Complex interaction between shallow groundwater and changing woodland, surface water, grazing and other influences in partly wooded duneland in Anglesey, Wales

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Abstract Newborough Warren, a coastal area of late-glacial blown sand dunes over weakly permeable glacial till, is situated in the island of Anglesey off the Welsh coast of the UK. It was partly forested with Pinus nigra var. laricio trees between 1948 and 1965. It is now a Special Area of Conservation designated for, amongst other things, humid dune slacks and dunes with creeping willow. The dune slacks regularly flooded during the winter in the period prior to planting the northern sector of the dunes however since the mid 1950s flooding has become increasingly rare. Today there are conflicting pressures, one that would see the Warren maintained as it is, partly wooded and partly open, another that would see the restoration of active dune processes and the restoration of slacks through partial or total removal of the trees. This study highlights the complex interaction between groundwater and vegetation and illustrates the difficulty of providing certainty when dealing with natural habitats.

Keywords: duneland, water table, vegetation, ecosystem, uncertainty

1. Introduction

Newborough Warren (Figures 1 and 2) is located on the south-west coast of Anglesey (SH 423636) and is part of the Abermenai to Aberffraw Dunes Special Area of Conservation (SAC). Afforestation of 700ha of the dune system between 1947 and 1965 assisted the stabilisation of a large swathe of the dunes, running 2km inland from the shoreline. Since this time, the water table in the warren has declined. For example Hill & Wallace (1989) noted that the unplanted forest slacks (unplantable due to winter flooding) had since dried out. There is anecdotal evidence that winter standing water is now a rare occurrence in dune slacks within or adjacent to the forest, though long-term data reveal no significant change in rainfall between the 1950s and 1990s for Anglesey. Ranwell (1959) reported extensive winter flooding (including areas within and adjacent to the present forest) during 1950-51, and noted that some areas may remain under water for 3 to 4 months in high rainfall winters. The shallow dune system water table is crucial in determining the geomorphological development and the resulting biota of sand dune ecosystems. The observed decline in groundwater levels is having a negative impact on the integrity of the SAC and a desire to mitigate this is the driving force behind the restoration efforts.

Coastal dune conservation areas (SSSI and SAC) are monitored according to Common Standards across the UK (JNCC, 2004). In line with wide European thinking, such as the UK Biodiversity Action Plan – Habitat Action Plan for Coastal Dunes, these recognise the importance of structures and functions of this naturally dynamic landform, particularly the zonation of habitats and the role of sediment movement, hydrology and vegetation management in determining the condition of the sites (Davy, 2006). 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 the dune slacks. At Newborough Warren, however, lowered groundwater levels in the dune sands have been assigned variously to afforestation of the dunes since the late 1940s, damage to a weir which reduced the elevation of water standing in an upstream pond and changes in vegetation. The study described here concentrates on the complex issues observed at Newborough Warren and attempts to identify causes and effects that have taken place in the last 60 years that may have influenced an observed drying out of the dune system.

1.1 *Hydrological Setting*

The conceptual groundwater flow model is shown graphically in Figure 3. There is a rock ridge running from south west to north east through the dunes, with a significantly lower hydraulic conductivity than the sands that creates a groundwater divide. The piezometric 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. Importantly, the watershed, described by various workers (e.g. Ranwell, 1959) as lying to the south of the lake, is unlikely to be a static fixture. It is now perceived to be in that position only under wet (winter) conditions, and that it migrates northwards towards the lake during dryer (summer) conditions. In this way the lake feeds the groundwater system in summer but gains from groundwater in the winter. This is caused by the lake acting as a near fixed head whereas the dune water table elevation fluctuates above and below that head. In addition, the foreshore around the warren must be considered a part of the groundwater flow system. Groundwater discharge above low water mark (not high water mark as previously modelled) is the active drainage area for the system.

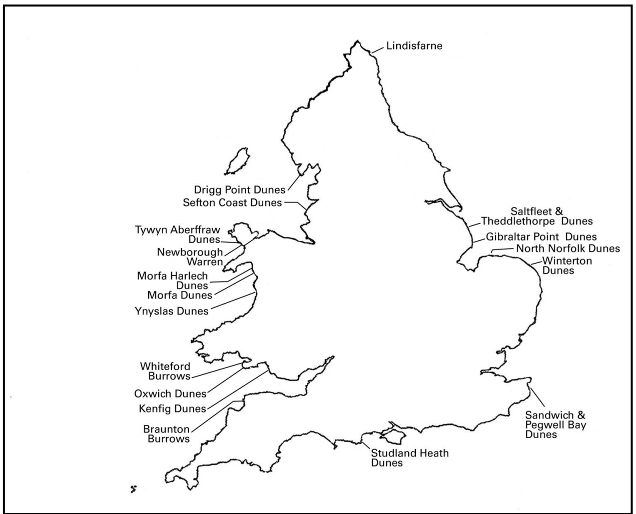

Fig. 1. Coastal dune sites in England and Wales

The hydraulic history is complex. Anecdotal evidence indicates that the lake has possessed various head stages over the last 60 years as the retaining structure has been modified although accurate lake levels have not been recorded. Grazing patterns have also changed the vegetation on the open duneland, and consequent recharge potential, following the dramatic decline in rabbit population in the 1950s due to myxomatosis and since 1986, the reintroduction of sheep, cattle, ponies and rabbits cropping the grass.

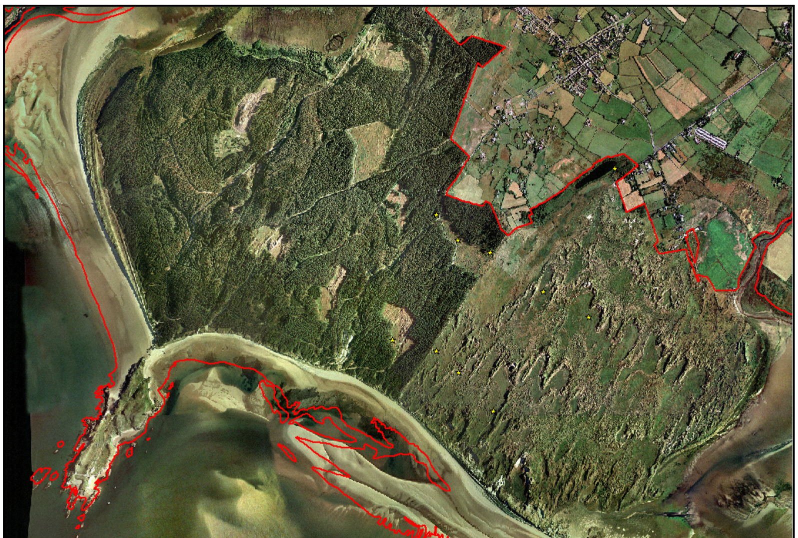

Fig. 2. Aerial view of Newborough Warren. The red line marks the SSSI boundary. © Getmapping plc.

1.2 *Previous Work*

Previous work at Newborough Warren described the lowering of the water table both in the forest and extending into the open dune system in contemporaneous dune slacks (Cottingham, 1994). Bristow & Bailey (1998) confirmed this using ground penetrating radar and found that the water table in the open dunes locally falls towards the forest suggesting that the forest has drawn the water table down. Kissiyar (1999) used these data to model the hydrology of the dunes with and without afforestation. Betson et al. (2002) extended this work, using more detailed geophysical information and modelled the effect of partial forest removal on the groundwater table of the dunes. Betson & Scholefield (2004) later refined the estimates of evapotranspiration.

However, several of these earlier studies do not adequately address all of the issues that could affect a falling water table. The notable shortcomings are:

- some of the work is influenced by a preconception that the trees are causing a lowering of the water table and are hence setting out to prove this rather than standing back and considering all the causal factors;
- transpiration has been overestimated in several cases for both the forest and the dune vegetation. Interception has been overestimated for the dune vegetation;
- the effects of soil moisture deficit, especially on shallow-rooting dune vegetation, have not been adequately accounted for;
- the groundwater model (Kissiyar, 1999; Betson et al., 2002) could only be made to work by using unrealistic values for recharge, suggesting an underlying problem with the conceptual model.

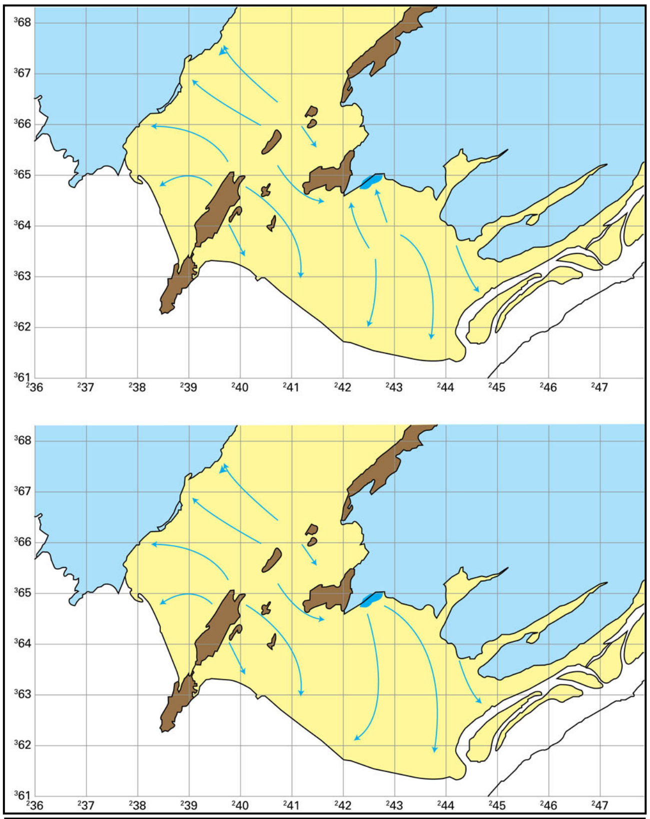

Fig. 3. Top: Groundwater flow under high groundwater consitions (Winter). Bottom: Groundwater flow under low groundwater conditions (Summer).

Proposals for the reduction of forest area, and changes to forest management such as conversion of the retained forest to mixed broadleaves or Continuous Cover Forestry (CCF), were jointly tabled by both the Forestry Commission as managers of the forest and the Countryside Council for Wales as managers of the open dune in order to restore typical dune zonation and enable dune mobility and geomorphological development of the system in response to a changing environment. The proposals have been challenged on the basis of the underpinning hydrological assumptions (Hollingham 2005, 2006).

The objectives of the current study, therefore, are to provide a critical assessment of the hydrological impact of the forest and to identify options to restore the hydrological regime of the site commensurate with an unafforested open dune landscape or a future, dynamic, partially wooded dune landscape, within the broad climatic envelope of north-west Wales. As the existing data were too patchy to merit new analysis and time constraints did not allow for the collection of new data, an in-depth review of related work was carried out in order to develop recommendations for management options of Newborough Warren.

2. Experience from other sites

2.1 Vegetation

A similar forest evapotranspiration study in The Netherlands at Castricum has been reported by Deij (1948, 1954) and discussed by Rutter (1968). There are some important similarities between Castricum and Newborough; both are coastal and at similar latitudes, Corsican pine was involved at both sites and annual rainfall and potential evapotranspiration is similar. Using lysimeters (25 x 25 x 2.5 m) constructed in the dunes at Castricum, Diej estimated the annual evapotranspiration of Corsican pine compared to mixed broadleaves (oak, birch and alder). With a mean annual rainfall of 840 mm, annual evapotranspiration from the Corsican pine was 655 mm and evapotranspiration from the broadleaves was 500 mm. Evapotranspiration from short vegetation was not measured though the net radiation receipt was equivalent to 550 mm a^{-1}. Experiencing no soil moisture deficit, which is unlikely in dune grassland, the net radiation equivalent might be reasonably equated to the annual evapotranspiration of short grass, though in practice this would probably only apply to areas of wet slack and would be significantly lower in dry slack and dune.

Therefore at Castricum, under the cover of Corsican pine, 100-150 mm a^{-1} (12 to 18 %) less recharge might be expected compared to broadleaved woodland or well watered grass. If a notional dune grass cover was experiencing significant soil moisture deficits, as appears likely at Newborough, the grass evapotranspiration would be less and consequently the difference in recharge compared to Corsican pine larger.

Another approach to estimating forest evapotranspiration might be regarded as the ‘substitution’ method that utilises appropriate historical data for transpiration and interception fractions drawn from appropriate published work. Roberts (1983) reviewed a wide range of studies reporting transpiration from forests in NW Europe. The annual average was 333 mm +/- 10%. This might be regarded as a plausible annual transpiration total for Newborough. Added to this is a rainfall interception fraction amounting to 32% of gross rainfall. If evapotranspiration of short dune vegetation is equivalent to potential evapotranspiration (500 mm a^{-1}), then around 100 mm a^{-1} less recharge would be available below the forest. Again this difference is likely to be greater as soil moisture deficit develops.

The greater evapotranspiration of coniferous woodland compared to other vegetation types has been illustrated by direct measurements of evapotranspiration from different vegetation types in dunes in The Netherlands (Bakker, 1981; 1990). In a region where average annual rainfall was 725 cm a^{-1} evapotranspiration for different vegetation types (Table 1) indicated least recharge below coniferous woodland, more under deciduous woodland or dune vegetation and most under bare dunes. Similar results have been modelled for woodlands on agricultural land in Nottinghamshire, England (Calder *et al.,* 2003)

Although the evapotranspiration totals of both forest and dune vegetation might have been overestimated in the work reported by Betson and Scholefield (2004), it is nevertheless probable that evapotranspiration from the forest substantially exceeds that from the dune vegetation and would result in significantly lower recharge from annual rainfall.

Doody (1989) suggests that water table lowering follows afforestation on dunes and in adjacent unforested areas this will reduce winter flooding of the dune hollows. The competitive ability of the existing dune vegetation is lower as a result and the species-rich dune slacks may be invaded by birch and pine causing a further loss of dune vegetation. Without active management, this growth of woody vegetation might further exacerbate the influence of the initial afforestation.

Table 1. Annual evapotranspiration for seven types of vegetation in the dunes of the Netherlands. Annual precipitation = 725 mm a^{-1}. (after Bakker, 1990).

Type of vegetation	Evapotranspiration (mm a^{-1})	Recharge (mm a^{-1}) assuming 725 mm a^{-1} rainfall
Bare dunes	180	545
Wet slack vegetation	550	175
Dry slack vegetation	360	365
Wet deciduous woodland	550	175
Dry deciduous woodland	400	325
Wet coniferous woodland	700	25
Dry coniferous woodland	550	175

As the forest canopy becomes less dense as a result of increasing age and/or thinning a more vigorous understorey may develop. Research in Thetford Forest in the UK showed that bracken in a Scots pine stand fully compensated in terms of water use for the transpiration differences between a Corsican pine stand, with no understorey, and the Scots pine stand (Roberts *et al.,* 1982). At Newborough, bracken is less frequent, but its role might be taken by species such as Rubus fruticosus agg. and R. idaeus. by an increasing component of Betula pubescens, Prunus spinosa, Cotoneaster simonsii and Populus alba. In the event of a likely age effect it might be reasonable, in terms of hydrological modelling, to impose a small reduction factor on evapotranspiration from areas covered with the older compartments.

The reviewed local studies omitted three important factors that significantly contribute to variations in forest water use. These factors are: the distance of the tree cover from the edge of the forest (or major cleared areas e.g. roads, fire breaks), the age of the trees in the forest stand, and the effect of advected energy from the nearby ocean. Each is discussed below:

- The UK Forestry Commission (2005) suggest that evapotranspiration might be enhanced within 20 m of the forest edge due to a number of factors such as increased leaf area at the edge, greater exposure to radiation, and penetration of external microclimate into the body of the forest. Kinniburgh and Trafford (1996) found that the effect could be detected as far as 50 m from the forest edge where soil cores were found to be drier than those taken deeper into the forest. In, perhaps an extreme example Chen *et al*., 1995 found that depending on external exposure, microclimate penetration could extend up to 240 m into the forest. It is not unreasonable to consider that at Newborough, particularly at the windward edge and at the rocky ridge, microclimate penetration into the forest exceeds 50 m. In general evapotranspiration might be enhanced by 10% within 50 m of a forest edge. This factor might prove substantial in raising the overall evapotranspiration of the forest when the forest perimeter, compartment edges and major forest roads at Newborough are taken into account.

- As the bulk of the Newborough forest was planted between about 1952 and 1967, making much of it 40 - 50 years old, and a substantial proportion of the older stands have been clear felled and replanted, it cannot be assumed that the Corsican pine is yet in the phase of declining water use. When canopy closure of a forest takes place after forest establishment, water use might increase in association with canopy size and forest vigour, in addition to interception, which seems to concur with anecdotal evidence of water table fall at Newborough. There is also accumulating evidence that forest water use on the Severn headwaters is declining, and that this is associated with the forest increasing in age (Hudson et al., 1998; Marc and Robinson, 2006). However, examination of information for Corsican pine in terms of age-related current annual increment (Hamilton and Christie, 1971) suggests that even a stand of modest yield class might still be achieving its maximum current annual increment (i.e. greatest water use) at age 55 to 60 years.

- Advected energy from the sea could enhance the evapotranspiration of intercepted rainfall from the forest, thereby increasing the interception loss. This effect has been implicated in enhancing evapotranspiration of intercepted rainfall at temperate coastal sites (e.g. Shellekens *et. al.,* 2000) and given the location of the forest at Newborough this should not be neglected. The magnitude of this effect is difficult to predict but might increase interception loss by a few percent.

2.2 Dune Systems

Similar dune systems have been studied elsewhere in the UK and Europe and these provide valuable experience. The key pieces of work are discussed below.

Ainsdale on the Lancashire coast is a particularly relevant parallel to the situation at Newborough, where afforestation with pine forests is considered to have lowered water tables both below the forest and in adjacent dunes. Atkins (2004) discusses the groundwater balance of the dune system and Neale (1999) considered the hydraulic processes active in the system. This describes a simple flow system directed towards the shoreline. The effect that the conifer plantation at Ainsdale has on the ground water levels as reported by Clarke (1980) included a reduction in the water table under the afforested dunes of up to 1 metre below that seen in the open dunes. The majority of woodland establishment at Ainsdale had occurred by 1925, i.e. around 35 years before groundwater observations began. Interception and evapotranspiration were considered to be the important factors, especially in the summer, when comparing the afforested areas and the open dune areas. Trees have a large interception capacity and re-evapotranspiration of water occurs in preference to transpiration. The estimated interception loss in the woodland is around 35% and evapotranspiration loss estimated at 30 mm per month in midwinter, which is 40% greater than for grasses.

Elsewhere in the UK the dune system at Braunton Sands, North Devon, has been investigated for the past 40 years particularly regarding the impact of military exercises on breaking up the dune structures. However, there is no afforestation on this site, although scrub and trees are now invading some parts of the dunes, and water levels have largely been affected by declining rainfall, peripheral land drainage and abstraction (Robins, 2007).

St Fergus, on the north-east coast of Scotland comprises a high seaward dune strip backed by a single large slack area, part of which, the Winter Loch, is seasonally under water. Soulsby *et al.* (1996) considered the hydraulics of the system following its breaching to land a gas pipeline, and use of part of the slack area as a landfill facility. The maximum water table fluctuation is 0.6 m.

In Holland, the dune eco-systems have also been extensively studied and the hydraulics of the sands is keenly investigated (e.g. van der Meulen & Jungerius 1989; Ritsema *et al.*, 1994, Bakker 1981;1990), providing the basis for much of our conceptual understanding of dune systems.

3. The Integrity of the Dune System SAC

In order to assess the impact of water table lowering on the integrity of the SAC dune slack features at Newborough it is necessary to define desirable hydrological conditions. An early definition of dune 'slacks' is that of Tansley (1949) who defined them as 'damp or wet hollows left between dune ridges, where the groundwater reaches or approaches the surface of the sand.' Ranwell (1959) collected depth-to-water-table data from 18 sites across Newborough between 1951 and 1953 and from this refined the definition stating that the seasonal drift of the water table shows a three phase pattern. The high-level phase, when there is either 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 considers wet, dry and transitional wet-dry slack plant communities and for each, presents the typical range of observed depth-to-water table values. The maximum observed ranges are summarised by slack type and timing (in relation to the three phase pattern) in Table 2.

Ranwell then went on to describe wet and dry slack dune associes according to broad water table conditions (Table 3).

Table 2 Range of observed depth-to-water table values for each of the three phases of the annual cycle grouped by plant community type.

	Depth to water table (+ve = above ground, -ve = below ground)		
Slack Type	November to April	April to August	August to November
Wet	+20 to -60	+20 to -90	-10 to -90
Transitional	0 to -90	-10 to -120	-50 to -120
Dry	-35 to -120	-35 to -160	-90 to -170

Table 3 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.

This provides a very broad set of hydrological conditions against which to judge the current situation at Newborough. As part of an MSc Thesis, Jennings (1990) collected water level data between 2/6/1989 and 29/8/1990 from two transects of dipwells running perpendicular to the forest/warren boundary (i.e. directly away from the forest in the direction of the warren). The water table elevation increases away from the forest and away from the shore and the depth to water table is typically 20 cm greater in the dipwells nearer to the shore and 40 cm greater in those away from the forest.

Ignoring the spatial variability across the slacks, the following general points can be made if the water table levels in the dipwells are compared to the definitions given by Ranwell:

- None of the dipwells exhibit a water level regime that would make them suitable for semi-aquatic wet slack or wet slack plant associes.
- All of the dipwells exhibit a water level regime that would make them suitable for dry slack plant associes.

The work of Hollingham (2006) suggests that 1988, 1989 and 1990 were all slightly drier than normal (up to 60 mm deficit in the annual water balance) so it is reasonable to expect that the water levels are also slightly lower than average however this crude assessment still indicates that if the restoration of wet slack plant associes is desired then the more recent (1989/1990) water table regime does not fluctuate within appropriate limits.

4. Potential Management Scenarios

4.1 Total or partial removal of the forest

Total or partial removal of the forest would result in a reduction in water use and water tables should rise, at least in the vicinity of the cleared area. As enhanced evapotranspiration at forest edges might, to some extent, counter the effect of creating clearings, there would be merit in considering creating fewer larger cleared areas rather than many smaller ones. Furthermore, large clearings, connected to the frontal dunes are more likely to enable renewed sand mobility, the re-working of calcareous soil layers, the formation of new dunes and slacks and natural response to predicted shoreline changes as a result of climate change. However, mobility is not a prominent feature of British west coast dune systems today and it is unlikely that the newly exposed soil would be mobilised and transported far. Thinning of trees, initially at least, would allow more recharge but in time this might be negated by canopy closure of the remaining trees and/or losses from understorey that might develop in improved light conditions below a thinned canopy. Roberts *et al*. (1982) showed the importance of understoreys in compensating for a difference in conifer canopy vigour. One option to alleviate the influence of a vigorous understorey, such as bramble or bracken, is to introduce grazing livestock at an appropriate density to control undergrowth.

Even if improved hydrological conditions could be re-established there are a number of factors that might hinder the development of dune slack vegetation. The return of a flora that existed prior to forest establishment is unlikely to occur quickly in the cleared areas if the forest has covered the area for more than 50 years. The paucity of a viable seed bank in the soil and a change in soil structure and chemistry following afforestation are significant constraints (Sturgess, 1992). Viable seeds of the earlier dune flora are unlikely to exist in the soil, though they may be blown in from adjacent areas, but a viable population of weed seeds will probably exist and will germinate to provide a dense ground cover unless appropriate grazing or ground disturbance occurs. The presence of the pine litter and changed nutrient status would also hinder the establishment of a typical dune flora, though experience at Ainsdale suggests that with time a convincing approximation can be achieved.

4.2 Alterations to forest management

One option that would maintain tree cover is the gradual conversion from a coniferous forest to a broadleaved forest. Evapotranspiration from broadleaved forest is less than from coniferous forest for two principal reasons. In winter the leafless canopy of broadleaved woodland allows less evapotranspiration of intercepted water and also in the period when the broadleaves are leafless, evergreen conifers may still be able to transpire if atmospheric conditions allow.

Continuous Cover Forestry, which is defined as a forest management system under which felling and regeneration are carried out continually and there is no clear felling of trees when they reach some pre-determined age (Helliwell, 1999), might fulfil objectives of reducing dramatic changes in forest cover and produce a more diverse tree complement. There is an unknown hydrological impact of producing a canopy with arguably more fully-exposed surfaces, and at this stage there is no research to inform about the effects of such a change of canopy structure. There is a distinct possibility of greater water use by CCF compared to conventional British forestry, due to its greater canopy surface area, increased turbulence of air flow and increased understorey.

5. Conclusions

The dune slacks at Newborough Warren regularly flooded during the winter in the period prior to planting the northern sector of the dunes, but since the mid 1950s flooding is increasingly rare. The perception that the trees are drawing the water table down beneath the afforested dunes is difficult to prove categorically, given the other variables that may have influenced the water table during the same period. Although some of the trees are now reaching maturity and their water demand is probably starting to reduce, in places new stands have been planted as trees have been felled and most old stands have been thinned, so changing the overall water demand of that stand. Re-growth, development of understorey and increased canopy roughness as age classes diverge, promise increasing water demand in the future. Assessment of all these variables in the light of experience derived from other coastal dunes suggests that the trees are the most likely cause of the observed water level change beneath the dune slacks during winter months. However, it is unlikely that removal of all or part of the woodland would cause a reversion to the pre-afforestation land cover and ecosystems due to other changes in the dynamics of the dunes. The complex interaction between groundwater and vegetation at Newborough highlights the difficulty of providing certainty when dealing with natural habitats.

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