Review of Hydrological Reports

For

Newborough Warren, Anglesey

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Crynodeb Gweithredol

Mae llaciau twyni Warin Niwbwrch wedi bod yn ganolbwynt llawer o ymchwil dros y 60 mlynedd diwethaf. Daw'r gofyniad am y gwaith hwn o ganlyniad i dystiolaeth sy'n awgrymu bod y lefel trwythiad yn ardal y llaciau wedi gostwng. Mae hyn yn debygol o achosi symud yn y planhigion cysylltiedig i ffwrdd oddi wrth rywogaethau'r llaciau twyni gwlyb y gellid yn eu tro gael eu gweld fel rhai oedd yn effeithio ar integriti system twyni'r ACA. Mae llawer o'r astudiaethau a wnaed hyd yma wedi awgrymu bod y defnydd uchel o ddŵr yng Nghoedwig Niwbwrch sy'n ffinio â'r warin wedi achosi'r gostyngiad yn y lefel trwythiad. Amcanion yr adroddiad hwn yw:

Amcan Un Gwneud arolwg beirniadol o astudiaethau hydrolegol blaenorol o Warin Niwbwrch. Cafodd y prosesau sy'n penderfynu ar y defnydd o ddŵr yn y goedwig (trydarthiad a rhyngdoriad) eu gor-amcangyfrif mewn adroddiad allweddol (Betson and Scholefield 2004). Ond cafodd y trydarthiad o lystyfiant byr y twyni ei or-amcangyfrif hefyd a theimlid nad oedd y diffyg yn lleithder y pridd, a fyddai'n arwain at gwtogi ymhellach ar y defnydd o ddŵr, yn arbennig gan lystyfiant y twyni, wedi ei drin yn ddigonol. Daethpwyd i'r casgliad fod gwaith blaenorol a wnaed ar lystyfiant y goedwig a'r twyni yn Niwbwrch wedi tueddu i oramcangyfrif ei effaith ar ostwng y lefel trwythiad. Nid oedd y gwaith blaenorol i fodelu'r dŵr daear (Betson, Connell a Bristow, 2002) wedi creu model a weithredai gyda gwerthoedd realistig o adlifiad ar gyfer llystyfiant y goedwig a'r twyni. Ni theimlid felly bod y rhediadau dilynol yn y model a oedd yn efelychu effeithiau symud ardaloedd o goedwig yn ddigon cadarn ac ni ddylent ffurfio sail ar gyfer unrhyw benderfyniadau rheoli.

Amcan Dau Cynghori ynglŷn ag effeithiau hydrolegol tebygol y goedwig ers 1947. Adolygwyd corff helaeth o lenyddiaeth a cheir tystiolaeth gadarn iawn bod sefydlu coedwig o goed conwydd yn Niwbwrch wedi achosi gostyngiad yn y lefel trwythiad. Mae'r defnydd uchel o ddŵr gan rywogaethau bytholwyrdd fel pinwydd yn cael ei dderbyn yn helaeth a dangosodd dadansoddiad byd-eang yn ddiweddar o 504 o arsylwadau blynyddol o ddalgylchoedd fod coedwigo glaswelltiroedd a thiroedd lle roedd prysg yn tyfu wedi achosi gostyngiad cyfartalog yn llif nentydd y dalgylchoedd o 38% (Jackson *et al* 2005). Roedd nifer o brosesau a deimlid oedd yn berthnasol i Niwbwrch (e.e. effaith ymyl y goedwig a gwell anweddu ar lawiad wedi ei ryng-gipio) yn rhai nad oedd wedi eu cynnwys mewn astudiaethau blaenorol, a'u heffaith fyddai cynyddu'r defnydd o ddŵr gan y goedwig ymhellach. Noda cyfrifiadau yn seiliedig ar ymchwil Ewropeaidd blaenorol fod adlifiad o dan orchudd o binwydd Corsica hyd at 150 mm^{-1} y flwyddyn yn llai nag y gellid ei ddisgwyl o laswellt sy'n cael ei ddyfrio'n dda. A derbyn y byddai adlifiad o dan lystyfiant byr y twyni yn fwy na'r hyn a fyddai o dan laswellt wedi ei ddyfrio'n dda oherwydd effaith pwysedd dŵr, gallai'r gwahaniaeth rhwng adlifiad rhwng llystyfiant conwydd Corsica a llystyfiant byr y twyni fod yn fwy nag 150 mm^{-1} y flwyddyn. Nid ydym wedi gallu mesur effaith cwtogi ar adlif ar y lefel trwythiad ac i wneud hyn argymhellwn gyfnod o glirio, monitro a modelu rhagbrofol. Bydd adroddiad sydd ar fin ymddangos gan English Nature (Davy *et al*) yn gymorth hefyd i ddiffinio'r amodau hydrolegol gorau sy'n angenrheidiol ar gyfer sefydlu cymunedau llaciau twyni llaith. Bydd cyfuniad o fodel sy'n gweithio a dealltwriaeth o'r drefn hydrolegol angenrheidiol yn ei gwneud yn bosibl i asesiad cadarn gael ei wneud o effaith y goedwig ar integriti ACA y llaciau twyni.

Amcan Tri Nodi dewisiadau i adfer trefn hydrolegol y safle. Ystyriwyd ystod o ddewisiadau rheoli. Yn achos symud coed, cyflwyno rhywogaethau o goed llydanddail a theneuo, daethpwyd i'r casgliad y byddai gostyngiad yn y defnydd o ddŵr yn digwydd, ond gallai ffactorau eraill fel datblygiad prysg mewn ardaloedd sydd wedi eu clirio leihau effeithiolrwydd rheolaeth o'r fath a gall fod hyn angen rheolaeth ychwanegol. Teimlid bod dewisiadau eraill fel ail-lenwi dŵr daear yn artiffisial ac ail-broffilio'r tir yn rhai a fyddai'n creu problemau ac y byddent yn anodd i'w gweithredu.

Executive Summary

The Newborough Warren dune slacks have been the focus of much research over the past 60 years. The requirement for this work comes as a result of evidence suggesting that the water table in the slack area has fallen. This is likely to cause a shift in plant associes away from wet dune slack species which in turn could be seen as impacting on the integrity of the dune system SAC. Many of the studies conducted to date have suggested that the high water use of Newborough Forest, which borders the warren, has caused the drop in water table level. The objectives of this report are:

Objective 1. To undertake a critical review of previous hydrological studies of Newborough Warren. The processes that determine the water use of the forest (transpiration and interception) were overestimated in a key report (Betson and Scholefield, 2004). However, the transpiration from short dune vegetation was also overestimated, and it was felt that soil moisture deficit, the effect of which would be to further reduce water use, especially by dune vegetation, had not been adequately dealt with. It was concluded that previous work on both the forest and dune vegetation at Newborough had tended to overestimate its impact on lowering the water table. The previous groundwater modelling work (Betson, Connell and Bristow, 2002) had not created a model that operated with realistic values of recharge for forest and dune vegetation. The subsequent model runs that simulated the effects of removing areas of the forest were therefore not felt to be robust and should not form the basis of any management decisions.

Objective 2. To advise on the probable hydrological impacts of the forest since 1947. An extensive body of literature was reviewed and there is overwhelming evidence that the establishment of coniferous forest at Newborough has caused a lowering of the water table. The high water-use of evergreen species such as pines is widely accepted and a recent global analysis of 504 annual catchment observations showed that afforestation of grasslands and shrublands caused an average decrease in catchment streamflow of 38% (Jackson *et al*., 2005). Several processes that were felt to be pertinent to Newborough (e.g. forest edge effect and enhanced evaporation of intercepted rainfall) had been omitted in previous studies, and their effect would be to increase the water use of the forest further. Calculations based on previous European research indicate that recharge under the cover of Corsican pine is up to 150 mm year^{-1} less than might be expected from well watered grass. Given that recharge under short dune vegetation would be greater than that under well watered grass due to the effect of water stress, the difference in recharge between Corsican pine and short dune vegetation could exceed 150 mm year^{-1}. We have not been able to quantify the effect of reduced recharge on the water table and to do this we recommend a period of trial clearance, monitoring and modelling. A forthcoming English Nature report (Davy *et al.*) will also help to define the optimum hydrological conditions required for establishment of humid dune slack communities. The combination of a functioning model and an understanding of the required hydrological regime will enable a sound assessment of the impact of the forest on the integrity of the dune slack SAC.

Objective 3. To identify options to restore the hydrological regime of the site. A range of management options were considered. In the case of tree removal, introduction of broadleaved species and thinning, it was concluded that there would be reduced water use, however other factors such as the development of scrub in cleared areas could lessen the effectiveness of such management and may require additional control. Other options such as artificial groundwater replenishment and terrain reprofiling were felt to be problematic and difficult to implement.

Contents

1. Background

Newborough Warren 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), designated for:

Embryonic shifting dunes,
Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes'),
Dunes with Salix repens ssp. argentea (*Salicion arenariae*),
Humid dune slacks,
Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation,
Petalwort *Petalophyllum ralfsii*,
Shore dock *Rumex rupestris.*

The shallow dune system water table is crucial in determining the geomorphological development and the resulting biota of sand dune ecosystems. Ranwell (1959) reported extensive winter flooding (including areas within and adjacent to the present forest) during 1950-51, and Onyekwelu (1972) will do noted that some areas may remain under water for 3-4 months in high rainfall winters. Afforestation of 700ha of the dune system took place between 1947 and 1965 and this contributed to the stabilisation of the dunes. Since this time, evidence indicates that the water table in the warren has dropped. For example Hill & Wallace (1989) noted that the unplanted forest slacks (unplantable due to winter flooding) had 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 rainfall data from the nearby RAF Valley indicates no significant change in rainfall between the 1950s and 1990s for Anglesey.

The research to-date can be summarised as follows: Depression of the water table both in the forest and extending into the open dune system has been observed in contemporaneous dune slacks by Cottingham (1994) using dipwells established by the Nature Conservancy Council in 1989. Bristow & Bailey (1998) confirmed this using Ground Penetrating Radar (GPR) and suggest that the water table in the open dunes locally falls towards the forest indicating that the forest has drawn the water table down. Kissiyar (1999) used this data to model the hydrology of the NNR dunes with and without afforestation. Betson, M., Connell, M. and Bristow, C. (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) refined the estimates of evapotranspiration.

Proposals for the reduction of forest area, and the conversion of the retained forest to mixed broadleaves, have been tabled by FC & CCW in order to enable dune mobility and geomorphological development of the system in response to a changing environment, to address (in part) the issue of groundwater depression and also to achieve BAP targets for dune management and the creation of more natural dune woodland. The proposals have been challenged on the basis of the underpinning hydrological assumptions (Hollingham 2005, Miller 2005).

The aim of this report is:

- to provide an independent expert review of the work that has been done thus far;
- to provide an independent critical assessment of the impact of the forest;
- to identify options to restore the hydrological regime of the site.

2. Terms of reference

1. To undertake a critical review of previous hydrological studies of Newborough Warren. *This is required to take into account the adequacy of the methodology employed and the extent to which the results support the conclusions drawn in each case, with particular reference to the stated effects of afforestation upon seasonal and long-term groundwater behaviour.*

2. To advise on the probable hydrological impacts of the forest since 1947. *Based on work undertaken for objective 1, an independent critical assessment of the impact of the existing forest on the hydrology of the dunes is required. This should draw upon further published and other relevant work obtained from comparable studies elsewhere in north-west Europe, including W.S. Atkins Consultants Ltd (2004). This work will be wholly desk-based and should seek to discriminate between the specific hydrological consequences of afforestation over and above the general trend of an increasing (herbaceous) vegetation cover. Based on this assessment, the consultant should also indicate what further work would be required (if any) to improve our quantitative understanding of the hydrological impacts of afforestation. Forestry impacts should be assessed with respect to current climatic conditions, but a qualitative assessment will also be required of the interaction between anticipated climatic change over the next century (based on the predictions outlined in National Assembly for Wales (2000) and a substantial long-term forest cover.*

3. Identify options to restore the hydrological regime of the site to: (a) that commensurate with an unafforested open dune landscape or (b) that commensurate with a future, dynamic, partially wooded dune landscape, within the broad climatic envelope of north-west Wales. *The study should identify and scope in outline options for reducing and ultimately eliminating the effects (if any) of Newborough Forest upon site hydrology. Options should include total or partial removal of the forest, the desirability of removing discrete forest blocks at specific locations, alterations to forest management, artificial groundwater replenishment and terrain re-profiling.*

3. Review of previous studies

The key reports discussed in this section are:

- Betson, M. and Scholefield, P. 2004. Review of evapotranspiration of herbaceous and afforested duneland ecosystems: The implications for the water balance in Newborough Warren National Nature Reserve, Anglesey, Wales. Report to the Countryside Council for Wales, ADAS Consulting Ltd., Wolverhampton, UK. 42pp.
- Betson, M., Connell, M. & Bristow, C 2002. Groundwater modelling of Newborough Warren: A report for the Countryside Council for Wales, Volume 5, Hydrogeology, The Impact of Forestry on Coastal Geomorphology at Newborough Warren/Ynys Llanddwyn NNR, SSSI, pSAC.
- Kissiyar, O 1999 The design of a groundwater flow model as a tool for environmental management in Newborough, North Wales. MSc Dissertation, University College London.

3.1 Vegetation

The ADAS report (Betson and Scholefield, 2004) is incomplete, lacking essential detail in places. The authors of the report have opted to parameterize models for coniferous forest and the various dune vegetation types using published values. While appreciating the difficulty that can be encountered finding suitable parameters, particularly for dune vegetation, some of the values chosen are not likely to be representative. For Corsican pine the authors discuss a value of 2.5 mm s^{-1} for the stomatal conductance (g_s). This value seems to have been derived as the average maximum stomatal conductance (g_s) of 53 values for conifers tabulated by Breuer *et al*. (2003). A leaf area index (LAI) of 5.1 is used to scale up the stomatal conductance (gs) to a canopy conductance (g_c). The equation in the report ($r_c = r_s/0.25LAI$) defines how the canopy resistance (r_c, the reciprocal of the canopy conductance) is calculated from the stomatal resistance (r_s). The canopy conductance is the fundamental vegetation parameter determining levels of transpiration calculated by the Penman-Monteith equation. The value of 5.1 for LAI seems reasonable as a maximum value for Corsican pine but is not a representative mean value. In a separate study of Corsican pine (Roberts *et al*., 1982), leaf area index was 5.21 at maximum, falling to 3.97 as a minimum. The canopy conductance arrived at using the g_s of 2.5 mm s^{-1} (r_s = 0.4 s mm^{-1}) and LAI of 5.1 (Equation 17 of ADAS report) is 3.18 mm s^{-1}. This is a very low canopy conductance and would be a constant through the day. Canopy conductance of Scots pine at Thetford from Gash and Stewart (1977) and Stewart (1988) were around 8 mm s^{-1} at 06h00 hr falling to 2 to 3 mm s^{-1} by 18:00 hr. Therefore one might conclude that forest transpiration would be underestimated if these values were used in a model.

At the same time the ADAS report states that the interception fraction used in the modelling was 0.4. For discussions of the impact of interception losses of the Newborough forest it is possible to provide values for the interception loss of Corsican pine based on actual measurements. Table 1 presents three sets of measured values and a fourth based on a modelling approach. The range illustrated in the measurements is from around 30 to 35 per cent. From these measurements a more realistic value for Newborough is likely to be around 0.33. This overestimation of interception may to some extent compensate for the underestimation in transpiration however a quantitative reassessment would be required to determine to what extent this was the case. It is also likely that canopy conductance (g_c) was also overestimated. Calculating canopy conductance based on the text in the ADAS

Report (Appendix B, page 38) would give a surface conductance of 12.75 mm s^{-1}. While this is not dissimilar to the early morning value of g_c given by Gash and Stewart (1977), holding this value throughout the day would lead to an overestimation of forest transpiration. The conclusion regarding the ADAS report is therefore that they have overestimated forest evaporation.

It is likely that the two components (interception and transpiration) have been modelled incorrectly and therefore we cannot be confident that the report gives a robust estimate of the recharge occurring under the forest.

Table 1. Interception losses from Corsican pine at UK sites

Site	Age (Years)	Stocking	Height (m)	Rainfall (mm)	Interception loss (mm)	Interception loss (%)
Bramshill, Surrey. (1)	40	600	20	1176 (830)	415	35.3
Culbin, Highlands. (2)	38-40	2110	12.4	1231 (630)	385 419 372	31.3 34.1 30.2
Thetford, East. Anglia (3)	26-27	2420	9.6	965 (551)	312	32.3
Clipstone, Notts. (4)	Not available	Not available	Not available	640	280*	43.7*

(1) Rutter, A.J., Kershaw, K.A., Robins, P.C. and Morton, A.J. 1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican pine. *Agricultural Meteorology*, 9, 367-384.

(2) Miller, H.G., Cooper, J.M. and Miller, J.D. 1976. Effect of nitrogen supply on nutrients in litter fall and crown leaching in a stand of Corsican pine. *Journal of Applied Ecology*, 13, 233-248

(3) Roberts, J., Pitman, R.M. and Wallace, J.S. (1982). A comparison of evaporation from stands of Scots pine and Corsican pine in Thetford Chase, East Anglia. *Journal of Applied Ecology*, 19, 859-872.

(4) Calder, I.R., Reid, I., Nisbet, T. And Green, J.C. (2003). Impact of lowland forests in England on water resources – application of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research*, 39, 1319-1328.

* Modelled values

The plant physiology model parameters used for the dune systems have relied heavily upon information collated by Breuer *et al*. (2003). As well as listing the source data, Breuer *et al*. also provide averages and their statistics for different vegetation types. The ADAS report uses some of these means as parameters. A significant issue with these means is that they include a number of high values which influence the mean value. Figure 1 illustrates the issue for the stomatal conductance and leaf area index of the herb and shrub data. The graphs demonstrate what is clear from the statistics namely that there is a large coefficient of variation related to a number of extreme values. How representative a mean value is in these circumstances must be questioned. Some high values come from mire species and, given the differences between mires and dunes, it does not seem appropriate that they are included in deriving a mean parameter for dune vegetation.

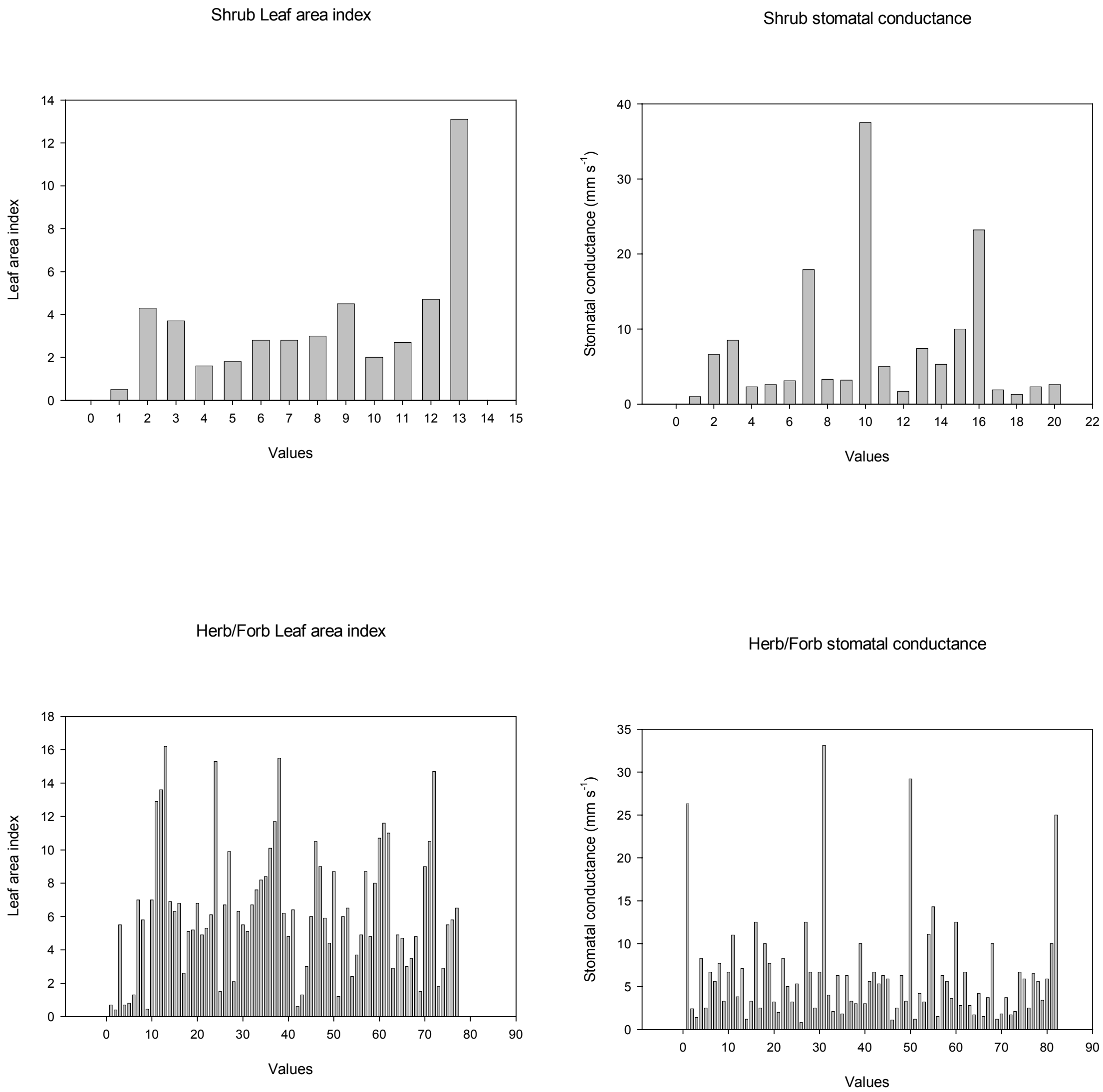

Figure 1. Value ranges for leaf area index and stomatal conductance for shrub and herb/forb species. Data from Breuer *et al*., 2003.

Calluna vulgaris and *Salix repens* are given the same stomatal conductance parameter. This does not seem reasonable on the basis that *Calluna* is a xerophyte while other *Salix* species (e.g. grown as short rotation coppice) have very high water use and even though *S. repens* is very different to other *Salix spp* this would not limit transpiration if the stomatal conductance (g_s) is high as observed for other willow species. There is no readily-available data about g_s of *S.repens.* Nevertheless it might not be unreasonable to assume that it is capable of high transpiration in a similar way to its congenerics that have been studied. Also, its favoured habitat is one where soil water is readily available. The effect of reducing stomatal conductances and leaf area indices of the dune vegetation types would be to reduce transpiration and increase the differences in evaporation between the dune and the forest. Furthermore, dune vegetation is largely shallow rooting, compared to the deep-rooting behaviour of forest trees. Thus dune vegetation is likely to experience soil moisture deficit and further reduced evapotranspiration at a much earlier stage in the summer than deep rooting forest trees which may access the water table directly throughout the year.

This preliminary assessment seems to suggest that: (a) the use of the formula for surface conductance in Appendix B of the ADAS report has resulted in an overestimation of forest transpiration, (b) the forest interception losses are also overestimated, (c) transpiration of dune vegetation is overestimated because of the use of unrealistically high surface conductances and (d) the effects of soil moisture deficit on dune vegetation have not been adequately accounted for. Therefore overall the evaporation estimates of both the forest and dune vegetation are overestimated. At this stage, however, it is less easy to speculate whether the forest or dune vegetation was overestimated more than the other.

3.2 Hydrogeology

Of the various assessments of the hydrogeology of Newborough Warren that have been carried out, the key document is that by Betson *et al.* (2002), which is based partly on earlier student activities at University College London (Kissiyar 1999). The Newborough Warren sands are partly forested, partly open, and there exists a hypothesis that the afforestation is responsible for an overall decline in groundwater levels such that the dune slacks no longer flood. In order to test the hypothesis various attempts at creating a conceptual groundwater flow model for the area have been undertaken and one (Betson et al., 2002) has been undertaken to test the conceptualisation using a digital flow model. The temptation in developing the model has been to prejudge the results with the trees the cause of the observed reduction in elevation of winter season water tables.

However, only one author (Hollingham 2005) has so far considered the prevailing causes and effects that are controlling the hydraulic environment at Newborough Warren. The Hollingham (2005) analysis lists possible process effects and raises a number of questions. Collectively these can be summarised:

1. Is the idea that the Warren is hydraulically self contained, i.e. no groundwater crossflow from bedrock, no unaccounted surface water inflow etc, accurate?
2. Could wetter winter and drier summers (climate uncertainty) be relevant?
3. Has the lowering and subsequent raising of the level in Llyn Rhos Dhu affected groundwater head?
4. What is the effect of drainage ditches on the recharge potential?
5. What is the hydraulic relationship between ditches and the lake with the sand aquifer?
6. Borehole data do not indicate a homogenous sand environment – is it valid to treat the sand aquifer as homogeneous in the assessments?

Discussion on the areal distribution of groundwater chemistry (Turner undated) is inhibited by scale, with any real areal variation masked by the prevailing maritime aspect. However, Malcolm & Soulsby (2001) have successfully identified hydrochemical regimes in a small coastal dune system in north-east Scotland. Turner also suggests that areas of higher elevation water table, such as the wooded area, are the principal recharge areas. He goes on to suggest that the trees are critical in reducing this perceived recharge. In reality, recharge occurs throughout the Warren area except in the vicinity of active discharge zones.

3.3 Groundwater Modelling

A single layer MODFLOW groundwater flow model of the dune system has been developed as an MSc thesis (Kissiyar, 1999) and later developed into a report (Betson *et al.* 2002) containing more detail on the modelling undertaken than the MSc thesis. The modelling is relatively simple, but there are concerns over the positions of boundaries, the parameter changes during the calibration process and treatment of the lake.

The main report on the modelling (Betson *et al*., 2002) presents a clear description of what was undertaken. However, the conceptual model is presented as part of the model construction, and this creates a confused picture of the understanding of groundwater system and that of the model construction. These two aspects need separating.

The main features of the model are summarised in Table 2.

Table 2. Summary features of the Betson *et al.* (2005) model

Feature	Description	Issue
Grid	50 m square; oriented with national grid	
Boundary conditions	Single layer with impermeable boundaries and fixed heads: • North-west – groundwater divide NO FLOW • North – cropping out of sand NO FLOW • South and East coast Fixed heads @ 0 m aOD	Boundaries may need to be extended, i.e. model may be too small
Lake and stream	Situated north of warren connected to mouth of river (Afon Braint) by stream Lake is represented by fixed heads that can change with time Stream is represented by river package elevation of lake to 0 m aOD	Groundwater system may be supplying lake
Hydraulic conductivity distribution	Hazen analysis used to calculate k values for sand min and max values 1.7 to 19.7 m/d. Uniform distribution over warren	If uniform, why end with distribution after calibration?
Top elevation	Determined from previous work (Docherty *et al.,* 1990)	Why needed? Groundwater models do not usually recognize ground surface
Bottom elevation	Derived from geophysics (seismic refraction) and borehole logs	High in middle of warren caused by “small graben” structure. Is this real?
Storage coefficient and porosity	Recognised as not required for steady state model, but specific yield of fine sand given by Fetter (1994) as 0.21 and Freeze and Cherry (1979) as between 0.25 and 0.5. Porosity of 0.37 as measured by the permeameter experiments (Table 5.1)	Ranwell (1959) suggests specific yield of about 0.30.
Recharge	Tried recharge and EVT in model, but was unsuccessful and required values outside of expected range to get model to work Penman-Monteith to calculate PE.	

	Interception considered to determine difference between forest and grassland SMD calculation performed on monthly basis.	

The model calibration depends to a large extent on groundwater levels collected between June 1989 and July 1996 by CCW (Hesketh 1998). These data have been averaged to produce calibration targets. The drought of 1989-1992 may have influenced the levels (i.e. reducing them), although there is little apparent change in the north-west corner of the model. Meteorological data for the recharge calculation are taken from Anderson (1994). The results of the model calibration exercise reveal a problem with dry cells especially in the north-west of the model where bed-rock rises close to the surface. The authors tried various ways to remedy this: they reduced the depth of the bottom of the model, changed solvers, and then used a combination of increased depth and hydraulic conductivity. Four zones of hydraulic conductivity were created (Figure 8.1, Betson *et al.,* 2002) with hydraulic conductivity ranging from 3 m d^{-1} in the north-west of the model area to 9 m d^{-1} in the south and eastern part.

The recharge under the afforested area and the vegetated area is calculated using a soil moisture deficit (SMD) method. The recharge under the forested area is calculated to be half that of the open dunes, i.e. 0.51 mm d^{-1} for the forest as opposed to 1.1 mm d^{-1} for the open dunes (see Table 8.1, Betson *et al*., 2002). However these values were changed in the final 'calibrated' model such that the recharge value under the forest was 0.55 mm d^{-1} and the recharge value under the open dunes was 0.65 mm d^{-1}. Bakker (1990) indicates that evapotranspiration (albeit in coastal Holland) could be 1.0 mm d^{-1} for dry dune vegetation and between 1.51 and 1.92 mm d^{-1} for coniferous woodland depending on its access to water. It would be reasonable, therefore, to expect a difference of not less than 0.51 mm d^{-1} in effective rainfall/recharge and the original values of 0.65 and 1.1 mm d^{-1} are more realistic than 0.65 and 0.55 mm d^{-1} for woodland and open dune respectively. That the model could not cope with the original values suggests it is flawed in some other way, perhaps in basic assumptions regarding boundaries or other input data.

A tracer test was used to assist in the calibration of the model. The test was undertaken by injecting brine into a borehole on the eastern edge of the forest and the plume development was tracked using geophysics. Analysis of the results for the tracer test showed velocities of 0.1 m d^{-1} and a direction of transport of $210^{o} \pm 7.5^{o}$. This was matched with the velocity vectors derived from the model.

Various predictive runs, both steady state and time variant, were undertaken with the model. Only steady state runs were reported in Betson *et al*. (2002). For this work, the model was used to make predictions on the effect of reducing the area of the forest and the impact of changing the afforested areas on groundwater levels in the observation boreholes. This was undertaken by changing the recharge rate from that used to represent forest to the value used for the vegetated dunes. Three sections were considered: northern, eastern and southern. Increasing the recharge rate to the forested area did raise the water table, and the greater the area of the forest "removed", the greater was the predicted rise in water levels. The greatest effect for each individual section was found by removing the northern section of the forest. As would be expected, the maximum water level rise occurred when all three sections of woodland were removed.

The main concern with the modelling is that the recharge values under the forested area and the open dunes are used as calibration parameters and the difference between the two values is much smaller than would be expected. Consequently, it is not possible to conclude from the modelling work that the forest causes the lowering of the water table.

3.4 Conclusion

Although many studies of Newborough Warren have been undertaken, it is not felt that they adequately address all the issues relating to the issue of the falling water table. The main concerns, in our view, are that:

- Many of the studies have started off from the view point 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 for both the forest and the dune vegetation. Interception has been overestimated for the forest vegetation.
- The effects of soil moisture deficit have not adequately been accounted for.
- The groundwater model could only be made to work by using unrealistic values for recharge, suggesting an underlying problem with the conceptual model.

For these reasons it is not felt that any questions relating to the effect of the forest on the water table can be adequately answered by the reviewed reports.

4. Site visit (13/14 March 2006) and development of understanding

Itinerary

Monday 13th March

1. Get "overview" from west of Newborough village (near ancient settlement Llys Rhosyr) – system much larger than expected
2. Drive though forest to the shore - seepage to hollow fresh-ish
3. Drive along rock ridge - highly broken up/fractured
4. Springs/seepages of west of rock ridge: one/two flowing streams (shore dock site)
5. Dune slack with excavated-pool - water in bottom "unusual", pool sits on relatively recent (~200 years old) blown sand, deep ditches drain the site
6. Lake (Llyn Rhos-ddu) larger than expected, size increased by recent rainfall, has ferruginous discharge

Tuesday 14th March

1. Walk to high ground in Warren – large numbers of wet slacks
2. Walk across to forest edge to examine area of recently cleared trees
3. Walk along forest edge to see stream from diverted spring (under road to lake) has very little discharge and ferruginous
4. Walk from eastern (Braint) car park to estuary (observed seepage from clays)

Observations:

- Bedrock probably comprises Coal measures and Red Measures, maybe Millstone Grit, to the north-west of the rock ridge. The rock ridge is Precambrian (Gwna Group) Spillitic Lavas and associated formations. To the east of the rock ridge are the metamorphosed schists of the Penmynydd Zone which are juxtaposed with Carboniferous Limestone beneath the Afon Braint. The whole sequence follows the Caledonian trend.
- The Quaternary geology presumes a near complete cover of till and marine clay. At outcrop in the estuary of the Afon Braint the clay is fresh and unweathered forming a weakly permeable cover over the bedrock. Above the clay are the aeolian dune bedded sands characteristic of Newborough Warren. These give way to riverine and marine alluvium in the north along the lower part of the Malltraeth Marsh, now drained by the canalised Afon Cefni.
- The rock ridge consists of weathered and fractured Spillitic Lavas of the Gwna Group which offer adequate secondary storage and permeability for several significant spring arisings. One of these is reputed to maintain a near constant discharge of about 1 to 3 $l\ s^{-1}$ regardless of the prevailing weather. This suggests a sufficiently large capture zone for storage to buffer recharge events and for permeability to release water in store at a near constant rate. The secondary permeability of the rock ridge only becomes significant in modelling terms should a head difference exist in the sand either side of it. No such head difference exists.
- Groundwater discharge is visible on the foreshore around much of the Warren. At the mouth of the Afon Braint the seepage is accentuated by an outcrop of marine clay/till exposed as a weathered and breaking clay horizon covered by only 2 to 3 m of sand.
- Recharge to the sands is the result of direct rainfall recharge. Rates of recharge are controlled both by topography and more particularly by vegetation. It is, therefore, presupposed that the effective recharge to the forested area is

different to that of the open duneland. There is little effective surface runoff from the sands.

- Llyn Rhos Ddu does, however, receive drainage from the easternmost forested area. Additional drainage from the rock ridge area to the north adds to the lake input, as does groundwater discharge from the sand from the area immediately to the south-east of the lake. In turn the lake discharges via a ditch directly into the Afon Braint.
- The lake sits directly on the sands with a thin silty horizon at its base which might inhibit ingressing groundwater but which would not prevent it. The head of the lake has varied with time and this will have affected the flow system in the sands.
- The overall transpiration of the woodland is variable, given constant ageing of the trees and possibly reduced water demand with age (though it is not clear that the Newborough forest crop has reached biological maturity), coupled with thinning of the woodland over the last 30 years, albeit with some replanting, development of understorey and the influence of forest edges. The arrival of red band blight might also cause a reduction in tree vigour.
- The dune land vegetation has changed from very sparse in the early 1950s to a thick and tall grass cover during the 1960s and 70s whilst grazing was prevented from the open Warren until the gradual reintroduction of grazing from 1986 and more recently with short cropped grass currently maintained by grazing ponies, cattle and sheep. In addition, following a serious reduction in their numbers due to the myxomatosis outbreak in 1954, rabbits have returned in abundance and now contribute to a very short vegetation.
- The coastal boundary of the aquifer may lie somewhere towards low tide mark, rather than as currently assumed at the head of the foreshore.

The hydrogeological boundaries of the groundwater system at Newborough Warren are more extensive than previously thought. The main issues are:

- Role of the rock ridge – is this really impermeable and does it form a barrier boundary?
- Tidal effects - how is the sea moving onto and off the large flat sands that interact and form part of the aquifer?
- Is the boulder clay universally present beneath the sands and is it wholly impermeable?

It is, therefore, necessary to expand the boundaries of the study area further north-west to take into account the forested dunes north-west of the rock ridge, further north to cover the outcrop of the boulder clay and further south-east to take into account the impact of tidal movements. The aquifer system is potentially more extensive than just the blown sands. The rock ridge forms a fractured aquifer that provides a high elevation store of groundwater which is discharged to the adjacent sands via springs and streams or directly to the sand. It does not form a barrier to the groundwater flow system.

The boulder clay is absent at the rock ridge and possibly for some distance away from it. The north-westerly side of the rock ridge is fault bounded and steep, whereas the south-easterly side is a more gentle dip slope passing beneath the sand. There is a likelihood of good hydraulic contact between the bedrock and the sand for some distance from the rock ridge outcrop on its south-easterly flank.

5. Independent assessment of the hydrological impacts of the forest

5.1 Vegetation

The study of forest evaporation that is perhaps most relevant to the Newborough situation is that reported by Deij (1948, 1954) and also discussed by Rutter (1968). There are some important similarities between Castricum (in The Netherlands) and Newborough; both are coastal and at similar latitudes, Corsican pine was involved at both sites and annual rainfall and potential evaporation are similar. Goudie and Brunsden (1994) indicate that the annual potential evaporation for Anglesey is 500 mm. Using Lysimeters (25 x 25 x 2.5 m) constructed in the dunes at Castricum, Diej estimated the annual evaporation of Corsican pine compared to mixed broadleaves (oak, birch and alder). With a mean annual rainfall of 840 mm, annual evaporation from the Corsican pine was 655 mm and evaporation from the broadleaves was 500 mm. Evaporation from short vegetation was not measured though the net radiation receipt was equivalent to 550 mm yr^{-1}. Experiencing no soil moisture deficit the net radiation equivalent might be reasonably equated to the annual evaporation of short grass.

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

Another approach to estimating forest evaporation 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 (see data for Corsican pine in Table 1). The 1988 to 2005 average annual rainfall measured at Bodffordd is 1066 mm, and therefore annual evaporation might be (1066 x 0.33 + 333) = 685 mm. Clearly not a very different value to that measured at Castricum (655mm). If evaporation of short dune vegetation is equivalent to potential evaporation (500 mm yr^{-1}), then around 150 mm yr^{-1} less recharge would be available below the forest. If significant soil water deficits occur below the dune vegetation and evaporation is reduced further, the difference in recharge between forest and grass is very likely to be even greater.

The greater evaporation, and hence reduced recharge, of coniferous woodland compared to other vegetation types has been illustrated by direct measurements of evaporation from different vegetation types in dunes in The Netherlands and these have been reported by Bakker (1981, 1990). In a region where annual rainfall was 725 cm, evaporation for different vegetation types (Table 3) indicated least recharge below coniferous woodland, more under deciduous woodland or dune vegetation and most under bare dunes.

Table 3. Annual evapotranspiration for seven types of vegetation in the dunes of the Netherlands. Annual precipitation = 725 mm yr-1. (After Bakker, 1990).

Type of vegetation	Evapotranspiration (mm yr-1)
Bare dunes	180
Wet slack vegetation	550
Dry slack vegetation	360
Wet deciduous woodland	550
Dry deciduous woodland	400
Wet coniferous woodland	700
Dry coniferous woodland	550

Therefore although the evaporation totals of both forest and dune vegetation might have both been overestimated in the work reported by Betson and Scholefield (2004), it is nevertheless probable that evaporation from the forest substantially exceeds that from the dune vegetation and therefore would result in significantly lower recharge from annual rainfall. There are very few situations where runoff or recharge from forested areas exceeds or equals that from areas under short vegetation (Calder, 2002). Where this does occur, it can be attributed to specific factors that do not apply to Newborough.

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. This growth of woody vegetation might further enhance the influence of the initial afforestation. Up to the present there is no evidence that this is occurring at Newborough since scrub development is controlled partly by grazing.

Elsewhere, the development of woody vegetation on the dunes has been implicated as at least a partial cause (along with reduced precipitation and adjacent drainage work) in the reduction of water tables in the Braunton Burrows dune ecosystem (Packham and Willis, 2001). Packham and Willis report that many British dune systems suffer from management problems, including those associated with hydrology, similar to Braunton. The invasion of scrub has caused concern in very many dune systems since the decline in rabbit populations resulting from myxomatosis. The sea buckthorn (*Hippophae rhamnoides*) is singled out for special mention as a serious invasive plant of coastal dune systems, although since the 1990s this has been largely eradicated from the Newborough dunes.

Surprisingly, none of the evaluations of the hydrological impact of the forest at Newborough have addressed three aspects of forests that have been identified as contributing to variations in forest water use. These factors are: the effect of advected energy from the nearby ocean; the distance of the tree cover from the edge of the forest (or major cleared areas e.g. roads, fire breaks), and the age of the trees in the forest stand. Each is discussed below:

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

Evaporation is often enhanced within 20 m of the forest edge (FC, 2005). Kinniburgh and Trafford (1996) found that this 'edge 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. The enhancement of evaporation at a forest edge is due to a number of factors such as increased leaf area at the edge, greater exposure to radiation as well as penetration of external microclimate into the body of the forest. All of these factors will serve to increase both the transpiration and interception losses at the edge. 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. Unfortunately, our research findings at the present time do not allow us to be more quantitative about the edge effect. As a crude estimate we might surmise that evaporation 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.

There is accumulating evidence from the Plynlimon catchments (Hudson et al., 1998; Marc and Robinson, 2006) that forest water use on the Severn headwaters is declining, and that this is associated with the forest increasing in age. This assertion is supported by independent catchment studies in Australia and South Africa. When canopy closure of a forest takes place after forest establishment, water use might increase in association with canopy size and forest vigour, which seems to concurr with anecdotal evidence of watertable fall at Newborough (Ratcliffe *pers. comm.*). In assessing forest yield, foresters study the 'current annual increment' which varies with age. 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 at age 55 – 60 years. As the bulk of the forest was planted between about 1952 - 67, making much of it 40 - 50 years old, and a substantial proportion of the older stands have been clearfelled and replanted, we cannot assume that the Corsican pine at Newborough is yet in the phase of declining mean current annual increment. A new survey for canopy cover of the forest compartments at Newborough might indicate if there is a significant age influence on canopy properties. It might also indicate a reduction in average canopy cover since extensive and repeated thinning of the crop began in mid 1980s. In the event of a likely age effect it might be reasonable, in terms of hydrological modelling, to impose a small reduction factor on evaporation from areas covered with the older compartments.

For completeness, two further forest effects that have not been referred to in any of the reports, but can be discounted in the explanation of falling water tables associated with afforestation are (i) the very small increase in ground level height due to litter accumulation and (ii) the storage of water in the forest biomass which will increase with forest age.

5.2 Hydrogeology

Similar dune systems have been studied elsewhere in the UK and Europe. As much as these provide valuable experience, their relevance to Newborough is limited given the site-specific nature of groundwater movement. For completeness, the most significant studies are outlined below.

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 and water levels have largely been affected by peripheral land drainage and abstraction.

St Fergus in 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). The Dutch probably have the most intimate knowledge of coastal sand hydraulics of any nation.

5.3 The Ainsdale study

Ainsdale on the Lancashire coast (Atkins, 2004) 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. Prior to experimental clearance the mainly Corsican Pine woodland covered 176 ha and was divided into 28 ha of poor quality seaward frontal woodland and 148 ha of more healthy landward rearward woodland (Simpson and Gee, 2001). Two phases of scrub and woodland clearance were carried out: the first in 1992 cleared a total of 11 ha, of which 4.5 ha was pine forest, at the northern end of the frontal woodland, and the second phase in 1995/1996 cleared a total of 16 ha of scrub and woodland.

Atkins summarise the work of a PhD candidate who looked at 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.

5.3.1 The effect of the conifer plantation

The effect that the conifer plantation has on the ground water levels as reported by Clarke (1980) was as follows:

- The water table contours bend away from the coastline within the area of the conifer plantation - the break in slope of the water table begins almost directly beneath the boundary between the unforested and the partially forested areas of the reserve.

- There is 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.

- There is also a narrowing of the distance between contours within the frontal woodland when compared to the open dunes to the north, demonstrating a steepening of the water table gradient.

- Effective rainfall has a direct influence on the groundwater table level. If the water table levels were only a function of rainfall then the autumn would be the wettest time of year and the spring would be the driest. However the reverse is true.

- Interception and evapotranspiration were considered to be the most important factors, especially in the summer, when comparing the afforested and the open dune areas. Trees have a large interception capacity and re-evaporation of water occurs in preference to transpiration. The estimated interception loss in the woodland is around 35% and evaporation loss estimated at 30 mm per month in midwinter, which is 40% greater than for grasses.

The maximum annual water table fluctuation is 1.5 m with wooded areas clearly drawing down the water table by about 1 m. Brassington and Preene (2003) highlight the sensitive nature of the water table in the dune system by demonstrating the advantages of a horizontal gallery over a conventional borehole for groundwater abstraction purposes.

5.3.2 The effect of deforestation

Boreholes were established in various types of dune cover, ranging from open fixed dunes to coniferous woodland, outside the areas where clearfelling would occur. These were designated as control boreholes. Additionally, boreholes were established in the same range of dune cover types in an area where clearfelling would occur. Clearance schemes were undertaken in 1992 and 1996 and the impact on the water table of these schemes monitored. However, groundwater monitoring was only conducted between 1991 and 1993 and then again between 2001 and 2003 leaving no data for the period from 1994 to 2000.

Over the monitoring period the average rise in water level in the clearfelled area was 0.82m and 0.51m in the control areas. The higher water levels in the clearfell fixed dunes in comparison to the fixed dune control boreholes indicates that the clearfell of the pinewoods within the dune restoration area has had an impact on the water levels in the associated surrounding fixed dunes. The increase in water levels within the clearfell area occurs against a background of a general groundwater rise along the Sefton Coast independent of management of the reserve. Within the clearfell boreholes, water level rises in those boreholes originally within the woodland vegetation are greater than those in the open fixed dune system. However for the control boreholes, the vegetation type does not appear to have any relationship with the water level rise over time. There are two issues which make the effect less clear. First, there were two episodes of water level monitoring – 1991 to 1993 and 2001 to 2003. No levels are presented for the period between these two episodes. Without these additional data it is not possible to comment on how quickly the water table rise occurred. Secondly, the early 1990s exhibited low rainfall and winter 2000/1 was very wet, so it is difficult to conclusively state that the reduction in forest area has improved the groundwater situation.

The overall conclusion of this study is that boreholes within the original 11 ha clearance area, of which 4.5 ha was pine woodland showed a rise in groundwater level of around 0.3 m compared to the boreholes in the control areas. The lack of continuous water level time series data makes more detailed analysis of the factors impacting on the water level rise impossible.

5.4 Conclusion

The consensus derived from the scientific literature on forested dune areas is 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. This difference indicates an overall decrease in recharge potential to the groundwater store under wooded areas compared to that beneath open or short grassed areas. Depending on physical the controls on the water table, such as streams maintaining a near constant head on the adjacent water table, the shore line itself or in some cases natural barriers which may create an underground dam to groundwater flow (of which none are known in the Warren), then the lower recharge potential is likely to result in a lowering of the water table when compared with the groundwater system prevailing before the trees were introduced.

There is overwhelming evidence that the coniferous forest at Newborough has a greater water use than would an equal area of short dune vegetation. Recharge beneath the forest is expected to be between 100 and 200 mm yr^{-1} less than that under short dune vegetation. A reduction in the afforested area (and conversion to short dune vegetation) would be likely to result in a rise in the water table. Predicting the magnitude of water table rise is more complicated and will require detailed monitoring of meteorological and physical parameters for a period of not less than three years followed by an intensive modelling assessment to understand all the active processes. Given a satisfactory correlation between historical observations and model output, predictive scenarios could then be generated to show what might happen if some or all of the trees were removed and the vegetation was returned to open dune land.

There are other features of the system that influence the groundwater head in the dune aquifer. These are:

- The vegetation has changed since the woodland was first planted, trees have matured and grazing practices have altered on the grassed areas.
- The outlet level of the lake has varied.
- The groundwater system is more complicated than previously envisaged, for example, bedrock and the rock ridge do play a part in storing and transmitting groundwater.

These features will need to be included in any future modelling.

6. The effects of anticipated climate change

Although climate uncertainty over the next four decades is widely heralded, its impact remains unclear. A report compiled by the National Assembly for Wales states that by 2080, Wales may experience:

- up to 24% more winter rainfall
- up to 14% less summer rainfall
- up to 27% less evapotranspiration
- a sea level rise of up to 79 cm

Extremes will also tend to increase, with very dry and very wet becoming more common, so that water table fluctuations may tend towards a greater range than at present.

These changes relate specifically to Newborough in the following ways:

Forests

There may be risks to the security of forests because of increased windiness, the occurrence of severe gales, from pests that can more readily overwinter in warmer temperatures and forest fires will be a greater risk. There is a very strong link between temperature and vapour pressure deficit (D) and in temperate woodlands (conifers and broadleaves) a strong negative correlation between D and stomatal conductance (g_s). So, as temperatures (and D) rise, transpiration will not necessarily rise because g_s has fallen in association with the increase in D (Roberts, 1983). This response could be expected of both coniferous and broadleaved woodland.

Evaporation may increase in both conifers and broadleaves if the growth season is extended. If spring temperatures rise, leaf emergence may occur earlier but a prerequisite will be that sufficient low temperatures have occurred in winter to fulfil the chilling requirement for normal leaf emergence. In trees, the end of the growth season is more closely related to shortening daylengths so will not be influenced by climate change. The link between D and g_s means that transpiration is rather constant at around 300 mm yr^{-1} (Roberts, 1983). Dry spells in summer may have little influence on transpiration if there is sufficient water stored in the soil and the trees have access to the water table.

The increase in annual rainfall and greater concentration in the winter period will have different influences depending on whether the forest cover is coniferous or broadleaved. In the case of evergreen coniferous woodland (larch being the exception) there would be an increase in interception loss throughout the year. Broadleaved species would only really contribute to increased interception if summer rainfall increased. If there was a major switch to a predominance of winter rainfall a greater recharge below broadleaved woodland might be expected because the interception loss falls by around two thirds when the trees are leafless.

Short vegetation

The major effect of increased temperatures and evaporative demand on short vegetation is likely to be a greater risk of water stress and therefore decreased evapotranspiration, particularly for the most shallow-rooted vegetation. An increase in temperature will extend the growing season and will also increase evaporative demand. Generally, short vegetation does not exhibit the same negative feedback of

g_s to D that is seen in trees so increases in potential transpiration might be matched by actual transpiration until a soil water deficit develops. This might occur earlier in the growing season, particularly for shallow-rooted vegetation. Severe water/heat stress reaching lethal limits might be the case for shallow-rooted vegetation. Temporarily this might mean more recharge below shallow-rooted vegetation but in the longer term might mean a low capacity to compete with deeper-rooted species, especially those with some access to the water table.

Groundwater conditions

The projected increase in sea level by up to 79 cm will increase the base level of the groundwater system accordingly and will impact a corresponding rise in the water table when it is not affected by other influences – constant head boundaries, flooding of slacks etc. Change in annual rainfall distribution and evapotranspiration may tend to balance themselves out so that recharge potential may be largely unchanged.

Conclusion

In summary we might expect transpiration of forests to remain largely unchanged in a changed climate. Interception losses (in absolute terms) would increase if annual rainfall increases. A shift to more winter rainfall might be exploited as an intervention to increase recharge by introduction of areas of broadleaved woodlands that intercept least in the months they are leafless. Increased soil water deficits are envisaged for more of the rooting depth of shallow-rooted short vegetation. This situation might reduce the competitive ability of such vegetation. Sea level rise is likely to increase the level of the groundwater system.

7. Potential implications of management scenarios

The following specific management scenarios are discussed:

- total or partial removal of the forest,
- the desirability of removing discrete forest blocks at specific locations
- alterations to forest management
- artificial groundwater replenishment
- terrain re-profiling

7.1 Total or partial removal of the forest

Total or partial removal of the forest is very likely to result in a reduction in water use and water tables should rise, at least in the vicinity of the clearing. In the Ainsdale study the removal of 27 ha of scrub and woodland between 1991 and 1996 resulted in an average water level increase in the clearance areas of 0.3 m when comparing average water levels from 1992 and 2002. However this result may not be very representative of the situation at Newborough as even if the age and density of the Ainsdale forest were comparable to Newborough, the other physical and biological processes that influence the water table are almost certainly not replicated. In addition the current lack of clear definition of the hydrological requirements of dune slack habaitats makes it difficult to comment on what increase in water table would effectively reduce the impact on the integrity of the SAC.

Other factors that should be considered are:

- The newly exposed soil could be mobilised and transported to unforested dune areas.
- The return of a flora that existed prior to forest establishment is unlikely to occur in the cleared areas if the forest has covered the area for 50 years or more.
- The lack 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 but a viable population of weed seeds may exist and could germinate to provide a dense ground cover.
- The presence of the pine litter and changed nutrient status would also hinder the establishment of a typical dune flora although this could offer opportunity for the establishment of interesting acid dune components.
- Cleared areas could be invaded by herbaceous weeds and woody scrub. Over the course of time, without significant management intervention, a scrub woodland might develop with a similar hydrological function to that of the existing pine forest. However, normal management of light grazing could preclude this outcome.
- The forest serves as a significant amenity and a drastic change to forest cover is likely to be strongly resisted.
- Conifer forest in some form or other at Newborough is a *sine qua non* for aspirations to expand the red squirrel population at Newborough.

7.2 The desirability of removal of discrete forest blocks at specific locations

Removal of blocks of woodland would be expected to reduce water use and enhance recharge. Enhanced evaporation at forest edges might, to some extent, counter the effect of creating clearings. Because forest edges might be the zones of enhanced transpiration there would be merit in considering creating fewer larger cleared areas rather than many smaller ones. Modelling to-date (Betson *et al.,* 2002) suggests that removal of the northern section of the forest would have the most effect on groundwater level however given the inadequacies of the modelling it would be unwise to act on this information. There may be benefit to selecting areas of higher ground (which may therefore have a thicker unsaturated zone) for clearance however small scale effects such as this would be difficult to quantify without conducting a very detailed investigation. The effects of selectively clearing areas of the forest can be better investigate once a properly functioning model has been constructed.

7.3 Alterations to forest management

7.3.1 Introduction of broadleaved trees

Evaporation from broadleaved forest is less than from coniferous forest for two principal reasons. In winter the leafless canopy of broadleaved woodland allows less evaporation 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 and soils are not frozen (which in this location they seldom are) . There may be some losses from an understorey that might thrive under a leafless broadleaf canopy in spring but because of low evaporative demand that loss is not likely to be great. So the introduction of broadleaves is likely to reduce water use. It is possible that additional edges will be created and enhanced edge effect may to some extent counteract the reduced water use of broadleaves.

In addition to any hydrological considerations, a significant consideration in deciding the future species composition and spatial location of woodlands at Newborough would be a desire to create suitable habitat for the red squirrel (Sciurus vulgaris L.). Over and above the prerequisite that the grey squirrel should be excluded from areas intended to be colonised by red squirrels, Shuttleworth and Gurnell (2001) indicate a number of woodland habitat requirements that should favour colonization by red squirrels. Large forest blocks (over 200 ha) should be provided and there should be wooded corridors between blocks. Freely-seeding conifer species (Scots pine is regarded as particularly suitable) should form the bulk of the forest cover. Some broadleaf species with large seeds e.g. beech and oak might be included. Clearly a woodland cover at Newborough that is optimised for low water use (extensive areas of mature/semi-mature, even-aged broadleaved woodland having a small number of large clearings and minimum edges) is quite unlike one that might provide the best red squirrel habitat.

7.3.2 Thinning

The removal of trees would initially result in greater recharge however in time this might be compensated for by canopy closure of the remaining trees and/or losses from an understorey that might develop in improved light conditions below a thinned canopy. Roberts *et al*. (1982) showed the importance of understories 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 a shallow-rooted, low water use, drought-tolerant species to serve as an understorey and to suppress establishment and growth of species like bramble or bracken. However this may be undesirable in terms of compatibility with other objectives.

7.3.3 Continuous Cover Forestry

Continuous Cover Forestry (CCF) is defined as a forest management system under which felling and regeneration are carried out continually or irregularly throughout the whole of the woodland area, and there is no clear felling of trees when they reach some pre-determined age (Helliwell, 1999). It is not clear how this option might be implemented but the final result, involving broadleaves might appear in side view like Figure 2b. Figure 2a might represent a single species, single age broadleaf woodland. While CCF might fulfil objectives of reducing dramatic changes in forest cover and producing a more diverse (age and species) tree complement, there is an unknown hydrological impact of producing a canopy with arguably more fully-exposed surfaces (Compare Figure 2a and 2b). At this stage there is no research to inform about the effects of such a change of canopy structure although a greater water use by CCF compared to conventional British forestry is a distinct possibility, due to its greater canopy surface area, increased turbulence of air flow and increased understorey.

7.3.4 Establishment of Atlantic woodland

The current EU definition of Wooded dunes of the Atlantic, Continental and Boreal region or "Coastal dunes with near-natural woodland" (which is proposed as the new name for this habitat type) is:

"Natural or semi-natural forests (long established) of the Atlantic, Continental and Boreal region coastal dunes with a well developed woodland structure and an assemblage of characteristic woodland species. It corresponds to oak groves and beech-oak groves with birch (*Quercion robori-petraeae*) on acid soils, as well as forests of the *Quercetalia pubescenti-petraeae* order. Pioneer stages are open forests with *Betula* spp. and *Crataegus monogyna*, mixed forests with *Fraxinus excelsior*, *Quercus robur*, *Ulmus minor* and *Acer pseudoplatanus* or, in wet dune slacks, pioneer forests with *Salix alba* which develop into humid mixed forests or marsh forests. On southern Atlantic coasts, it mainly corresponds to mixed *Pinus pinaster-Quercus ilex* forests, forests of *Quercus suber* and *Quercus robur* or forest stage with *Quercus robur* or *Quercus pubescens*. On Baltic coasts also pioneer forests of *Alnus* spp. or *Pinus sylvestris*. Plant species are highly varied and depend on local site conditions. This habitat includes semi-natural forests with typical undergrowth, spontaneously developed from old plantations. These forests are generally associated with dune scrubs (pre-forest stages-16.25), dune moors, grey dunes (16.22) and wet dune slacks (16.3)." "The criterion for the delimitation of this habitat type is the presence of semi-natural deciduous (North Sea and Baltic) or mixed deciduous woodland (Baltic) on coastal dunes. Pine forests without a near-natural understory (e.g. for resin production) are excluded."

In the UK, the Joint Nature Conservation Committee (JNCC) considers that there are no substantive examples of this habitat at the present time in the UK. The UK Sand Dune BAP recognises that it may formerly have been present and proposes the selection of 5 sites for the experimental creation of Atlantic Dune Woodland.

Atlantic Dune Woodland could potentially develop at Newborough in time. The main native trees would probably be birch and oak as in many continental examples. Sycamore would fit in well ecologically, but treatment depends on whether it is accepted as an "honorary native" (given its relatively recent introduction to GB and its limited faunal association). Dune slacks would probably be willow dominated; alder would perhaps be less abundant because of less effective dispersal in this sort of terrain. Ash might occur where water levels are stable and an understorey of hazel, elder, hawthorn etc., may develop. Arguably these species might be expected to show two separate behaviours in terms of their water use. Birch, sycamore and oak would form the first group whilst willow, alder, ash and poplar would make up the second. With respect to interception losses there might not be large differences between stands dominated by species from either group. It is likely however that transpiration losses would be higher from the second group, so the overall water use of the second group is likely to be greater than that of the first group.

Due to the varied topography of the terrain there are likely to be quite sudden spatial variations, e.g. from oak/birch to willow dominance at edges of slacks so overall there could be quite a tight mosaic of types. Corsican and lodgepole pines would be likely to remain the overlying structure of the forest for a considerable period, with possibly some increase in Scots pine in landward areas. Regardless of its species composition, the Atlantic woodland might have an open heterogeneous structure with a well-ventilated canopy that might lead to efficient transpiration and interception losses as suggested for CCF. Additional management may be required to minimise the establishment of high water-use species (e.g. willow) around the wetter slack areas where they are likely to further impact on the water table lowering.

7.3.5 Groundwater replenishment

Although surface water is abundant in the local area the sources for artificial recharge of groundwater are as yet unknown to the authors. The cost and practicality of getting the water to the dune system may prove prohibitive. If these issues can be addressed then the quality of the replenishing water must be considered. There are examples of artificial recharge schemes in Holland that are used to replenish dune systems, but these create problems in terms of water quality and growth of unwanted plant species (Ranwell and Boar, 1986). It is, therefore, suggested that an artificial recharge scheme is impractical due to cost and the mismatch of water quality leading to ecological problems.

7.3.6 Terrain reprofiling

At this stage it is unclear as to what is the desired outcome of reprofiling. If it is to lower the ground surface such that the depth to water table is reduced then an indication of the desired area over which this would be conducted should be indicated. It may be that up to 1 m may need to be removed in places in order to bring the ground surface to within the desirable distance from the water table and this would raise a number of further issues including: what would be the direct effects of this level of disturbance on the site; where would the removed material be deposited; and would the newly uncovered surface be suitable for establishment of the desired dune vegetation. It is difficult to see how this option would help to achieve the required outcome.

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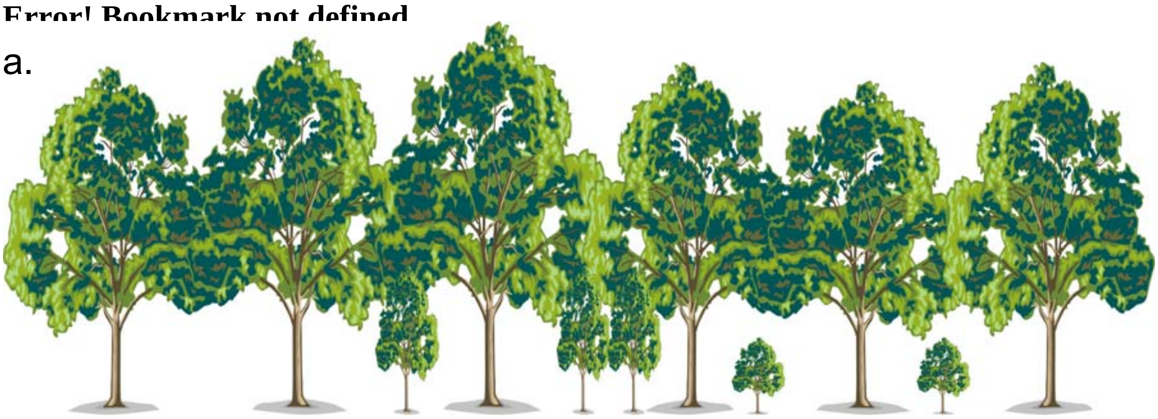
a.



b.

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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 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, in a wet year, is marked by widespread flooding and 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 4 below.

Table 4. 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

Ranwell then went on to describe wet and dry slack dune associes by the following broad water table conditions (Table 5).

Table 5. 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. The range of these data are summarised in table 6, whilst the time-series data are shown in figure 3. The transects are parallel to each other and run perpendicular to the forest/warren boundary (i.e. directly away from the forest in the direction of the warren). The letters indicate increasing distance from the forest (i.e. D is closest to the forest and G is furthest away). Transect 2 is nearer to the shoreline than transect 1.

Although it is accepted that this is a very crude method of comparison, it will help to indicate whether in 1989/1990 the water table in the warren was behaving in a similar way to 1951 – 1953. It is also noted that it is unrealistic to base any management decision on such a short time-series of data. A more robust judgement would be possible once all previous data have been collated in a comparable form.

Table 6. Range of observed depth-to-water table values for each of the three phases of the annual cycle, and for each dipwell in the warren area.

	Depth to water table (+ve = above ground, -ve = below ground)		
Dipwell	November to April	April to August	August to November
1D	-52 to -135	-94 to -168	-128 to -148
1E	-5 to -98	-63 to -114	-91 to -102
1F	-5 to -75	-31 to -108	-56 to -93
2E	-40 to -113	-76 to -136	-103 to -127
2F	-34 to -107	-72 to -132	-98 to -123
2G	-14 to -85	-58 to -119	-78 to -108

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.

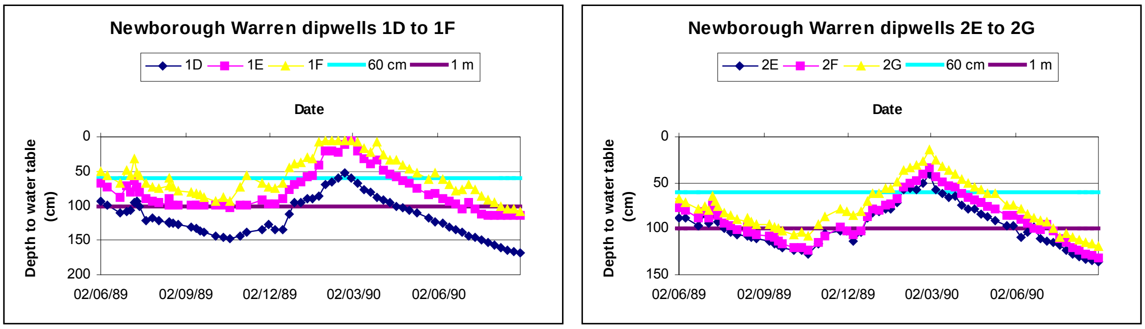

Figure 3. Time series of dipwell data collected between 2/6/1989 and 29/8/1990 . The left hand graph shows time data collected from dipwells D to F in transect

1 and the right hand graph shows data collected from dipwells E to G in transect G. On both graphs the 60 cm and 1 m levels that appear in Ranwells definition are marked.

There appears to be a spatial trend with the depth to water table decreasing as one moves away from the forest and away from the shore. The depth to water table is typically 20 cm greater in the dipwells nearer to the shore (transect 2), and in transect 1 the water table away from the forest (1E and 1F) is typically 40 cm higher than that near to the forest (1D).

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.

This crude assessment 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. This is based on very limited data and is therefore not intended to be anything more than a general 'first look' analysis. It is noted that a forthcoming English Nature report (Davy *et al.*) will go much further in defining the eco-hydrological guidelines for dune habitats.

With that in mind, the answers to the following questions are therefore:
Q1. Does the afforestation of the dunes have a likely significant effect on the integrity of the dune system SAC?
A. If plant associes of wet dune slacks, including semi-aquatic associes, (as defined by Ranwell) are desired then the water table regime in the vicinity of the monitoring dipwells does not appear to be appropriate. This could be seen as a significant effect on the integrity of the SAC. Whether or not afforestation has caused this cannot at this stage be answered. The reasons for this have already been discussed in this report and to restate these are:

- Existing studies both of the water use of the forest and dune vegetation, and of the groundwater system are flawed.
- Even though it is generally accepted that the forest water use will exceed that of short dune vegetation, it is not possible to quantify how much lowering has been caused by the forest.

Q2. Does the retention of the forest have a likely significant effect on the integrity of the dune system SAC?
Q3. Do changes envisaged for the forest; notably either conversion to mixed woodland, replanting of Corsican pine or introduction of maritime pine have a likely significant effect on the integrity of the dune system SAC?
The effect of retention of the forest (Q2), or of the management options suggested in Q3 can not be answered at this stage because the effect of the forest on the water

table has not been adequately quantified. It is anticipated that these points could be answered if the recommended monitoring and modelling are carried out.

9. Recommendations

As a result of the work carried out in this report we propose a revised conceptual groundwater flow model (Figures 4 and 5). It shows the rock ridge to be part of the system, albeit with a significantly lower hydraulic conductivity than the sands. 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 (Ranwell onwards) as lying to the south-east of Lyn Rhos Dhu, is unlikely to be a static fixture. In the new model it is perceived to be in that position only under wet (winter) conditions, and that it migrates towards the lake during dryer (summer) conditions. In this way the lake feeds the groundwater system in winter but gains from groundwater in the summer. 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 modelled so far) is the active drainage area for the system.

The key to moving the current situation forward is to improve understanding of the hydrological effect of the forest on the water table. To do this we make recommendations for both desk-based and field-based activities. The desk-based activities include:

1. Collate and present the existing data sets.
    a. Observation borehole data from Ranwell onwards into a database
    b. Plot contours at various time intervals (including both summer and winter data)

2. Examine the additional well logs for the area including the deep BGS borehole.

3. Map the locations of springs and streamlets.

The focus of the field-based activities should be the establishment of a trial clearance area. This should include the following steps:

1. Identification of the proposed clearance site. This should aim to satisfy the following criteria:
    a. A minimum size of 200 m x 200 m.
    b. Positioned in a relatively densely forested area to give maximum contrast when the area is clear felled. Access for a borehole drilling rig should be considered and proximity to a forest track would be beneficial.
    c. Abutting the open dune area.
    d. Ideally positioned over one of the existing borehole transects.

2. Installation of required piezometers and boreholes. The extent to which this will be necessary will depend on criteria 1d above. It is anticipated that if the clearance is over an existing transect then a further ~5 piezometers would be required.

3. Install additional monitoring including an automatic weather station, automatic water level recorders, and possibly soil moisture probes and direct evaporation measurement equipment.

4. Monitor the area for 1 year to get good baseline data. In addition to boreholes, piezometers and equipment detailed in step 3 above, monitoring should include water levels in nearby surface-water bodies. The age of groundwater should be determined using CFC and SF6 speciation, and occasional groundwater sample collection for chemical analysis.

5. Clear the trial area and employ any proposed management (e.g. grazing).

6. Monitor as before for 3 years following clearance.

Once the data have been collected from this campaign there will be a much better conceptual understanding of the whole area taking into account the enlarged boundaries mentioned earlier. A water balance and groundwater model for the larger area can then be developed giving an understanding of all the active processes occurring. Given a satisfactory correlation between historical observations and model output, predictive scenarios could then be generated to show what might happen if some or all of the trees were removed and the vegetation was returned to open dune land. Importantly this will avoid any prejudgement as the new model would be founded on process understanding only.

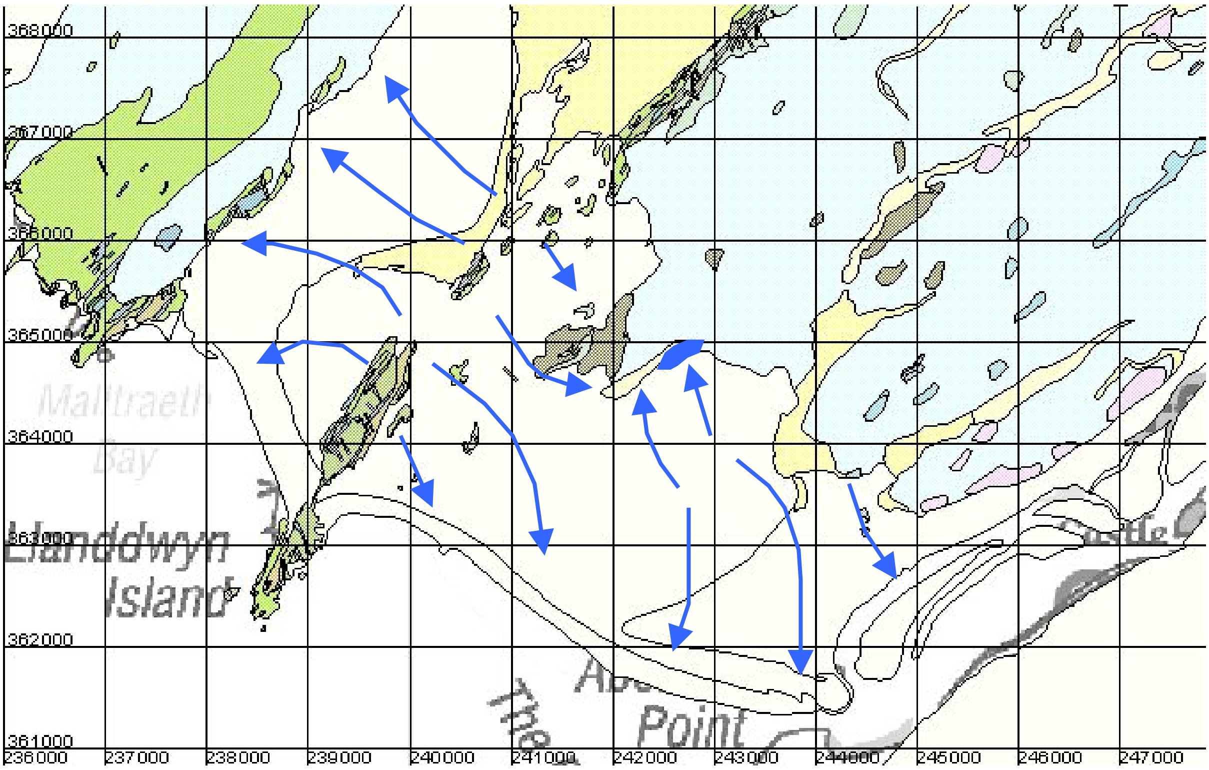

Figure 4.Groundwater flow under high groundwater conditions (Winter)

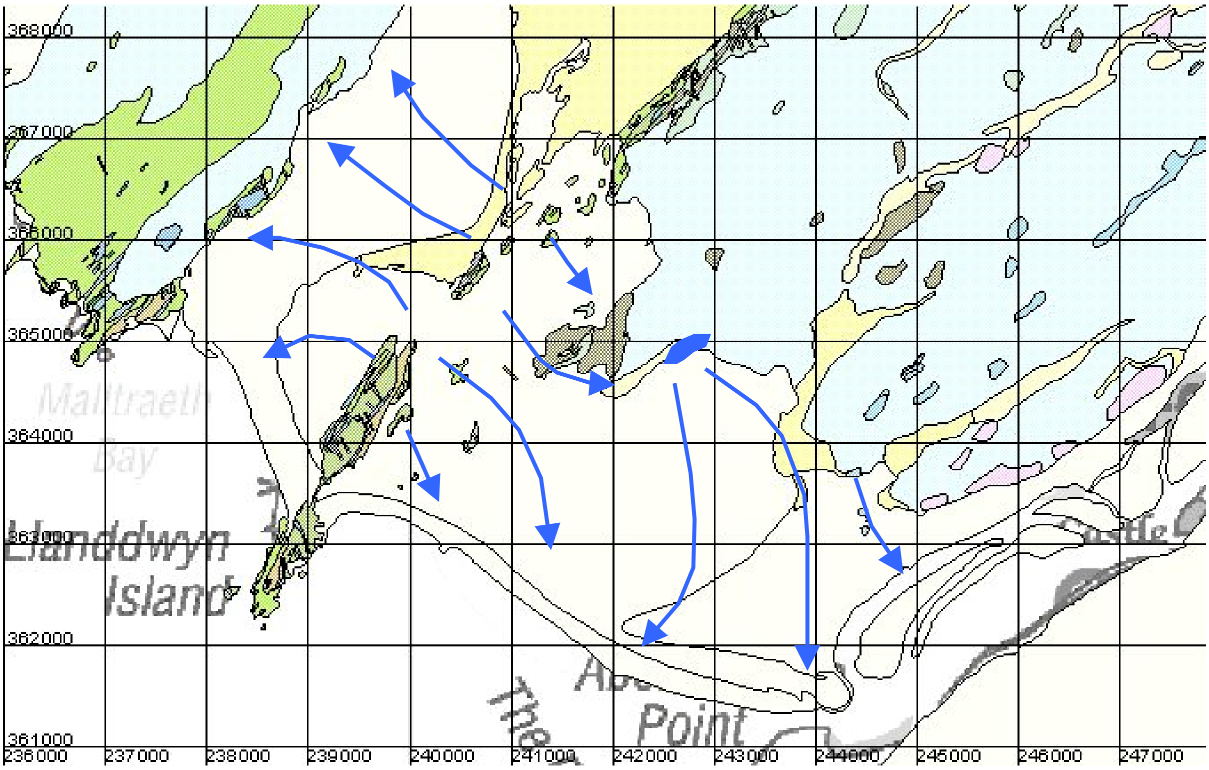

Figure 5. Groundwater flow under low groundwater conditions (Summer)

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