An assessment of the interactions between hydrology, land use and climate change at two coastal dune systems in Wales, UK.

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Abstract Coastal dune areas are naturally dynamic landforms supporting a wide range of habitats and species. The structures and functions of these systems, such as sediment movement, hydrology and vegetation management are all important factors in determining site and habitat condition. Many sites show evidence of loss or damage due to constraints on such structures and functions, for instance coastal erosion has changed the base level of sites and local drainage of adjacent marsh lands has tended to reduce the occurrence of seasonal flooding in dune slack areas. This study concentrates on two Welsh sites; Newborough Warren SAC, a 1300 ha area of late-glacial blown sand dunes over weakly permeable glacial till situated in the island of Anglesey, and Whiteford Burrows NNR, a 160 ha coastal spit dune system founded upon Millstone Grit/Coal Measures with limestone outcrops, located on the north coast of the Gower Peninsula in Swansea. Both of these sites have been subjected to pressure from forestry and the effect of the forested areas on the adjoining dune slack areas is now in question. The possibility that the trees are overdrawing the available groundwater beneath the afforested dunes so lowering the water table has been suggested. However, proving that the trees are the cause of the lowered water table is not easy. Many complicating factors exist, such as the change in water use as a forest matures and changing grazing patterns.
Keywords duneland, water table, vegetation, ecosystem, uncertainty

INTRODUCTION

Two important coastal dunelands in Wales are drying out. Newborough Warren on the island of Anglesey in North West Wales and Whiteford Burrows on the Gower Peninsular of South Wales have systems of dune slacks that are trending consistently away from humid to a dryer winter environment. The reasons why this is occurring are complex and interactive although at Whiteford Burrows erosion of the foreshore which is effectively draining the groundwater to sea at an increasing rate, has exacerbated the issue. Both sites comprise wind blown sand over till or boulder clay.

Newborough Warren (Fig. 1) is a coastal area of late-glacial blown sand dunes over weakly permeable glacial till which rests on ancient basement type rocks. It has been designated a Special Area of Conservation for, amongst other things, humid dune slacks and dunes with creeping willow, and is a valuable recreational amenity. The dunes reach a maximum thickness of 15 m. 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 *Pinus nigra* var. *laricio* trees between 1948 and 1965 in an attempt to stabilize the dunes. The plantation has attracted red squirrels, which 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. There has been a consistent trend over the past 60 years or so from humid slacks that flood each winter towards a dryer environment in which the slacks only flood in exceptional wet winters.

Fig. 1 The coastal dunes of Wales

The Whiteford Burrows comprise an area of Holocene blown sand over glacial till. The foredunes give way to beach sands and the back of the dunes to the east, give way to clays and silts of tidal flat deposits. The sand rests on till, or boulder clay deposited beneath a Quaternary ice sheet. Steep northerly dipping Carboniferous Limestone strata disappear beneath the burrows at the landward (southern) edge, although the Millstone Grit succession underlies the majority of the burrows area. It is unlikely that groundwater in the Carboniferous Limestone can ingress the burrows sands due to the steep bedding of the Limestone, in which dilated bedding plains will tend to drain to the base of the upstanding outcrop and because of the presence of the impermeable barrier of till over the limestone. Since about 1996 there has been a sudden reduction in the groundwater level beneath dune slacks in the central dune area, such that these slacks now rarely flood in winter and no longer justify the designation humid slacks. A decline in the water table elevation has been observed in the existing dipwell network since about 1995, and this represents a reduction in the volume of groundwater stored in the sand aquifer due to some change in the environment or in the configuration of the aquifer and its discharge zone.

This study highlights the complex interaction between groundwater and vegetation at the two sites and illustrates the difficulty of providing certainty when dealing with natural habitats.

HYDROLOGICAL SETTING

Newborough Warren

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 (Fig. 2). 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 in the northern part of Newborough Warren and a groundwater divide lying to the south of it which migrates northwards towards the lake during dryer (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.

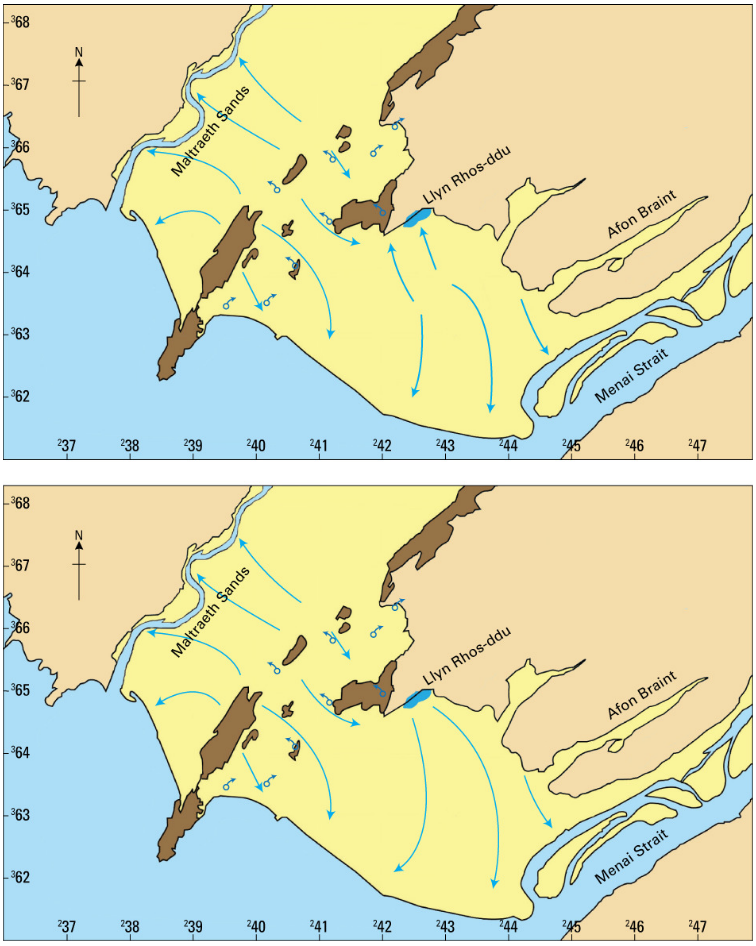

Fig. 2 Winter (top) and summer (bottom) conceptual flow models for Newborough Warren showing ephemeral springs where bedrock intercepts groundwater flow in the sands. The sand cover is shown in yellow, the rock ridge in brown, and the sea below low water mark in blue, the foreshore being an important part of the groundwater flow system.

Hollingham (2006) reports that the potentiometric level beneath the forested area in the north western half of the warren is higher and more ‘flashy’ than elsewhere, 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 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 at the eastern shoreline. 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. The coast is currently subject to erosion, a recurring feature first reported by Ranwell (1958). To the north west the dunes are bounded by sandflats and to the east north east by salt marsh.

The dune slacks regularly flooded during the winter in the period prior to planting the northern sector of the dunes. 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 show only two slacks where the water table was above ground surface during 1951-1953. He described a single rainfall event and equates 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. By the 1970s it was noticeable that the dune slacks were trending towards a drier phase (Hollingham, 2006).

Whiteford Burrows

The burrows sands act as a small unconfined aquifer perched over impermeable till which forms a shallow base to the aquifer. Water contained in the sand derives solely from direct rainfall recharge. The groundwater stored in the sands discharges naturally to the foreshore while a small amount discharges to the salt marshes behind the dunes. There are no external contributions to the water balance although standing water on the shore side of the burrows does enhance evaporative losses from this area.

HYDRO-ECOLOGY

Ranwell (1959) 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 wet and dry slack dune associes according to broad water table conditions (Table 1).

Table 1 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.

Ranwell's findings contrast with more recent observations. Jennings (1990) collected water level data between June 1989 and August 1990 from two transects of dipwells running perpendicular to the boundary between the forest to the north west and the open warren to the south east (i.e. directly away from the forest into the warren). The water table elevation increases in the dipwells (normally in slacks or at the edge of slacks) away from the forest and away from the shore and the depth to water table is typically 20 cm greater in the dipwells nearer the shore and 40 cm greater in those away from the forest (Fig 3.).

By 1990 none of the dipwells reflected a water level regime that was compatible with a semi-aquatic wet slack or wet slack plant associes, but a regime that was more compatible with dry slack plant associes. Hollingham (2006) suggests that 1988, 1989 and 1990 were slightly drier than normal years (up to 60 mm deficit in the annual water balance) and that the prevailing water levels were slightly lower than average (Fig. 4). Nevertheless, the slacks had dried out.

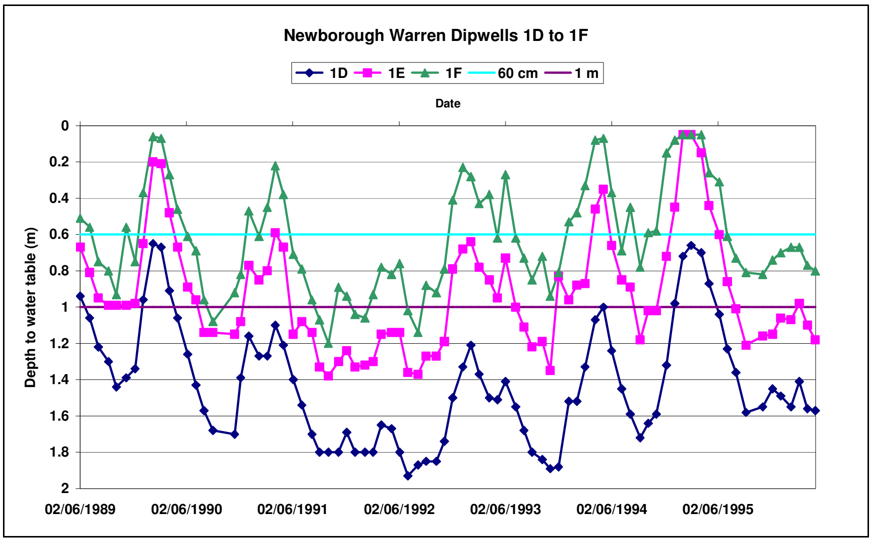

Fig. 3 Time series of dipwell data collected between June 1989 and May 1996. Dipwells 1D to 1F are all located in the non-forested area with dipwell 1D nearest to the forest and dipwell 1F furthest from the forest. However 1D is located within an area of damp grassland rather than true slack. The 60 cm and 1 m levels that appear in Ranwells definition are marked.

Direct comparisons of recent measurements with those of Ranwell (1959) are only possible for one slack, (Ranwell's Slack A, site 8). The average annual range in water table measured over the period 1989-1995 was 75 cm (+/- s.d. 26.7 cm), while Ranwell's measurements also give an annual range of 75 cm for 1951 and showed the winter maximum water table close to ground surface.

The hydro-ecological setting at Whiteford Burrows is essentially similar but with smaller discrete wooded plantations placed on the inshore and higher elevation dunes. Like Newborough the water table rises into the dune field towards the base of the dune slacks. Observation and monitoring at Whiteford, however, has not recorded a gradual decline in water level but rather a sudden drop in level since about 1996.

LIKELY CAUSES OF WATER TABLE DECLINE

Newborough Warren

A common perception at Newborough Warren is that the trees are overdrawing the available groundwater beneath the afforested dunes so lowering the water table. There are, however, several other factors that may contribute to the reduction in elevation of the water table and the consequent drying out of some of the dune slacks so that the trees may now have only a minor influence on the water table elevation (Stratford et al., 2007). Apart from the effect of the trees, which have a reduced water demand as they reach maturity, there are a number of other possible influences including: altered climatic patterns, digging of drainage ditches north of the rock ridge, successional development of vegetation and soils leading to increased evapotranspiration, morphological change, past changes in stage of the small lake in the Warren and the possible effects of nutrient enrichment.

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 has probably assisted the stabilization of the dunes (Ranwell 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 shrinking from 70 % to around 6 % since 1951 (Rhind et al. 2001; Rhind et al. 2007). Increased vegetation cover and soil organic matter content has led to increased interception and evapotranspiration of rainfall, leading to reduced recharge over the whole warren area, again at its maximum in the mid-1980s (Hodgkin 1984).

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 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, the amount of exposed forest edge and the proximity to advected energy from the nearby ocean.

Grazing patterns have also modified the vegetation on the open duneland and consequently its recharge potential. Since the reintroduction of sheep, cattle and ponies in 1986, an element of dune stabilization coupled with shorter grass has evolved. Large-scale managed grazing post-1986 has reduced evapotranspiration, potentially contributing to greater recharge.

Long term average (LTA) effective rainfall over the area is 847 mm and as runoff is essentially absent except for the most intense rainfall events LTA direct rainfall recharge is of a similar magnitude. Although LTA rainfall has declined by only 2.3 mm over the 45 year period up until 2005, changes in the seasonal pattern of rainfall over that period show a trend towards wetter spring and autumn periods and drier summer and winter periods (Fig. 4).

Shoreline erosion is reducing the area of the Warren and reducing 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 is greatest nearest the beach, decreasing rapidly inland.

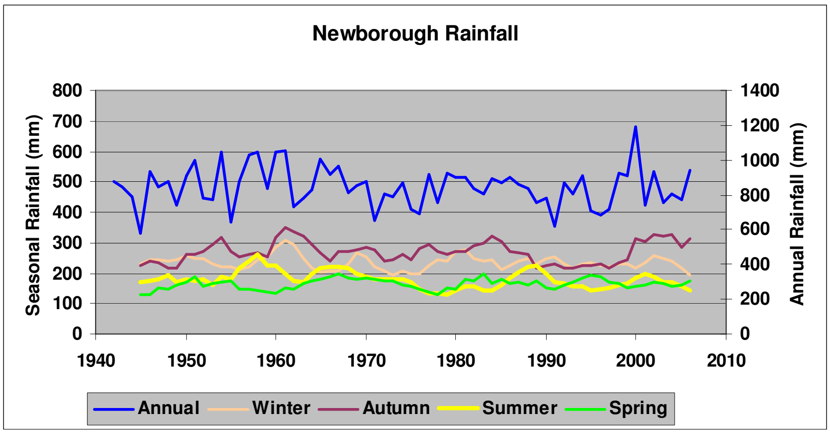

Fig. 4. Patterns in annual and seasonal rainfall recorded at RAF Valley, 1945-2005. Three-month seasons defined as: Autumn (Sep-Nov), Winter (Dec-Feb), Spring (Mar-May), Summer (Jun-Aug).

Changes in landforms over time can alter slack floors, and their relationship with the water table. The level at which the slack floor stabilises depends on the water level at the time of erosion. Furthermore, once established, slack floor levels may be modified, either through erosion or re-scouring, or in older slacks the floor level may be considerably raised through deposition of wind-blown sand (Ranwell 1959). These factors make comparisons of water levels over time difficult unless they can be accurately accounted for.

The hydraulic history of the warren is complex. Anecdotal evidence indicates that the small lake, Llyn Rhos-ddu, has possessed various levels over the last 60 years as the retaining structure has been modified. However, accurate lake stages have not been recorded.

Whiteford Burrows

The processes at Whiteford Burrows are less complex with one dominant process overriding all other possible influences including the water taken by the wooded areas. Recent aerial photography indicates a large semi-circular erosion feature in the foreshore sands roughly in the central section of the Whiteford Sands beach. Investigation of this area on the ground reveals active erosion and undercutting of the dune front where there is evidence of recent fallen ground. In front of this active erosion front is a semi-circular scour area in which the beach deposits have been removed to expose heavy grey clay grade till. The erosion is clearly ongoing because the newly exposed till is rapidly degraded to cobble beds as the sea works the clay grade material and the small stones from the till. From the dune front down to the sea at low tide in the centre of the erosion feature is an upper sloping beach sand with an increased gradient falling to the erosion front and exposed till.

The undercut front of the central dunefield and the erosion of the foreshore to expose till reflects some recent change in the offshore environment. It has effected a thorough narrowing of the central foreshore which has reduced the capacity of the dunefield to retain groundwater by increasing the hydraulic gradient across the foreshore and accelerating the transport of groundwater towards the sea (Fig. 5). Darcy's law, which defines flow through a porous media states that:

$$Q = kiA$$

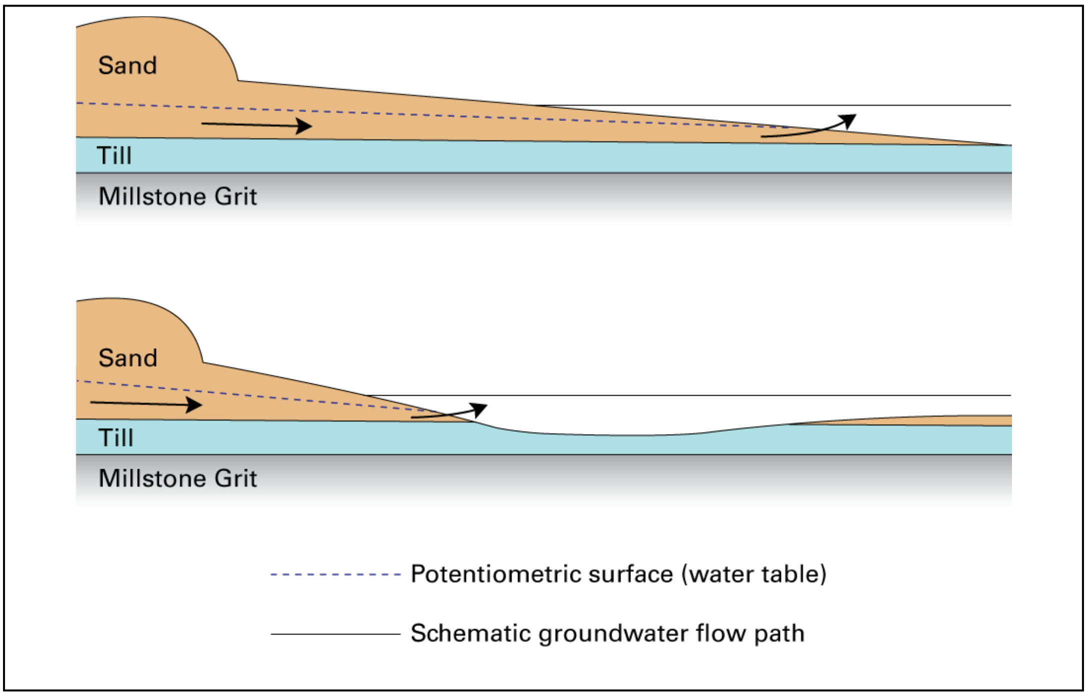

Fig. 5 Schematic cross section of the central foreshore showing the steepening of the hydraulic gradient away from the dune front.

Where Q is flow,
K is the coefficient of permeability of the media,
i is hydraulic gradient across the media, and
A is the area of the media or aquifer,
and shows that flow Q, or in this case discharge from the dunes to the sea, is proportional to the hydraulic gradient i.

The erosion has increased the hydraulic gradient across the foreshore at low tide, and reduced the flowpath length. Darcy's Law shows that this will increase the throughflow and will encourage more groundwater held in the dunes above the till to discharge to the beach. This in turn is reducing the volume of water retained in the sand and is lowering the water table beneath the slacks in the central dunefield area. The reduction in groundwater storage is changing the slack environments from humid to arid as the water table declines with some slacks that rarely, if ever, nowadays flood. That this has happened over just a few years reflects the catastrophic and rapid onset of erosion of the foreshore which in turn may reflect some local change in tidal conditions.

The central foreshore is wet at low tide. The water tastes fresh to brackish and this is an expression of the groundwater table in the sand intercepting the beach surface along the upper foreshore. Dryer sand further down the foreshore towards the erosion front represents an area where the water table is still at a lower elevation than the beach surface. At the erosion surface there are numerous actively discharging spring sources undercutting the sand and discharging over the till. These sources are the discharge end of the burrow groundwater system.

The other side of the burrows abuts the salt marsh flats. These are clays and silts which offer little permeability. Drainage from the burrows does occur to the salt marsh but is hindered by a marginal peaty area and by entrance into the low permeability salt marsh strata. Only a small part of the overall discharge from the burrows takes this route.

It appears that some catastrophic change to the offshore environment occurred in the mid-1990s which commenced scouring sand from the central foreshore of the burrows. This sand may have been deposited to the north eastern end of the beach or to the sand flats at the south west end of the beach. Scouring of the foreshore has exposed the underlying till and is providing an accelerated pathway for groundwater discharge from the burrows. This in turn is promoting the lowering of the water table as storage is depleted with consequent drying out of the central area slacks.

CONCLUSIONS

The one time humid dune slack systems at both sites are drying out. A combination of interrelated reasons is the cause of this and it is unlikely that removal of the trees would reverse this trend at either site.

A complex set of factors influence water levels at Newborough Warren, most of which are likely to override any effect from the now mature stands of trees. The dominant effects are: altered climatic patterns, digging of drainage ditches north of the rock ridge, successional development of vegetation and soils leading to increased evapotranspiration, morphological change, past changes in stage of the small lake in the Warren and the possible effects of nutrient enrichment.

At Whiteford Burrows the scouring and undercutting of the foreshore is a dynamic and modern feature which coincides with the lowering of the water table observed in some slacks. It is such a dramatic and pronounced feature that it is likely to be the dominant process currently affecting trends in the water level. The pine stands are drawing less water in maturity than they did in the 1960s and 1970s when they were subject to vigorous growth and it is unlikely that they currently impact groundwater levels. Other possibilities, such as change in rainfall distribution or overall long term average effective rainfall need to be investigated but such effects are likely to be minor compared with the erosion of the foreshore.

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