Modelling groundwater flow at the RSPB wetland reserve, Malltraeth Marsh, Anglesey.

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ABSTRACT

The Royal Society for the Protection of Birds (RSPB) has made Malltraeth Marsh a new RSPB reserve of 3.5 km^2 for breeding bitterns with water level control structures and new reedbeds being planted. An initial hydrological study for the establishment of a wetland identified groundwater loss as a possible area for concern.

The study area, on part of the former estuary of the River Cefni lies at less than 3m above msl between the canalised Cefni and the Berw fault scarp. The climate is temperate maritime with a mean annual rainfall of 960mm and Et of 630mm. Groundwater recharge in the marsh sediments is mainly from direct rainfall.

Geophysical methods and shallow boreholes were used to establish a near surface hydrogeological model. This model and monitored water levels were then used as input to MODFLOW to simulate water balance between recharge, Et and possible groundwater outflow from the reserve. Previous models proved to be unrealistic because of over-complex layering, inappropriate boundary conditions and a shallow surface layer.

Recent work has extended the network to 30 dipwells in order to apply MODFLOW to groundwater conditions throughout the site during the summer of 1999 with a simplified 3-layer ground model. A model period was chosen to simulate the water table response to periods of both high Et and recharge by rainfall. Seepage loss to a major drainage ditch was estimated and rapid water table decline monitored locally over 24 hour periods suggested some seepage loss through buried channels. Model simulation of palaeo-channels has not been attempted to date. However residuals between observed and computed heads gave an indication of seepage loss which is small by comparison with the major components (rainfall and Et) of water balance for the reserve, but significant where the maintenance of surface water levels is critical for the survival of the wetland habitat.

RESUME

La Societé Royale pour la Protection des Oiseaux (RSPB) a fait le marais de Malltraeth (Malltraeth Marsh) une nouvelle réserve de la RSPB, destinée à la reproduction des butors, contenant des structures de régulation du niveau de l’eau et dans laquelle des nouveaux lits de roseaux sont plantés. Une étude hydrologique initiale sur la possibilité de créer un marais a identifié la perte d’eau souterraine comme une possible zone de problème.

La zone d’étude, une partie de l’ancien estuaire de la rivière Cefni, se situe à moins de 3 mètres au dessus du niveau de la mer, entre la rivière Cefni qui a été canalisée et l’escarpement de la faille de Berw. Le climat est maritime-tempéré, avec une moyenne de précipitations annuelles de 960 mm et une évapo-transpiration de 630 mm. La recharge de l’eau souterraine est principalement due aux précipitations directes.

Des méthodes géophysiques, ainsi que l’utilisation de trous de sondage peu profonds ont été utilisées pour déterminer un modèle hydrogéologique proche de la surface. Toutes les données ont été entrées dans le programme MODFLOW pour simuler l’équilibre entre la recharge, l’évapo-transpiration et l’écoulement d’eau souterraine vers l’extérieur de la réserve. Des modèles antérieurs se sont révélés irréalistes à cause d’une disposition trés complexe des sédiments, des conditions de limite inappropriées et une surface peu profonde.

Des travaux récents ont étendu le réseau à 30 trous d’observation pour pouvoir appliquer MODFLOW à l’eau souterraine à travers le site, durant l’été 1999, avec un modèle simplifié à 3 strates du sol.

Une période a été choisie pur le modèle, de façon à simuler la réponse du niveau hydrostatique à des périodes d’évapo-transpiration intense, ainsi qu’à la recharge par la pluie. Les pertes par infiltration vers un fossé d’écoulement principal ont été évaluées et le declin rapide du niveau hydrostatique, surveillé locallement sur des périodes de 24 heures, suggère une perte par infiltration à travers des canaux enterrés. Aucune simulation de ces paleo-canaux n’a été tentée à ce jour. Cependant la comparaison entre les niveaux observés et ceux prévus par le modèle donnent une idée de la quantité d’eau perdue par infiltration. Celle-ci est peu importante, comparée aux autres composants (precipitations et evapo-transpiration), mais tout de même importante aux endroits où le maintien d’un niveau d’eau de surface est primordial pour la survie de l’habitat du marais.

Introduction

1.1 The RSPB Reserve and its water needs

Reedbeds are a nationally threatened habitat, highly valued for their conservation interest in Europe. Many rare plants and animals rely on common reed, *Phragmites australis,* including the bittern, *Botaurus stellaris* which is of greatest concern. It ceased breeding in this country in the late 19th century but returned to breed in Norfolk in 1911, subsequently expanding to 80 booming (breeding) males by the 1950s. Today, however, there are fewer than 20 booming males in the whole of Great Britain. The Royal Society for the Protection of Birds (RSPB) has identified the creation of suitable new reedbeds as a key strategy for saving the bittern. Anglesey was chosen as one of the core areas because there were thought to be up to 11 booming birds on the island in the 1970s, breeding took place until 1984 and bitterns are still attracted to the area during winter.

The 154 hectare site at Malltraeth Marsh, acquired in 1984, was chosen for a number of reasons. First, some reed already existed there, secondly bitterns have been known here in the past and thirdly the presence of clay soils on a low lying site was thought to provide suitable conditions. Reed grows in flooded areas with up to two metres depth of water. For successful development of a new reedbed, control of water levels is crucial as low water levels encourage the growth of other more vigorous competitive plant species in place of reed.

A topographical survey of the reserve revealed that by raising surface water levels to 2.0m AOD, more than 60% of the land would be suitable for growing reed. This has been achieved by the installation of water retaining banks and associated sluices, together with pumping from the surrounding drainage ditch system during periods of low rainfall and high evapotranspiration.

There has also been concern about possible groundwater outflow, particularly during the dry summer months and it has been the primary aim of the present study to try to locate any old channels of the former estuary and to quantify possible losses through them and the surface drainage network. Water balance in the former estuary, (including possible groundwater movement to or from the underlying solid geology) is also important in estimating pumping requirements and costs which are likely to be a significant part of the site running costs. To date this aspect has not been assessed adequately because of lack of data and difficulty of access to the underlying strata.

Identifying those areas of minimal water loss can assist in targeting the best areas for reedbed creation and extension. Quantification of water loss to the drainage network allows a cost benefit analysis of engineering measures to reduce this. Ultimately, a model that accurately simulates water flux to and from the site could provide estimates of likely water requirements in drought years.

1.2 Previous Studies

The possibility of using numerical modelling to evaluate wetland hydrological processes has been investigated through a number of studies. Bradley (1996) successfully simulated water table flux though organic deposits at a floodplain wetland in the British Midlands. By varying river stage in the model, the vulnerability of the wetland to external hydrological changes was evaluated.

A study by Gilvear et al (1993) of Bradley Moor Fen in East Anglia utilised a steady state three-dimensional model to demonstrate that nearby major abstractions would have a significant impact on the survival of the site. Gerla and Matheney (1996) also used MODFLOW to evaluate the potential impact of long term climatic variability in the prairie pothole region of the United States.

2. Study Area

2.1 Background

Malltraeth Marsh covers an area of approximately 1600 ha, situated on the floodplain of the Afon Cefni in south-west Anglesey, North Wales. The topography of Anglesey is generally low lying, with Malltraeth Marsh forming one of the lowest points on the island (Williams, 1997). A topographic survey of the site revealed that the surface elevation ranges between 1.25 and 3.5m AOD.

Prior to anthropogenic influences the area now occupied by the marsh was estuarine, with high spring tides reaching to within three miles of Red Wharf Bay on the north coast of the island. The nine miles of inlet were partially reclaimed in 1790, when an earth bund (“The Cob”) was built across the lower valley. Six miles of land were subsequently reclaimed and used predominantly for pasture due to the high salt content and sandy nature of the soils. Around this time the course of the Afon Cefni was also altered, abandoning the former meandering path to create a straight course to the south-east of the original (Baker, 1984). Land drainage was achieved through construction of two main drains, which are connected to the Cefni by tidal flaps, and to the sea by tidal gates in the cob. Lateral drainage across the marsh was facilitated through a series of minor drains (Bentley, 1997). Of the marsh reserve, 1248 ha is protected as an SSSI because of the numbers of rare and endangered species found here. The RSPB site lies within this SSSI.

2.2 Geology

The oldest rocks in the Malltraeth Marsh and sands area are micaschists of the Mona complex. These lie to the south east of the Berw Fault, which forms one edge of the depression containing the Marsh. Lying against this fault and underlying the floor of the marsh are limestones, grits, redbeds and Coal Measures of the Carboniferous. These rest unconformably on green schists and some minor tuffs of the Mona complex. The solid geology is overlain by variable thicknesses of estuarine and marine alluvium. Figure 1 shows a sketch section across the valley. The marsh was the site of coal mining from the Coal Measures beneath Alluvium from the 1850s until the early part of the 20th century and some old workings and shafts remain, within the reserve. Access to these is unsafe and hence groundwater movement through the carboniferous strata is unknown. Knowledge of the solid geology is provided in the classic account of the geology of Anglesey by Greenly (1918)

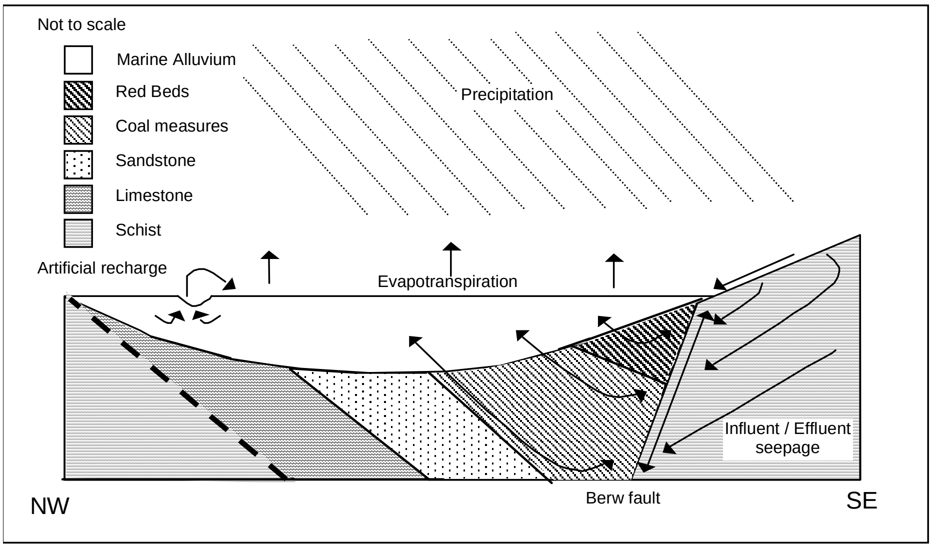

Figure 1 Conceptual Model of Malltraeth Marsh

2.3 Hydrology

Rainfall is the major source of recharge to the site, and Et the greatest sink. Inflow from the surrounding slopes and regional groundwater and outflow through the surface drainage network may also be of local significance. Mean annual rainfall is 949mm as recorded at the nearby RAF Valley weather station. (Williams, 1997)

2.4 Previous Work at Malltraeth

Dipwell and geophysical investigations have been carried out previously at Malltraeth by Williams (1997), Gloth (1997), Bentley (1997) and Kavanagh (1997), the work gradually being extended in successive years of MSc projects. The first work concentrated on the four fields (41.01 to 41.04) between the Cefni and the No. 10 drain on the NW side of the reserve (Fig.2). A combination of EM31, resistivity soundings and dipwell logs allowed a three dimensional ground model to be developed, while monitoring of water levels in the dip wells allowed a simple flownet to be drawn which indicated groundwater movement in a north-easterly direction into fields 34.11 and 34.17.Subsequent work extended the coverage north-eastwards and the geophysics suggested a possible palaeochannel, indicated by the low conductivity feature running in a general ENE to WSW direction through the centre of the surveyed area (Fig. 2). This has minor tributary channels entering it from fields 41.03 and 41.04, which could account for the movement of groundwater from SW to NE towards the main palaeochannel.

3. Geophysical Investigation

The EM31 allows rapid surveillance of ground conductivity with an effective depth of penetration of about 6m. The technique therefore assisted in delineation of fluvial depositional features such as paleochannel networks and extensive clay lenses created during the historical tidal inundation and river migration across the valley.

The data collected during an extensive survey was contoured using minimum curvature as seen in Figure 2. This suggests that significant clay lenses underlie fields 41.03 and 40.02. Bands of low conductivity material in fields 41.01 and running between fields 34.11 and 34.12 were indicative of the coarse infill associated with paleochannels.

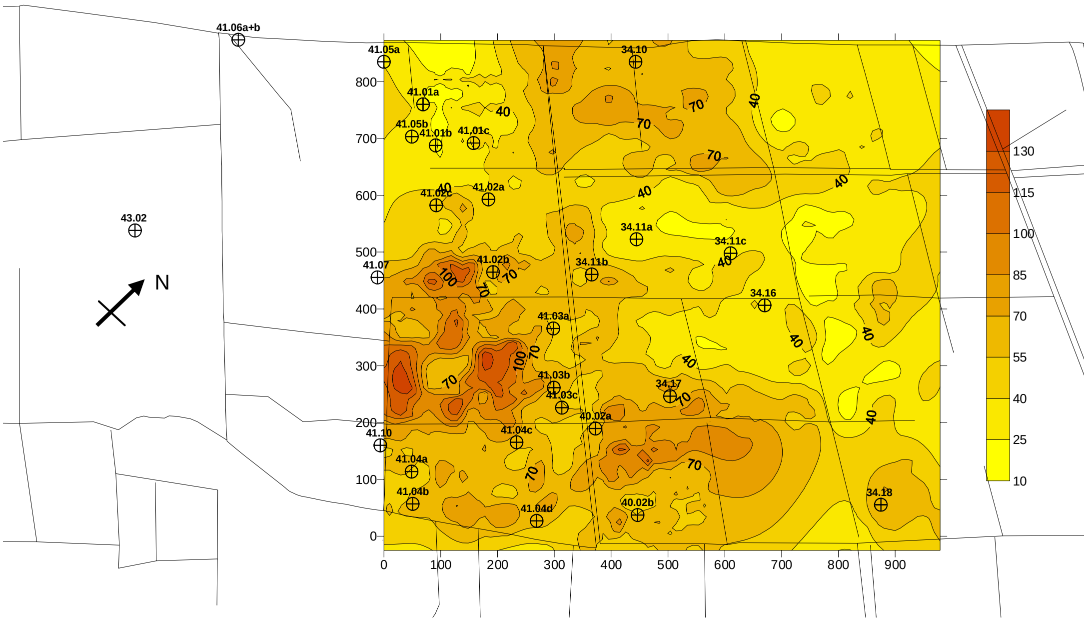

Figure 2. EM31 conductivity data & dipwell locations (with field boundaries & metric grid)

4. Borehole Investigation

29 dipwells with 0.045m dia. PVC casing were installed at the site using percussion driven corer. The majority of the wells were sunk to a depth of 3m, with an average of two undisturbed sediment samples collected from each core. The PVC pipes were installed, with 0.3mm slits and 0.063mm aperture fine mesh in the lower 2m. Two 0.15m diameter wells were also installed in fields 41.06 and 41.03 to a depth of 2m. This allowed continuous monitoring using 24-hour chart recorders. Dipwells were levelled relative to ordnance datum.

Borehole logs demonstrated that sediments within the upper 3m of the marsh are highly variable, due to the estuarine environment in which they were deposited. Beyond this sediment distributions are unknown. However evaluation of geophysical and geological information suggests that alluvial material extends to depths in excess of 10m. Particle size analysis (PSA) was undertaken for 66 samples taken from various depths in the boreholes. The Hazen Formula and Shepherd (1989) approximations were applied to the data to provide estimates of the hydraulic conductivity (K) for each sample. The Shepherd formula was deemed more reliable due to the poor sorting of the majority of samples. Calculated K values ranged from 0.001 to 150m/d.

5. Hydrological monitoring

Intermittent monitoring of water levels in the 29 small diameter dipwells was undertaken over a three-year period, generally on a weekly basis over the summer months when research projects on the marsh were scheduled. In order to evaluate the significance of groundwater flow between the marsh and the drainage ditches, a stilling well and 7-day chart recorder were installed in the Left Hand Main Drain (LHMD), adjacent to well 41.06c. Water levels in a number of other ditches around the site were monitored on a weekly basis. On-site meteorological data was generally limited to approximately weekly readings of precipitation. Additional data were available from the RAF Valley weather station, located 15 miles north-west of the site.

The 24-hour chart recorders were installed in wells 41.03d and 41.06c to record water table response and subsequent decline following a number of measured rainfall events. Data was limited by a 1:1 gearing ratio, which limited the maximum recordable head change to 0.3m. Consequently a total of three events were recorded at well 41.03d and one at the more responsive well 41.06c during the 6-week monitoring period.

Specific yield was estimated for boreholes 41.03d and 41.06c through analysis of water table response to known rainfall events. Calculations were made on the basis that Sy = Total recharge/Change in head. Values of 0.112, 0.041 and 0.083 were subsequently found for well 41.03d under rainfall events of varying sizes and intensities. Variations were attributed to differences between effective and actual rainfall, and varied seepage loss with changes in water levels. Specific yield at well 41.06c was found to be 0.074.

6. Numerical modelling

6.1 Defining model properties

A numerical model of the site was developed using the Groundwater Vistas (GWV) MODFLOW package. The primary aim was to simulate observed water table flux across the site over two given periods.

The varied stratigraphy of the site was simplified initially to a two layer homogeneous, isotropic model, with an average 3m thickness. Boundaries comprised a general head of 1.55m AOD on the north-east, south-east and south-west borders. The Afon Cefni, which defines the north-west boundary of the model, was represented using the river module, with the average of water level readings taken over the study period used as a fixed head (1.1m AOD). Riverbed permeability was assumed to be the mean of values determined during the falling head tests undertaken in 17 of the boreholes on the site.

Although the monitoring wells installed at the site only cover an area of approximately 0.75 km^2, the finite difference grid was set to include a 2.5km^2 section of the marsh. The margins of the model were associated with a high degree of uncertainty in terms of groundwater flux. The extended area therefore reduced the potential for prescribed boundary conditions to unduly influence model simulations in the area of interest. The surface drainage network was also included in the initial model, using the drain module and readings taken from the chart recorder and gaugeboards. Spot heights recorded during a topographic survey of the site were used to create a surface elevation model for layer 1.

The varied stratigraphy of the site was simplified initially to a three layer homogeneous, isotropic model, with an average 3m thickness. Evaluation of borehole logs suggested that finer materials dominate the upper profile, grading towards coarser sandy deposits at depth. Hydraulic conductivity in layers 1 and 2 was therefore defined as 0.12 and 2.13m/d respectively, based on the results of application of the Shepherd formula. Specific yield and porosity (P) were set as 0.12 and 0.29, and 0.5 and 0.46 for layers 1 and 2 respectively, based on empirical data and laboratory classification of the sediment samples. Layer 3 was essentially included to prevent water loss through the base of the model, thus K, Sy and P were defined as $3x10^{-6}$, 0 and 0 respectively.

6.2 Preliminary Calibration

An initial calibration was undertaken using weekly water levels recorded in 10 dipwells over a 40-day period. This was divided into stress periods, i.e. time intervals in which all external stresses are constant (McDonald and Harbaugh, 1988). The temporal resolution of rainfall data was the limiting factor in this, since this was available only as roughly weekly totals during this period. Each stress period was therefore approximately 7 days long. Initial heads recorded at the dipwells were contoured to provide a model water table at the start of the simulation. Potential daily Et was calculated using the Penman formula.

Artificial recharge is applied to the marsh as water pumped from the Left Hand Main Drain into a series of connected ponds and ditches, when water levels begin to fall below 2m AOD. Since MODFLOW excludes surface flow simulation, this input was applied as recharge to cells in the appropriate areas. This introduces some uncertainty to the model since the true redistribution of the recharge across the marsh from the point source is unknown.

An initial sensitivity analysis was then undertaken to determine the impact of changes in a number of model parameters on water level predictions. This demonstrated that layer 1 specific yield was the most sensitive parameter. Changes in layer 1 K in excess of one order of magnitude also influenced modelled water table flux. Perturbing K, Sy and P in layers 2 and 3, river and drain bed permeability and heads at general head boundaries had little influence on water level predictions *as a whole*.

The results indicated that a reduction in layer 1 Sy would minimise model residuals and a new value of 0.09 was subsequently set. Since layers 2 and 3 had little influence on modelled water flux, layer 3 was deleted. Layer 2 was used only as a means of preventing leakage through the base of layer one, with the surface of the layer defined as a no-flow boundary. The model may therefore in essence be considered as comprising one layer, which excluded the possibility of influent or effluent flow to the deeper groundwater system. Layer 1 K was also redefined as 3.5 m/d; the mean of values determined through a combination of falling head tests and application of the Shepherd formula to PSA data.

6.3 Model Period 1

The model was then tested more thoroughly over a 120-day period, from 11th March to 9th July 1997.

Following a more detailed calibration involving determination of optimum values of K and Sy in individual areas, the model was able to replicate the general trend of water table rise and decline over a four-month period at the majority of monitoring points, as seen in figure 3. The error margin was in the region of ± 10-15cm.

Since a model that excluded influx of water from the boundaries of the marsh was able to simulate water levels within reasonable bounds, it was concluded that the balance between Et and rainfall primarily controls water levels in the marsh over this period and within this area.

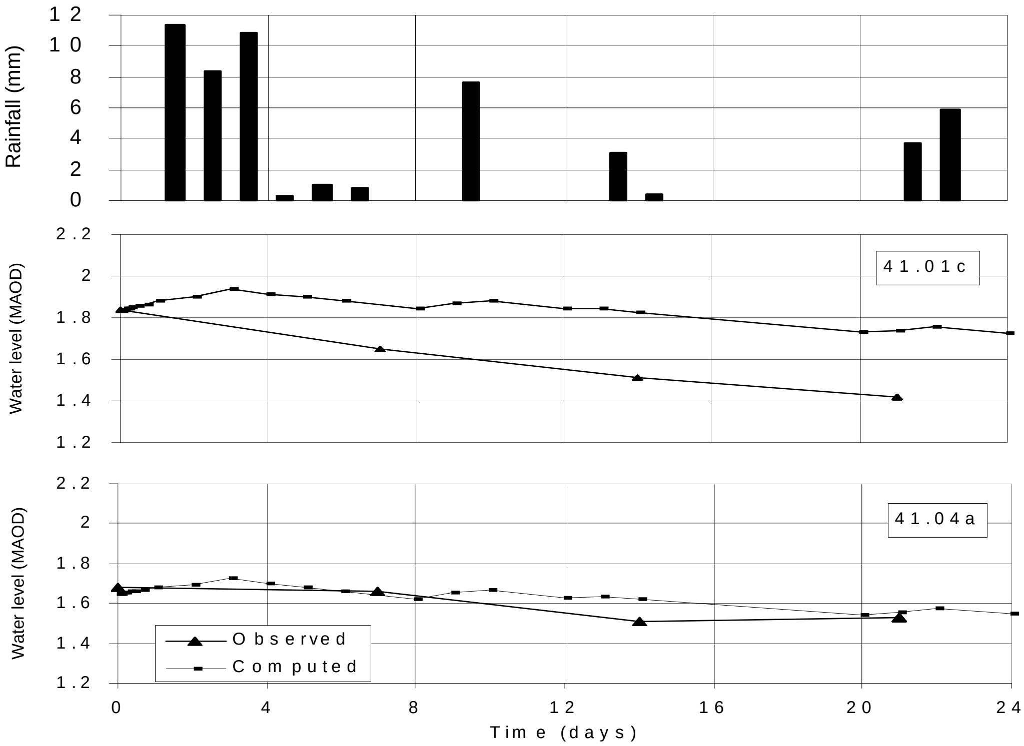

Figure 3. Rainfall and well hydrographs during model period 1

Differences between observed and computed levels (residuals) were attributed to a number of factors. For instance, a consistent problem was overestimation by the model of water table rise due to rainfall between the 19th and 23rd March (days 9-13). This is likely to be the result of the difference between effective and actual rainfall, a factor not considered in the model. The use of weekly rather than daily rainfall totals meant that differences in rainfall intensities were not included. Since a given volume of rain falling in a 24 hour period is likely to result in a lower Et loss and therefore greater water table rise than the same volume falling over 7 days, errors in model predictions are likely to occur. The problem is likely to be of particular significance over the summer months when Et rates are at their maximum. Use of potential rather than actual Et data was likely to be a further error source. The response to different rainfall events was not directly proportional to the size of the event in certain areas. This was thought to be due to a combination of factors such as variations in the rate of decline in Et with depth, soil moisture deficits and the inherent complexity of the sedimentary deposits.

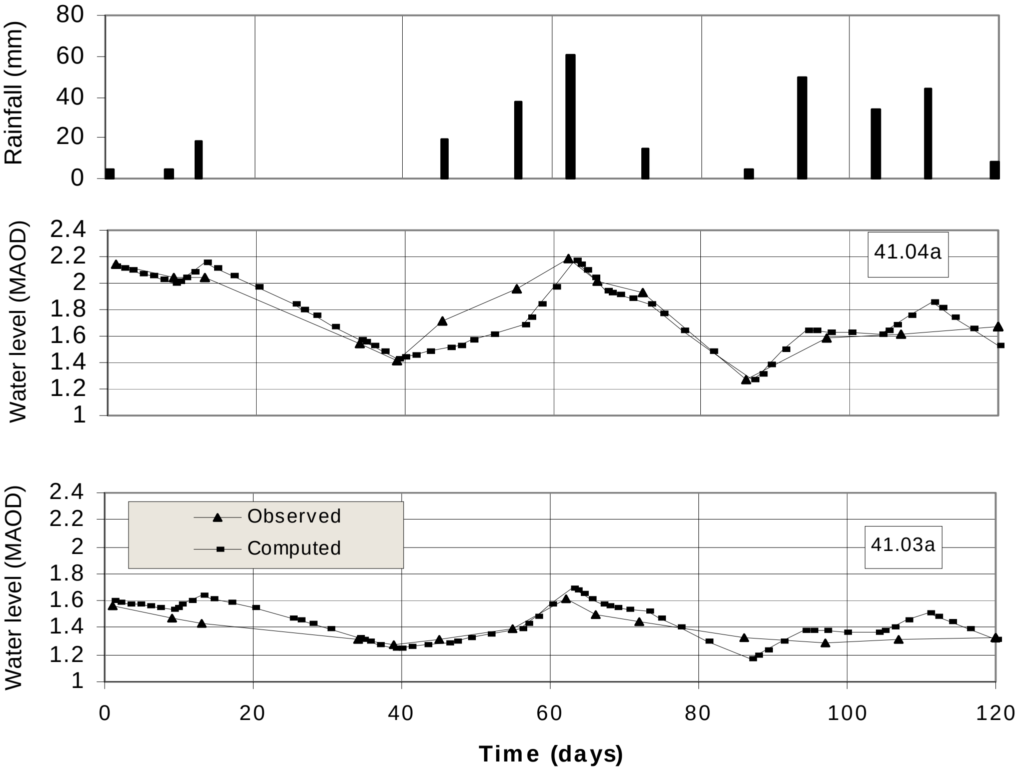

Figure 4. Rainfall and well hydrographs during model period 2

6.4 Model period 2

A second period was chosen to include 23 days from 5th to 28th August 1999 (Figure 4). Water levels in all 29 monitoring wells had been recorded during this interval, along with daily rainfall totals collected from an on-site tipping bucket gauge. These were input as calibration targets and total recharge per stress period (each stress period being one day long) respectively. Artificial recharge was significant over this period. This was applied to the model using the method described previously.

The accuracy of simulated flux was again variable, with computed and observed water levels at 10 of the 30 wells corresponding to within 10cm. Errors varied in the remaining wells, to a maximum of 40cm. The largest residuals occurred in those areas where the water table continued to decline throughout the period, despite a total of 54mm rainfall. The failure of the model to simulate this decline was thought to be the result of a combination of factors. Water loss to the surface drains and effluent flow through a buried channel system was either based on very crude approximations of the likely hydrogeology, or ignored altogether. Effluent seepage of this nature, as discussed in section 5 above would therefore lead to divergences between observed and computed water table decline. The most significant errors consequently occurred during attempts to simulate water levels close to the (LHMD) or the low conductivity channel deposits characterised during the EM31 survey. It was also noted that those dipwells with homogeneous deposits within the response zone provided the best correlation between modelled and observed water levels; the correlation was poor where clay lenses were observed in dipwells within the response zone, suggesting perched water table conditions.

Contour plots of water table levels during August 1999 demonstrated a hydraulic gradient towards the LHMD. Using sensitivity analyses, the hydraulic conductivity of the fluvial deposits and ditch lining required in order to replicate observed water table fluctuations at the four dipwells located within close proximity of the LHMD were determined. Mass balance calculations based on model results using these parameters suggested a rate of water loss between 7×10^{-3} and 9×10^{-3} m/day. Evaluation of seepage loss based on continuous monitoring data had suggested losses of between 7×10^{-3} and 28×10^{-3} m/day.

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7. Conclusions

The project has demonstrated that seepage loss through a surface and subsurface drainage network occurs on the site. Hydrological monitoring and mass balance calculations using a numerical mode of the site indicated that seepage rate in areas adjacent to surface drains and buried channels during August 1999 was in the region of 9×10^{-3} m/day. These regions should therefore be avoided during the development of further reedbeds. Numerical models of this nature may be a useful tool in assessing the additional water requirements in managed sites of this type under water stress conditions associated with increasing climatic variability.

References

Baker, P.N. 1984. *A geophysical survey of Malltraeth Marsh*. M.Sc. Thesis, University of Wales, Bangor.

Bentley, A. 1997. *An evaluation of groundwater movement using geophysical, geotechnical, hydrological techniques and applying the numerical modelling package ‘MODFLOW’ at a wetland reserve on Anglesey*. M.Sc. Thesis, University of Wales, Bangor.

Bradley, C. 1996. *Transient modelling of water table variation in a floodplain wetland, Narborough Bog, Leicestershire*. J. Hydrology **185,** 87-114.

Curry, A. 1983. *A geophysical Survey of Malltraeth Marsh and Sands, Anglesey, using resistivity and seismic reflection techniques*. MSc Thesis, University of Wales, Bangor.

Gerla, P.J. and Matheney, R.K. 1996. *Seasonal variability and simulation of groundwater flow in a prairie wetland.* Hydrological Processes. **10: 7**, 903-920.

Gilman, K. 1993. *Initial feasibility study of the creation and operation of a wetland reserve at Morfa-Mawr, Malltraeth Marsh, Anglesey*. Report to the Countryside Council for Wales.

Gilvear, D.J., Andrews, A., Tellam, J.H., Lloyd, J.W. and Lerner, D.N. 1993. *Quantification of the water balance and hydrogeological processes in the vicinity of a small groundwater-fed wetland, East Anglia*, UK. J. Hydrology **144**, 311-334.

Gloth, S. 1997 *Hydrogeological investigation of the RSPB site, Morfa Mawr, Malltraeth Marsh, Isle of Anglesey.* M.Sc. thesis, University of Wales Bangor

Greenly, E. *1919 The Geology of Anglesey, Vol 2.* Mem. of Geological Survey. HMSO, London

Macdonald, M.G. and Harbaugh, A.W. 1988. *A Modular Three Dimensional Finite-Difference Groundwater Flow Mode*l. GWV Electronic Format

Shepherd, R.G. 1989 *Correlations of permeability and grain size*. Groundwater 27, no 5

Williams, F. 1997. *An Investigation of the Former Creeks and Channels of the Afon Cefni, at Morfa-Mawr, Malltraeth Marsh, Anglesey*. M.Sc Thesis, University of Wales, Bangor.