The water balance, water levels, apparent specific yield and relative recharge at Newborough Forest and Warren

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Summary

Water levels at Newborough Forest and Warren are thought to be falling. This has implications for the conservation of species and habitats there and has been of such concern that the Countryside Council for Wales (CCW) has commissioned several research projects into the hydrology of the Warren. Information gathered by these research projects for the period June 1989- May 1996 was analysed.

There are two sets of water level records for Newborough Forest and Warren. The first set collected by CCW over June 1989 - May 1996 consists of the average water levels for 12 dipwells, 7 of which are located in the Warren, the other 5 in the Forest. The second set consists of 23 individual dipwell and surface water levels within the Forest collected by the Forestry Commission (FC) and monitored over March 1989 – June 1995.

The Warren water level records were first analysed with the aim of producing a predictive model for water levels of the Warren based on the water balance based on regression. The Forest water level records were analysed with the aim of determining the comparative behaviour of the water table under the Forest and under the Warren.

Water levels within the Forest are generally greater than in the Warren and fluctuate more. There is little evidence that water levels under the Forest are suffering from the effects of increased interception and evaporation compared to the Warren. The effects of interception and evaporation appear to be masked by greater recharge received by the Forest from the rock ridge. There are indications that drainage at Penlon and in fields draining to the Warren are reducing the amount of recharge received.

It was also found that when the water table is low, there is a diminished response to changes in the water balance, probably as a result of water storage in the larger unsaturated zone above the water table.

A significant linear relationship was found between the monthly average water level of a predominantly fixed dune area of the Warren, and the monthly water balance calculated using forest evaporation estimates. A change in 1 mm in the water balance resulted in a 1.9 mm rise in the water table of the Warren. It was found that the Warren water table could be modelled accurately over the period June 1989 – May 1996.

Further analyses of the response of the water table of the Warren to changes in the water balance on an annual and monthly basis found that for 1989-1996 net recharge was less than average for the complete meteorological record, and lacked months with high rainfall. The 1950's and 1960's were comparatively wet compared to other decades.

1. Introduction

Newborough Forest and Warren form part of a dual spit dune system on the SW corner of Anglesey, stretching from the mouth of the Menai Straits near Caernarfon to the mouth of the Cefni estuary (Figure 1). Prior to 1947 the whole area was mainly shifting sand dunes. Rabbit grazing pressure prevented vegetation becoming established. Within the dune system, dune slack pools formed caused by wind erosion of dry sand at the base of the windward edges of the dunes. The depth of these pools in a mobile dune system like Newborough Warren is controlled by the height of the water table.

The northern spit system, the Precambrian ridge which separates them and the northern part of the southern spit system were afforested from 1947 by the Forestry Commission (FC) and became known as Newborough Forest. Areas of the Forest were drained, and those areas which could not be drained were not planted.

The remaining southern part of the southern spit system became known as the Warren and became a national nature reserve (NNR) and a site of special scientific interest (SSSI) coming under the management of Countryside Council for Wales (CCW) because of the dune habitats and species.

About the same time Myxomatosis wiped out the rabbit population and vegetation became established within the protected dune system, fixing the mobile dunes. CCW introduced horses and sheep to increase the grazing pressure on the Warren and remobilize the dune system.

During the late seventies and 80's there were concerns that the water levels across the Warren were falling with the result that winter flooding was not to the same depth and that dune slack pools were drying out sooner, especially within the Forest. This had implications for some plant communities within the dune slack pools reliant on annual winter flooding and submergence to prevent colonization from other plant species.

As a result the CCW commissioned some hydrological research, installing 12 dipwells in two transects from the Forest out into the Warren. The hydrological investigations covered the soil moisture balance, the depth to bedrock and the water table, extent and the hydraulic properties of the sand dune aquifer.

This information was used to create a MODFLOW model (McDonald and Harbaugh, 1988) of the Forest and Warren. The effects of clearance of different parts of the Forest on the water levels of the Forest were modelled (Betson et al, 2002). In 2004, CCW commissioned ADAS to investigate evaporation and interception losses for broad vegetation classes within the Forest and Warren (Betson and Scholefield, 2004).

The conclusions of this research were that the Forest was having an adverse affect on the water table of the Warren, but that further research was needed to quantify the effect of the Forest. Recommendations were to remove parts of the Forest, especially upon the rock ridge.

The exact behaviour of the water table under the Warren is still a bit of a mystery. Why for instance, does the unforested Aberffraw sand dune system just up the coast from Newborough, not flood to the same extent as Newborough? In the winters of 2001, 2003, 2004 and 2005 frequent flooding returned to the Warren and to some ploughed and planted areas in the Forest. It seemed that other hydrological factors not influenced by the forest where having a larger effect.

This report is an attempt to model and compare water level records in Newborough Forest and Warren and hopefully aid future researchers investigating the hydrology of Newborough Forest and Warren.

The first part is an introduction to the hydrology of the Forest and Warren and gives details of the meteorological and water level records used in this report. The next part is an examination of the CCW well record against the forest water balance. Regressing the CCW well record against the forest water balance led to an estimate of the response of the water table of the Warren to the water balance, other wise known as apparent specific yield (Sy). True specific yield refers to the response of the aquifer material due to dewatering, rather than the response of wells to recharge occurring within a catchment. The estimate of apparent Sy was used to make a model of the water tables response to the water balance.

The CCW well record and the forest water balance were then analysed by comparing annual water level rise to the positive water balance. This provided another estimate of apparent Sy, but also allowed the estimation of recharge and discharge if a constant apparent Sy was assumed.

Well records from the Forest were analysed in a similar way to the CCW well records, however this offered the opportunity to look for differences in the response of the water table to the water balance in the Forest and Warren. Only a limited attempt was made at modelling the Forest water table response to the water balance. It is from the analysis of the positive water balance and the water table rise in the Forest that most of the conclusions are drawn.

The conclusion summarizes the findings of the analyses of the two sets of well records, and in the discussion the various explanations for the differences in apparent Sy, recharge and discharge are tested against the expected effects of interception, forest evaporation, aquifer properties and external recharge.

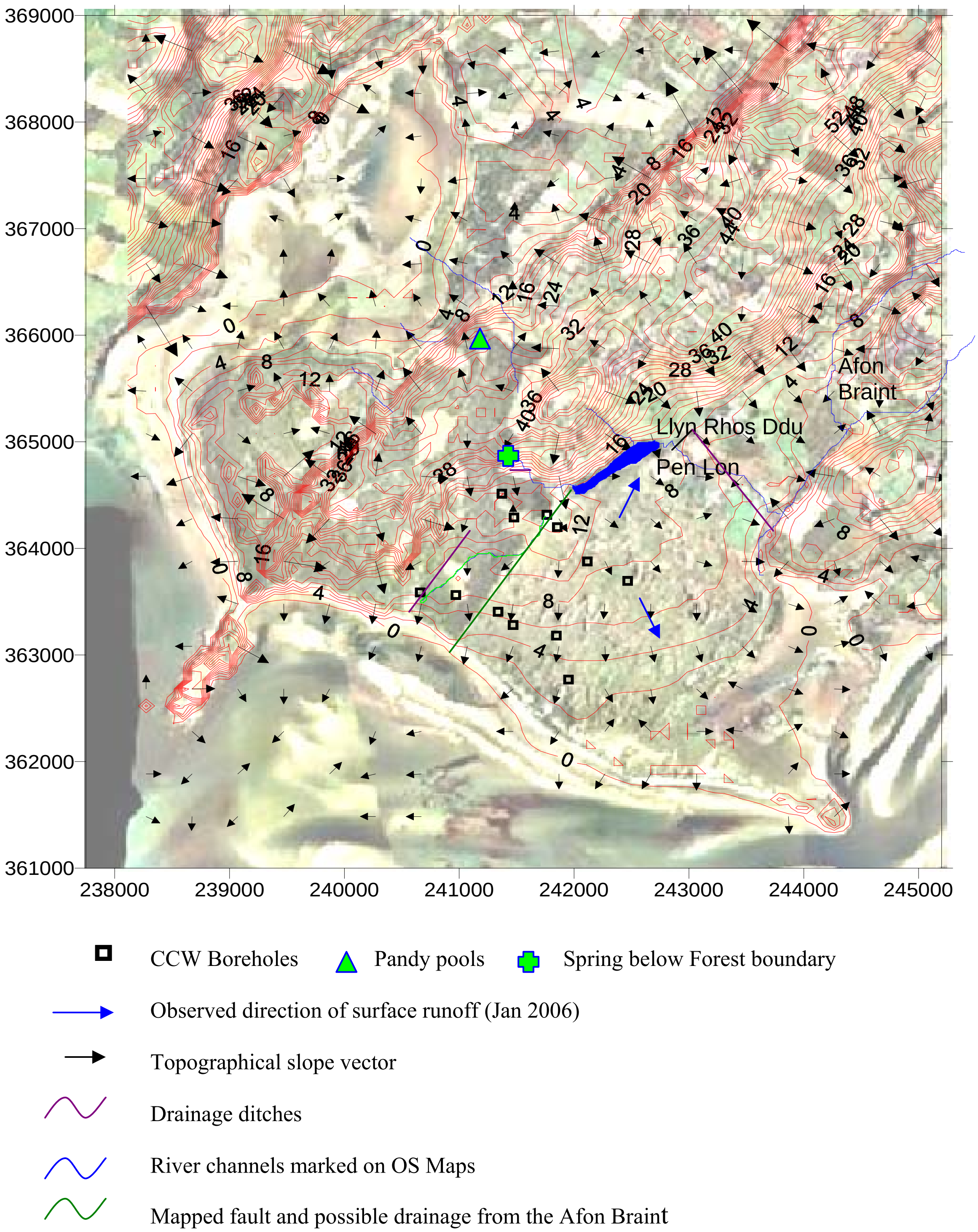

Figure 1: Map of hydrological features of Newborough Forest and Warren including the location of boreholes used to calculate average water levels across the Warren (derived from figure 5.2 Betson et al, 2002.). Plotted Borehole locations are approximate.

2. The hydrology of Newborough Forest and Warren.

The bedrock is a mixture of Palaeozoic and Precambrian rocks. The Precambrian rocks out crop as a ridge which separates the two spit dune systems, which is thought to create a hydrological boundary. However there is evidence that this ridge is fractured along its length in a NE-SW direction following the line of the Berw fault, and also transversely in a NW-SE direction (Figure 2). There are two perennial streams draining from the rock ridge, forming the Pandy pools in the northern spit system and a spring below the Forest main entrance in the southern spit system, which may result from transverse intersecting faults of the main fault. The bedrock and ridge are overlain by glacial till deposits and Holocene sand deposits which form perched water tables on some parts of the rock ridge.

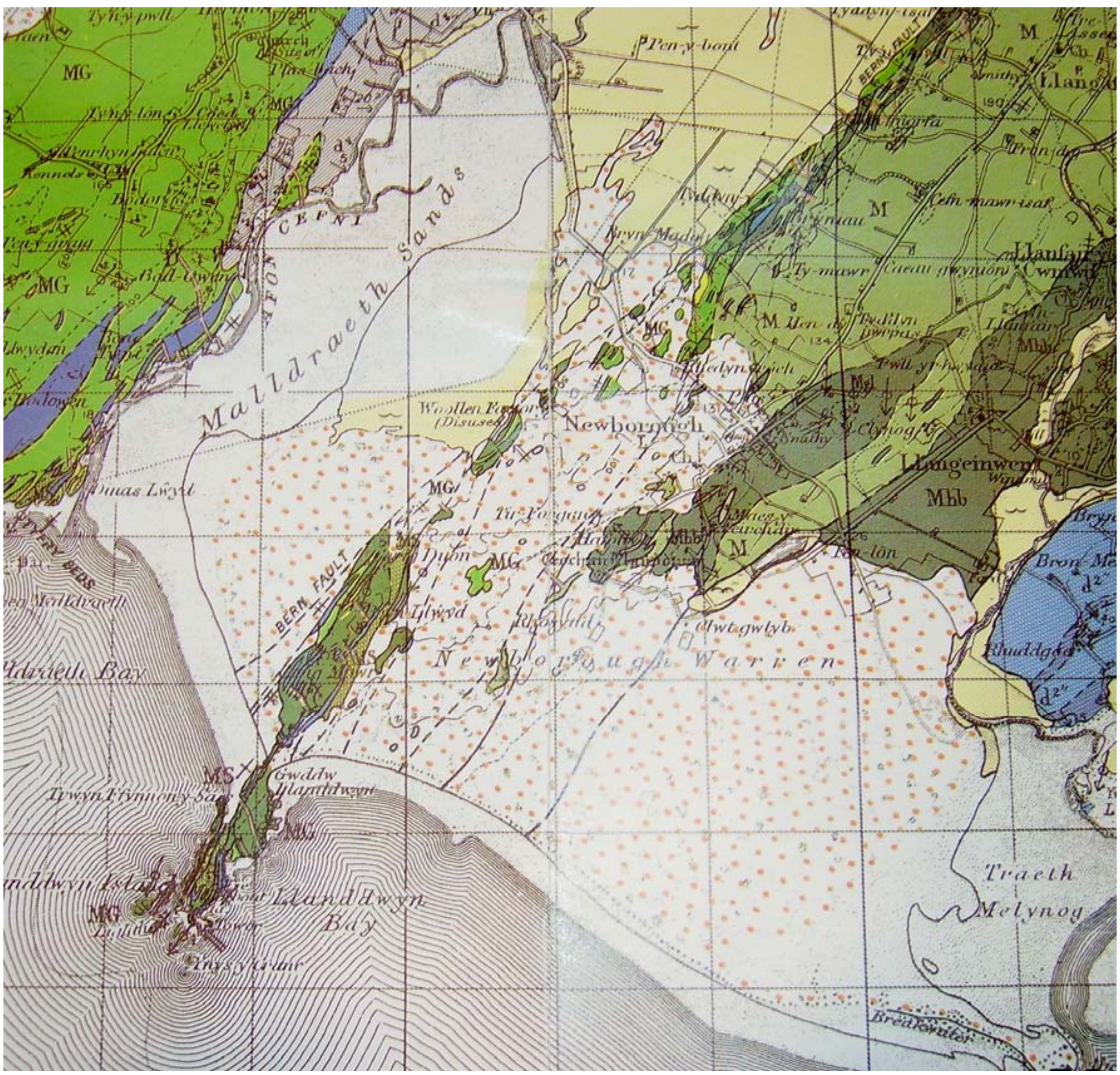

Figure 2: Geological Map of Newborough Warren (BGS)

Runoff from the higher ground of the rock ridge drains into the sand deposits of the spit systems (note topological vectors in Figure 1). In the north there are a number of natural channels draining NE, while in the south, the majority of runoff drains into Llyn Rhos Ddu. This also includes drainage from the southern slopes of the rock ridge west of the church and the water from the spring below the Forest entrance, which would otherwise drain towards the central dome of the sand dune system. Further west of the Forest entrance, the topography directs surface and subsurface flows towards the sea rather than in to the centre of the Warren.

The Newborough Warren sands are also connected to Llyn Rhos Ddu within the southern spit system. Llyn Rhos Ddu drains out south along the eastern edge of the Warren past residential developments at Pen Lon into the Afon Braint. The Pen Lon area is prone to flooding and the Llyn Rhos Ddu sluice was vandalized and reduced in height by a meter in the 1990s, possibly by residents. Llyn Rhos Ddu sits upon a marked fault (Figures 1 and 2) and it is thought that the Braint may have once drained through Llyn Rhos Ddu along this fault (Robinson, 1980).

There is some evidence of ephemeral surface runoff from the rock ridge along forest tracks, drains, and relic channels. Runoff has also been observed on a few occasions within the Warren with water draining from one slack to another. This was seen during January 2006 a few days after a 10mm rainfall event when water levels were already high (Figure 1). At present there are no records of spring flows or surface runoff.

2.1. Hydrogeology

The full extent of the superficial sand deposits is not fully known. Some limited work has been done by the British Geological Survey and University of Wales Bangor (Bennell, 2006) in the northern spit system and more extensive work by Bristow (2002) within the southern spit system using seismic and ground penetrating radar. The western seaward edge of the area consists of sand and gravel deposits which grades into marine clay and glacial till inland and north eastwards along the Menai Straits and the Malltraeth estuary. Whilst towards the Menai Strait the basement Palaeozoic rock of the gradually descends to 20m below the surface topography, and then the Warren is underlain by lithified or partly lithified sand and clay deposits at a similar depth which outcrops along the banks of the Braint.

The Palaeozoic basement also contains a downthrown block structure in a line roughly from the southern wetlands of Llyn Rhos Ddu to the Forest car park. It is approximately 2m deep and 120m at the southern wetlands of Llyn Rhos Ddu and narrows to 40m and 10-15m deep at the foreshore below the Forest car park (Bristow, 2002). There is also a fault line further south marked on the geological map which probably marks the southern boundary of the downthrown block (figure 3).

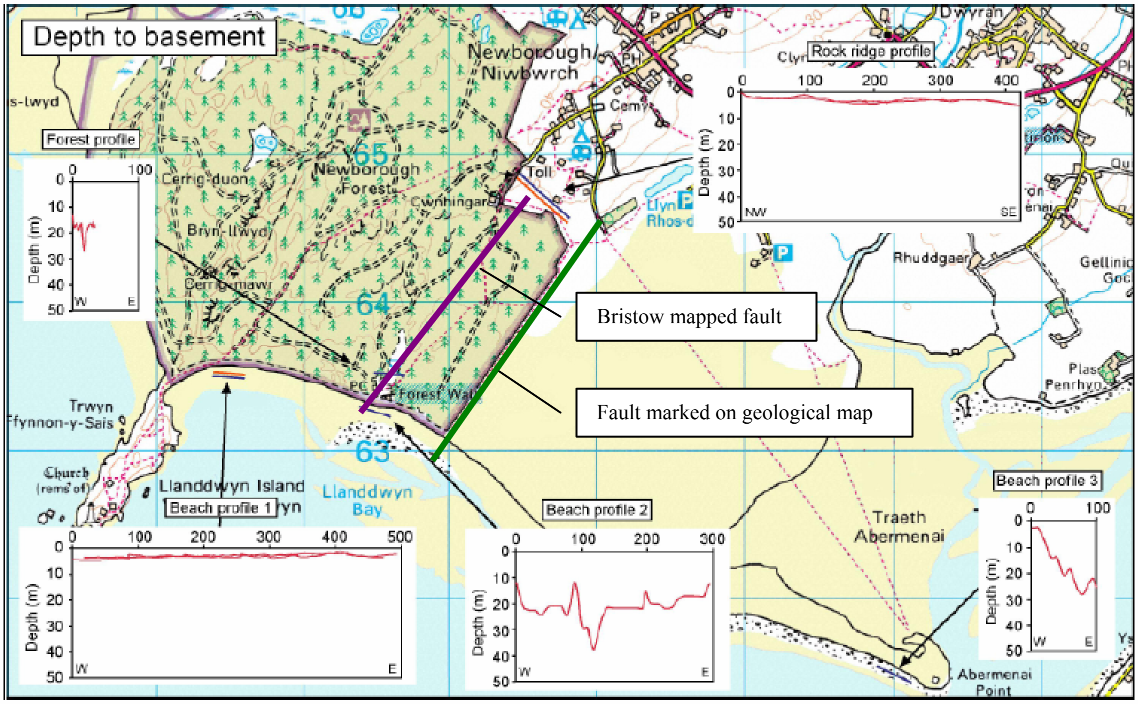

Figure 3: Geophysical survey results from Bristow (2002)

The rate of ground water seepage to and from the Warren is positively correlated to water table height of the aquifer and supporting aquifers, but is difficult to quantify as seepage rates depend upon the properties of the sand and the underlying rock. Ground water seepage has not been directly measured. The best available methods short of extensive aquifer testing rely on groundwater modelling by altering the aquifer properties so that the modelled water levels match those observed.

Ground water modelling has been carried out by Betson et al. (2002) using the widely used U.S.G.S. finite-difference groundwater model, MODFLOW, (McDonald and Harbaugh, 1988). Betson et al (2002) used a single layer model with the height of the layer defined by topography, while the bottom layer was inferred from their geophysical work, however they found difficulties in modelling the water table at Newborough and working models relied on creating zones of varying conductivity. The only water budget details presented are for evaporation, details of zone estimates of groundwater seepage and runoff are not presented.

Both the surface and basement topography identified by Bristow (2002) is likely to direct groundwater seepage along the down faulted block toward the main Forest car park rather than into the Warren, especially when the ground water level is below that of the Warren edge of the down throw. The travel times of groundwater in sand are approximately 10m/day, and the distance from the ridge to centre of the Warren is over 0.5 km. Groundwater seepage from the rock ridge may take as long as 1.5 - 2 months to arrive at the edge of the Warren assuming that the downthrown block has no influence.

2.1.1. Warren water level records

As part of CCW research 12 dipwells were placed in two transects from the Forest out into the Warren. Water levels were recorded from June 1989 to May 1996. The average water level of all the boreholes were presented in a graph (figure 4) within a report for CCW in 2002 (Betson et al., 2002). The values of the water table were transcribed and entered into an Excel spreadsheet. The records for individual wells are not presented in the Betson et al. (2002) report. Five of these wells are inside the Forest, the rest are within the Warren.

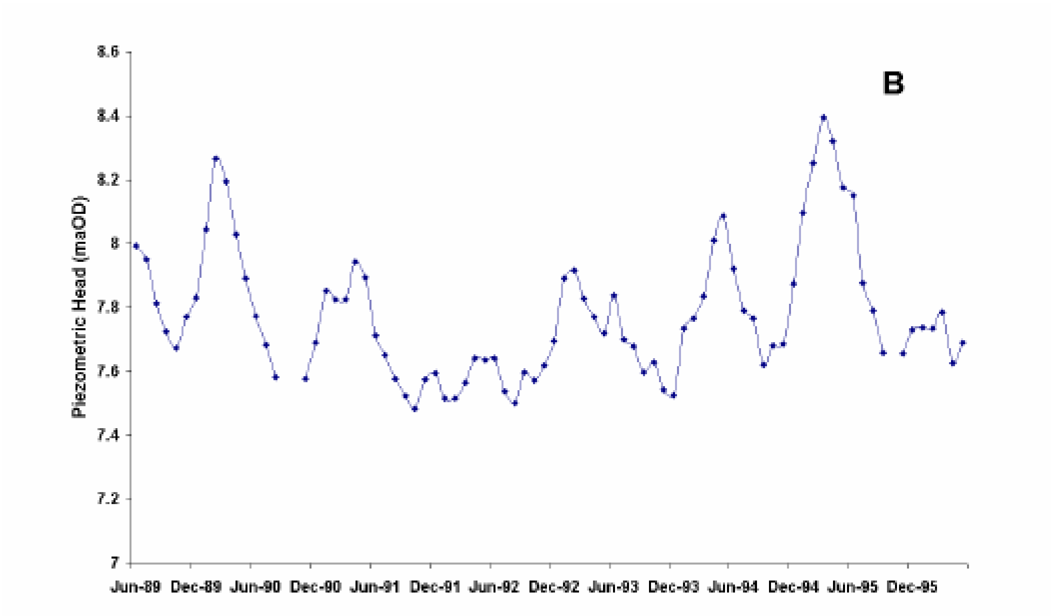

Figure 4: The average piezometric head in m AOD for all target wells during each month of the year determined from the June 1989 – May 1996 (Betson et al., 2002)

Water levels within the Warren have been recorded by the author since April 2005. Earlier records do not exist apart from observations by Ranwell (1959) and other anecdotal evidence. Ranwell made the observation that in the winter of 1951 the water table rose to 1.5m. This level was also recorded by Betson et al. (2002) in 2001 and by the author in 2005.

The opinion of some Newborough villagers is contradictory, residents recognise that flooding is not as common on the Warren as it once was, but one farmer claimed that he had never seen so much water on the Warren in the winter of 2005 – 2006. This was after a summer which received only 80% of the average rainfall followed by the heaviest monthly rainfall on record in October 2005.

2.1.2. Forest water level records

Individual water level records for the period March 1989 - May 1995 for various wells and pools with in the Forest area (Figure 5) were collected by Martin Gould the forest warden. The water level values have not all been levelled against the topography. They can be grouped into 4 main areas: wells 1-6 on the forested rock ridge; wells 7-9 within the forested south spit system and within the area of the downthrown block; wells 10, 14-17 within the forest next to the salt marsh in the northern spit system; wells 11, 12 and 19; , all of which are on the northern spit system.

There is no location given for wells 13 or 18. Records also exist for Llyn Parc Mawr (LPM), Canada pool and the Dune slack pool, LPM is an artificial lake within a fixed dune area in the north of the Forest on the south side of the Malltraeth estuary.

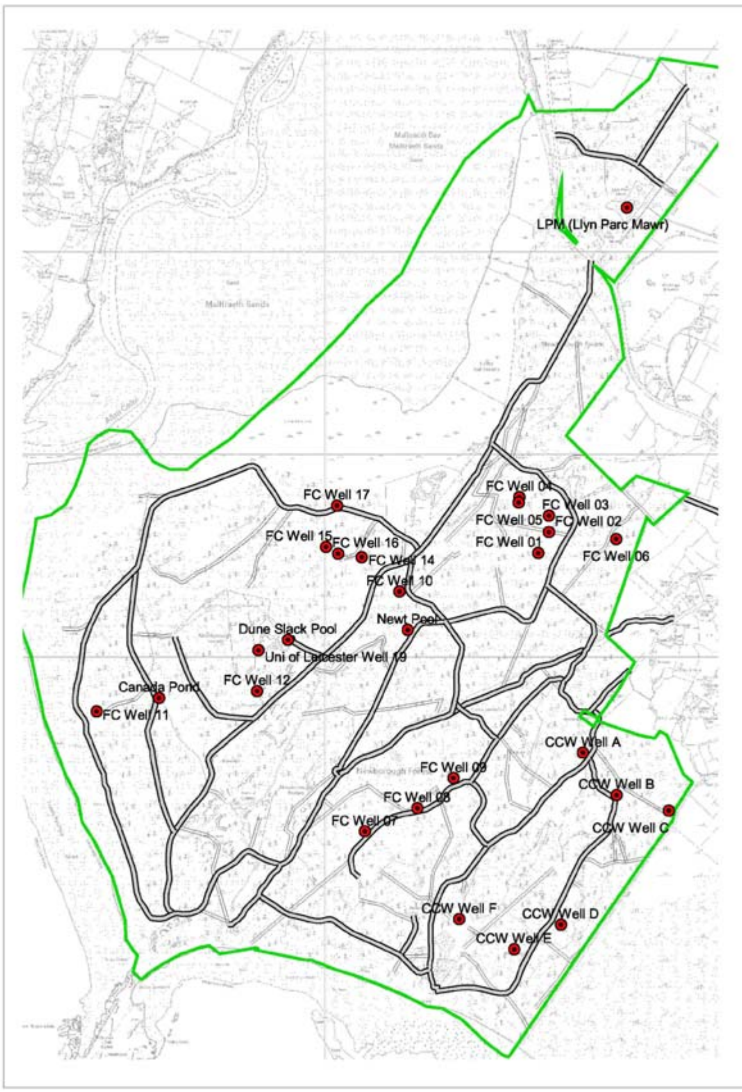

Figure 54: Map of FC water level monitoring points

The well records (figures 5-8) were examined and it was apparent that the water level had dropped below the bottom of some of the wells (1,5,7,8, 10, 14 and 19), in addition there were periods during which the surface pools were not monitored.

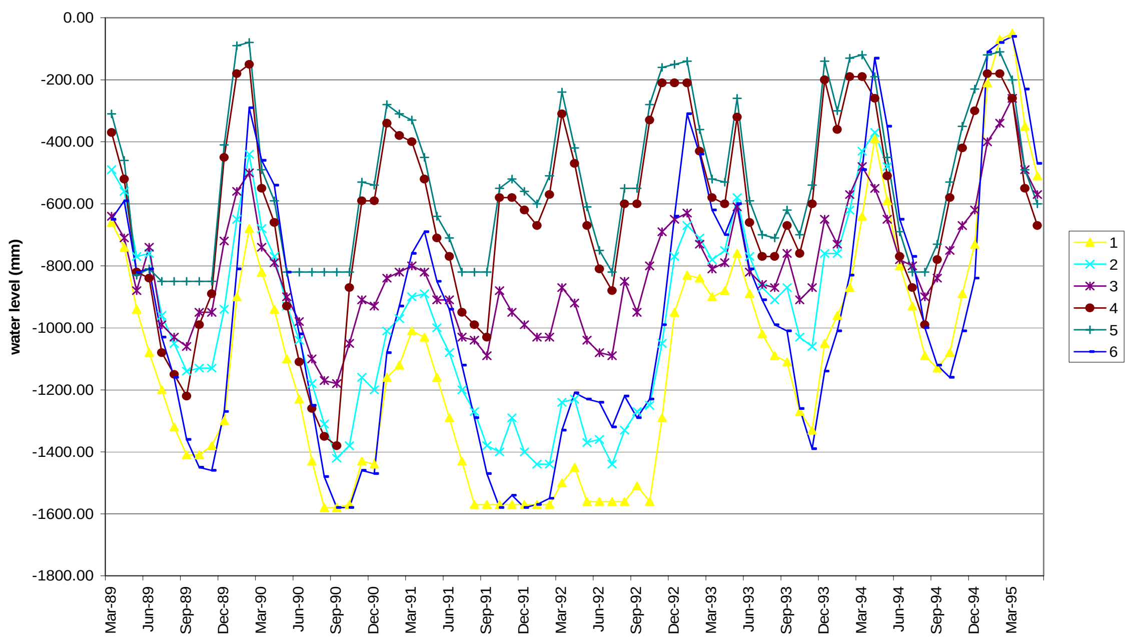

Figure 6: Water levels for the Forest wells 1-6

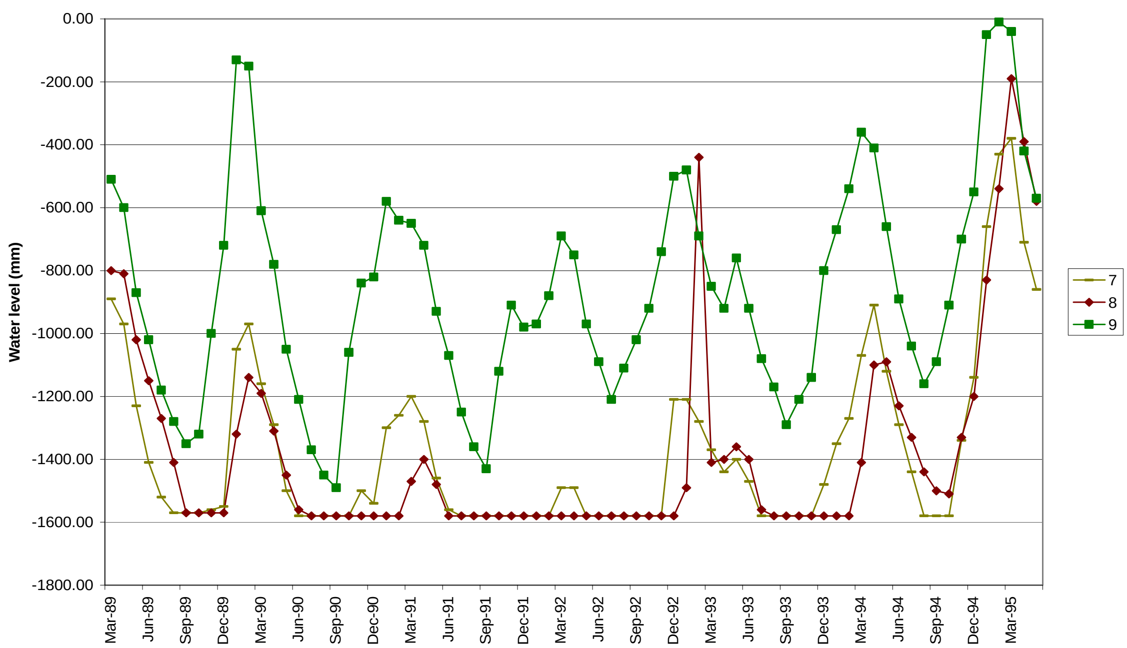

Figure 7: Water levels for the Forest wells 7-9

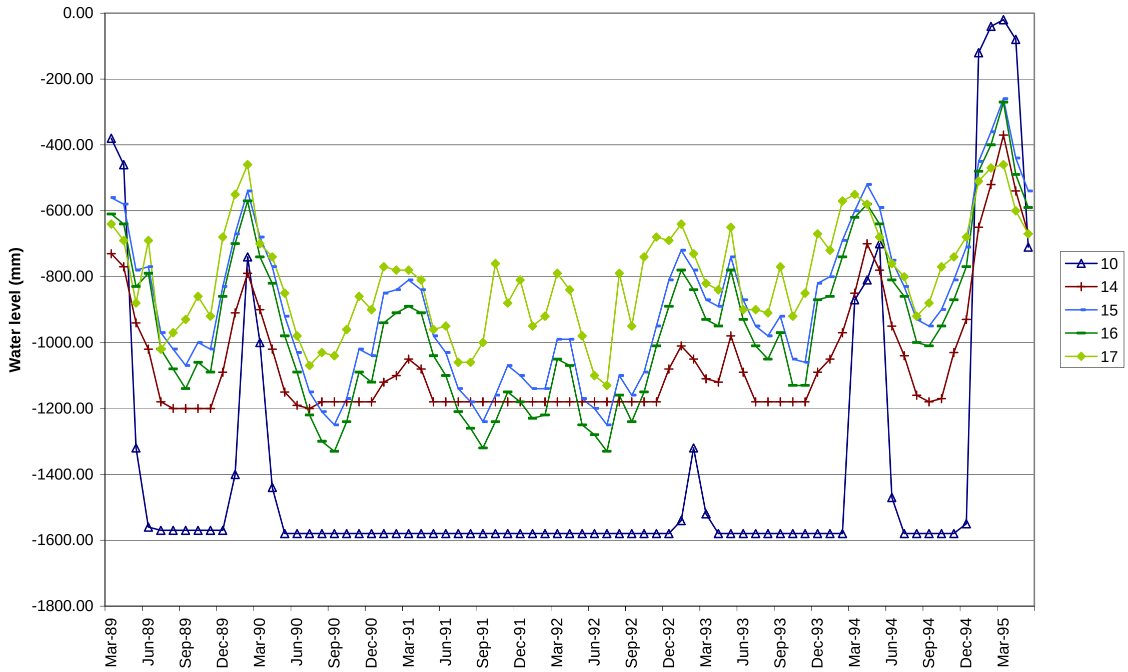

Figure 8: Water levels for Forest wells 10, 14-17

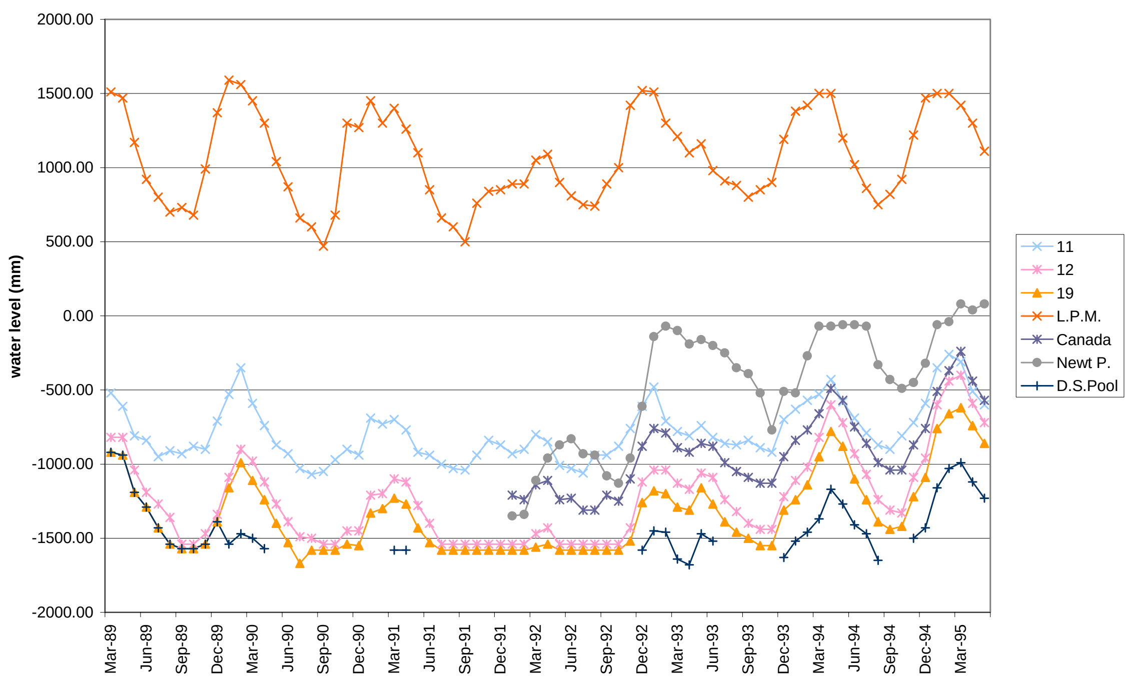

Figure 9: Water levels for Forest wells 1,12, and 19 and surface water pools

2.1.3. Hydrological properties of the superficial sand deposits.

Betson et al (2004) measured the particle size of the sands at Newborough and found it to be almost uniformly fine sand in the range 0.1 - 0.3 mm. They also measured the saturated hydraulic conductivity and porosity in the horizontal and vertical orientations in dunes, slacks and close to the coast (Table 1). The overall average effective porosity was estimated as 37% by Betson et al (2004).

The response of the water table height to amounts of water added or subtracted in an unconfined aquifer is described in hydrology as the 'specific yield' (Sy), which is the volume of water draining under gravity (sometimes referred to as field capacity) from a volume of an aquifer. The typical range of Sy for sand ranges from 35% to 10% (Table 2 (Fetter, 1994)).

Table 1: The results from the peremeametry conducted on undisturbed sand samples in horizontal (H) and vertical (V) orientations, plus the porosity of the samples (Betson et al, 2002).

Location	Orientation	K (m/d)	Porosity
Dune	V	9.1	0.38
Dune	H	12.2	0.36
Dune	V	11.53	0.38
Dune	H	15.18	0.35
Coast	V	12.61	0.4
Coast	H	17.56	0.36
Slack	V	7.27	0.38
Slack	V	7.05	0.36
Slack	V	5.26	0.36
	H average	11.37	
	V average	8.42	
	Overall average		0.37

Table 2. Typical Sy values for earth materials

Material	Max %	Av %	Min %
Clay	5	2	0
Sandy Clay	12	7	3
Silt	19	18	3
Fine Sand	28	21	10
Medium Sand	32	26	15
Coarse Sand	35	27	20
Gravelly Sand	35	25	20
Fine Gravel	35	25	21
Medium Gravel	26	23	13
Coarse Gravel	26	22	12

The specific yield is closely related to the effective porosity in sands, but is not quite the same as some water is retained within the spaces within the sand when water drains by gravity. However the difference between effective porosity and Sy in sand are only marginally different, and the effective porosity estimate of 37% used by Betson et al. (2002) in modelling the Forest and Warren water table is close to that expected for coarse sand, however this nearly 10% greater than that expected for fine sand which has a predicted maximum value of 28%.

The Sy is likely also to decrease with depth as the sand is compressed. Betson et al. (2002) used a storativity coefficient of 21% in their hydrological modelling of the Warren. Storativity describes the volume of water released from a unit change in piezometric height in a confined aquifer. In an unconfined aquifer like the sands of Newborough Warren, storativity is equal to the specific yield.

The apparent Sy is response of the water levels to the water balance; as well as incorporating the Sy of the aquifer material, this also includes the effects of other processes occurring in the catchment.

2.2. The water balance

Water levels are dependant on the water balance, the balance between inputs: rainfall (P); and outputs: interception (I) of rainfall by the vegetation, evapotranspiration (Et), surface runoff (Q) and groundwater seepage (S). Water can only be evaporated from the ground water if within the range of roots or < 2m below the surface, and actual evapotranspiration (AEt) rather than potential evapotranspiration (PEt) takes into account the increasing difficulty in extracting water from a soil with decreasing water content. Accordingly the water balance (WB) used is:

$$WB = P - AEt - I \qquad (1)$$

Rainfall data is readily available from RAF valley, and interception and actual evapotranspiration have been modelled for various vegetation types within the Warren (Betson and Schofield, 2004).

The water balance, if positive indicates an excess of rainfall which will seep through the ground, filling pores and raising the water levels. A negative water balance indicates that the water levels will fall as water is evapotranspirated.

2.2.1. Evapotranspiration

The CCW also commissioned an ADAS report to quantify evaporation within the Forest and Warren (Betson and Scholefield, 2004) (table 3). This modelled the evaporation and interception for the various vegetation types using the model Soil Water Air Plant (SWAP) developed by Kroes and van Dam (2003). The SWAP model is very comprehensive, which can account for plant physiology as well as the moisture retention capacities of soils. However details of the exact parameters used in the model are not available in the Betson and Scholefield (2004) report. The interception rates of forests are known to vary with forest age. Results from Plynlimon show that in the 1970's interception was of 60% of rainfall when the Sitka spruce Forest there was 15-25 years old, while in the 1990's the interception rate was reduced to 18% of rainfall when the Forest was 35-40 years old (Hudson et al., 1997).

Table 3: SWAP Model results for AET + Interception from the identified dune ecosystems (mm) (Betson and Scholefield, 2004) **.**

Month	Rain	Fore Dune	Semi-Fixed Dune	Fixed Dune	Meadow	Wet Slack	Scrub	Forest
Jan	103.1	269	301	313	319	319	382	423
Feb	89.6	274	308	322	328	328	375	406
Mar	77.4	315	411	450	468	468	507	533
Apr	72.1	365	530	596	625	625	652	667
May	57.8	421	712	829	804	804	904	924
Jun	70.9	418	710	827	756	756	888	956
Jul	60.1	417	712	830	724	724	874	994
Aug	72.7	432	636	718	690	690	737	871
Sep	82.9	380	504	554	572	572	606	686
Oct	112.6	361	428	454	497	497	541	576
Nov	124.4	308	339	351	360	360	439	487
Dec	110.1	262	292	303	308	308	377	420
Total	**1033.8**	**422**	**588**	**655**	**645**	**645**	**728**	**795**

More accurate evapotranspiration data could be obtained by calculating actual evaporation and interception for the whole May 1989 – June 1996 period using the meteorological data from RAF Valley in the SWAP model.

2.2.2. Rainfall

As the water balance is being calculated using monthly average evaporation, and rainfall records, rainfall is therefore the major determinant and deserves close examination.

The nearest UK meteorological station to Newborough is RAF valley, which is on the same coast line, but 13 miles north. Records are available from September 1941. Comparison of the RAF Valley rainfall records and records kept by the author indicate that rainfall at Newborough is 20% higher (appendix 1).

Comparison of rainfall (Figure 10) for the periods June 1989 - May 1996 and June 1942 - May 2005 shows that during June 1989 – May 1996 there was no monthly rainfall greater than 138 mm, while for the rest of the monthly rainfall record there were 48 months (6% of total record) with rainfall greater than this. The monthly average rainfall has marginally decreased over the time period by 0.003 mm / month, equivalent to 2.27 mm over September 1941- October 2005. The period June 1989- May 1996 was also the longest period without monthly rainfall greater than 150 mm.

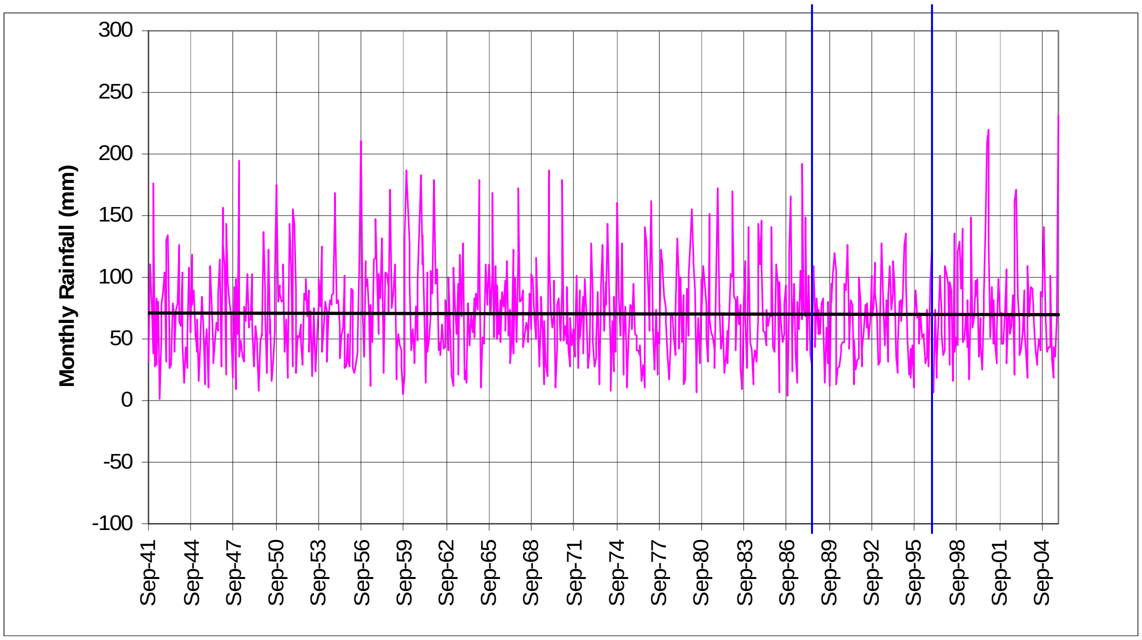

Figure 10: Monthly rainfall for RAF Valley: September 1941- October 2005

As a clear difference can be seen in Figure 10 between the June 1989-May 1996 monthly rainfall and the monthly rainfall for June 1942 -May 2005, further detailed statistical analysis was conducted. The June 1989 - May 1996 rainfall was removed from the June 1942 - May 2005 rainfall series. Descriptive statistics of both rainfall series were produced, a Levene's Test was used to test whether the standard deviations were statistically different and a Mann Whitney U test assuming unequal variance was conducted (Appendix 1).

The June 1989 - May 1996 rainfall monthly mean (64.2 mm) is slightly lower than the June 1942 - June 2005 rainfall monthly mean (71.1 mm) and the maximum monthly rainfall for June 1989 - May 1996 (135.8 mm) is a lot less than the June 1942 -June 2005 (220 mm) monthly mean.

3. Analysis of CCW well records

This was attempted using 2 different methods. The initial analysis concentrated on finding a model based on the regression of theCCW water level records for the Warren against the water balance. The second compared the water table rise and fall to the respective positive or negative water balance.

3.1. The regression based analysis

The response of the CCW water level record presented by Betson et al. (2002) to the water balance was modelled. A further set of regression analyses based on individual years and months was then attempted. Inferences about the net effect of surface runoff, groundwater seepage and changes in aquifer storage were made by comparing the water level response to that predicted from the estimated Sy for the sands of the Warren.

3.1.1. Modelling the response of the water table to changes in the water balance

The basis of the initial model is that the change in the water levels (ΔWL_i) over a period equals the change in the water balance (ΔWB_i) over the same period, divided by the apparent specific yield (ASy). Adding this to the water level in the previous time period (WL_{i-1}) will give the water level for the time period in question.

$$WL_i = WL_{i-1} + \Delta WB / ASy \qquad (1)$$

The data available for AEt, I and WL are only available in monthly periods and so this was the time interval chosen.

This model does make some assumptions:

- The effects of interception, surface runoff and ground water seepage are largely ignored and are lumped within the apparent Sy estimate.
- Ponding water has a specific yield of 1 and hence increases the specific yield of the Warren as a whole as the water table rises and pools form.
- When the water level falls, AEt and seepage losses decrease, so the water table may not respond and have a high apparent Sy
- Using a monthly time period makes it difficult to account for intense rainfall likely to generate runoff. However it suits the evaporation estimates because the difficulty in making accurate daily AEt and I estimates.

3.1.2. Choice of Actual Evaporation and Interception rates to calculate the water balance

Water balances for the Warren for the period Jan 1989 – June 1996 were calculated for each vegetation type using the rainfall records from RAF Valley and the actual evaporation and interception estimates from table 3. The CCW water level for June 1989 – May 1996 (Betson et al., 2002) presented in figure 4 was correlated against the 2 months previous, 1 month previous, the same month, and the next months water balances for each vegetation type (Table 4). It was found that for each vegetation type, a 1 month lag in the water balance provided a slightly better correlation coefficient than having no lag at all.

The one month lag indicated in the model might be due to differences in the dates that the data was compiled for. It is possible that the water level sampling date may have been at the beginning of the month.

Table 4: Correlation coefficients for the CCW water level for the period June 1989 –May 1996 correlated against the 2 months previous, 1 month previous, the same month, and the next months water balance for each vegetation type

Water balance Period	Fore Dune	Semi-Fixed Dune	Fixed Dune	Meadow	Wet Slack	Scrub	Forest
March 1989-April 1996	0.16	0.25	0.33	0.31	0.31	0.53	0.77
April 1989 – May 1996	0.17	0.27	0.37	0.34	0.34	0.59	0.92
June 1989 – May 1996	0.17	0.26	0.35	0.33	0.33	0.56	0.88
July 1989 – July 1996	0.15	0.22	0.29	0.27	0.27	0.45	0.70

The best correlation coefficient (92%) was found using the water balance calculated using the forest actual evaporation and interception estimates with a 1 month lag. Scrub had the next best correlation with a coefficient of 59%. All other vegetation types had coefficients below 35%. Additional tests were conducted to test the sensitivity of the AEt and I estimates and are presented in appendix 2.

Possible reasons for the forest AEt +I being the most apt are:

- that the forest is having a much greater effect than predicted;
- evapotranspiration estimates calculated by Beston and Scholefield (2004) for other vegetation types are underestimates;
- or that evapotranspiration estimates need to be high to account for water losses related to groundwater seepage and surface runoff which are not included in the model.

3.1.3. Regression of the water balance against the CCW water level

When the previous monthly forest water balance and the CCW water level are plotted (figure 11), visually there seems to be a good correlation within individual years.

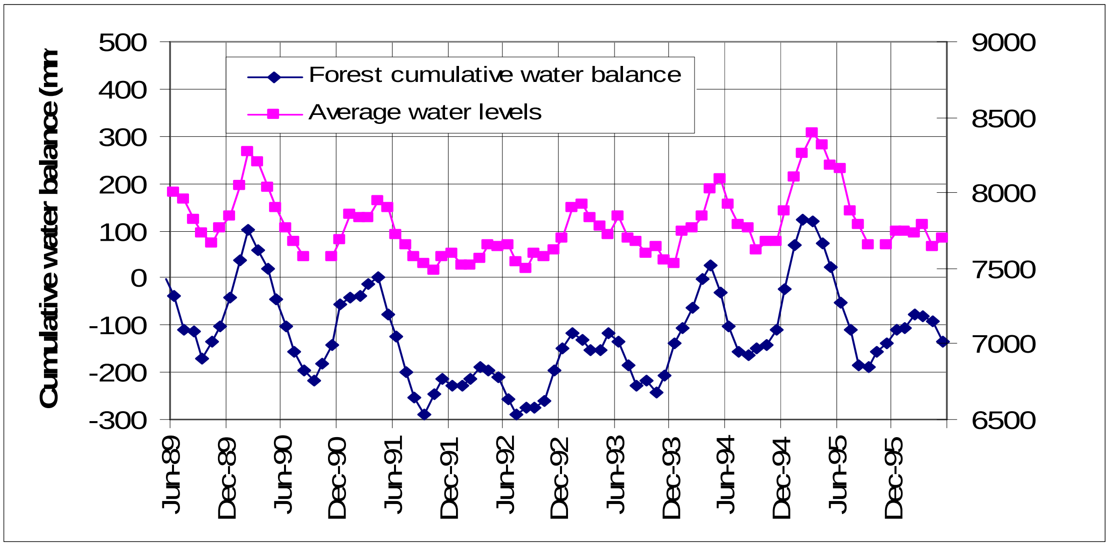

Figure 11: Forest water balance and the CCW water level for June 1989- June 1996

The water balance for each vegetation type with a 1 month lag was then regressed against the CCW water levels and the results are presented in table 5. The coefficient of determination was highest for the forested water balance at 85%, and was 35% for the scrub water balance and the other vegetation water balances had coefficients of less than 14%. (A full regression analysis of the CCW water level and the forest water balance is presented in appendix 3).

Table 5: parameters for the CCW water levels for June 1989 –May 1996 regressed against the water balance for each vegetation type for the period May 1989 – May 1996.

	Fore Dune	Semi-Fixed Dune	Fixed Dune	Meadow	Wet Slack	Scrub	Forest
Slope	0.047	0.129	0.249	0.220	0.220	0.715	1.902
Intercept	7715	7689	7673	7677	7677	7682	8003
r^2	0.030	0.074	0.136	0.118	0.118	0.348	0.846

3.1.4. Deriving model parameters

The above regression analyses of the CCW water levels, and AEt and interception rates imply that the model should be based on the previous months Forested water balance, and that the model formulae should be

$$WL_i = WL_{i-1} + \Delta WB_{i-1} / Sy \qquad (2)$$

Where WL_i = monthly water level (mm)
WL_{i-1} = previous month's water level (mm)
ΔWB_{i-1} = change in water balance over the previous month (mm)
Sy = apparent specific yield

Whilst the regression formulae is

$$WL_i = 8003.2 + WB_{i-1} \times 1.902 \qquad (3)$$

Where WB_{i-1} = the previous month's water balance
8003.2 = the value of the intercept from the initial model
1.902 = the value of the slope form the initial model

The slope coefficient from the regression model describes the response of the water table to inputs and outputs of water derived from the water balance. Whilst this includes the main factor describing this relationship, the specific yield of the aquifer, it also includes errors associated with other factors such as incorrect AEt and I measurements, runoff and groundwater seepage.

The greater the slope term in the equation 1, the greater the response of the water table to the change in the water balance, while in equation 2, smaller values of apparent Sy cause a greater response in the water table. The apparent Sy is therefore related to the slope coefficient by taking its reciprocal, and a slope coefficient of 1.902 is equivalent to a Sy of 52.5%, and 525mm of rain would cause the water level of the Warren to rise by 1m, and 1mm of water would raise the water level by 1.902 mm.

The intercept (8003.2 mm) is assumed to equal to the water level for May 1989, which is the product of the water balance as of April 1989, multiplied by the slope (1.902). Using equation 3 to calculate water levels for May 1989:

$$WL_i = WB_{i-1} \times 1.902 = 8003.2 \text{ mm} \qquad (4)$$

Assuming the water balance multiplied by the slope, equals the previous month's water level (equation 4) and that the water balance in April 1989 is equal to the water balance in March 1989 plus the change in the water balance during April 1989, then:

$$WB_{i-1} = WB_{i-2} + \Delta WB_{i-1} \qquad (5)$$

And the water level in May 1989 equals the water balance in March 1989 plus the change in the water balance during April 1989.

$$WL_i = \left(WB_{i-2} + \Delta WB_{i-1}\right) \times 1.902 \qquad (6)$$

Replacing the previous water level for April 1989, WL_{i-1}, with the water balance term for March 1989, WB_{i-2}, the formulae for the water level in May 1989 equals the water level in April 1989, plus the change in April 1989's water balance multiplied by the regression slope.

$$WL_i = WL_{i-1} + \Delta WB_{i-1} \times 1.902 \qquad (7)$$

Any month's water level can thus be calculated from the previous month's water level plus the change in the previous month's water balance multiplied by the regression slope coefficient.

3.1.5. Comparison of the CCW water level and predicted CCW water level using the model

The predicted water level for the CCW wells was calculated using the equation 7. The initial water level for May 1989 was set at the value of the intercept (8003 mm). The predicted water level for June 1989 - May 1996 was then plotted against the actual water level (figure 12).

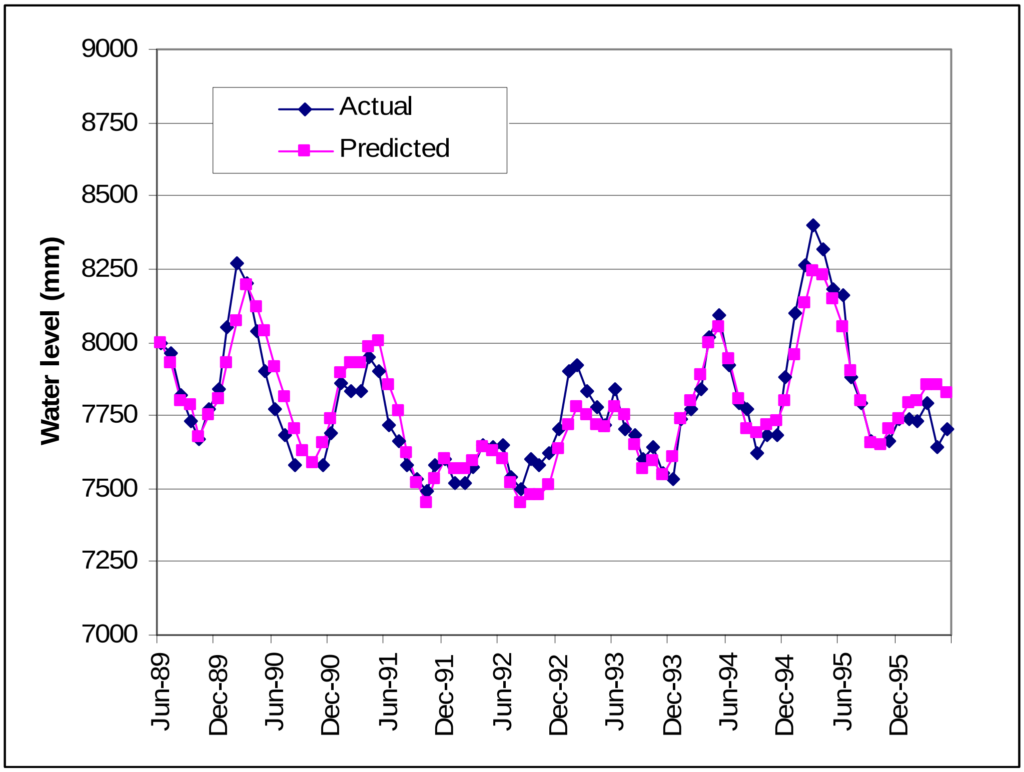

Figure 12: Predicted water level derived from the forest water balance, and the CCW water level, June 1989 – May 1996.

The predicted water level matches closely the actual CCW water level and has a correlation coefficient of 92%, which is the same as the correlation for water balance against theCCW water levels. There are however some discrepancies: Feb 1990 – Sept 1990 where the predicted water levels seem to be advanced by one month, and Mar-April 1991, Sept 1992- May 1993, Jan 1994-May 1995 and April - June 1996 when the water level is underestimated.

3.1.6. Using the model to predict past and future water levels

The forest water balance was then calculated from the beginning of rainfall records at RAF Valley, to October 2005, using June 1989 as the base year (Figure 13).

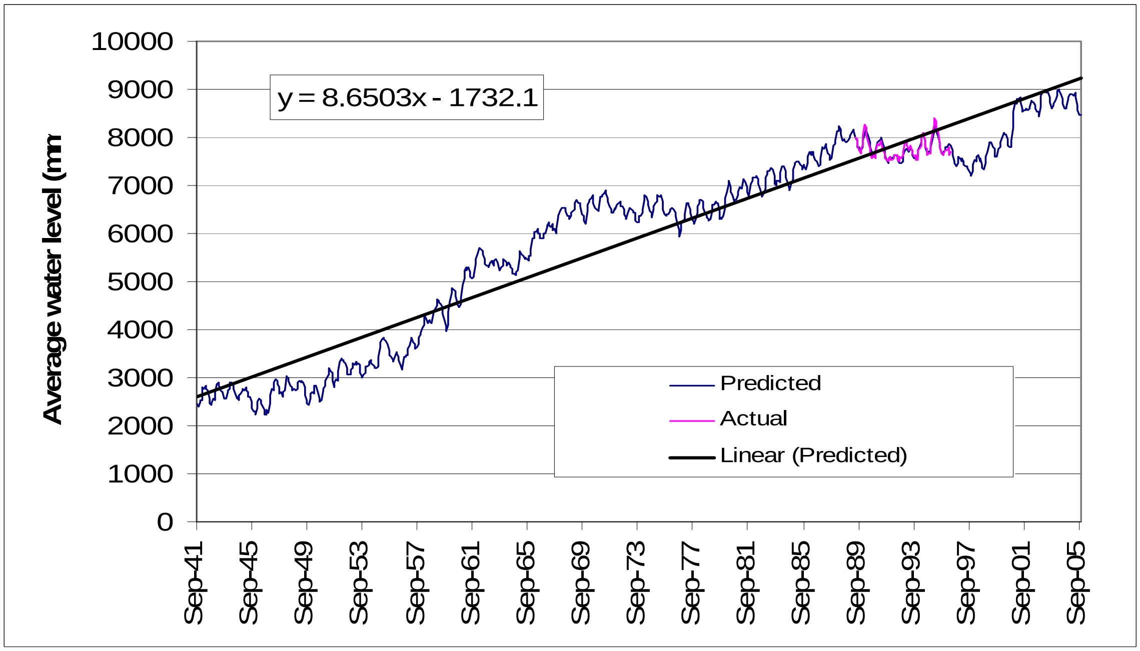

Figure 13: Predicted water level for CCW wells, Sept 1941 – Sept 2000 and CCW water level (June 1989- May 1996).

From Figure 13 the predicted water table in June 1941 was 2731 mm, some 5270 mm lower than in 1989, and that the water level in June 2005 was at 8828 mm, 825 mm higher than in June 1989. A trend line fitted to the predicted water level indicates that the water level should have risen by 8.65 mm a month.

This would tend to support the idea that the forest is responsible for lower water tables (Betson et al, 2002). However water levels within the Warren are not noticeably higher in 2005 compared 1941. Also in 2001 the Warren (Betson et al., 2002) reportedly flooded to the same height recorded by Ranwell in 1951 (flooding to a similar depth also occurred in January 2004 and 2005).

As there has not been a net change in the water table across the Warren as suggested by the model, then the reason for the climbing water table must be caused by an error not accounted for within the model. Likely sources of error are incorrect evapotranspiration estimates, surface water runoff or and ground water seepage. The earlier comparison of the rainfall for June 1942 – May 2005 against the June 1989 –May 1996 showed that June 1989 - May 1996 was a period of rainfall. It is likely that during this period, runoff, evapotranspiration and ground water seepage were also much reduced.

3.2. Further Analyses of the water balance and water balance records

As the water levels are affected by the water balance, trends in the water balance were examined and a series of further regression analyses were carried out. These consisted of regressing the actual water levels against the water balance for individual years, and for each month within the June 1989 –May 1996 CCW data set. This was done to help identify periods when other factors like runoff, ground water seepage and AEt and I were having the greatest influence.

An additional analysis was conducted which compared the rise of the water level and the positive water balance to estimate apparent Sy and recharge. A similar analysis is conducted upon the negative water balance to estimate discharge.

3.2.1. Examination of the water balance

The forest water balance for the period June 1989 – May 1996 with June 1989 as the base was calculated and plotted (Figure 14). This shows a clear increasing trend over the period and the rate of increase in the forested water balance for the period June 1989 – May 1996 is noticeably below the forested water balance for September 1941 – August 2005 (Figure 15).

The forested water balance for September 1941 – August 2005 grew on average by 4.5 mm/ month. This is in contrast to the forest water balance for June 1989 –May 1996 which grew by only 0.27 mm /month. This confirms the earlier conclusion from the analysis of the rainfall data, that this period was exceptionally dry. This may account for the models poor ability to predict past and future water levels.

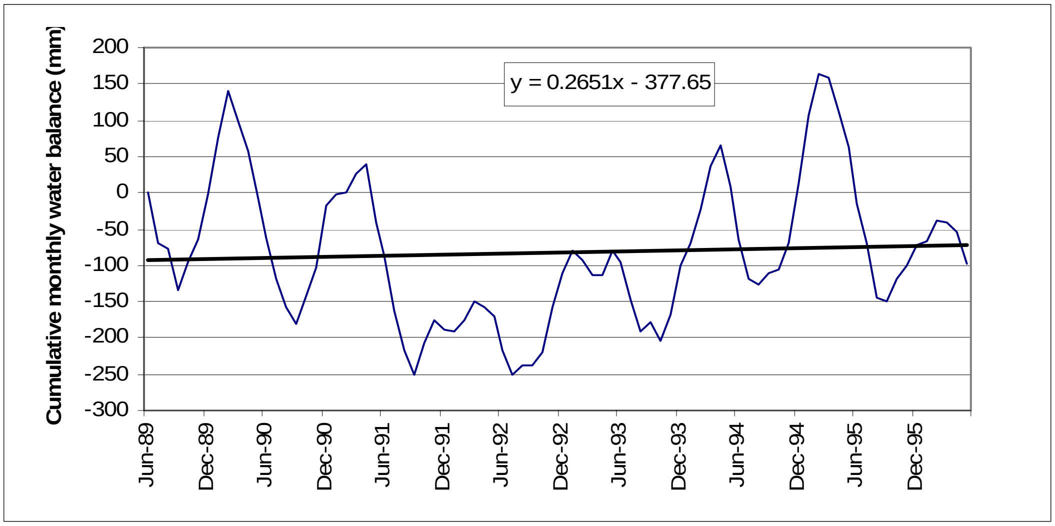

Figure 14: Forested water balance for June 1989 – May 1996

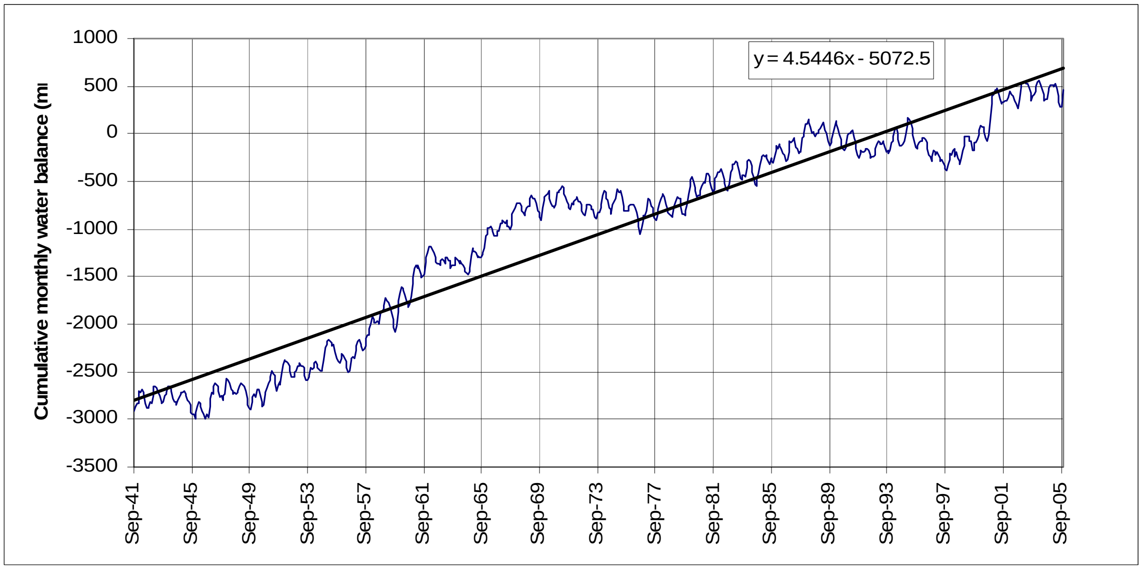

Figure 15: Forested water balance for Sept 1941- Oct 2005with June 1989 as the base year

Figure 15 shows that the rise in the water balance is not linear. There are some periods in which the water balance rises at a steady rate, and there are other periods where the water table increases at a greater rate, and others less. This is perhaps easier to see in figure 16 where the annual water balance is plotted. This shows that longest extended wettest period was 1956 – 1961 not long after the forest was established. Since then the number of continuous successive years with a positive water balance has diminished and so has the magnitude of positive water balance years with the exception of 2001. Also since 1961 the magnitude of negative water balance years has also increased.

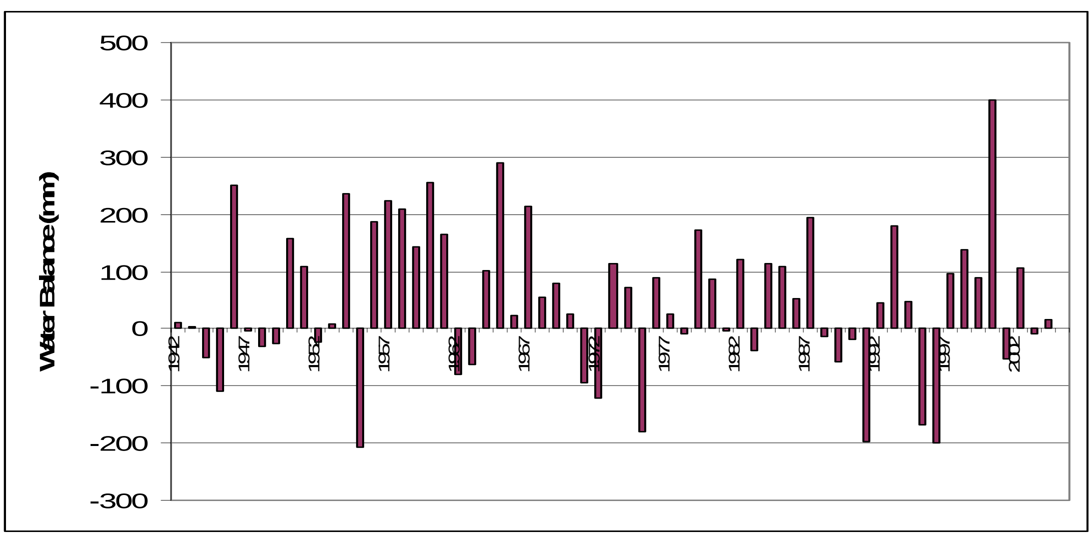

Figure 16: Annual water balance, 1942 – 2004. *(The hydrological year runs from May to April of the year stated)*

Taking zero mm of water balance as the divisor between wet and dry years then the wet years are presented in table 6.

Table 6: Number of wet and dry years according to the Forested water balance

Decade	Dry years	Wet Years	% wet years
40's	44, 45, 47, 48, 49	42, 43, 46,	38
50's	52, 55,	50-54, 56-59	80
60's	62, 63	60, 61, 64-69	80
70's	71, 72, 75 ,78	70, 73,74,76,77,79	60
80's	81, 83, 88, 89	80, 82, 84-87	60
90's	90, 91, 95, 96	92-94, 97-99	60
00's	01, 03,	00, 02, 04,	60

3.2.2. Regression analysis of annual subsets of the CCW water level records

When the previous month's forest water balance and the CCW water level are plotted (figure 11), there seems to be a good correlation within individual years, however it can be seen that the water table is much lower in June 1991 – May 1992 and that the response of the water table is dampened during this period compared to other periods. Annual subsets of the CCW average water level record for June 1989 – May 1996 and the previous month's forest water balance over the same period were compared.

The water level and the water balance (calculated from January 1989) for May 1989 – April 1996 where grouped in periods on an annual basis as shown in the table 7 below.

Table 7: Annual monthly water levels and monthly water balance

Annual Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Water balance period	May 1989 - April 1990	May 1990 – April 1991	May 1991 – April 1992	May 1992 – April 1993	May 1993 – April 1994	May 1994 - April 1995	May 1995 - April 1996
Actual average water level period	June 1989 - May 1990	June 1990 – May 1991	June 1991 – May 1992	June 1992 – May 1993	June 1993 – May 1994	June 1994 - May 1995	June 1995 - May 1996

Boxplots of the water balance and the CCW water level were drawn (Figure 17) and both boxplots show a similar pattern, the water level was lower in period 3 than in periods 1, 6 and 7; and the water balance was lower in periods 3 and 4, than for periods 1, 2, 6 and 7.

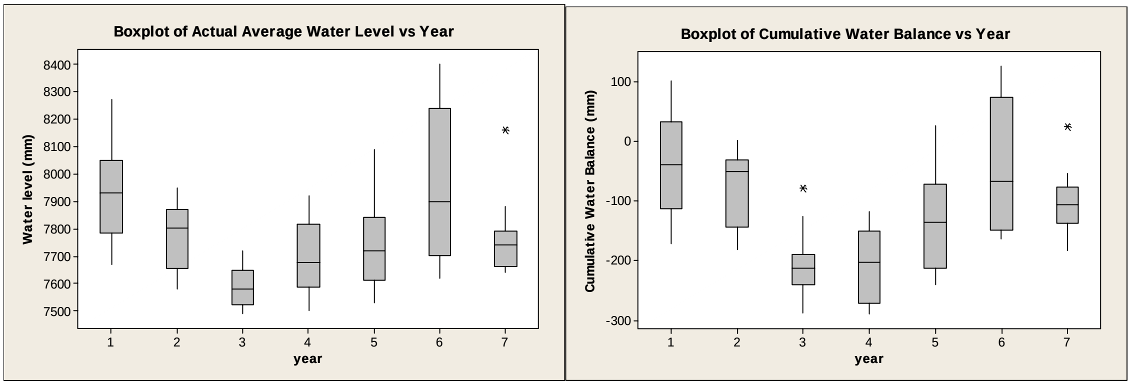

Figure 17: Boxplots for CWW water levels June 1989 – May 1996 and the forest water balance for May 1989 – April 1996 grouped by year

A series of further correlation and regression analyses were carried out on the CCW water level against the previous months forest water balance for May 1989 – April 1996, for individual years (table 8).

Table 8: Correlation and regression parameters, for annual subsets of the CCW water levels against the forest water balance with a one month lag.

Annual Period	***1-7***	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Water balance period	*May 1989 - April 1996*	May 1989 - April 1990	May 1990 – April 1991	May 1991 – April 1992	May 1992 – April 1993	May 1993 – April 1994	May 1994 - April 1995	May 1995 - April 1996
Actual average water level	*June 1989 - May 1996*	June 1989 - May 1990	June 1990 – May 1991	June 1991 – May 1992	June 1992 – May 1993	June 1993 – May 1994	June 1994 - May 1995	June 1995 - May 1996
Correlation coefficient	*0.92*	0.88	0.80	0.33	0.84	0.61	0.81	0.57
Slope	*1.90*	1.89	1.62	1.10	2.03	1.92	2.38	2.10
Intercept	*8003*	8015	7900	7814	8113	8009	8065	7983
r2	*0.85*	0.77	0.86	0.81	0.87	0.93	0.95	0.72
1/slope (Sy)	*0.526*	0.529	0.618	0.908	0.492	0.520	0.420	0.475

Good coefficients of determination were found for all years. The intercepts can be ignored as they are a result of the starting CCW water level and water balance for the period in question. However the slope is of interest and varied from 1.6 to 2.38 giving corresponding apparent Sy values of 42% to 62% for all years, except for the water levels for period June 1991-May 1992 which gave a slope value of 1.1 and an apparent Sy of 90%.

The annual periods can be grouped. Water levels for the periods June 1989 - May 1990, June 1992 – May 1993 and June 1993 – May 1994 have slope values close to that of the initial regression model using the full data series of 1.902. Water levels for June 1994 –

May 1995 and June 1995 – May 1996 have slightly higher slope values close to 2.2, and June 1990 – May 1991 has a lower slope value of 1.68.

There appears to be no link between the slope values and the range of water balance values presented in the boxplots, except for the relatively dry period June 1991-May 1992 which gave an exceptionally small slope value of 1.1, almost half that of the average for all the other annual periods. Changes in the water balance in this period caused an almost equal change in the water table in contrast to the other annual periods where changes in the water balance had on average double the effect on the water table. The period June 1991 - May 1992 also had a poor correlation coefficient compared to the other annual periods.

A lower slope value for the annual model than that predicted by the initial model implies that in those years the water balance had relatively little impact on the water levels, and that other errors derived from incorrect AEt and I estimates, runoff and groundwater seepage had a greater influence on the water levels.

3.2.3. Regression analysis of calendar month subsets of the CCW water level record

The CCW water levels and the previous month's water balance for the period June 1989 – May 1996 were sorted by month. Boxplots were then drawn for the two data series (Figure 18). The boxplots show that the CCW water levels and water balance reach a maximum during February – May and their lowest during September –November.

The boxplots also show that the CCW water level September - November were much lower than January – July, while for the previous month's forest water balance, August - December were lower than for January – July.

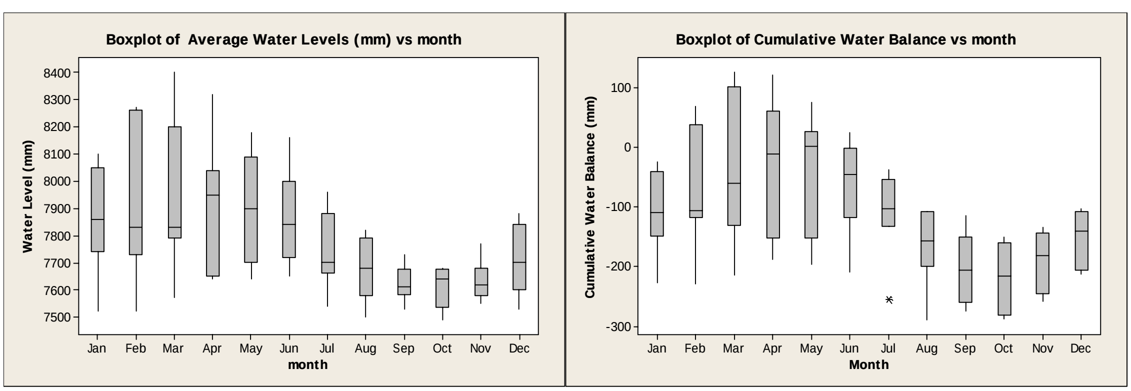

Figure 18: Boxplots for the average water levels sorted by month and the previous month's forest water balance grouped by month.

The CCW average water level and the previous month's forest water balance were sorted by month, correlated and regressed (Table 9). The slope coefficient values of April –

August were similar to the initial regression model, while September - November were less, and December - March were greater. This can be related to the general trend of the water table for these periods: April – August are periods when the water table falls, while September and November are months when the water table remains static, and December - March are months when the water level rises.

Table 9: Correlation, regression parameters and reciprocal slope values based on CCW water levels and water balance for the period June 1989 May 1996

	N	Correlation coefficient	Intercept	Slope	r^2	1/slope (Sy)
January	7	0.88	7960.61	2.44	0.78	0.41
February	7	0.93	7986.58	2.56	0.87	0.39
March	7	0.96	7966.56	2.22	0.92	0.45
April	7	0.91	8105.18	1.99	0.83	0.50
May	7	0.92	7813.42	1.85	0.85	0.54
June	7	0.83	7956.16	1.85	0.69	0.54
July	7	0.91	7987.83	1.83	0.82	0.55
August	7	0.86	8081.69	1.69	0.73	0.59
September	5	0.84	7813.42	0.93	0.71	1.07
October	6	0.93	7847.61	1.19	0.86	0.84
November	7	0.77	7873.49	1.10	0.59	0.91
December	7	0.90	8017.26	2.40	0.81	0.42

The regression slope was plotted against the previous month's average rainfall, AEt and I, the average monthly forest water balance increment and the average forest water balance (Figure 19) this revealed that there is a close relationship between previous monthly average rainfall and the monthly regression slope with a correlation coefficient of 84%.

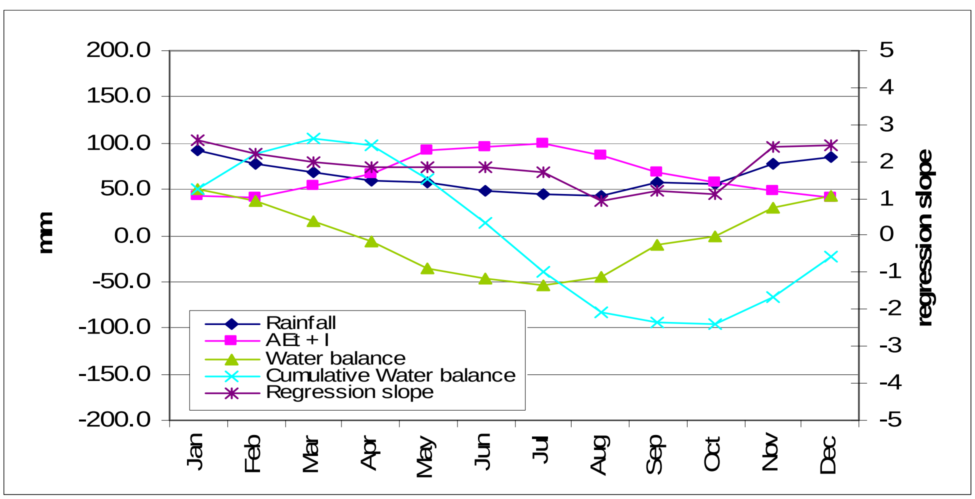

Figure 19: Previous month's average rainfall, AEt and I, the monthly average forest water balance increment and the average monthly forest water balance plotted with the regression slopes obtained from table 9 (note x axis labels for the regression slope are advanced by 1 month, i.e. January refers to December).

The regression slope coefficients were plotted against the previous month's rainfall (Figure 20). This revealed hysteresis, the relationship between rainfall and the monthly regression slope coefficients depended upon whether the water levels were falling or rising. In general monthly regression slope coefficients for the falling water levels were higher than the rising water levels when the average monthly rainfall was between 45-60 mm.

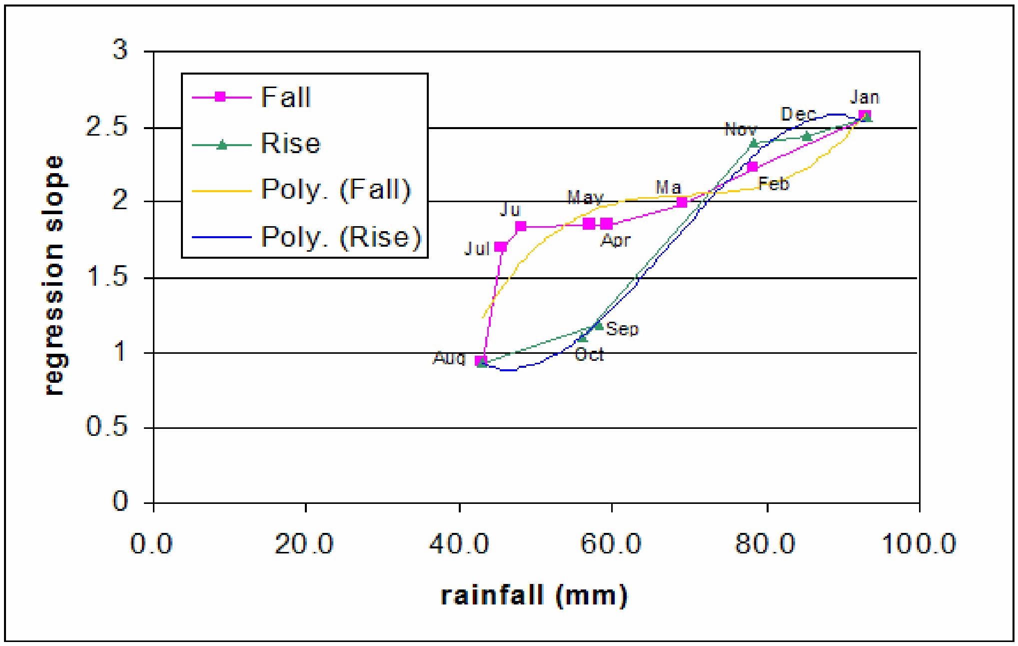

Figure 20: Monthly regression slopes from Table 9 plotted against the previous month's rainfall (note that named month refers to the following months regression slope coefficient. i.e. the slope for Jan refers to Feb)

Third order polynomial regression was applied to the monthly regression slope coefficients for both the rising water levels and falling water levels. Details of the polynomial regressions are given in the table 10 below.

Table 10. Polynomial equations for regression slope and rainfall (Figure 15)

Water levels	Polynomial regression equation	R^2
Falling	$4E-05x^3 - 0.0082x^2 - 0.571x - 11.339$	0.835
Rising	$-4E-05x^3 + 0.0088x^2 - 0.5392x + 11.23$	0.993

An attempt was made at modelling the water table using the above polynomial equations in table 10, but the results were disappointing and far worse than the initial model. However further analysis along these lines perhaps using water balance instead of rainfall, may aid the development of a model which accounts for runoff and groundwater seepage.

3.3. Estimation of recharge and discharge using the Water Level Method

Risser et al. (2005) present the water level method for calculating recharge using the mean annual rise of the water level in an observation well and multiplying this by Sy. The results are presented below. Missing values in the CCW actual average water level series were filled using those predicted from the initial regression model.

Similarly groundwater discharge was also calculated but using the mean annual fall. This model assumes that there is no discharge from the water table during periods of water table rise and similarly there is no recharge during periods of water table fall.

The Sy value of 21% as used by Betson et al (2002) was found to give poor results, and an apparent Sy value of 42.5% was found to give a good agreement with the recharge calculated using the water balance (Table 11).

It would appear that on average recharge was 18 mm/ year less than discharge through out the period.

Table 11: Estimated recharge and discharge for CCW average water levels

Year	Total water level rise (mm)	Recharge (mm)	Total water level fall (mm)	Discharge + AEt + I (mm)
June 1989 - May 1990	600	255	830	352
June 1990 – May 1991	517	210	627	267
June 1991 – May 1992	250	106	410	174
June 1992 – May 1993	560	238	460	194
June 1993 – May 1994	660	281	580	247
June 1994 - May 1995	728	309	748	316
June 1995 - May 1996	200	85	160	67
Annual Average	**502**	**213**	**545**	**231**

The positive and negative previous month's forest water balance were summed and compared against the recharge and discharge calculated using the water level method, and is presented in Table 12.

The annual average recharge and the positive water balance agree well (213 mm), but the negative water balance (226 mm) is slightly below the estimates discharge estimated using the water level method (231 mm).

When the discharge and recharge and the positive and negative water balances are plotted (Figure 21), it is apparent that although the average negative water balance agrees with the average water level estimate of discharge, it does not follow the same temporal pattern as that of recharge and discharge calculated using the water level method.

Table 12: Comparison of estimated recharge and discharge for the CCW average well level using the water level and water balance methods

Year	Recharge (mm)	Positive water balance (mm)	Missing WB Recharge (mm)	Discharge +(AEt+ I) (mm)	Negative Water balance (mm)	Missing WB discharge (mm)
June 1989 - May 1990	255.0	272.0	-17.0	352.1	329.2	22.9
June 1990 - May 1991	219.7	218.0	1.7	267.1	238.0	29.1
June 1991 - May 1992	106.3	116.0	-9.8	174.0	218.0	-44.0
June 1992 - May 1993	238.0	171.0	67.0	194.3	127.0	67.3
June 1993 - May 1994	280.5	316.0	-35.5	246.9	137.0	109.9
June 1994 - May 1995	309.4	289.0	20.4	315.7	241.0	74.7
June 1995 - May 1996	85.0	110.0	-25.0	66.8	289.0	-222.2
Average all years	**213.4**	**213.1**	**0.3**	**231.0**	**225.6**	**5.4**

This indicates: that discharge from the aquifer is not dominated by AEt and I and that discharge is closely related to the recharge of the water table. This also implies that as the regression model is based on the water balance it too is poor at estimating falling water levels.

It can be seen in figure 21 that the water level estimated discharge is greater than recharge for June 1989 – May 1992 suggesting dewatering of the aquifer, and then between June 1992 and May 1994 estimated discharge is less, suggesting that the aquifer is recharging. In June 1994 - May 1996 water level estimated discharge matched recharge.

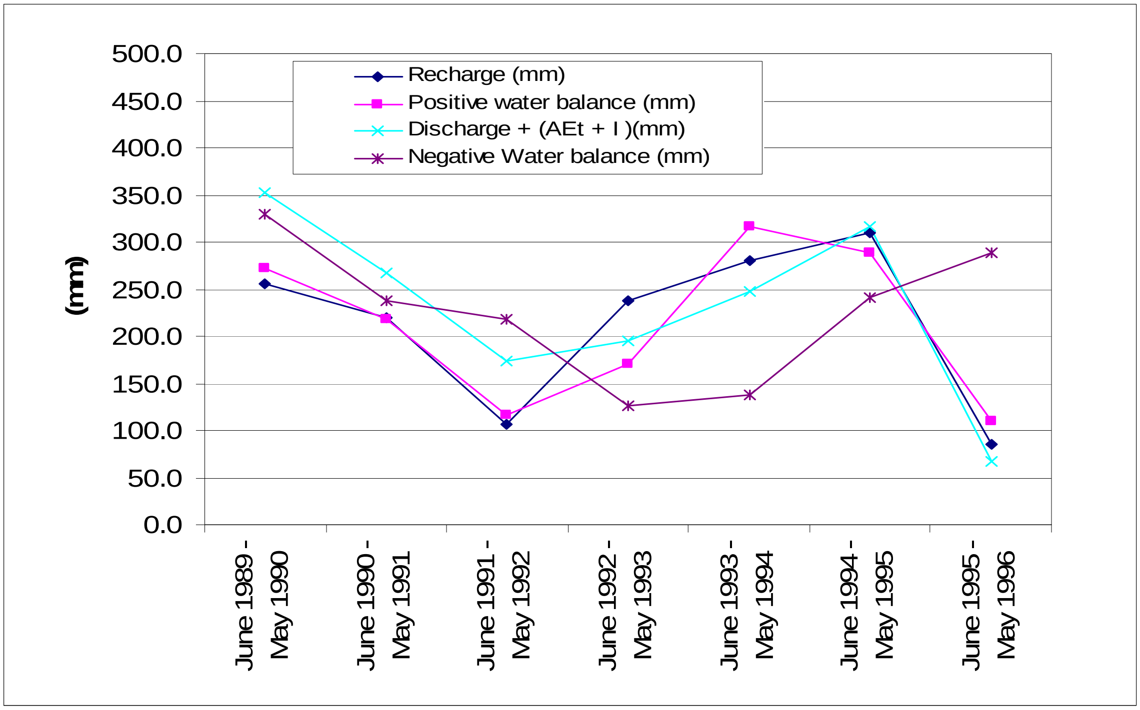

Figure 21: Graph of recharge and discharge calculated for the CCW well level using the water level and water balance methods.

The water level estimates of recharge and discharge show a good correlation (83%) and were then regressed (Figure 22). This indicates that the annual discharge rate is 33.5 mm + 0.925 of the recharge.

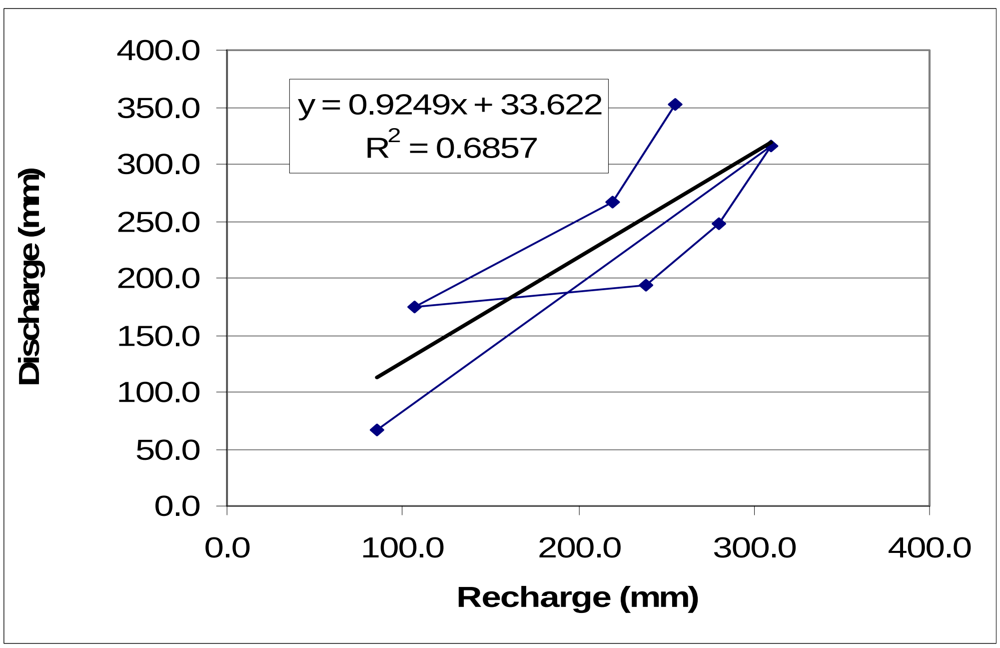

Figure 22: Regression of recharge and discharge calculated by the water level method

The recharge estimated by Betson and Scholefield (2004) for the Forest vegetation using the SWAP model was 255 mm, This is 42 mm greater than the 213 mm estimated using the positive water balance and the water level methods. This could point to errors in the Risser et al. (2005) water level method when applied to Newborough or the Betson and Scholefield (2004) results.

This could be because the period was drier than average, however less than half of the Newborough Warren area is forested, and so the recharge calculated using the water level method should lie some where between Betson and Scholefield's (2004) estimates for forest (255 mm) and fixed dune systems (396 mm). However Betson and Scholefield's (2004) AEt + I estimates are good for calculating a water balance which can be used in the regression models, hinting that the Forest AEt and I estimate is representative of the Warren and Forest.

3.4. Discussion of apparent Sy estimates for the CCW wells

Analysis of the response of the water table to the water balance has yielded a variety of estimates for Sy which require further examination.

Risser et al. (2005) in their comparative study of estimating recharge by various methods found that generally the estimates of recharge using the water level method were (20%) less than those estimated from the daily water balances of lysimeters. The apparent Sy estimated by matching the water balance to the recharge estimated from the water level rise was 42.5%. To match the estimated water level rise to 80% of the water balance, the corresponding Sy value is 34% which is a more realistic value for the Sy of sand, but still greater than the maximum expected of 28% for fine sand, Betson et al's (2002) estimate of 21%, and less than the apparent Sy values predicted from the regression models.

Slug tests need to be conducted within the wells to determine the true Sy values and this will then remove some of the ambiguity around the correct Sy, recharge and discharge rates. For the following discussion on the Sy values determined by the regression models an Sy value of 42% is assumed.

Most of the apparent Sy values obtained from the regression models are greater than 42%, At an apparent Sy of 42% each millimetre of water balance would expect to raise the water table by 2.5 mm, The initial regression model had an apparent Sy estimate of 52.5%.

The monthly regression analysis indicates that there is a difference depending upon whether the water tables are rising or falling. There is a dramatic drop in the response of the water table from July (ASy = 55%) where each mm of the water balance causes a 2 mm change in the average water levels to September (ASy = 93%) where changes in the water balance cause almost equal changes in the water levels.

Reasons for the variation in apparent Sy are not clear but are probably linked to:

- Interception losses
- The depth to the water table: during periods when the low water tables are low transmission times of rainfall to the water table are increased because of decreased hydraulic conductivity resulting from unsaturated soils above the water table.
- Ground water seepage from the Precambrian ridge
- Groundwater seepage from the sand aquifer of the Forest and Warren.

The last 3 reasons are linked to the height of the water table. When groundwater levels are high, the water table response to rainfall will be greater because of enhanced recharge from the rock ridge, and during dry periods discharge from the aquifer to the sea will also be greater. Both these effects will result in a greater water table response to the water balance and a lower specific yield.

When water levels are low, groundwater recharge from the Precambrian ridge ceases, and the aquifer continues to discharge to the sea and the water table response to rainfall and evaporation are all reduced, resulting in a lower water table response to the water balance and a higher apparent Sy.

Water levels are highest in February and this is when the water table response is at its greatest and also when regression apparent Sy estimates are at their lowest of 39%, which is close to the recharge method estimate for apparent Sy of 42%. During this period the sands, soil, and the interception stores of the Forest and dune vegetation are nearly saturated.

As the water table recedes during March – July, the apparent Sy increases to around 50% increasing in August, September and October to around 90%. This increase in apparent Sy could be explained by the increasing travel time for recharge to reach the water table as the water table recedes.

3.5. Conclusions from analysis of CCW water levels

- The Betson and Scholefield (2004) PEt and I, AEt and I, and net recharge estimates for the different vegetation types are incorrect as the Betson and Scholefield (2004) average monthly estimate for forest AEt and I is appropriate for modelling the water balance for the area monitored by the CCW dipwells, which is a mixture of forest and fixed dune vegetation types.

- The specific yield for the sands of Newborough are in the range of 28-34%, but the apparent Sy estimated by matching response of the water table rise to the positive water balance was found to be nearer to 42%.

- The response of the water table to the water balance depends upon the height of the water table. A greater response occurs when the water table is high, and a lesser response occurs when the water table is low and is probably due to storage effects of the perched aquifers on the Precambrian ridge and runoff from the ridge, as well as interception storage, and varying groundwater seepage from the Warren.

- The apparent specific yield estimated from regression analysis of the water levels and the water balance can vary from 39 - 91% and is on average 52%, implying that the response of the water table to changes in the water balance, is on average twice that of the water balance.

- There is evidence that the water balance was wetter during the 1950's and 60's when the forest was planted and fixed dune slack vegetation became established. The 1970's, 80's and 90's were drier as the forest established. The effects of increased interception and evaporation as a result of the forest vegetation would also have been exacerbated by the drier water balance over the same period. Since 2000 the water balance has become wetter and winter flooding is now a common occurrence and this also coincides with decreased forest AEt + I caused by the maturing forest.

- Both the water balance and the regression analysis methods model less accurately falling water levels rising water tables, probably as a result of extended travel times of rainwater recharge to the water table. This prevents the regression model being used to extrapolate long term water table movement.

- The water balance over the period over which the CCW research data was collected was not representative of the long-term water balance. The period June 1989 – May 1996 was unusual in that it did not have rainfall over 150mm.

- The average recharge to the area of the CCW wells is 213 mm /year and the discharge 226 mm /year. Discharge from the area to the sea is generally 6% greater than recharge to the area.

4. Analysis of Forest borehole records

Water level records for the Forest were analysed using the regression technique outlined in sections 3.1 and 3.2 and the water level method in outlined in section 3.3 to see if there was a difference in the behaviour of the water table in the Warren represented by the CCW water level records (2.1.1), and the Forest represented by dip wells and lake levels in the Forest (2.1.2). A full regression analysis was not possible in the time available, and conclusions and discussion are derived from this approach are not included.

4.1. Regression analysis of Forest water levels

From Table 14 it can be seen that the best correlation between all the Forest water levels and the forest water balance could be obtained using the water balance for the same month as the water level record, in contrast to the water levels for the CCW wells which had stronger correlation coefficients if the previous months water balance was used. This may be a result of the time of month that water level records were taken. The CCW water levels may have been recorded at the start of the month and the Forest water levels recorded at the end of the month.

It was found that for the CCW wells, similar regression equations were obtained to those using the June 1989 - May 1996 records (Section 3.1), but the regression coefficients for the Forest wells were disappointing. The forest AEt + I estimate was modified to determine the best possible regression fit between the Forest wells and pools and the water balance.

The regression coefficient could be improved if the forest AEt + I estimate was reduced to 96%. This in itself suggests that the AEt + I estimate is too large for the Forest. For the purposes of direct comparison of the Forest water levels with the CCW water levels, the AEt + I estimate used was 96% of its original value.

The water level records with missing data or where the water table had dropped below the base of the dip well were excluded from further analysis. The monthly water level records were regressed against the forested water balance and the results are presented in table 14.

When the forest estimated AEt + I estimate is reduced to 96% of its original value, most of the wells have good coefficients of determination above 60% except for wells 4, 5, and 18 and LPM.

The response of the water table monitored by the CCW wells during June 1989 – June 1996 (1.9 mm for every 1 mm of water balance), is slightly less than the response over June 1989 – May 1995 (1.95 mm for every 1 mm of water balance) and the average response for all the Forest water monitoring points (1.92).

Table 14: Regression analysis results of Forest water level records against the reduced forest water balance.

	Slope	Intercept	(Et x 0.96) R^2	(Et x 1) R^2	Apparent Sy
CCW	1.62	7885	0.79	0.86	0.62
2	3.25	-634	0.73	0.42	0.31
3	1.43	-729	0.78	0.53	0.70
4	1.45	-536	0.32	0.18	0.69
6	2.92	-789	0.72	0.58	0.34
9	2.35	-720	0.67	0.58	0.43
11	1.40	-700	0.79	0.64	0.71
13	2.89	-1098	0.75	0.66	0.35
15	1.76	-790	0.91	0.76	0.57
16	1.86	-845	0.90	0.76	0.54
17	1.05	-744	0.63	0.49	0.95
18	1.59	-537	0.25	0.41	0.63
LPM	1.84	1178	0.55	0.54	0.54
Average 2, 3, 6	2.10				0.48
Average 15-17	1.81				0.64
Forest average	1.98				0.50
CCW	1.62				0.62

The range of response of the water table to the water balance in the Forest monitoring points ranges from 3.25- 1.05, however if the monitoring points are grouped by location, the response for wells 15 and 16 (1.8) is close to the average for all the monitoring points in the Forest and the CCW wells. The average response of wells 2, 3, 4 and 6 (2.1) is greater.

The slopes and apparent Sy calculated using this method rely on regression equations, some with a low coefficient of determination. The information presented is a rough working meant to show the possibilities of using a regression modelling approach. Further work is required to refine this approach before a detailed analysis can be conducted.

4.2. Analysis of normalised water level records

The CCW and Forest water level records were normalized to the water level on June 1989. This was to make comparison easier. Sets of Forest monitoring points were grouped by location (Figure 5) and the average water levels calculated. The CCW levels were also normalised, however the CCW levels have already been averaged by the height above sea level, but this has no effect on the normalized values.

Sets of graphs were produced of the normalized water levels for June 1989 to May 1995 for all Forest monitoring points and the CCW wells, based on location (Figures 23-28). All graphs contain the CCW water level record as well as the average for the Forest wells as well as the average for that location. The Forest average includes all wells including wells 13 and 18 for which there is no location, but excludes water levels from pools.

Wells 1-6

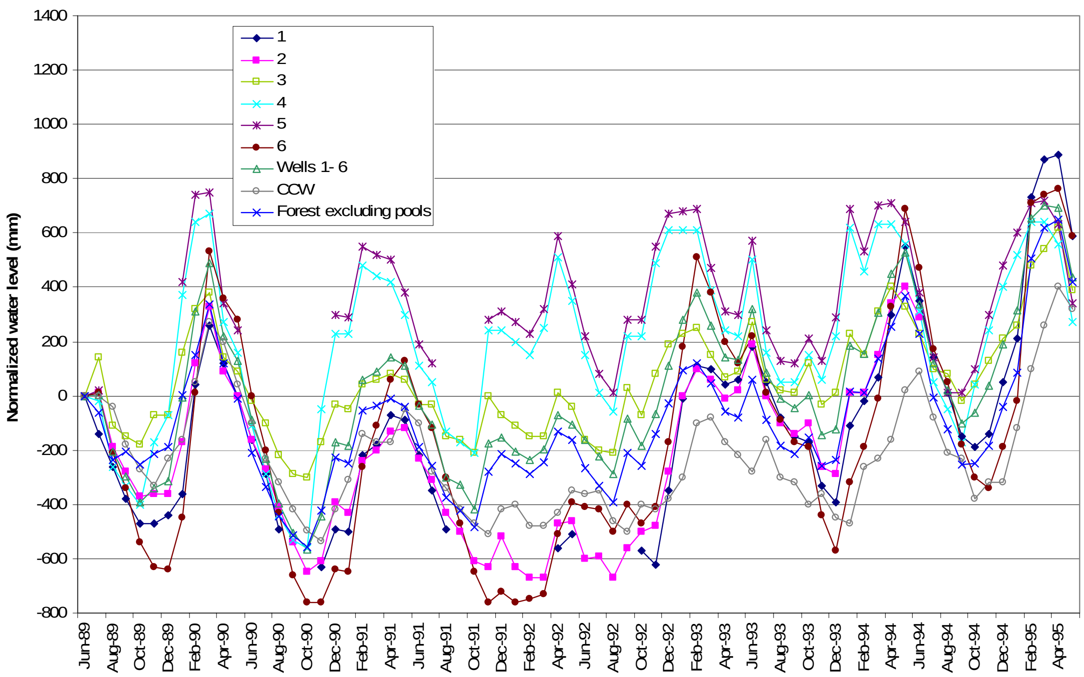

Figure 23: Normalized water level records for wells 1-6

Wells 1 - 6 are situated on the rock ridge near Pandy pools and can be grouped by response. Wells 4 and 5 are very close together both in location and response. They are on the midslope of the rock ridge as it slopes down to the northern spit system. The water levels in these wells remains consistently high, but also have rounded peaks suggesting drainage when water tables are high. They do not have low water levels during 1991-1992.

Wells 1, 2 and 6 behave similarly to each other. 1 and 2 are located close together within a relic dune slack, but well 6 is about 300m away close to the edge of the forest and may be receiving runoff from fields. Wells 1, 2 and 6 behave similarly to the CCW wells, but are more responsive and reach higher and lower levels relative to the CCW wells.

Well 3 is located close to wells 1 and 2 but near the point of discharge of the relic dune slack. The water level in well 3 oscillates between the levels of wells 1, 2 and 6 and wells 4 and 5, and it is close to the average for wells 1-6, and the average for all the dipwells in the Forest.

Wells 7 - 9

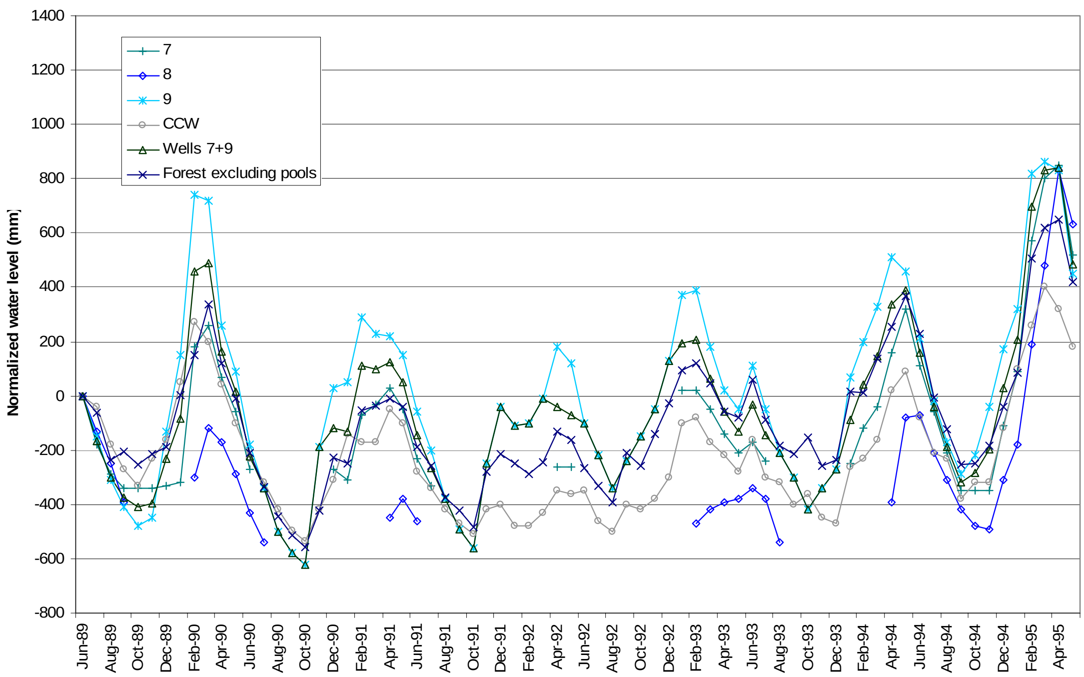

Figure 24: Normalized water level records for wells 7, 8 and 9

Wells 7, 8 and 9 are located in a line parallel and midway from the ridge to the Warren within the southern spit system, NW of the downthrown block. The records for wells 7 and 8 are incomplete. The water level in well 7 is close to that of well 9 but not as responsive. The records for well 8 are below the depth of the well for a considerable period, what is surprising is its recovery in 1994.

All wells have a relative water level higher than the CCW wells, except for well 8, for this reason well 8 has not been included in the average in this area. The average for wells 7 and 9 is used instead.

Wells 10, 14-17

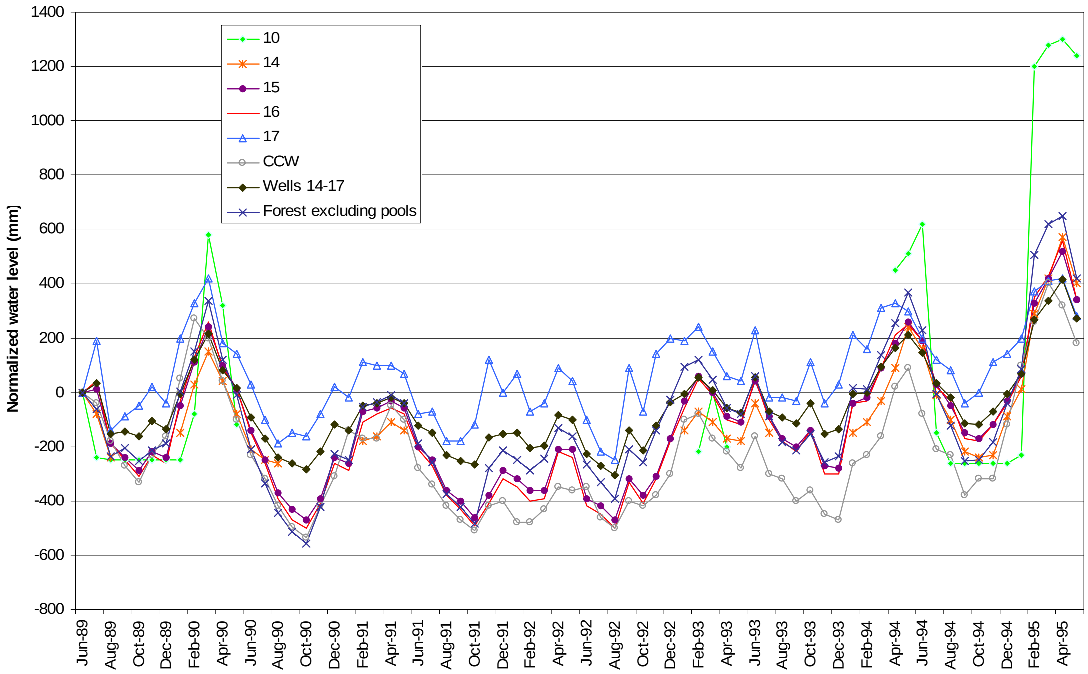

Figure 25: Normalized water level records for wells 10, 14-17

Wells 14, 15 and 16 are located on fixed dune not far from the rock ridge within the northern spit system. Well 10 is on the Berw fault and next to the rock ridge. Well 17 is in the edge of the fixed dune very close an area of tidal salt marsh. These wells are in a similar location to that of the CCW wells, i.e. within fixed dune below the rock ridge, only they are closer to the rock ridge and sea and they are not as widely distributed as the CCW wells.

Wells 14, 15 and 16 behave similarly, and water levels are similar to the CCW wells until March 1993 when they become much greater. The water level in well 17 is a lot higher and less responsive than the other wells in this area. The aquifer here is perhaps supported by its closeness to the sea. The record for well 10 is incomplete but shows signs of similar behaviour to well 8. Well 10 has been excluded from the average for this area.

Wells 11, 12, 19

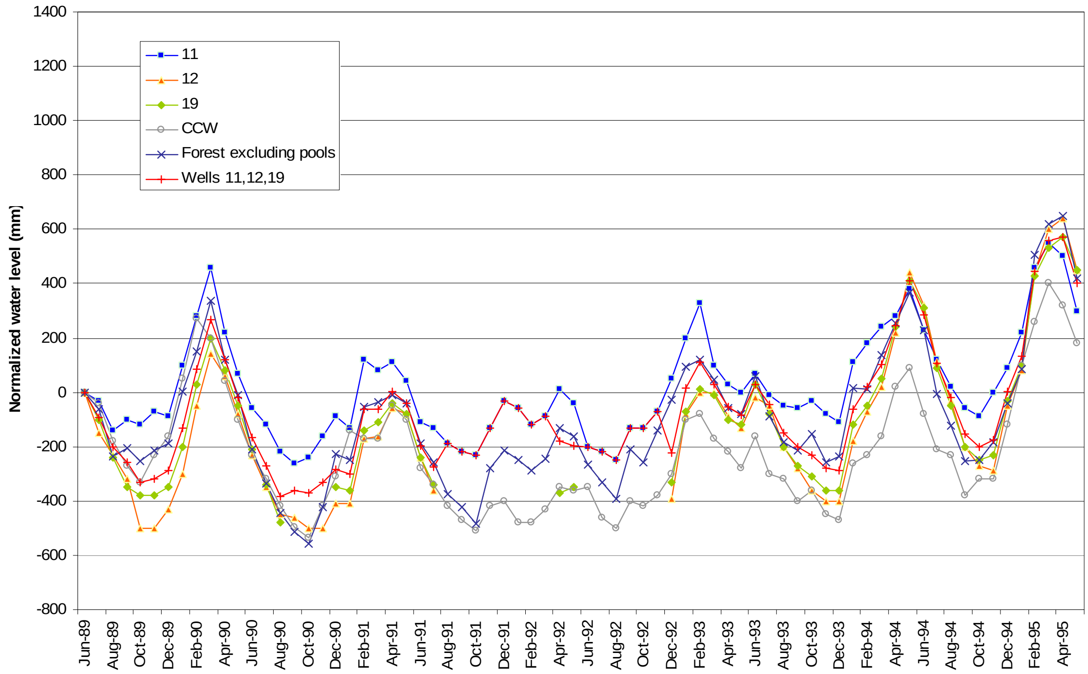

Figure26: Normalized water level records for wells 11, 12 and 19

The wells in this group are dispersed but located in the northern spit system and lie on a line almost parallel to the rock ridge. Well 11 is adjacent to a large artificial dune ridge, and wells 12 and 19 are located within a large dune slack within which is the dune slack pool.

The water level records for wells 12 and 19 are incomplete from Aug 1991 – Jan 1993, and the average water level during this period reflects the behaviour of well 11 alone. Well 19 seems to follow closely the behaviour of the CCW wells upto July 1992.

Well 11 has the highest water level. All wells have a similar response and are higher than the CCW wells after Dec 1992.

Forest Pools and Lakes

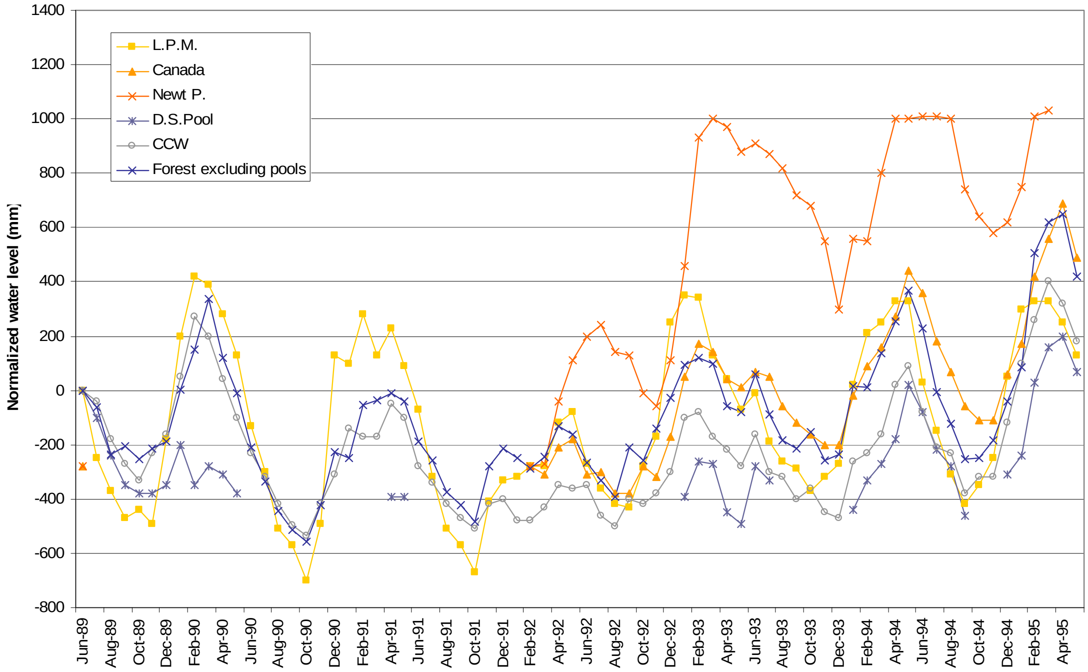

Figure 27: Normalized water level records for pools and lakes within the Forest

All pools and lakes are located in the northern spit system. Canada pool and the Dune slack pool are located within fixed dune slacks. The Newt pool is located halfway up the slope to the rock ridge. Llyn Parc Mawr (LPM) is an excavated pool within fixed dune.

Only the LPM records were complete. The Canada, Newt and Dune slack pool water levels were normalized to the first water level recorded, and so the apparent high level of the Newt pool may be an artefact. The Newt pool shows signs of drainage at high water levels. The Canada pool seems to behave like LPM, and the Dune slack pool like the CCW wells after Dec 1993. Further analysis of pools was not carried out because partial records made it difficult to normalize them and calculate an average water level. Also there are signs that the height of water within the LPM and Newt pools are artificially controlled.

Comparison of grouped sets of wells by location

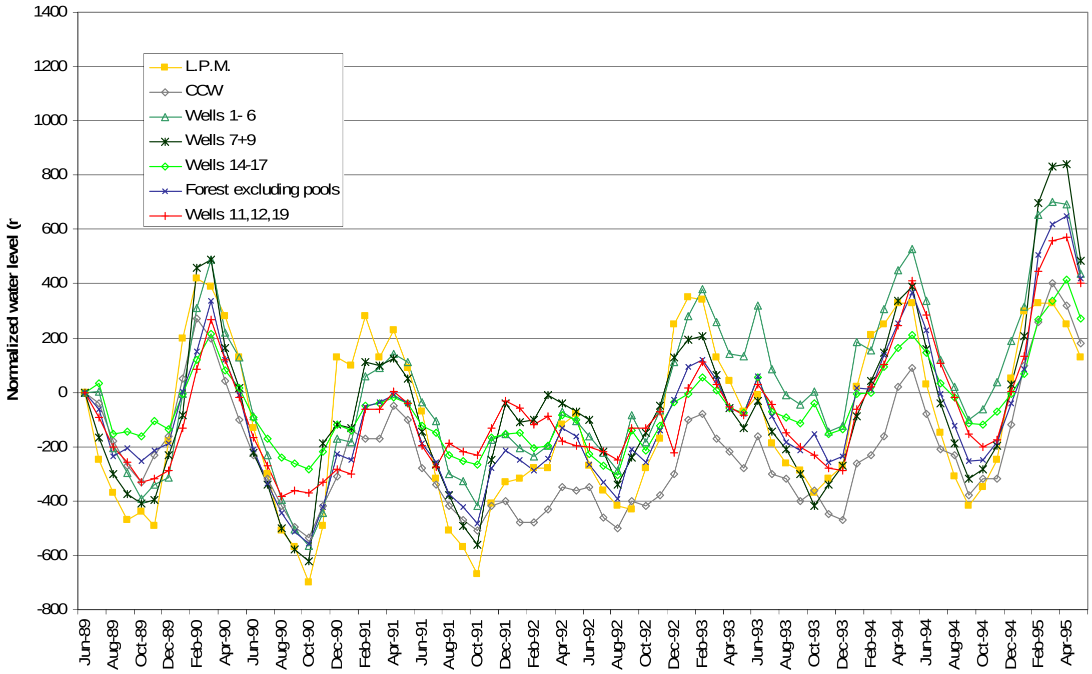

Figure 28:Normalized water level records for groups of wells within the Forest

Wells 1-6 have the highest water levels, wells 14-17 and wells 11, 12 and 19 have similar water levels and have the most damped response of the Forest wells. The Forest average water level (excluding pools) is also similar to these 3 groups of wells. Wells 1 - 6 are almost as responsive as LPM . All groupings of Forest wells generally have greater water levels than the CCW wells.

There is good agreement with all the well records between June 1989 and October 1990 and June 1994 and June1995. The water level fluctuations for all sets of Forest wells and the CCW wells are small between Oct 1991 and Jan 1993. The average water levels of wells 1 - 6 closely follow that of the CCW wells.

4.3. Analysis of rising and falling water levels

The normalised water levels were grouped by location and the average water level calculated. These values were then analysed using the water level method based on the annual period June to May. (Risser, 2005). The annual average water level rise and falls are shown in table and figures. The annual positive and negative water balance to which the water table responds was also calculated and plotted.

4.3.1. Rising water levels

Table 22: :Annual rise in water levels in the Forest and CCW wells

	1989 - 1990	1990 - 1991	1991 - 1992	1992 - 1993	1993 - 1994	1994 - 1995	Average
Wells 1- 6	882	726	434	763	940	804	758
Wells 7+9	900	765	620	545	910	1160	817
Wells 14-17	443	285	240	436	563	532	416
Wells 11,12,19	600	413	317	517	810	773	572
CCW	600	517	240	450	720	780	551
Forest wells	617	565	424	559	836	901	651
Positive water balance	282	232	124	226	296	301	243

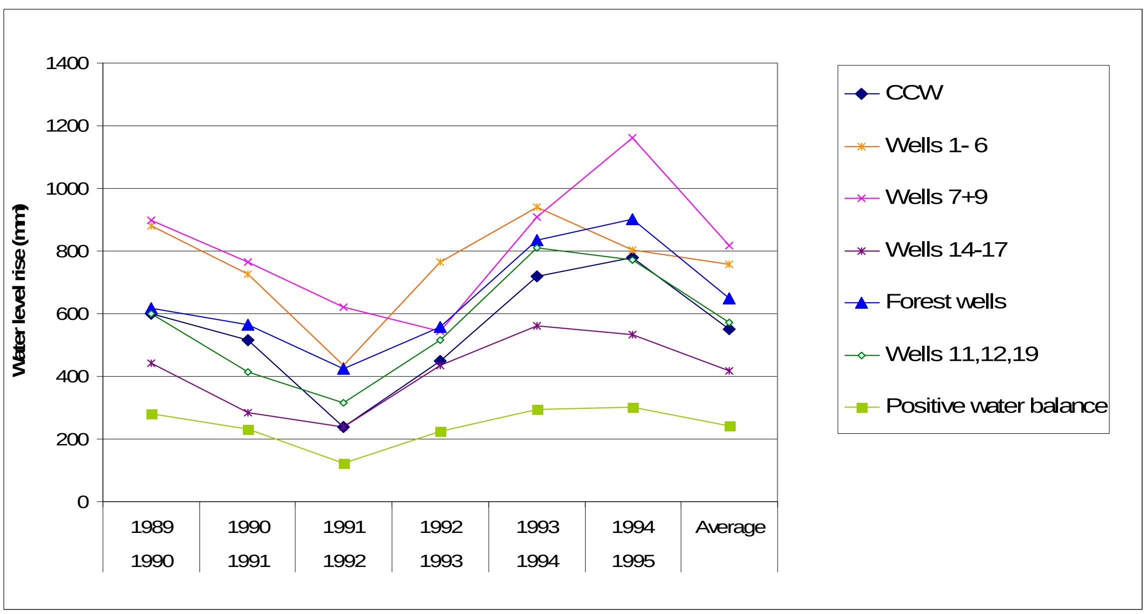

Figure 29: Annual rise in water levels in the Forest and CCW wells

When looking at the rise in water levels (Table 22 and Figure 29) as a result of a positive water balance, wells 14 - 17 had the lowest water table response to the positive water balance and wells 7 and 9 the greatest. All well levels follow the trend of the positive water balance apart from wells 7 and 9, which seem to lag in their response to the low water balance in 1991-1992. The Forest average water level rise is 100 mm greater than the CCW wells, but the pattern is very similar.

4.3.2. Falling water levels

Table 23: Annual fall in water levels in the Forest and CCW wells

	1989 - 1990	1990 - 1991	1991 - 1992	1992 - 1993	1993 - 1994	1994 - 1995	Average
Wells 1- 6	754	744	651	522	547	896	686
Wells 7+9	885	730	740	605	390	1065	736
Wells 14-17	427	343	301	408	279	470	371
Wells 11,12,19	620	433	472	405	317	783	505
CCW	700	517	500	370	350	690	521
Forest wells	629	593	547	478	388	848	580
Negative water balance	261	234	223	102	177	214	202

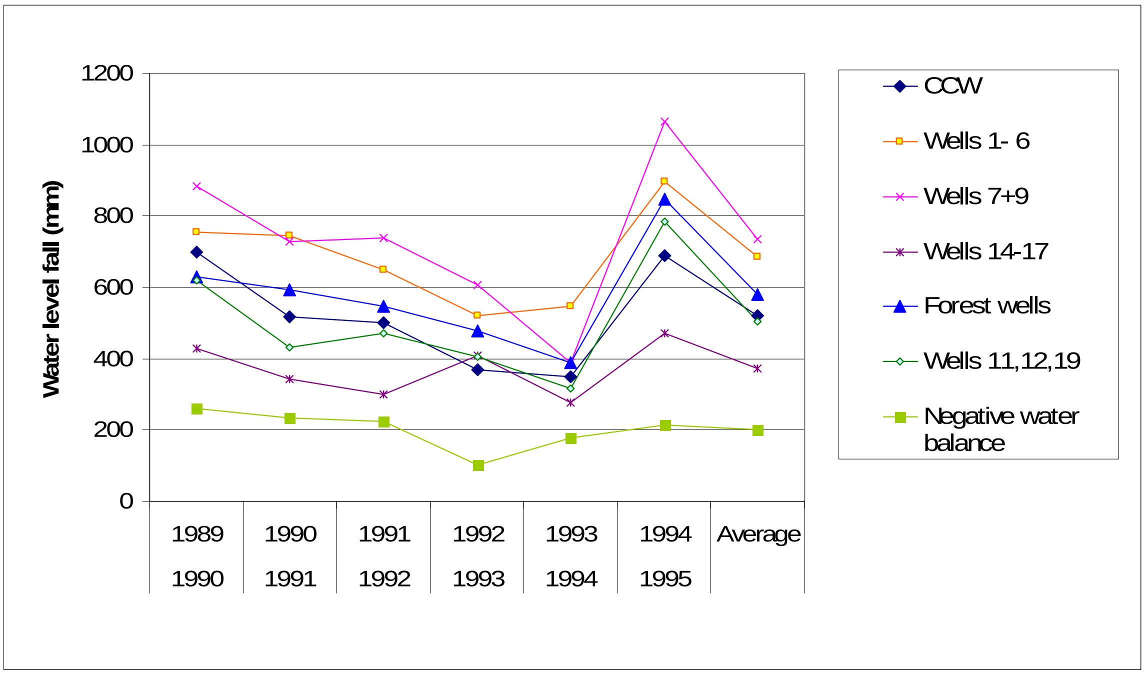

Figure 30: Annual fall in water levels in the Forest and CCW wells

When looking at the fall of the water table in response the negative water balance (Table 23 and Figure 30), none of the wells appear to follow the trend of the water balance. If they do they all appear to have a 1 year lag. In 1992- 1993, wells 14 – 17 water levels fell more despite the negative water balance decreasing that year.

Wells 14 -17 had the lowest water level fall and wells 1 – 6 and wells 7 and 9 the greatest water level fall in response to the negative water balance. Wells 11, 12, and 19 had a similar water level fall to the CCW wells. In general, the annual fall in the water table was greater for all groupings of Forest wells than the CCW wells. The water table fall for the Forest wells was on average 60 mm greater than the CCW wells, but broadly similar.

4.3.3. Comparision of water table fall and rise.

The percentage of annual water table rise to the water table fall was calculated and plotted (Table 24 and Figure 31). The percentage of positive water balance to the following negative water balance is also presented.

Table 24: Ratio of water level rise to water level fall

	1989 - 1990	1990 - 1991	1991 - 1992	1992 - 1993	1993 - 1994	1994 - 1995	Average
Wells 1- 6	1.17	0.98	0.67	1.46	1.72	0.90	1.11
Wells 7+9	1.02	1.05	0.84	0.90	2.33	1.09	1.11
Wells 14-17	1.04	0.83	0.80	1.07	2.02	1.13	1.12
Wells 11,12,19	0.97	0.95	0.67	1.28	2.56	0.99	1.13
CCW	0.86	1.00	0.48	1.22	2.06	1.13	1.06
Forest wells	0.98	0.95	0.78	1.17	2.16	1.06	1.12
Water balance	1.08	0.99	0.56	2.22	1.67	1.41	1.21

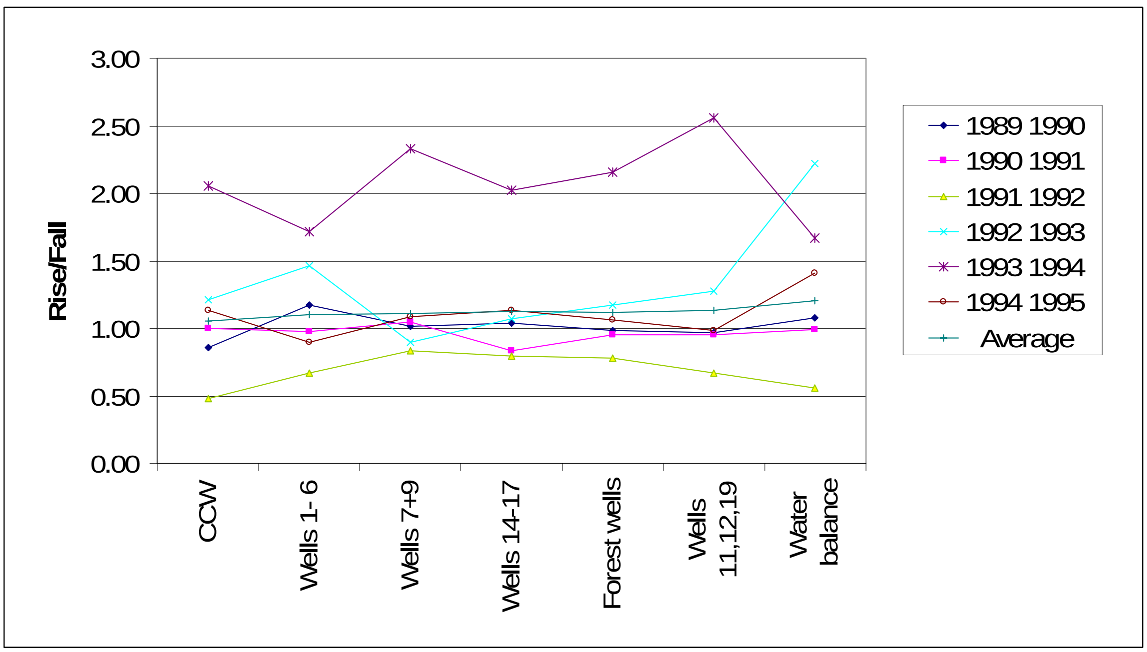

Figure 31: Ratio of water level rise to water level fall

Table 24 and Figure 31 show that the ratio of annual water table rise to the following water table fall in 1989 - 1990, and 1990 - 1991, and 1994 - 1995, are close to 1. For all years, the ratio is just in favour of recharge, except in 1991 – 1992 and 1993-1994. In 1991 - 1992 water level fall was much greater than water level rise. In 1993 – 1994 the ratio was very strongly in favour of rise. The water balance positive to negative water balance ratio was on average 1.20.

None of the ratios for groups of wells follow the pattern of the water balance. 1991 - 1992 was a particularly dry year, rainfall was below normal for most of the year and as a result water levels dropped in all wells and water level fall was greater than water level rise in this year. In 1992 - 1993 the positive water balance was a lot greater than normal but water levels did not discharge a similar amount indicating that the aquifer was recharging. In 1993 – 1994 there was a normal proportion of recharge and this allowed caused the water table to rise and consequently discharge. This rise was greatest in wells 11, 12 and 19 and lowest for the CCW wells.

4.4. Estimation of apparent Sy, recharge and discharge

There are two ways of further analysing the results based on the water level method (Risser et al., 2005) but both are mutually exclusive until accurate Sy measurements are taken. The first calculates apparent Sy assuming that the response of the water table is due to differences in the apparent Sy of the aquifer where each well is located. The second calculates recharge and discharge and assumes that the apparent Sy is constant for all wells.

4.4.1. Apparent Sy for all wells

The apparent Sy was calculated by calculating the ratio of average annual water table rise (or fall) to annual recharge (or discharge) for each group of wells (Table 25 and Figure 32).

Table 25: Recharge and discharge apparent Sy values

	CCW	Wells 1- 6	Wells 7+9	Wells 14 -17	Forest wells	Wells 11,12,19
Recharge	0.44	0.32	0.30	0.58	0.37	0.43
Discharge	0.39	0.29	0.27	0.54	0.35	0.40
Average	0.41	0.31	0.29	0.56	0.36	0.41
Difference	0.05	0.03	0.02	0.04	0.03	0.03

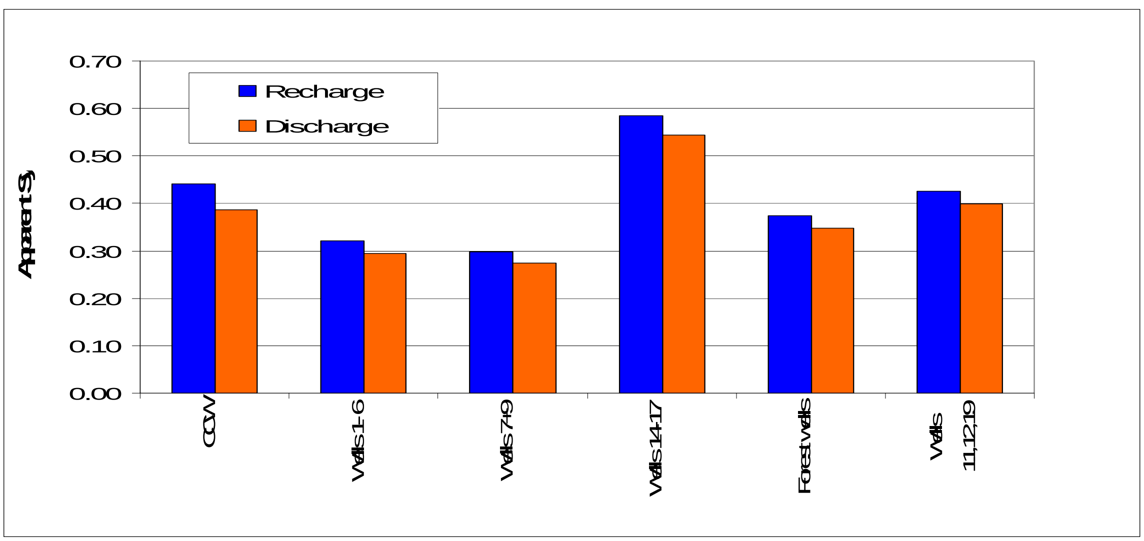

Figure 32: Recharge and discharge apparent Sy values

Wells 11, 12, and 14 have similar apparent Sy values to the CCW wells of around 40%, while wells 14-17 have the greatest apparent Sy values of about 55%. The other sets of wells within the Forest have apparent Sy values around 28%. The apparent Sy for all the Forest wells (35%) is slightly lower than for the CCW wells.

The CCW wells have the greatest difference in apparent recharge and discharge Sy.

4.4.2. Calculated recharge and discharge using the water level method.

The recharge (Table 26 and Figure 33) and discharge (Table 27 and Figure 35) for all sets of wells was calculated using an apparent Sy value of 39%, which is the average for the CCW wells and the Forest wells.

4.4.2.1. Recharge

Table 26: Recharge calculated from the positive water balance assuming an apparent Sy of 39%

	1989 - 1990	1990 - 1991	1991 - 1992	1992 - 1993	1993 - 1994	1994 - 1995	Average
Wells 1- 6	344	283	169	298	367	314	296
Wells 7+9	351	298	242	213	355	452	319
Wells 14-17	173	111	94	170	219	207	162
Wells 11,12,19	234	161	124	202	316	302	223
CCW	234	202	94	176	281	304	215
Forest wells	241	220	165	218	326	351	254
Positive water balance	282	232	124	226	296	301	243

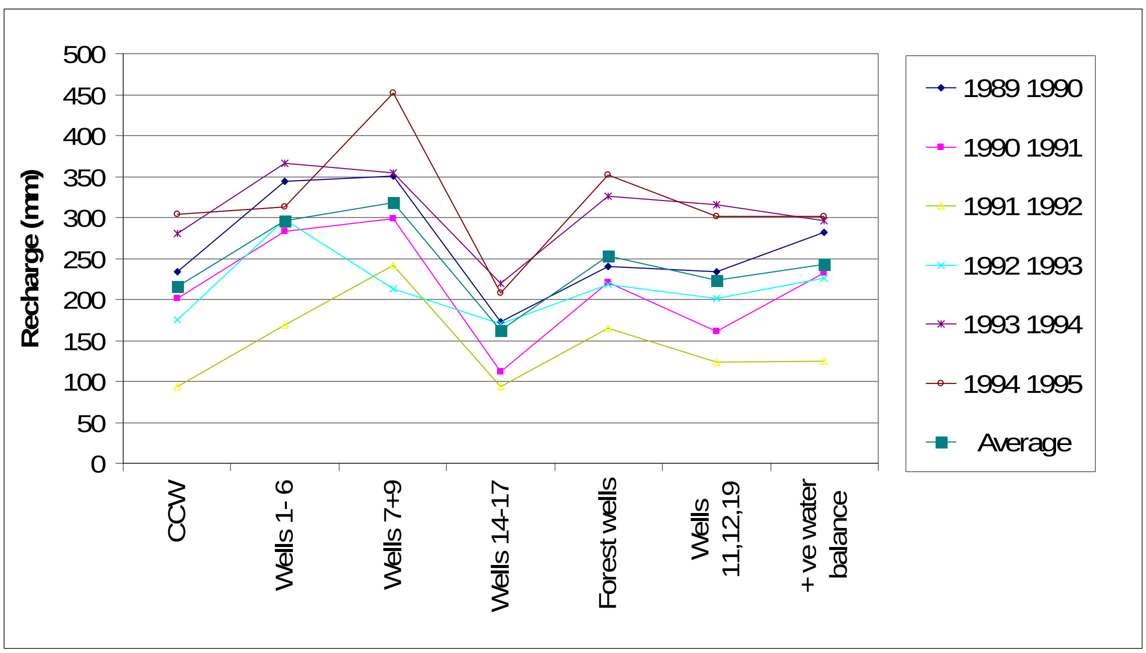

Figure 33: Recharge calculated from the positive water balance assuming an apparent Sy of 39%.

If the Forest was intercepting rainfall then recharge should be less under the Forest than the Warren; however this is not the case. Only wells 14 -17 (162 mm) have less recharge than the CCW wells (215 mm). Recharge is generally greater in the Forest (254 mm) than under the Warren. This could be due to some areas of the Forest receiving more recharge from the rock ridge than the Warren.

On average all of the CCW wells, wells 14-17, and 11, 12 and 19 received less recharge than the water balance indicating that these wells are not receiving runoff or are affected by interception, while the forest wells, wells 1-6, wells 7 and 9 had more recharge indicating that these wells are receiving recharge.

Wells 1-6 are up on the rock ridge and could be receiving recharge from surface drainage from adjacent farm land, while wells 7 and 9 are below the rock ridge could be receiving drainage from there. Wells 11, 12, and 19 are situated similarly to the CCW wells and seem to receive the same amount of recharge.

The Forest wells, compared to the CCW wells, receive 40 mm more recharge than the CCW wells. The CCW wells received on average 30 mm less recharge than the water balance and the Forest wells 10 mm more.

The recharge for the Forest wells and the CCW wells was plotted and regressed against the positive water balance (Figure 34). The Forest wells show a decreasing response to the positive water balance compared to the CCW wells. The regression intercepts indicate that the Forest is receiving more recharge while the CCW wells seem to be loosing recharge.

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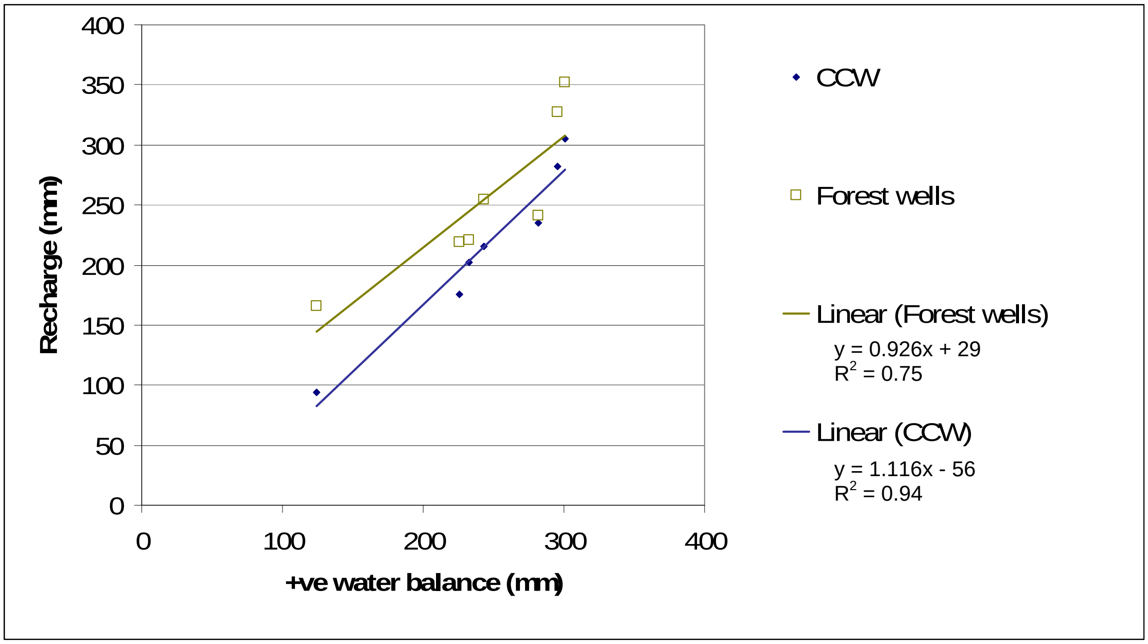

Figure 34: Forest and CCW well recharge regressed against the positive water balance

4.4.2.2. Discharge

Discharge was calculated using an apparent Sy of 39%, the negative water balance and the water level falls (Table 27 and Figure 35).

Table 27: Discharge calculated from the negative water balance assuming and apparent Sy of 39%

	1989 - 1990	1990 - 1991	1991 - 1992	1992 - 1993	1993 - 1994	1994 - 1995	Average
Wells 1- 6	294	290	254	203	213	350	267
Wells 7+9	345	285	289	236	152	415	287
Wells 14-17	167	134	117	159	109	183	145
Wells 11,12,19	242	169	184	158	124	306	197
CCW	273	202	195	144	137	269	203
Forest wells	245	231	213	186	151	331	226
Negative water balance	261	234	223	102	177	214	202

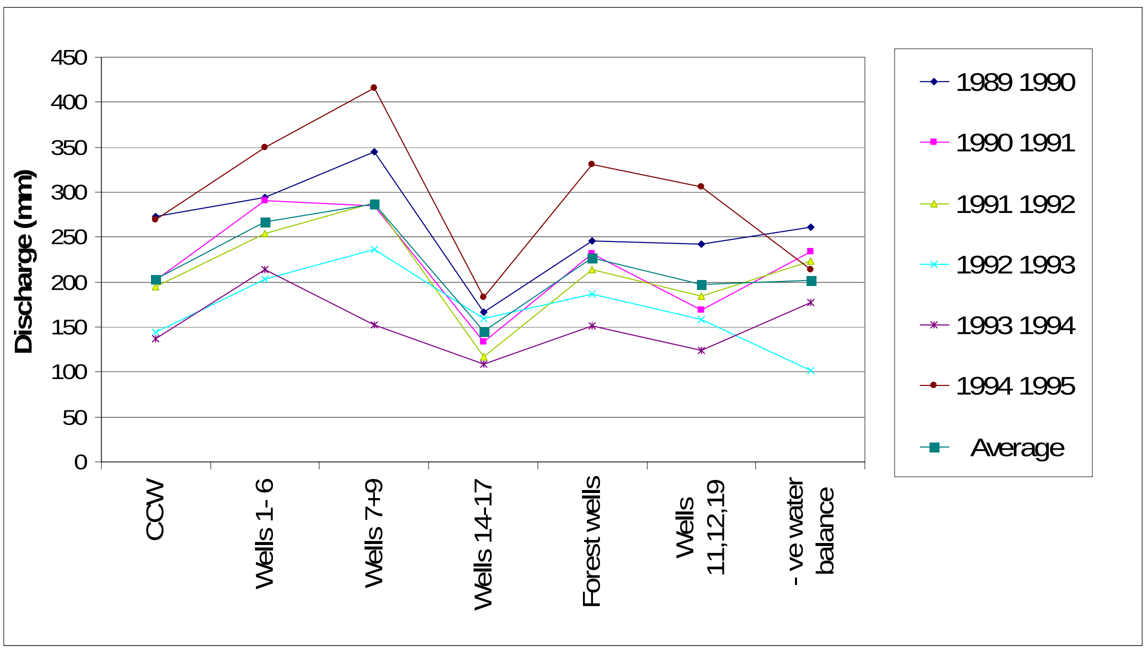

Figure 35: Discharge assuming an apparent Sy of 39%

Wells 14-17 had the lowest amount of discharge (145 mm) and the narrowest range of discharge values indicating that recharge here was largely independent of the negative water balance. Wells 7 and 9 had the greatest amount of discharge (287 mm) and the greatest range of discharge. Wells 1-6 (267 mm) had a similar range of response to wells 11, 12 and 19 (197 mm). Wells 11, 12 and 19 also had a similar average annual response to the CCW wells (203 mm) except in 1994 – 1995 which was in turn similar to the negative water balance (202 mm). The Forest well discharge (226 mm) was on average 20 mm greater than the CCW wells and the negative water balance.

If the Forest was intercepting rainfall then discharge should be less under the Forest especially in dry years than the Warren because of decreased interception in the Forest. Discharge however might also be expected to be greater as a result of increased evapotranspiration by the Forest especially during dry years. There does seem to be increased discharge in the Forest wells as the years become wetter.

4.4.2.3. Relative proportion of Recharge to Discharge

The relative proportion of recharge to the positive water balance and the relative proportion of discharge to the negative water balance was calculated. This produced identical results to the comparison of the water table rise to water table fall.

The recharge and discharge was expressed as a proportion of the respective positive or negative water balance (Table 29 and Figure 37)

Table 29: Recharge and discharge was expressed as a proportion of the respective positive or negative water balance

	Recharge / positive water balance	Discharge / negative water balance	Recharge/ Discharge
Wells 1- 6	1.21	1.32	1.11
Wells 7+9	1.31	1.42	1.11
Wells 14-17	0.67	0.72	1.12
Wells 11,12,19	0.92	0.98	1.13
CCW	0.88	1.01	1.06
Forest wells	1.04	1.12	1.12

Recharge in the CCW wells was 88% of the positive water balance, while discharge was 101% of the negative water balance, while for the Forest wells recharge was 105% of the positive water balance and discharge 1.12% of the negative water balance. Wells 11, 12 and 19 were the most similar set of Forest wells to the CCW wells.

The proportion of recharge to discharge was similar for all groupings of Forest wells at 112%, while for the CCW wells it was only 106 %. The Forest would therefore seem to be retaining a greater proportion of recharge than the Warren area.

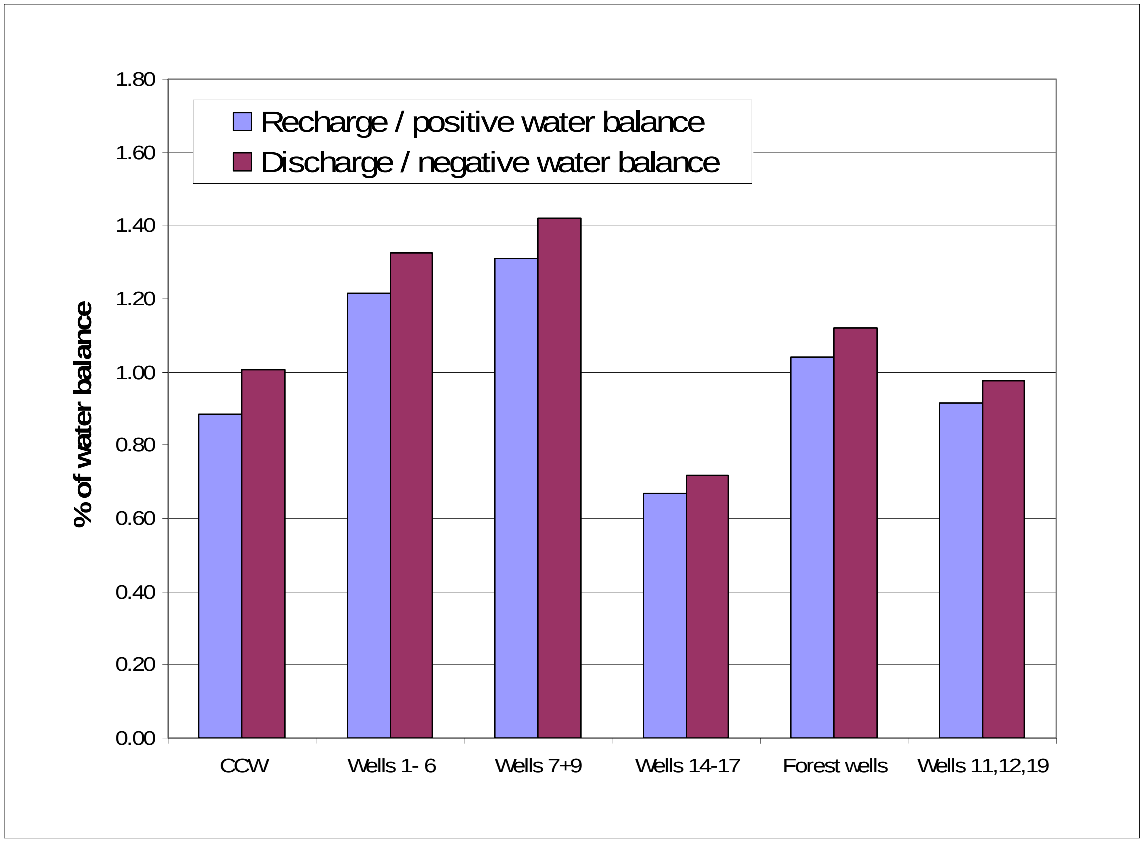

Figure 37: Recharge and discharge was expressed as a proportion of the respective positive or negative water balance

Discharge is greater than recharge for all groupings of wells. The Forest wells generally have a similar difference between recharge and discharge than the CCW wells. Wells 14 - 17 had the lowest proportion of discharge and recharge compared to the water balance. Wells 1 - 6 and wells 7 and 9 received and discharged far more water than indicated by the water balance. Wells 11, 12, and 19 received a similar proportion of discharge and recharge to the CCW wells. The Forested wells had about 10% more recharge and discharge compared to the CCW wells.

4.5. Discussion of the forest well record analysis

The water level records can be interpreted in two distinct ways using the water level method, either as differences in the apparent Sy or the amount of recharge and discharge.

No matter which interpretation is used the groups of wells can be split up by their similar properties:

- Wells 1-6 and Wells 7 and 9 have a low apparent Sy (28%) or receive and discharge a large amount of water (275 mm).
- The CCW wells, the Forest wells and wells 11, 12 and 19 have a medium apparent Sy (40%) or receive and discharge a modest amount of water (200-226 mm).
- Wells 14 -17 which have a high apparent Sy (55%) or receive and discharge a small amount of water (145mm)

Concentrating on the average differences between the CCW wells and the Forest wells,

- Water level fluctuations
    - The average water levels in the Forest were greater than the CCW wells except prior to October 1991.
    - The Forest water levels rose 100mm more than the CCW wells in response to a positive water balance and fell 60mm more than the CCW wells in response to a negative water balance.
    - The relative proportion of water level rise to water level fall was 1.06 in the CCW wells and 1.12 in the Forest wells, while the positive / negative water balance ratio was 1.21.
    - The Warren would appear to suffer from decreased recharge compared to the Forest, or the Forest was hindering discharge compared to the Warren.

- Assuming that differences in water level response to the water balance is due to differences in the apparent Sy
    - The apparent recharge Sy in the CCW wells was 44% while for the Forest in was 37%.
    - The apparent discharge Sy in the CCW wells was 39% while for the Forest was 35%. The discharge Sy was 84% of recharge in the CCW wells and 94% in the Forest.
    - The difference in apparent recharge and discharge Sy of the Forest wells was less than the CCW wells, as a result the Warren discharged less water than the Forest. The Warren had a greater apparent Sy.

- Assuming an apparent Sy of 39 %
    - The calculated recharge that the Forest wells are receiving is 254 mm and 215 mm in the CCW wells.
    - Both the CCW wells received less recharge than indicated by the positive water balance for the period (243 mm) and the forest slightly more.
    - The CCW wells are receiving 88% of the positive water balance and the Forest wells 104%

- The calculated discharge in the Forest wells is 226 mm and the 203 mm in the CCW wells.
- The CCW wells are loosing a similar amount of water through discharge and evapotranspiration to that indicated by the water balance (202 mm), but the forest wells only lose 112 % of the water balance.
- The Warren is receiving and discharging less water than the Forest.

The 3 main findings are:

- **The Warren water levels were lower and dampened compared to the Forest.**

  This is contrary to what would be expected if interception was a major process affecting the Forest. Recharge under the forest should be hindered by interception, leading to lower water levels. This could however indicate that the Forest is receiving recharge from the rock ridge or that the water levels of the Warren are affected by drainage upon the rock ridge or at Pen Lon.

  This apparent difference could be due to differences in the aquifers under the Warren and Forest and if this is the case then any conclusions should be based on the analysis of the apparent Sy. If not the case then conclusions should be based on differences in recharge and discharge calculated using a constant apparent Sy for all wells.

- **From assuming that differences are due to differences in aquifer properties; the difference in apparent recharge and discharge Sy of the Forest wells, was less than the CCW wells. As a result the Warren discharged less water than the Forest. The apparent Sy was greater in the Warren.**

  It would appear that there is less storage under the Forest than in the Warren. Thinking in terms of interception losses caused by forest vegetation, if interception occurred then the water table would not respond to rainfall as much, and neither would it to evapotranspiration at times, as the intercepted water would have to evaporate. The effects of interception would be more noticeable in summer, as in winter, interception loss would be a small part of rainfall, and evapotranspiration losses are low.

  It would be expected that the response to a positive water balance would be less under the Forest than in the Warren, leading to a greater recharge apparent Sy in the Forest. This is not the case.

  It could also be argued that the response to a negative water balance would be greater under Forest due to greater evaporation leading to a smaller apparent Sy in the Forest. This is the case; however you would also expect a greater difference in the apparent recharge and discharge Sy, as discharge Sy decreases under increased evapotranspiration, which is not the case. The CCW wells have the greatest difference in apparent recharge and discharge Sy.

There would appear to be little evidence for increased interception and evaporation from assuming that the differences in water level response to the water balance was due to differences in the properties in the aquifer. Certainly other processes must be taking place which are masking the interception and increased evaporation effects of the Forest.

The apparent Sy from recharge is greater for all sets of wells. This demonstrates that more water is required to make the water table rise than fall.

- **From assuming that there is no difference in aquifer properties: that the Warren is receiving and discharging less water than the Forest, and that the Forest wells always have a greater recharge/ discharge ratio than the CCW wells, only this difference in recharge/ discharge ratios diminishes in years with heavy rainfall.**

  If the Forest is having an effect then it would seem to be the opposite of that expected. The Forest appears to be enhancing recharge and reducing discharge. There seems to be little evidence of an interception effect, the Forest seems to be able to reduce evaporative losses in comparison with the Warren.

  If the Forest was intercepting rainfall then recharge should be less in the Forest than in the Warren especially in dry years because of increased interception in the Forest. This is not the case.

  Discharge might also be expected to be greater as a result of increased evapotranspiration by the Forest. This seems to be the case as discharge in the Forest wells increases as the years become wetter.

  If the Forest was receiving more water from the rock ridge than the Warren this could mask the effects of interception and evaporation loss. Other wise the general effect of the Forest appears to be to mitigate the extremes of the water balance.

  The Forest wells, although similar to the CCW wells, receive 35mm more recharge than the CCW wells. The CCW wells received on average 45 mm less recharge than the water balance and the Forest wells 15 mm less.

The analysis of water levels records from within the Forest and Warren do not show an appreciably large difference in the behaviour of the two systems as a result of tree cover. This is contrary to other Forestry research which indicates that trees intercept more water than other types of vegetation (Hudson et al., 1997).

The CCW wells are predominantly located within the Warren or on the edge of the Forest; all are in the southern spit system. All the Forest wells are located within the Forest or small clearings within it. All wells except wells 7 -8 are located in the northern spit system.

Differences in the response of the water table to the water balance can be attributed either to differences in the northern and southern spit systems or the influence of the Forest. It is reasonable to assume that the sand that makes up the aquifer in both spit systems has the same properties. What may differ is the depth of sand over the underlying bedrock which would have the effect of reducing the apparent Sy.

In wells 1-6 up on the rock ridge and wells 7 and 9 this is probably the case. The CCW wells within the Forest may also have hard rock close to the base of the wells. Wells 11, 12 and 19 and wells 14-17 and the CCW wells within the Warren are likely to have a considerable depth of sand beneath them.

It could be argued that as there were 12 CCW wells, comparison with sets of Forest wells that contain less than 12 wells is not a true comparison. Also it could be said that as 5 of the 12 CCW wells are in the Forest, the CCW well record is not a true reflection of the Warren and the differences between the Forest and CCW wells is only about half of what it should be. If the Forest wells behaved like wells 7 and 9, then this would increase the observed differences between the Forest and Warren which can not be explained by increased interception and evapotranspiration in the Forest.

As wells 14 -17 appear to have their water levels dampened by the influence of the sea, perhaps these wells are not representative of the Forest and should not be included in calculating the average for all the Forest wells. If this was the case then the Forest wells would behave again like wells 7 – 9, and again this would increase the observed differences between the Forest and Warren which cannot be explained by increased interception and evapotranspiration in the Forest.

It could be argued that only wells 11, 12 and 19 are truly representative of Forested fixed dune slack and should be the only group of records to compare against the CCW wells, as both these groups of wells are some distance from the rock ridge and located on a deep sand aquifer. If this is the case then both sets of wells would have similar apparent Sy and estimated recharge and discharge, only wells 11, 12 and 19 receive and discharge a slightly greater amount of water. Again there is no evidence of loss of recharge due to interception or increased evapotranspiration as a result of afforestation.

Differences in the behaviour of the Forest and Warren could be more easily explained by the presence of the rock ridge and drainage from there than by greater interception and evapotranspiration loss. There are indications that the Warren and adjacent areas to the rock ridge are receiving water draining from the Forested rock ridge.

5. Conclusions

- Water levels within the Forest are generally greater than in the Warren and fluctuate more.

- There is little evidence that water levels under the Forest are suffering from the effects of increased interception and evaporation compared to the Warren. The effects of interception and evaporation appear to be masked by greater recharge received by the Forest from the rock ridge. There are indications that drainage at Penlon and in fields draining to the Warren are reducing the amount of recharge received.

- The response of the water table to the water balance depends upon the height of the water table. A greater response occurs when the water table is high, and a lesser response occurs when the water table is low, and is probably due to storage effects of the perched aquifers on the Precambrian ridge and runoff from the ridge, as well as interception storage, and varying groundwater seepage from the aquifer.

- The specific yield for the sands of Newborough Warren are in the range of 28-34%, but the apparent Sy estimates are greater than this, estimated as 39 - 42.5% when calculated by matching water table fall and rise to the positive and negative water balance.

- The water balance over the period over which the CCW research data was collected was not representative of the long-term water balance. The period June 1989 – May 1996 was unusual in that it did not have rainfall over 150mm.

- The Betson and Scholefield (2004) PEt and I, AEt and I, and net recharge estimates for the different vegetation types are incorrect as the Betson and Scholefield (2004) average monthly estimate for forest AEt and I is appropriate for modelling the water balance for the area monitored by the CCW dipwells, which is a mixture of forest and fixed dune vegetation types.

- It was wetter during the 1950's and 60's when the Forest was planted and fixed dune slack vegetation became established. The 1970's, 80's and 90's were drier as the Forest established, therefore the effects of increased interception and evaporation as a result of the forest vegetation would also have been exacerbated by the drier water balance over the same period. Since 2000 it has become wetter and winter flooding is now a common occurrence and this also coincides with decreased Forest AEt + I caused by the maturing Forest.

6. Recomendations

Long term monitoring of the water levels in Newborough needs to be established so that the changes due to maturing vegetation, clear felling and thinning of the Forest and any changes in the surface drainage can be assessed. New boreholes should be placed in the Forest to replace those lost during felling operations.

Research should be conducted to assess aquifer properties, the relative influence of recharge and and drainage, and interception of the Forest.

- Slug tests should be conducted on individual wells to determine the true Sy of the sands of Newborough exist for the same period.

- Rain gauges should be installed in the Forest and Warren to assess the effects of interception. Evaporation estimates need to be refined.

- Chemical analyses are conducted on groundwater samples to assess the amount and sources of recharge and drainage.

Further work using the above approaches should be carried out using AEt and I estimates based on monthly meteorological data instead of monthly averages. This may improve the modelling of falling water tables.

The individual well data that comprises the average CCW water level, needs to be obtained so that a comparison of wells within and outside of the Forest can be conducted. This may also highlight areas of the aquifer which may be behaving differently because of differing aquifer conditions.

A new MODFLOW model of the Forest and Warren should be created that utilizes the water level records of both CCW and FC. This model should also include the possibilities of fractured flow within the rock ridge, the presence of perched aquifers on the rock ridge and decreasing hydraulic conductivity of the aquifer resulting from gravel deposits on the foreshore and clay deposits with in the Malltraeth estuary and the Menai straits.

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Appendix 1: Analysis of rainfall data

The nearest UK meteorological station to Newborough is RAF valley, which is on the same coast line but 13 miles north. Records are available from September 1941. A Dallas semiconductors weather station with a 0.25 tipping bucket raingauge was installed in Newborough village in July 2000 by the author. Comparison of the Newborough and RAF Valley rainfall records shows that rainfall at Newborough is 20% higher.

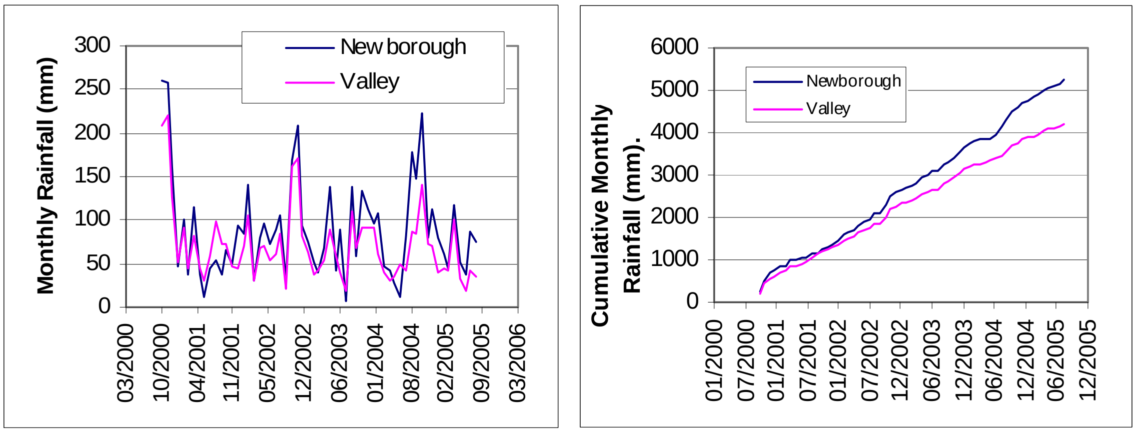


Figure A1.1: Monthly rainfall and cumulative monthly rainfall for Newborough and RAF Valley

As the water balance is being calculated using monthly average evaporation, and rainfall records, rainfall is therefore the major determinant and deserves closer examination.

Examination of Rainfall: periods June 1989 - May 1996 rainfall and June 1942 -May 2005.

The September 1941- October 2005 monthly rainfall record (Figure A1.2) shows that during June 1989 –May 1996 there was no monthly rainfall greater than 138 mm, while for the rest of the monthly rainfall record there were 48 months (6% of total record) with rainfall greater than this. The monthly average rainfall has marginally decreased over the time period by 0.003 mm/month, equivalent to 2.27mm over September 1941- October 2005.

It can also be seen that the period June 1989- May 1996 was the longest period without monthly rainfall greater than 150 mm

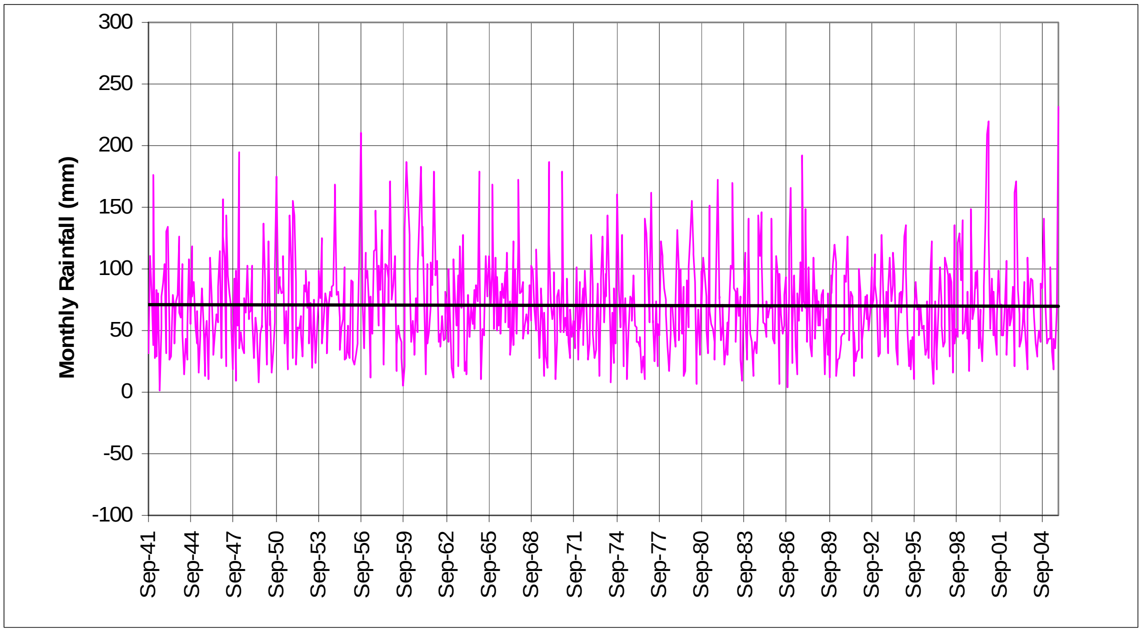


Figure A1.2: Monthly rainfall for RAF Valley: September 1941- October 2005

Probability plots of rainfall exceedence for RAF Valley for the whole of Sept 1941 – Aug 2005 and June 1989 – May 1996 shows that rainfall for June 1989 – May 1996 was markedly lower for the 0 - 30% exceedence probability.

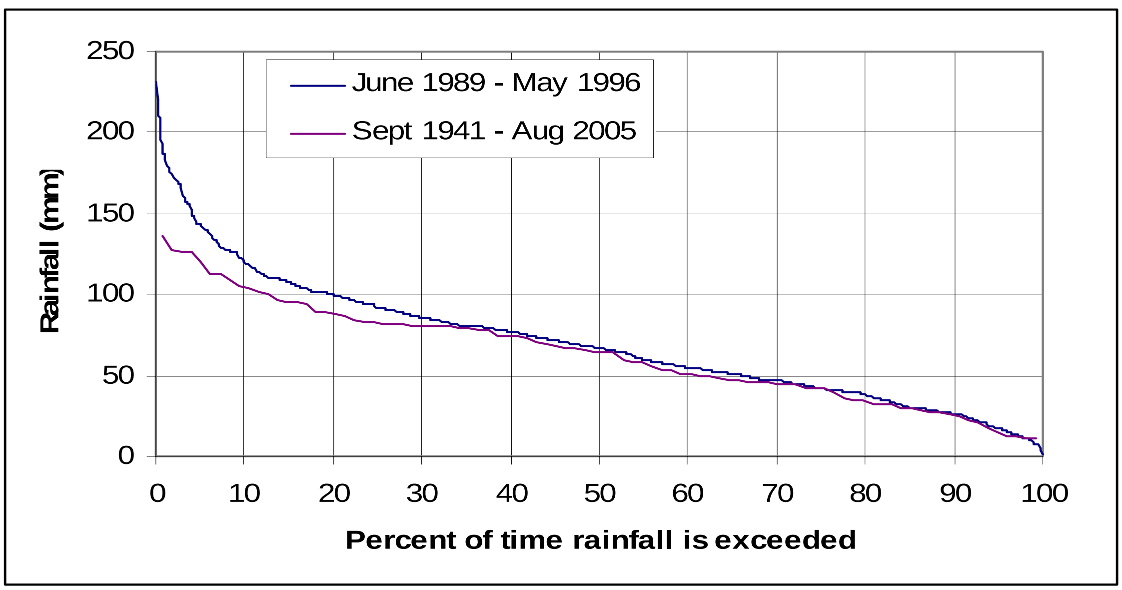


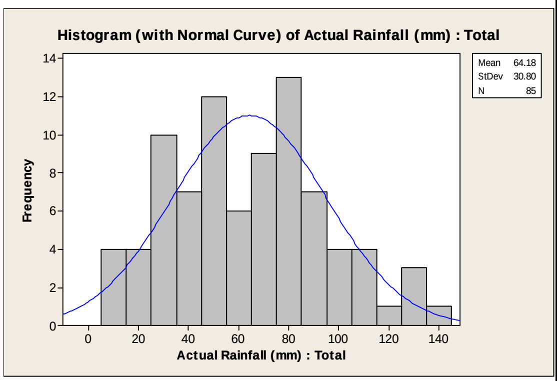
Figure A1.3: Rainfall exceedence graph for rainfall at RAF Valley

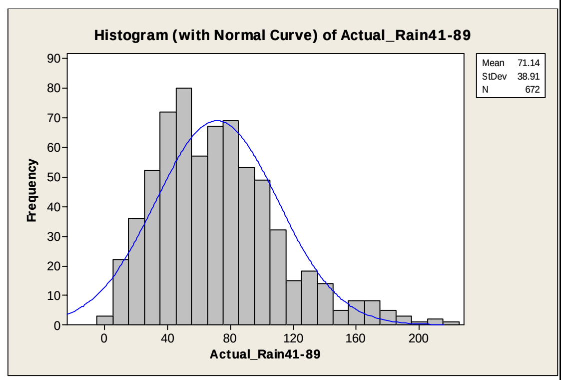
As a clear difference can be seen in figure 8 between the June 1989-May 1996 monthly rainfall and the monthly rainfall for June 1942 -May 2005 further detailed statistical analysis was conducted. The June 1989 - May 1996 rainfall was removed from the June 1942 -May 2005 rainfall series. Descriptive statistics of both rainfall series were produced, a Levene's Test was used to test whether the standard deviations were statistically different and a Mann Whitney U test assuming unequal variance was conducted.

Descriptive statistics for Rainfall

	n	Mean	SE Mean	St Dev	Skewness	Kurtosis
June 1989 - May 1996	85	64.18	3.34	30.80	0.26	-0.67
June 1942 – May 2005	672	71.14	1.50	38.91	0.82	0.73

	Minimum	Q1	Median	Q3	Maximum	Range
June 1989 - May 1996	11.10	41.75	64.80	83.85	135.80	124.70
June 1942 – May 2005	1.00	42.13	67.25	93.90	220.00	219.00





Examining the histograms and statistics for both data sets the median, the first quartile are similar, while the standard deviation, mean, minimum and third quartile are lower for the June 1989 - May 1996 rainfall by about 10mm than for the June 1942 -June 2005 rainfall. The histograms and the skew and kurtosis indicate that both datasets are non normal.

There is a difference in the means, medians, minima, third quartile, and standard deviations of both datasets, however the biggest difference is in the maximum values.

June 1989 - May 1996 rainfall mean (64.2 mm) is slightly lower than the June 1942 - June 2005 rainfall mean (71.1 mm) and the maximum rainfall for June 1989 - May 1996 (135.8 mm) rainfall is a lot lower than the June 1942 -June 2005 (220mm) mean. To see if this was significant a Mann Whitney U test was conducted.

Mann-Whitney Test for June 1989 - May 1996 rainfall and June 1942 -June 2005

To see if there was a significant difference between in rainfall between June 1989 - May 1996 and June 1942 -June 2005. A Mann Whitney U test was conducted.

Mann-Whitney Test for June 1989 - May 1996 rainfall and June 1942 -May 2005

	N	Mean	StDev	SE Mean
June 1989-May 1996	85	64.2	30.8	3.3
June 1942-June 2005	672	71.1	38.9	1.5

Difference = (June 1989-May 1996) – (June 1942-June 2005) is 4.50
Estimate for difference: -6.95979
W = 256863.0

Test of (June 1989-May 1996) = (June 1942-June 2005) vs (June 1989-May 1996) not = (June 1942-May 2005) is significant at 0.2523

The test is significant at 0.2523 (adjusted for ties)

The test is significant at 75% probability level but not at the 90% level. The difference between the median estimate of rainfall in both data sets are significantly different.

Levene's test

The Levene's test statistic was 2.91, which has a p-value of 8% showing that the standard deviations are different at the 90% confidence interval but not the 95% and therefore they are only marginally different.

Appendix 2: Examination of the AEt and I estimates

To test the robustness of the forest actual evapotranspiration and interception estimates a number of coefficients ranging from 0.995 to 1.05 were used to modify the evapotranspiration used in the water balance and the regression coefficients recorded.

Table A2.1: Table of coefficients used to modify the forest AEt and their associated coefficients of determination

Et coefficient	Coefficient of determination (r^2)	Correlation Coefficient
1.01	81.40	90.22
1.001	84.52	91.93
1	84.65	92.00
0.998	84.77	92.07
0.9975	84.78	92.08
0.997	84.77	92.07
0.995	84.63	92.00
0.95	55.29	74.36

The best coefficient is 0.9975, which is very close to 1. This implies that the actual evapotranspiration for forest vegetation and interception calculated by Beston and Scholefield (2004) is correct for the Warren as a whole. Unfortunately the whole of the Warren is not forested which implies that water loss from the Warren is greater than that calculated by Beston and Scholefield (2004).

As the Et coefficient of 0.9975 was very close to 1 and only marginally improved the correlation and determination coefficients, it was decided not to alter the Forest AEt and interception estimates. Undoubtedly a regression model with a better fit could be obtained by using the actual evapotranspiration and interception calculated using the SWAP model based on the meteorological records from RAF Valley and correcting these records using meteorological records from Newborough.

Appendix 3: Initial Model regression analysis

The average water levels recorded in the CCW wells were regressed against the previous months forest water balance.

```
The regression equation is
WL = 8003 + 1.90 Cumulative WB


81 cases used, 3 cases contain missing values


Predictor          Coef  SE Coef       T      P
Constant        8003.42    14.02  570.82  0.000
Cumulative WB   1.90138  0.09181   20.71  0.000


S = 82.0632   R-Sq = 84.4%   R-Sq(adj) = 84.2%


Analysis of Variance

Source          DF       SS       MS       F      P
Regression       1  2888232  2888232  428.88  0.000
Residual Error  79   532015     6734
Total           80  3420247


Unusual Observations

Obs  Cumulative WB       WL      Fit  SE Fit  Residual  St Resid
  9             36  8270.00  8072.63   16.70    197.37      2.46R
 44           -150  7900.00  7718.59    9.63    181.41      2.23R
 70            125  8400.00  8240.90   23.92    159.10      2.03RX
 71            120  8320.00  8232.34   23.54     87.66      1.12 X
 83            -80  7640.00  7851.50    9.70   -211.50     -2.60R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Durbin-Watson statistic = 0.568475


Predicted Values for New Observations

New
Obs      Fit  SE Fit        95% CI              95% PI
  1  7433.00   19.20  (7394.79, 7471.21)  (7265.25, 7600.75)
  2  7528.07   15.31  (7497.59, 7558.55)  (7361.91, 7694.23)
  3  7623.14   11.94  (7599.37, 7646.91)  (7458.08, 7788.20)
  4  7718.21    9.64  (7699.03, 7737.39)  (7553.74, 7882.67)
  5  7813.28    9.24  (7794.89, 7831.66)  (7648.90, 7977.65)
  6  7908.35   10.95  (7886.55, 7930.14)  (7743.56, 8073.14)
  7  8003.42   14.02  (7975.51, 8031.32)  (7837.71, 8169.13)
  8  8098.48   17.76  (8063.13, 8133.84)  (7931.36, 8265.61)
  9  8193.55   21.83  (8150.11, 8237.00)  (8024.53, 8362.58)
 10  8288.62   26.07  (8236.73, 8340.51)  (8117.24, 8460.01)X
```

```
X denotes a point that is an outlier in the predictors.


Values of Predictors for New Observations

New
Obs  Cumulative WB
  1           -300
  2           -250
  3           -200
  4           -150
  5           -100
  6            -50
  7              0
  8             50
  9            100
 10            150
```