Ecohydrological studies of dune slack vegetation at Kenfig dunes, South Wales, UK.

P.S. Jones*1, G.Farr2, R. Low3 & J.R. Etherington4.

* P. S. Jones

Peter.S.Jones@cyfoethnaturiolcymru.gov.uk
1 Natural Resources Wales, Maes y Ffynnon, Penrhosgarnedd, Bangor LL57 2DW, UK
2 British Geological Survey, Room 073, Cardiff University Main Building, Cardiff CF10 3AT, UK
3 Rigare Ltd, 28 Grosvenor Road, Abergavenny, Monmouthshire NP76AH, UK
4 Parc y Bont, Solva, Pembrokeshire SA62 6XX, UK

1. Introduction

Kenfig Special Area of Conservation (SAC) and National Nature Reserve (NNR) (UK National Grid Reference SS 792820) forms the larger part of an extensive c. 720 ha dune system located on the west facing coast of Swansea Bay in South Wales (Figure 1). The site is a classic example of a hindshore dune system (Ranwell & Boar, 1986; Doody, 2001) and bears a complex series of both well defined and more obscure overlapping dune ridges and secondary (parabolic) slacks aligned approximately west to east. The site comprises two general physiographic elements; dune sand blown inland up to 3 km from the coast overlying glacial till draped over bedrock comprising of Triassic Mercia Mudstone formation and Carboniferous Oxwich Head Limestone formation geology, and a c. 430 ha expanse of lower-lying dunes (c. 5 – 33 m aOD) which extend to the coast and overlie a sequence of estuarine clay, silt and coastal peat deposits (Figure 2). The extensive series of dune slacks which form the focus of this study are primarily confined to the latter element.

Dunes slacks comprise an important habitat element of many dune systems in NW Europe (Ranwell, 1972). Most examples exhibit a seasonal water table fluctuation which can result in flooding; accordingly, the vegetation of slacks is a specific and highly characteristic blend of duneland and wetland taxa. The conservation significance of dune slacks is reflected in the inclusion of 'humid dune slacks' (H2190) as one of the habitats listed under Annex I of the Habitats & Species Directive (92/43/EEC). The fen orchid *Liparis loeselii* var. *ovata* occurs at Kenfig (Jones & Etherington, 1992) and is listed as an Annex II species.

Understanding of the environmental controls which influence the composition and structure of dune slack vegetation is thus of significant importance and is reflected in a now significant literature. Much of the work described here is based on the hitherto largely unpublished doctoral research of the first author (Jones, 1993) undertaken at Kenfig between 1985 and 1989. The choice of Kenfig as a study site reflects the significant extent and ecological range of dune slack vegetation at the site.

This paper describes key aspects of the ecohydrology of the dune slack environment at Kenfig. It extends from an analysis of water table morphology and the principle factors which control the overall hydrological regime of the dune system, assessed using a hydrological budget approach, through to a consideration of the influence of hydrological regimes on the floristic composition of dune slack vegetation. A key motivation for undertaking the hydrological budget was to determine the potential influence of groundwater from adjacent/underlying bedrock, with the presence of Kenfig Pool and many wet slacks subject to deep and prolonged flooding indicating groundwater might be a significant factor in the ecohydrology of the site.

The paper includes some consideration f the main dune slack communities recorded at Kenfig. At the time the study was undertaken, no phytosociological appraisal of dune slack vegetation had been undertaken for the nationally significant suite of dunes in South Wales, and the samples collected for this study went onto form part of the population of dune slack samples analysed and assessed for the British National Vegetation Classification (Rodwell, 2000). Furthermore, at the time the study was undertaken, relatively little work on dune slack ecohydrology had been undertaken in the UK since the classic studies of Ranwell (1959) at Newborough Warren and Willis *et al* (1959) at Braunton Burrows, with Clark (1980) providing one of the very few investigations of the water balance of a British dune system.

2. Methods

2.1 Groundwater monitoring and aquifer properties

Seasonal water table behaviour was assessed by measuring groundwater levels in 1 m long flexible PVC dipwells. Dipwells were inserted vertically into the floor of dune slacks by hammering in a removable outer steel liner fitted with disposable nose-cones; these could not be recovered and were displaced from the end of the liner using a narrow solid steel rod immediately prior to insertion of the dipwell. This methodology avoided the problem of hand-augering into running sands, and enabled installation of dipwells even when slacks were flooded. In total 126 dipwells (Figure 2) were installed during 1985-86 across the full extent of the dune slack/ridge landscape of the lower dunes (c. 420 ha) in all of the main vegetation types apparent prior to survey. The density of dipwells was determined by the need to gain sufficient information on the overall water table profile and to calculate changes in storage for the water balance estimate. Groundwater levels were recorded at a typical interval of 2-4 weeks between 1986 and 1989 across the resultant network of 126 dipwells. Datum points were also located in key open water features, notably the 28 ha freshwater lake Kenfig Pool and also the River Kenfig (Figure 2). All dipwells and datum points were referred to a common datum (Ordnance Datum) using optical levelling. Water level records have been manipulated to provide mean levels for summer (April to mid October) and winter (mid October to March) for comparison with vegetation data. Duration of flooding for 1986 and 1987 was determined for all slacks with dipwell records.

2.2 Water table morphology

The morphology of the water table has been visualised using the Surfer® contour plotting package (Surfer® 8, Golden Software, LLC) based on water table elevations for maximum winter and minimum summer water level conditions for the 126 dipwells. The derivation of contour plots was constrained to the area of the site with an adequate dipwell network by defining a 'blanking layer' defined by the coastal margin to the west, marked at most locations by a sand cliff above the beach plain, and the boundary with the River Kenfig and its associated water courses to the north. The much less well defined boundary between the dune ridge/slack landscape of the lower dunes and the rising dunes to the east was determined from a series of four auger hole transects and isolated borings conducted to determine the point where the sloping drift surface dips below the typical position of the water table in summertime.

3. Derivation of a water balance

Water balance calculations were undertaken for 8 discrete winter-time periods of two weeks to one month duration. This approach was chosen to reduce the potential significance of evapotranspiration (Et) as a water balance component and thus avoid the necessity of obtaining reliable estimates of Et from such contrasting environments as high dunes with a significant thickness of unsaturated sand, and dune slacks in capillary contact with the water table for much of the year. The critical water balance elements of rainfall recharge (R), surface water inflow (SWi) and outflow (SWo) and groundwater inflow (GWi) and outflow GWo) were measured or estimated according to the methodology summarised in Table 1. The water balance equation can be expressed as follows, with b representing the residual term which includes all of the errors in the determination of the components considered as well as the values of components not taken into account by the equation;

$$b = R + (SWi + GWi) – (SWo + GWo)$$

3.3 Vegetation analysis

Vegetation was sampled from the full range of dune slacks at Kenfig, with sample collection reflecting the two main apparent gradients of wetness and successional stage. Vegetation records (cover abundance using the 10 point Domin scale) were collected from at least three 1 x 1 m quadrats located at random on the floor of slacks, with all rooted taxa being recorded. Vegetation data have been analysed using a combination of ordination (Detrended Correspondence Analysis [DCA], Hill 1979a) and classification (Two Way Indicator Species Analysis, Hill, 1979b) multivariate techniques to examine vegetation gradients and to define vegetation noda. Some manual re-assignment of samples to site-specific noda was undertaken to support the definition of robust phytosociological units. All samples ultimately formed part of the National Vegetation Classification (NVC) data-set (Rodwell, 2000), and the Kenfig noda have been referred to the NVC communities/sub-communities for the purposes of this account. Analysis of interactions between vegetation and hydrological variables has been undertaking using non-parametric correlation, Analysis of Variance and tests of the significance of differences between means.

4. Results

3.1Groundwater monitoring and aquifer properties

Seasonal changes in the water table were recorded from the 126 dipwells installed into the sand aquifer. Seasonal fluctuations ranged from c. 100 cm of standing water to c. 100 cm below ground level, though most slacks display a range of the order of +25 - -45 cm. This is shown well by the monitoring record at ‘Dipwell 5’ (Fig. 3) which has continued for 20 years, since the main body of this study, covering the period 1985 to 2005. Long term records are invaluable and this records shows a clear relationship between rainfall and water levels. The data series also illustrates the difficulties in defining mean levels, as different years could produce quite varying results. This has important connotations when designing monitoring networks for other dune sites, and considering how long they may need to be kept running.

Falling head tests in piezometers at ten aquifer margin sites and four central sites produced values of Hydraulic conductivity (*k*) 9.16 m day^{-1} (range 3.36 – 21.18, 75^{th} percentile at 9.78). Values for specific yield (Sy) were estimated by rewetting sand cores collected from ten locations, yielding a mean value of 0.26 (1 S.E. = 0.019). This compares well with a value of 0.293 from investigating water table response to discrete rainfall events with an automatic water level recorder.

3.2 Water table morphology

Data from the dipwells have been used to generate summer and winter groundwater table contour plots in the dune aquifer (Fig. 4). Both plots show a generally domed groundwater profile which is most apparent during high water table conditions in the winter and caused by radial drainage. The dome is less apparent during the summer but again shows pronounced drainage gradients north towards the river and west towards the coast. Kenfig Pool acts as a high point for the water table system of the southern dunes.

3.2Water balance calculations

Values for the residual term (b) for the 8 water balance periods are shown in Table 2 together with the estimated changes in aquifer storage (dS). The change in aquifer storage is less than the residual term for all periods with a net increase in storage, with periods of water table recession being associated with a larger (negative) change in storage than predicted from the residual error term. A significant 'external' groundwater influence might be expected to yield changes in storage greater than the residual term. However, the results obtained are heavily dependent on a range of factors, with the choice of values used for *Sy* and *k* especially critical. Sensitivity analysis of the outcome of the water balance calculations was undertaken using a value for *k* of 13 m day^{-1} which exceeds the value reported in a number of relevant coastal dune studies, for example 8 m day^{-1} (Van Dijk & De Groot, 1987), 10 m day^{-1} (Nieuhuis,1990) and 11 m day^{-1} (Clarke, 1980). The value used for specific yield of 0.293 is close to the mid-point of the range 0.25-0.35 reported for coastal dunes by Bell (2004). Re-runs of the water balance employing an *Sy* value of 0.35 and a value for *k* of 13 m day^{-1} resulted in values of dS greater than b for 2 out of the 8 water balance runs, with a difference of 3.2 and 10.8 mm respectively for the water balance periods 20/12/87-10/1/88 and 11/1-24/1/88.

3.3Vegetation

Ordination analysis suggests a correlation between scores for samples on DCA Axis 1 and a range of hydrological variables, with significant correlations (Kendall's Correlation Coefficient) at $P<0.05$ for duration of flooding (days, for each of 1986 and 1987), mean summertime water level for 1986 and 1987 and mean wintertime level for 1986 and 1987: no significant correlation was observed between axis 1 scores and total annual water table range for the years 1986, 1987 and 1989. A scatterplot of DCA axis 1 scores against the mean position of the water table for each sample in the summer of 1986 is shown in Figure 5 with vegetation community assignments superimposed. This indicates a clear relationship, with significant summertime flooding for the successionally young stands of the non-NVC *Litorella uniflora – Eleocharis palustris* community and SD14a and the more mature SD15a, and water levels sufficiently high for soils to be maintained in capillary contact with the water table for much of the summer for the majority of the other SD14 units. This relationship is also shown clearly when ordination axis 1 scores are plotted against mean summer-time water level (Figure 6).

4.0 Discussion

This study shows the strong relationship between hydrological regimes and the floristic composition of dune slack vegetation. Significant variation in water table variables between years do occur but have not been assessed as part of this study: however, the long-term monitoring record available for Kenfig (and now several other UK sites) offers significant opportunities for evaluating the importance of variations in water table behaviour in relation to climate, and in particular how this might affect dune slack vegetation under future climate change scenarios.

This study failed to detect any very significant influence from deep groundwater, but significant additional monitoring is now in place to measure hydraulic gradients between the dune sand body and the underlying sand and gravel aquifer, as well as other relevant aquifer properties (Dr Mike Streetly, pers. Comm.). These data would be invaluable as part of a follow-up assessment of changes in the overall hydrological behaviour of the dune system in response to medium and long-term processes. These include on-going vegetation succession and the accumulation of organic matter as soil profiles mature across the system, and the influence of the physiographical evolution of the dune system, including changes in river level resulting from the growth of a shingle ridge at its mouth. More intensive monitoring and modelling could also be used to assess the importance of changes in rainfall and evapo-transpiration, occasional sea-water incursions along the coastal fringe of the site (these were not observed during the period covered by the present study), and of course management measures to restore dune system mobility. These factors will all have a bearing on both the dune system water balance and long-term changes in seasonal water table behaviour, and is has not been possible to assess these effects here in a study focussing on one period of time.

The significant volume of hydrological data for individual slacks at Kenfig has not been fully analysed in this account. However, compilation of all available data from classified dune slack vegetation across those dune system sites subject to long-term monitoring would be very worthwhile, not least as a means of refining and revising the hydroecological guidelines for sand dune slack habitats (Davy et al., 2010).

References

Bell F. G. 2004. *Engineering Geology and Construction*. Taylor and Francis.

Cheney, C.S., Davies, J.R., Hughes, A.G.., Darling, W.G & Macdonald, D.M.J. 2000. An assessment of the possible effects of dewatering proposed extensions to quarries in the South Cornelly area, South Wales. British Geological Survey Report WD/00/21C.

Clarke, D. 1980. The groundwater balance of a coastal sand dune system: a study of the water table conditions in Ainsdale National Nature Reserve, Merseyside. Ph.D Thesis, University of Liverpool. (11 m/say, p175)

Doody, J.P. 2001. *Coastal Conservation and Management – an Ecological Perspective*. Conservation Biology Series, Springer, New York.

Hill, M.O. 1979 a. DECORANA – A FORTRAN program for detrended correspondence analysis and reciprocal averaging. Cornell University, Ithaca, New York.

Hill, M.O. 1979 b. TWINSPAN – A FORTRAN Program for arranging multivariate data in a ordered two-way table by classification of the individuals and attributes. Cornell University, Ithaca, New York.

Jones, P.S. 1993. *Ecological and hydrological studies of dune slack vegetation at Kenfig National Nature Reserve, Mid Glamorgan*. Ph.D Thesis No Dx201209. University College of Wales.

Jones, P.S & Etherington, J.R. 1992. Autecological studies on the rare orchid *Liparis loeselii* and their application to the management of dune slack ecosystems in South Wales, in : Carter, R.W.G et al (Ed.)Coastal dunes: geomorphology, ecology and management for conservation: Proceedings of the 3rd European Dune Congress, Galway, Ireland, 17-21 June 1992, pp 299-312/.

Ranwell D.S. 1959. Newborough Warren, Anglesey. I. The dune system and dune slack habitat. J. Ecol 57:571-601.

Ranwell D.S & Boar R. 1986. Coastal Dune Management Guide. Institute of Terrestrial Ecology, Huntingdon, UK.

Ranwell D.S. 1972. Ecology of salt marshes and sand dunes. Chapman & Hall, London.
Rodwell, D.S. 2000.

Rodwell J.S. (ed.) 2000. British Plant Communities Volume 5: Marine communities and vegetation of open habitats. Cambridge University Press, Cambridge.

Shaw, E.M., Beven, K.J., Chappell, N.A. & Lamb, R. 2011. Hydrology in Practice. 4th. Ed. Taylor & Francis.

Van Dijk, H.W.J & De Groot. W.T. 1987.Eutrophication of a coastal dune area by artificial infiltration. Water Research, 21. 11-18.

Willis A.J, Folkes B.F, Yemm E.W. 1959. Braunton Burrows: the dune system and its vegetation I. J. Ecol 47: 1-24.

Davy A.J, Hiscock K.M, Jones M.L.M, Low R, Robins N.S, Stratford C. 2010 Ecohydrological guidelines for wet dune habitats, phase 2. Protecting the plant communities and rare species of dune wetland systems. Ecohydrological guidelines for wet dune habitats. GEHO0310BSGV-E-P.

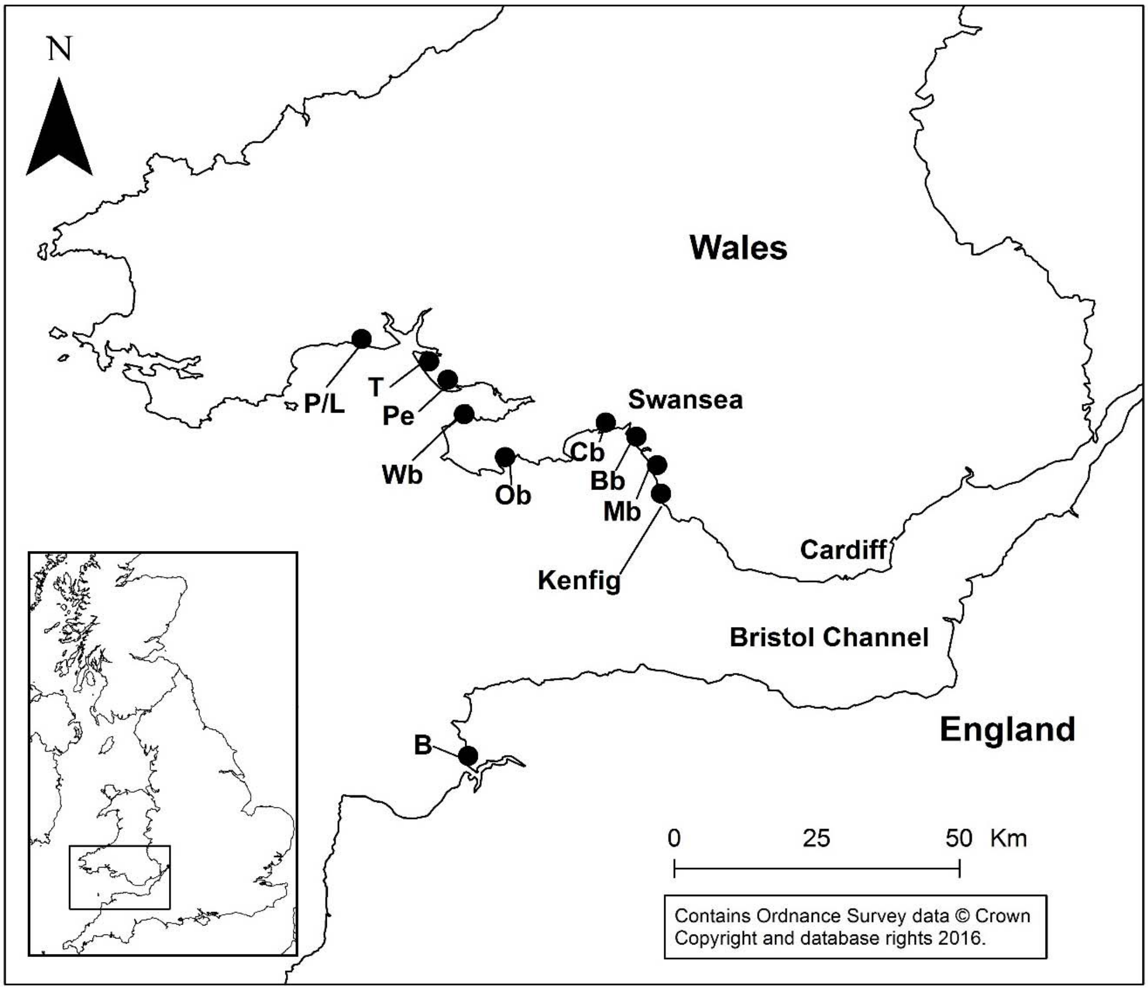

Figure 1. Location of Kenfig NNR and other notable designated dune sites in South Wales and South West England including; B: Braunton Burrows, Mb: Merthyr Mawr Burrows, Bb: Baglan Bay Dunes, Cb: Crymlyn Burrows, Ob: Oxwich Bay Dunes, Wb: Whiteford Burrows Pe: Pembrey, T Tywyn and P/L: Pendine – Laugharne dunes.

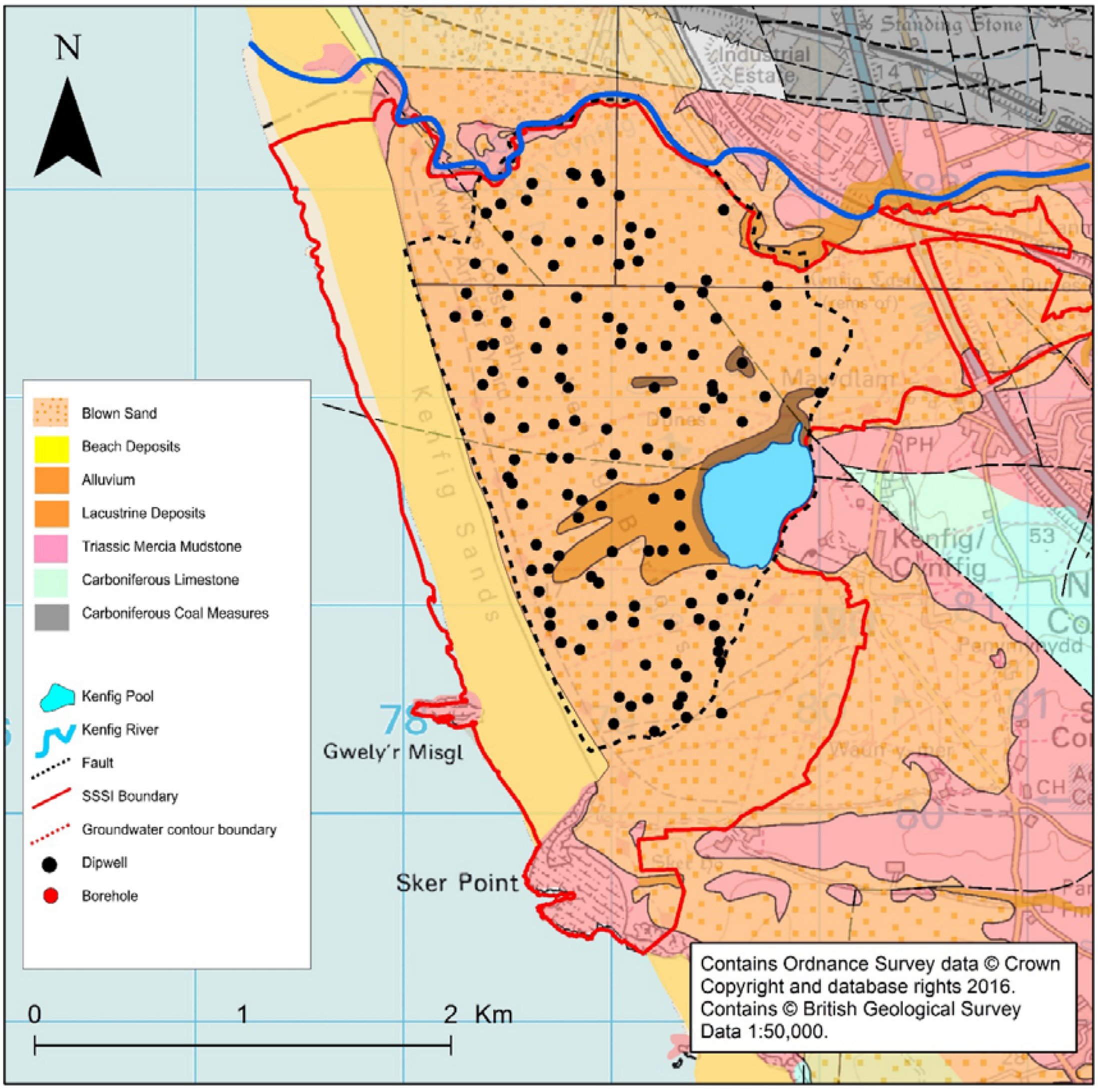

Figure 2. Bedrock and superficial geology and location of groundwater level dipwells at Kenfig NNR.

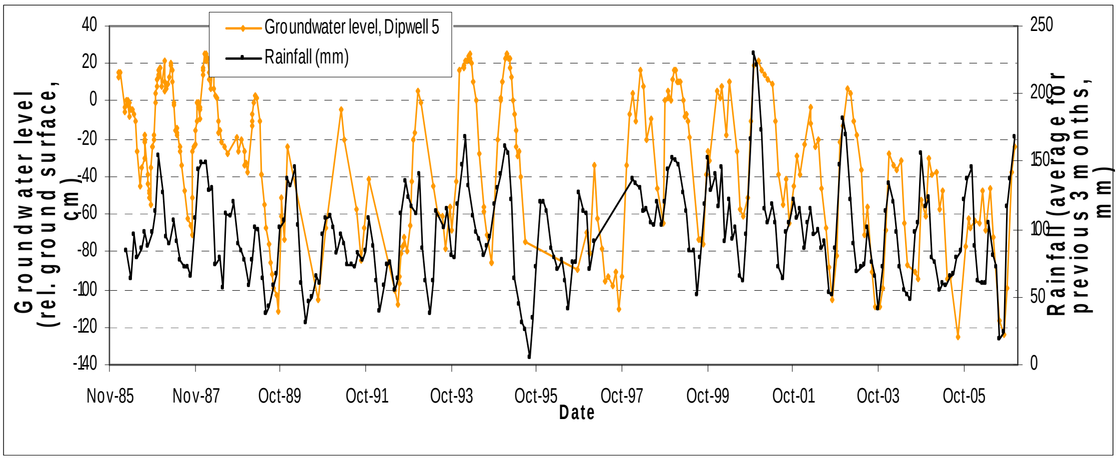

Figure 3. Long term water level 1985 to 2005 from Kenfig Dunes dipwell 5.

Figure 4. Kenfig groundwater contours in winter (left) and summer (right)). Aerial Images © UKP/Getmapping Licence No. UKP2006/01.

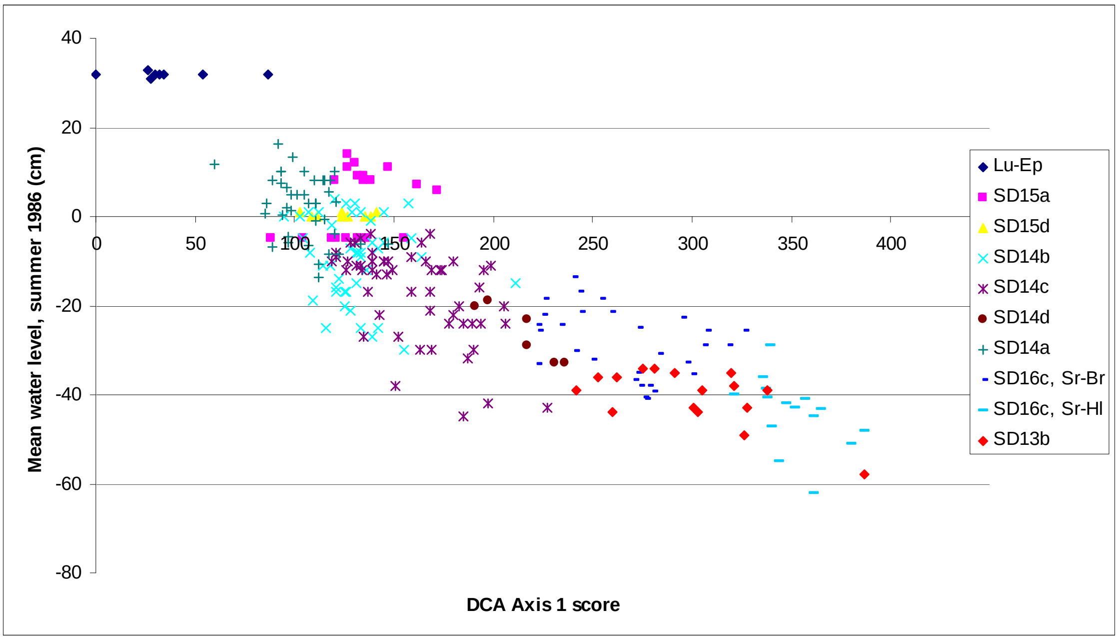

Figure 5. Scatterplot of DCA axis 1 scores against mean water table position for summer 1986 for quadrat samples referred to 10 NVC communities/sub-communities and non-NVC units.

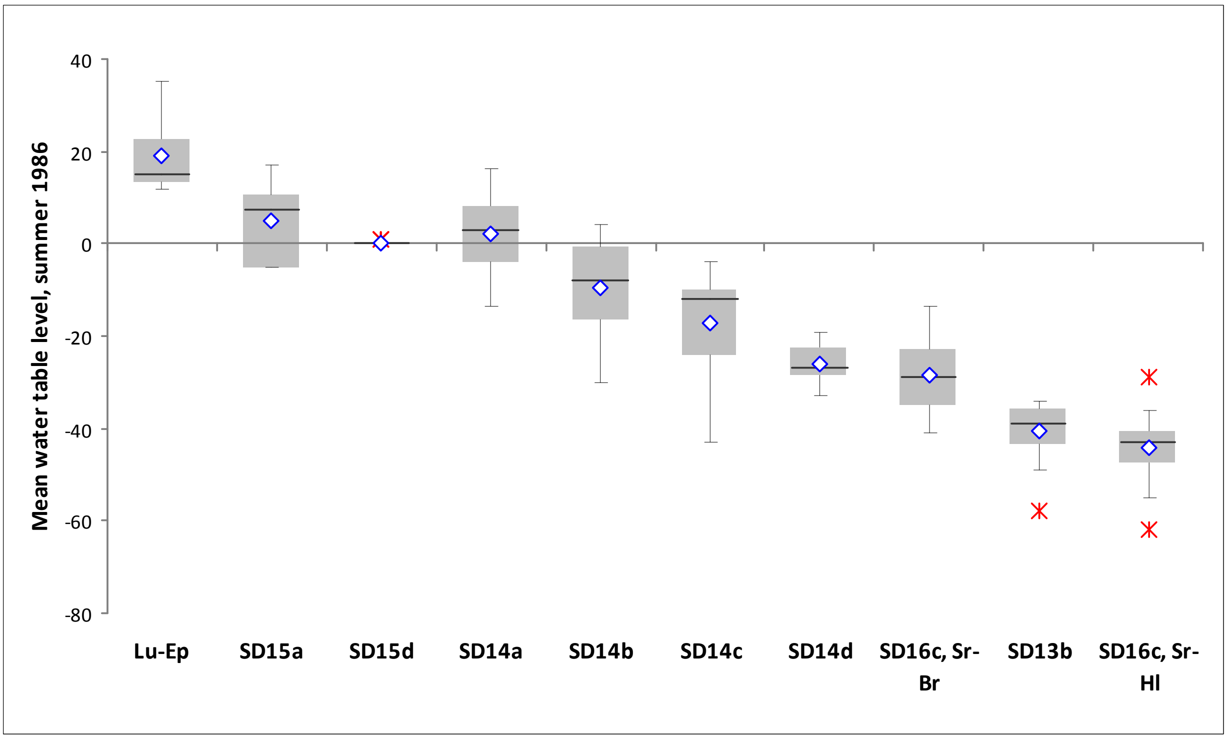

Figure 6. Box-plots showing maximum, minimum, interquartile range and mean summertime water level in 1986 for the main dune slack plant communities at Kenfig NNR

Water balance element	Methodology
Rainfall (P)	Daily on-site measurements using a standard rain gauge.
Evapotranspiration (Et)	Calculation of daily values based on monthly estimates provided by the UK Meteorological Office.
Recharge (R)	Estimated from rainfall and evapotranspiration using a daily soil moisture balance model.
Surface water inflow (SWi)	Direct volumetric gauging of three seasonal inflow streams from fields to the east of Kenfig Pool. Observation during the period of the water balance calculations reported here suggests the streams captured the majority of surface flow entering the dune system from the fields to the east: heavy rainfall events would be expected to generate diffuse runoff, but this was not observed during the assessment period. These were the only surface water inputs observed during the water balance periods assessed in this paper, with no inputs from river over-banking or overtopping of the foredunes by seawater.
Surface water outflow (SWo)	Calculation of outflow based on water level stage measurements at a single outflow point of known dimensions.
Seepage inflow/outlflow from high-lying dune sand to the east and along the seepage outflow margin to the west (beach) and north (river), (GWo, GWi)	Calculated using Darcy's Law, based on measurements of cross-sectional aquifer area along the inflow and outflow boundaries, water table profile measurements and site measurements of saturated hydraulic conductivity. Measurements of cross-sectional areas were based on measurements of sand sheet thickness based on borehole data (n=4), auger corings (landward margin only, as 4 transects and 7 isolated corings) and electrical resistivity geophysical measurements at 24 locations along the seepage outflow margin of both the beach and river. Groundwater slope was measured using 10 levelled transects of dipwells deployed at 90^{o} to the water table contour lines. Hydraulic conductivity (*k*) was estimated from falling-head piezometer tests at 10 aquifer margin sites and 4 sites towards the centre of the dune system, yielding an overall mean of 9.16 m day^{-1} (range 3.36 – 21.18, 75th percentile at 9.78).
Changes in aquifer storage (dS)	Values for specific yield (Sy) were estimated by rewetting sand cores collected from ten locations, yielding a mean value of 0.26 (1 S.E. = 0.019). This compares well with a value of 0.293 from investigating water table response to discrete rainfall events with an automatic water level recorder. Changes in aquifer storage (reflecting changes in overall water table level) volume have been calculated by dividing the water budget area into polygons centred on dipwell locations and delimited using the Thiessen method (Shaw et al., 2011). Changes in water volume were obtained by multiplying polygon area by the change in water level and by Sy. Areas of open water with an effective Sy of 1.0 were accounted for by measuring the area of each polygon subject to winter flooding. This takes no account of changes in the area of flooding with changes in water depth. The area of the lower dunes aquifer was delineated as 360.51 ha for this analysis.

Table 1. Summary of the methodological approach employed for each of the main water balance parameters at Kenfig NNR.

Water balance period	*P*	*R*	*SWi*	*GWi*	*SWo*	*GWo*	*b*	*dS*
28.12.1986 - 10.1.1987	69.7	66.4	1.0	1.7	5.9	19.2	44.0	25.9
20.1.1987 - 27.1.1987	7.7	2.0	1.0	2.0	5.5	21.0	-21.5	-41.6
13.3.1987 - 31.3.1987	85.2	60.4	0.9	2.0	3.4	22.0	37.9	18.8
5.12.1987 - 19.12.1987	35.5	28.1	0.5	1.6	0.0	17.9	12.3	4.0
20.12.1987 - 10.1.1988	138.3	129.2	1.5	2.0	10.9	26.9	95.0	79.7
11.1.1988 - 24.1.1988	91.5	83.8	1.5	1.5	22.8	18.5	45.5	44.8
14.2.1988 - 27.2.1988	0.3	-17.2	0.4	3.5	8.9	20.9	-43.1	-50.0
12.12.1989 - 28.12.1989	51.6	46.2	1	1.5	7.7	19.8	21.2	5.3

Table 2. Summary of 8 water balance calculations undertaken for the Kenfig dune system aquifer. Abbreviations: P, precipitation; R, recharge (based on a soil moisture balance model); SWi/SWo, surface water inflow/outflow; GWi/GWo, seepage income and losses from the high lying dunes to the east and the beach/river boundary respectively; b, water balance residual term; and, dS, changes in dune system aquifer storage. All results expressed in mm.