.
- Winter water levels differ by around 20 cm between slacks with the same vegetation community. However, detailed differences in vegetation composition between these slacks have not been studied.

Key issues are:

- The high mobility of the site, with new slack features being formed naturally, means that the system currently has the potential to adapt to changes in water level regimes.

Case study 3: Newborough Warren and Aberffraw, North Wales

Site description and management issues

Background

Newborough Warren and Aberffraw dunes, situated in the south west corner of Anglesey, form part of the 'Abermenai to Aberffraw Dunes' Special Area of Conservation (SAC). The SAC is designated for, amongst other things, the extent, variety and condition of its Humid Dune Slacks (2170) and Dune Slacks with *Salix repens spp. argentea* (Salicion arenariae). It is also a valuable recreational amenity. Newborough Warren was the focus for much of the early dune hydro logical work in the UK, conducted by Derek Ranwell, and the hydrological aspects of this case study focus on Newborough. The nearby dunes of Aberffraw are of interest to the case study primarily due to potential eutrophication of the groundwater underlying the dunes, although these issues are also of concern in parts of Newborough.

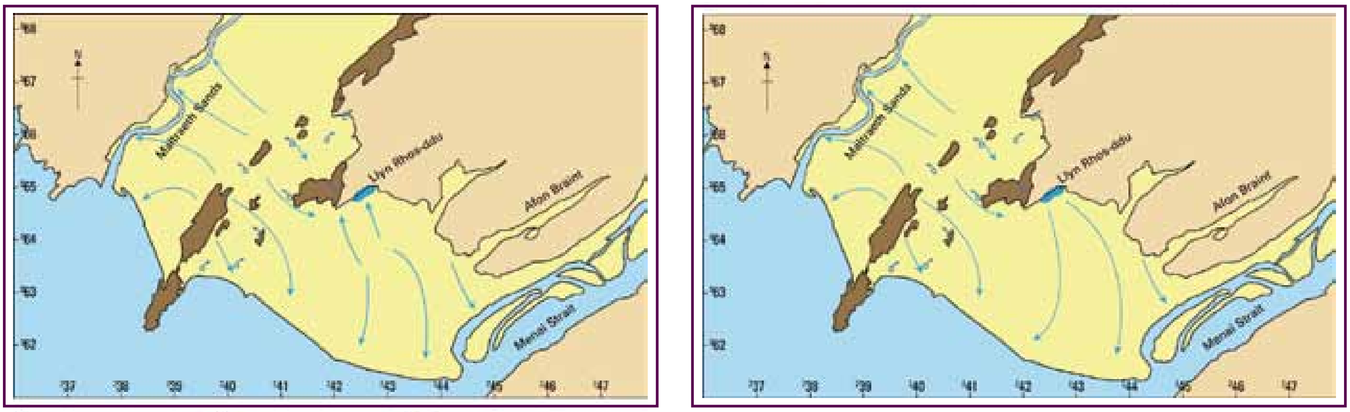
Newborough Warren is a coastal area of late-glacial blown sand dunes over weakly permeable glacial till. The bedrock underlying the warren comprises weakly permeable Palaeozoic and Precambrian strata. The overlying dunes reach a maximum thickness of 15 m rising to over 30 m elevation in the vicinity of a rock ridge that traverses the western part of the dunes. The dune field abuts a west facing and south west facing coast so that the coastal dunes receive the full force of the prevailing maritime westerly winds. The warren was partly forested with Corsican pine (*Pinus nigra var. laricio*) between 1948 and 1965 in an attempt to stabilise the dunes. The plantation has attracted red squirrels which, now supplemented by a breeding programme, provide a powerful motive for woodland management. The total area of dunes comprises some 1300 ha of which the northern 700 ha is now managed plantation and the southern part left as open dune land.

Hydrological setting, Newborough

There is a rock ridge running from south west to north east through the dunes, with a significantly lower hydraulic conductivity than the sands. It forms a groundwater divide which splits the hydraulics of the dunes into two distinct parts (Figure G1). The potentiometric surface is draped over the rock ridge rather in the manner of a tent ridge pole, with groundwater flowing off its flanks into the sand. There is a small lake, Llyn Rhos-ddu, on the northern edge of the open warren, which receives drainage both from the warren and the higher ground inland. A groundwater divide lying to the south of Llyn Rhos-ddu migrates northwards towards the lake during drier (summer) conditions. The lake, therefore, feeds the groundwater system in summer but gains from groundwater in the winter because the lake acts as a near fixed head whereas the dune water table elevation fluctuates above and below this level.

Hollingham (2006) reports that the potentiometric level beneath the trees is higher and more 'flashy' than in the Warren, probably due to runoff from the rock ridge, and that interception and evaporation by the trees is masked by this effect. The foreshore around the warren, which measures about 180 m wide at low tide, is an important part of the groundwater flow system. Groundwater discharges to the foreshore as the tide.

Figure G1 **Winter (top) and summer (bottom) conceptual flow models for Newborough Warren showing ephemeral springs where bedrock intercepts groundwater flow in the sands**



The sand cover is shown in yellow, the rock ridge in brown, and the sea below low water mark in blue, the foreshore being an important part of the groundwater flow system.

recedes and is an active drainage area for the system with fresh water discharging to the foreshore at low tide or seeping over the till surface where the till is exposed adjacent to the Afon Braint estuary at the eastern shoreline. To the north west the dunes are bounded by sandflats at the mouth of the Malltraeth estuary and to the north east by salt marsh. The base of the system is the upper surface of the till, although in the vicinity of the rock ridge it is bedrock. Available borehole data indicate an inhomogeneous sand containing fossil slack soils and other thin silty and peaty horizons. This coast is currently subject to erosion, a recurring feature first reported by Ranwell (1958). There is no saline incursion, or tidal influence on groundwater levels at the site (Ranwell, 1959).

The elevation of the water table across the site is determined by a combination of rainfall and evaporation, and the subsurface movement of water. Dipwell data show that there is considerable heterogeneity in water level across the site. Ranwell (1959) described widespread flooding of the slacks in the wet winter of 1950–1951 and an annual fluctuation in water table elevation of between 0.7 and 1.0 m, although data presented by Ranwell show only two slacks where the water table was above ground surface during 1951–1953. He described the groundwater response to a single rainfall event and equated the rise in water level in the slack to be in response to direct rainfall plus discharge from the recharged groundwater 'dome' between the slacks (the interfluves), reflecting a rapid recharge discharge mechanism within the sand aquifer. A study of diurnal variation revealed a 2–3 cm increase in water levels after sunset (Ranwell, 1959), providing evidence for a degree of direct influence of evapotranspiration on groundwater levels. Hydrological regimes at the site appear to have changed over time. By the 1970s anecdotal evidence suggests that the dune slacks were trending towards a drier phase (Hollingham, 2006), corresponding to a period of less than long term average (LTA) rainfall. However, since 2000, annual rainfall has tended to be greater than LTA and flooding of some of the slacks in the Warren has recurred, but not in slacks in the forest.

Ecohydrology, Newborough

Newborough Warren is one of only three sites in England and Wales to have representation of all five NVC slack communities. By far the dominant in extent is SD16 (*Salix repens – Holcus lanatus* dune slack) comprising 75 % of slack area, with SD14 (*Salix repens – Campylium stellatum*) and SD15 (*Salix repens – Calliergon cuspidatum*) next most abundant with ca. 11 % of slack area each (Dargie, 1995).

The dune slacks and their hydrological regime were studied in detail by Ranwell (1959). He collected depth-to-water-table data from 18 sites across Newborough between 1951 and 1953 and identified three distinct annual phases of the water table. The high-level phase, when there is either dune slack flooding or the water table is close to the surface, lasts from November to April, the water table then falls between April and August before recovering from August through to November. Ranwell described three main slack types, based on the water level regime and species assemblages in seven dune slacks monitored over 2.5 years (Table G1).

Analysis of more recent dipwell data against Ranwell's water table condition definitions indicates that in general the water levels in the slacks fall somewhere between the 'Wet Slack' and 'Dry Slack' definitions with the summer water table typically falling to between 1 and 2 metres from the surface. It should be noted however that as Ranwell's definitions were based on data collected from a wet period that it is possible that the water table at this time was unusually high.

Direct comparisons of recent measurements with those of Ranwell (1959) are only possible for one slack, (Ranwell's Slack A, site 8 (nearest current dipwell: nw5/2f)). Water level data for dipwell 2f are presented along with rainfall in Figure G2. The average annual range in water table measured over the period 1989–1995 was 75 (+/- s.d. 26.7 cm), while Ranwell's measurements give an annual range of 75 cm in 1951. Ranwell showed the winter maximum water table close to ground surface, while recent data from 2005–2006 showed an average winter maximum water table 2.5 cm above the ground surface (annual range in this period was 90 (+/- s.d. 12.7 cm).

Factors affecting the hydrology, focusing on Newborough

One of the big management issues at Newborough is whether the trees are overdrawing the available groundwater beneath the afforested dunes so lowering the water table, and what is the magnitude of any consequent effect on the open warren area. In this context it is often reported that the slacks regularly flooded in the 1950s. However, of the seven slacks studied intensively by Ranwell, only one showed maximum water levels consistently above ground level in winter, and only in January and February. The extensive flooding in the winter of 1950/51 is described in Ranwell's thesis (Ranwell, 1955) as an exceptional event in the memory of locals who had lived there more than 30 years. Other factors than afforestation may contribute to the reduction in elevation of the water table and the consequent drying out of some of the dune slacks (Stratford *et al.*, 2007). Hollingham (2006) also considered the prevailing causes and effects controlling the hydraulic environment at Newborough Warren over time, including alteration of drainage patterns and lake levels around Llyn Rhos Ddu. Clearly, the hydrological responses at Newborough are complex. A number of factors are likely to alter the hydrological regime and these are discussed below: altered climatic patterns, digging of drainage ditches, successional development of vegetation and soils leading to increased evapotranspiration, and morphological change. In addition, possible nutrient enrichment may impact on the local ecology.

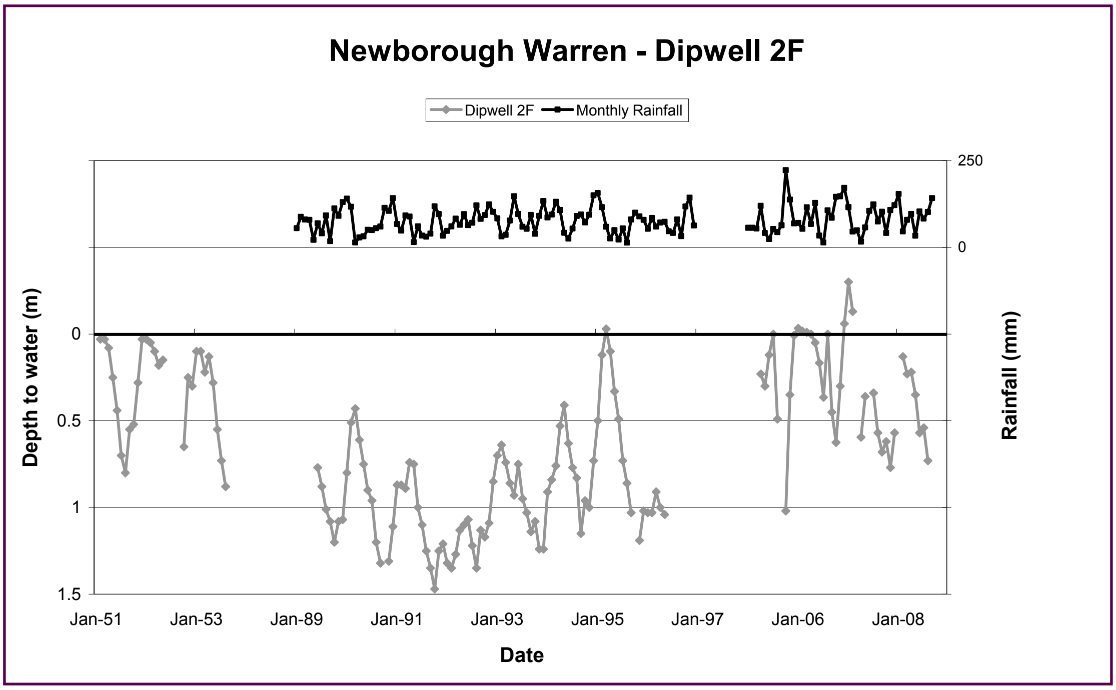
Maturation and successional development

Since the 1940s, the warren has progressively stabilised. Jones *et al.* (2007) show that the onset of stabilisation preceded myxomatosis and has a strong climatic influence, although the demise of the rabbit population through myxomatosis and control of the rabbit population by the foresters has probably assisted the stabilisation of the dunes (Ranwell 1955, 1960). Much of the mobile system described by Ranwell in the 1950s has now been transformed to a more stable dune field, with the proportion of bare sand reducing from 70 % to around 6 % since 1951 (Rhind *et al.*, 2001; Rhind *et al.*, 2007), and the forested area is now entirely stabilised. Increased vegetation cover and soil organic matter content will have led to increased interception and evapotranspiration of rainfall, leading to reduced recharge over the whole warren area. In the warren area, this will have been at its maximum in the mid 1980s when rank grassland covered most of the site, with some scattered shrubs (Hodgkin, 1984), and prior to the introduction of large-scale grazing (see below).

Table G1 **The water table conditions for defining wet and dry slack and dune associes (after Ranwell, 1959)**

Plant associes	Water table condition
Wet Slack (semi-aquatic)	Normally flooded for the entire winter, and waterlogged in the region of their roots for practically the whole summer. The water table is never below 50 or 60 cm in the driest periods.
Wet Slack	The summer (free) water table does not fall below 1 m from the surface.
Dry Slack	The summer water table is between 1 and 2 m from the surface.
Dune	The summer water table is below 2 m from the surface.

Figure G2 Time series of monthly dipwell for slack A and corresponding rainfall data



Three separate datasets are shown, x axis not continuous: Data collected by Ranwell (1951 to 1953); Data collected by CCW (1989 to 1996); and Data collected by Hollingham (2005 to present). Dipwell 2F is situated in Ranwell's slack A, site 8.

Afforestation

It is widely accepted that trees of almost any kind will increase the evapotranspiration over and above that of open or short grassed dunes. Evidence from case studies described in the literature suggests that this may be up to a fourfold increase in the case of trees with ready access to soil moisture. At Newborough, recharge beneath the forest is expected to be between 100 and 200 mm yr^{-1} less than that under short dune vegetation. The water use of the forested area is also influenced by factors such as forest age (evapotranspiration decreasing as trees reach maturity), the amount of exposed forest edge and the proximity to advected energy from the nearby ocean, increased canopy roughness and development of understorey and groundlayer vegetation associated with forest thinning. The slacks within the forested area have dried considerably since afforestation, aided by drainage ditches dug in some slacks before planting. The knock-on effects on water levels beneath the open dunes are less clear and hinge mainly on reduced drainage from the rock ridge. There is currently modelling work ongoing to better understand the influence of forestry on water levels at Newborough (Low & Taylor, Report in prep).

Grazing

Grazing patterns have also modified the vegetation on the open duneland and consequently the level of recharge to the groundwater. Subsequent to the reintroduction of sheep, cattle, ponies since 1986, an element of fixed dune grassland with shorter grass has evolved across large parts of the site. Large-scale managed grazing post 1986 will have reduced evapotranspiration slightly compared with the tall grass and scattered scrub present beforehand, potentially contributing to greater recharge.

Climatic influence

Long term average (LTA) rainfall recorded at RAF Valley, a coastal meteorological station 10 kilometres from Newborough is 847 mm. Although LTA rainfall has remained unchanged over the 45 year period up until 2005 (linear decline in average rainfall was -2.27 mm), there are clear patterns of change in rainfall within that period (Figure G3). The 1950s and 1960s were slightly wetter than the long term average, followed by a period of drier more stable climate between 1970 and 1995. The period since 1995 has been generally wetter than the previous forty years, particularly in autumn, and flooding of some dune slacks has now recurred. There are also changes in the seasonal pattern of rainfall over that period with a trend towards wetter spring and autumn periods and drier summer and winter periods. Clearly both decadal and seasonal rainfall patterns have changed over time and this will have influenced water levels at Newborough Warren.

Coastal Erosion

Shoreline erosion is likely to reduce the area of the Warren and reduce the volume of water that can be stored in the sand aquifer. Erosion is predicted to result in a loss of 50 m of shoreline by 2100 (Pye and Saye, 2005). This reduction in area causes a reduction in the elevation of the water table as the base of the aquifer moves slowly inwards. This effect will be greatest nearest the shoreline, decreasing rapidly inland.

Morphological change

Changes in landforms over time can alter slack floors, and their relationship with the water table. Figure G4 shows an example of three intermittent erosion phases in one dune slack. The level at which the slack floor stabilises depends on the water level at the time of erosion. Therefore, all three phases may produce slack floors at different elevations. Once established, slack floor levels may be modified, either lowered through erosion and re-scouring, or raised through deposition of wind-blown sand. Ranwell (1955) describes one slack floor raised by 20 cm over only two years by wind-blown sand. These factors may make comparisons of water levels over time difficult unless they can be accurately accounted for.

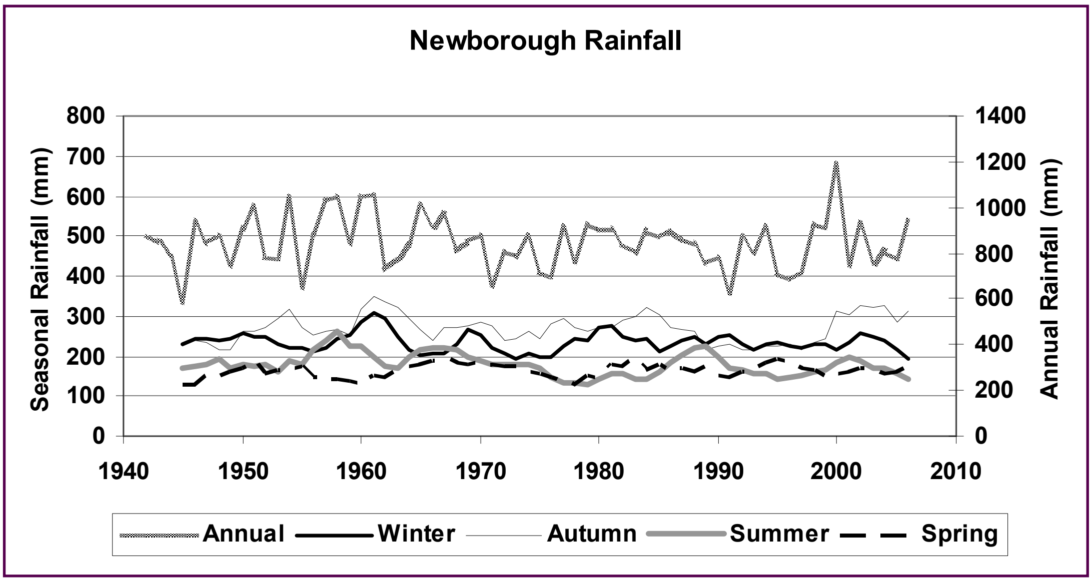
Other factors

The hydraulic history of the warren is complex. Anecdotal evidence indicates that the small lake, Llyn Rhos-ddu (see Figure G1), has possessed various levels over the last 60 years as the retaining structure has been modified. However, accurate lake stages have not been recorded. Drainage ditches near the inland edge of the Warren have also been modified over time.

Factors affecting the nutrient chemistry, focusing on Aberffraw and Newborough

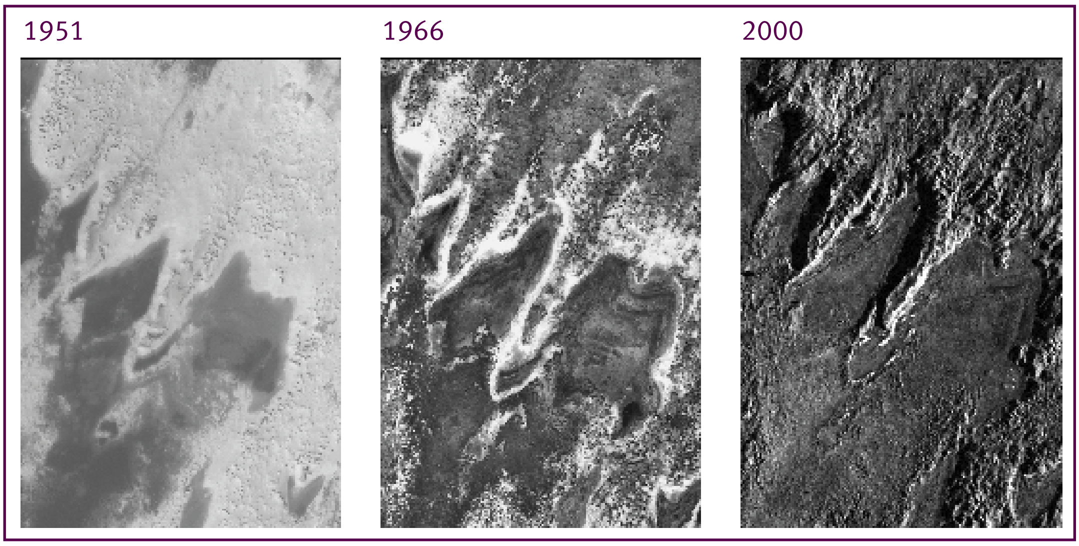
Newborough Warren forms part of a larger SAC together with Aberffraw dunes a few km to the north west. Groundwater chemistry at Newborough is reasonably well characterised. The majority of dipwells in the open warren show TIN concentrations < 0.20 mg N L^{-1} (see section in main report on nutrients). However, some dipwells show nitrate-N (NO_3-N) concentrations up to 0.73 mg N L^{-1} and one in the forested area near a cottage shows very high NO_3-N concentrations (~ 18.2 mg N L^{-1}) and is clearly contaminated (Mills, 2006). Aberffraw dunes have a larger eutrophication problem, although the groundwater chemistry is not well studied. A lake, Llyn Coron bounds the north east edge of the dune system and has oxidised N concentrations (nitrate-N plus nitrite-N) around 1.43 mg N L^{-1}. Seepage from the lake is likely to feed the groundwater below the dunes. The stream Afon Ffraw borders the north west edge of the dunes from the lake to the sea, with higher agricultural land on the other side, this has oxidised N concentrations ranging from 0.2–5.57 mg N L^{-1}.

Figure G3 **Patterns in annual and seasonal rainfall recorded at RAF Valley, 1945–2005**



Three-month seasons defined as: Autumn (Sep–Nov), Winter (Dec–Feb), Spring (Mar–May), Summer (Jun–Aug).

Figure G4 **Successive erosion phases in a dune slack at Newborough Warren**



At present the Afon Ffraw drains the groundwater body, but a planned conservation objective to re-wet some of the slacks by raising the river level with a sluice would mean that this eutrophic water would feed the groundwater body. Another stream, the Frechwen, drains agricultural land to the south east and runs across the inland part of the dune system to join the Fraw below the lake. Oxidised N levels in the Frechwen range from 2.2–5.8 mg N L^{-1}. Management of agricultural land in the surrounding catchment around Aberffraw poses considerable concern, specifically practices such as the spreading of sewage sludge, chicken manure and abattoir waste to grazing land. Despite such elevated nutrient levels, there has been little study of the groundwater chemistry or potential adverse impacts on the slack vegetation to date. This is urgently required and may help inform guidelines on nutrient levels in dune groundwater.

Summary

Groundwater hydrological regimes at Newborough Warren have changed over time due to a number of interacting factors. Decadal- and seasonal-scale patterns of rainfall are probably responsible for the majority of this variation. Other influences include increased evapotranspiration by afforestation and successional development of dune soils and vegetation, morphological change, forest and dune management, and human alteration of surface drainage around the site. Afforestation has lowered the water table below the forest, but the wider effects on recharge to the open warren area have yet to be reliably quantified. There are potential eutrophication issues both at Newborough and within the wider SAC at Aberffraw dunes.

Case study highlights

- Water level and NVC data from Newborough were used in the development of water level guidelines for dune slacks.
- Water chemistry data from Newborough were used in the development of the nutrient chemistry guidelines for dune slacks.
- Climate exerts the strongest influence on water levels in the open Warren at Newborough.
- Interpretation of changes in water level regime over time must take into account factors such as: geomorphological change, and successional development of soils and vegetation.

Key issues are:

- Effects of forestry on water levels at Newborough: Modelling and water level observations suggest that forestry has lowered water levels beneath the forest. However, the extent of any wider impact on the open Warren is less certain.
- Eutrophication of groundwater at Aberffraw and Newborough arising from surrounding land-use.

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