Predictive modeling of the creation and hydrological behaviour of waterfowl habitats resulting from sand and gravel extraction

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ABSTRACT

The working of floodplain sand and gravel deposits often results in the creation of pit lakes, typically containing good quality water which may be used for recreational purposes, municipal / industrial water supplies or (less commonly) deliberately developed as valuable habitat for wildfowl. In the past, pit lake creation has proceeded on an entirely 'accidental' basis, with the final forms of ponds and wetlands arising simply from the exigencies of gravel-winning. In a planned development in northern England, in contrast, the final form of pit lakes and wetlands has been deliberately planned *a priori* with avian ecology in mind. In order to advance these plans to detailed designs, substantial quantities of piezometric data have been gathered, and groundwater flow models constructed, in order to characterize the present hydrological functioning of the pristine floodplain, and predict the likely comportment of future pit lakes. It is concluded that *a priori* planning of habitat creation by means of sand and gravel winning is not only feasible but environmentally desirable, as it helps to redress the drastic loss of wetland habitats which has occurred in much of Europe over the last century.

INTRODUCTION

Sand and gravel deposits are essential commodities of the construction industry and can be extracted from a range of geological settings, in particular river floodplains, coastal dunes, glaciated environments and even bedrock. However, the working of floodplain sand and gravel deposits is the most common within the UK. Sand and gravel extraction often results in the creation of pit lakes, which are often subsequently restored to provide recreational facilities or valuable habitats for waterfowl. Although, in the past, the form of such lakes has been determined principally by the extraction of sand and gravel, a planned development in Northern England has considered waterfowl when planning the final form of ponds and wetlands. The planned development is located on the floodplain of the River Wear close to Low Harperley, County Durham, UK (Figure 1). The sand and gravel aquifer overlies sandstone of the Upper Carboniferous series and varies in thickness from approximately 4 to 13 m. The proposed extraction of sand and gravel is to take place over a number of years, incorporating a number of phases, with restoration of pit lakes to create a nature reserve in the form of wetlands and reed beds. As well as the River Wear, the area is drained by two small tributaries, the Bradley Beck and the Eels Beck (Figure 1), as well as several drains which run dry during the summer months.

A series of groundwater flow models have been developed for the area of the proposed quarry in order to characterise the present hydrological functioning of the aquifer and to predict the likely hydrogeological behaviour of the future pit lakes in hydraulic continuity with groundwater (Gandy & Younger, 2005). These include steady state, transient and predictive models. The approach to modelling is described within this paper and the intricacies of ensuring adequate mimicry of site behaviour (especially as regards groundwater / surface water interactions) are outlined. A number of groundwater monitoring boreholes have been installed at the site, both within the sand and gravel aquifer and the underlying sandstone, while river gauge boards have been installed in the River Wear, Bradley Beck and Eels Beck to monitor river stages.

DEVELOPMENT OF GROUNDWATER MODELS

Steady state groundwater model

An initial steady state groundwater model of the area comprising the proposed sand and gravel quarry near Low Harperley, County Durham, UK, was developed using the Groundwater Modelling System (GMS) software. The areal extent of the model was determined from the published geological maps (both solid and drift) of the region and generally corresponds to the area shown as alluvium on the drift map. A single layer model was used to represent the sand and gravel aquifer with the base of the model taken to be the boundary between the sand and gravel and the underlying sandstone bedrock. Borehole logs were used to define the top and bottom of the sand and gravel aquifer, with GMS interpolating in areas with sparse data.

The model boundaries were defined as shown in Figure 1. The southern / south western boundary was defined by the River Wear while the northern / north eastern boundary was generally taken as the northernmost edge of the sand and gravels outcrop, defined as a general head boundary. The sand and gravel aquifer almost pinches out towards the western boundary of the proposed development, which was defined as a specified head boundary, ranging from the stage of the River Wear at its southern extent to the observed groundwater head at its northern extent. At the downstream end of the site, the sand and gravel aquifer pinches out and is defined by the River Wear.

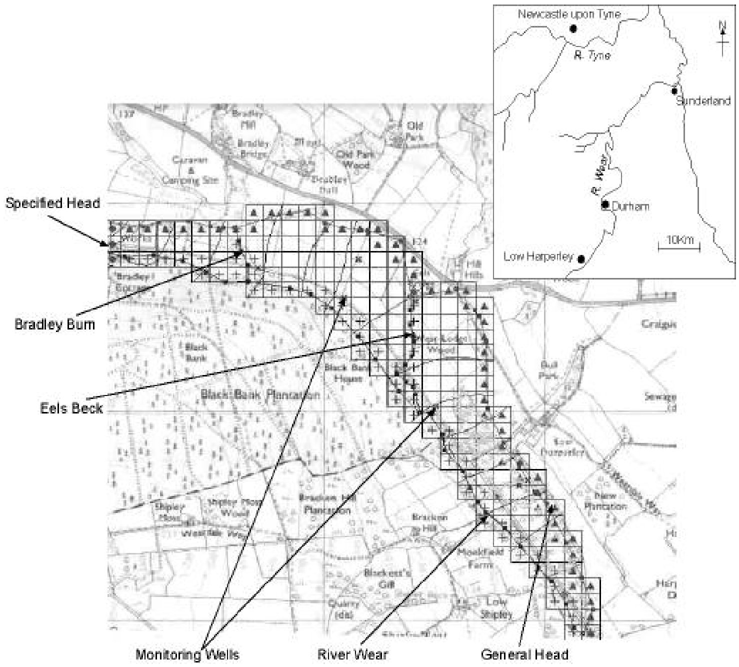

Figure 1: Conceptual model showing location of Low Harperley, boundary conditions, rivers and monitoring wells

As described above, the area is drained by the River Wear and two small tributaries, the Bradley Beck and the Eels Beck. The conductance term, relating to the hydraulic connection of the river to the underlying aquifer, is calculated according to the area of each model cell occupied by the river and the permeability and thickness of the riverbed sediments. For the River Wear, the permeability was initially estimated to be 0.05 m and the bed thickness estimated to be 0.5 m. The conductance term was then used as a means of calibrating the model, with an eventual conductance of between 1 and 4 m^2/d/m proving necessary for successful calibration. The Eels Beck and Bradley Beck were given lower conductance values of 0.005 and 0.0067 m^2/d/m respectively, corresponding to a bed permeability of 0.001 m and a bed thickness of 0.3 m.

Slug tests were carried out on two monitoring boreholes, one within the sand and gravel, the other within the sandstone. As expected, recovery of groundwater levels in the sand and gravel after addition of water was rapid but a maximum hydraulic conductivity calculated of 200 m/d compares favourably with values quoted in the literature (e.g. Freeze & Cherry, 1979). A value of 100 m/d proved adequate across the entire model domain for a successful calibration. In terms of recharge, a value of approximately 10% rainfall averaged over the summer months (0.0001 m/d) was entered into the model, with an increased level of 0.0002 m/d applied to the northern boundary to account for lateral flow from the sandstone. Daily rainfall and river flow data, over a 20 year period, were collected from the UK Environment Agency for nearby gauging stations.

The model was calibrated against observed groundwater levels recorded on 4th June 2004, which was taken to be an “average” day. As can be seen from Figure 2, which shows plots of computed versus observed groundwater heads (a) and observed head versus residual (b), a good correlation was achieved between predicted and observed groundwater levels. Predicted values are within half a metre of observed values for each monitoring borehole.

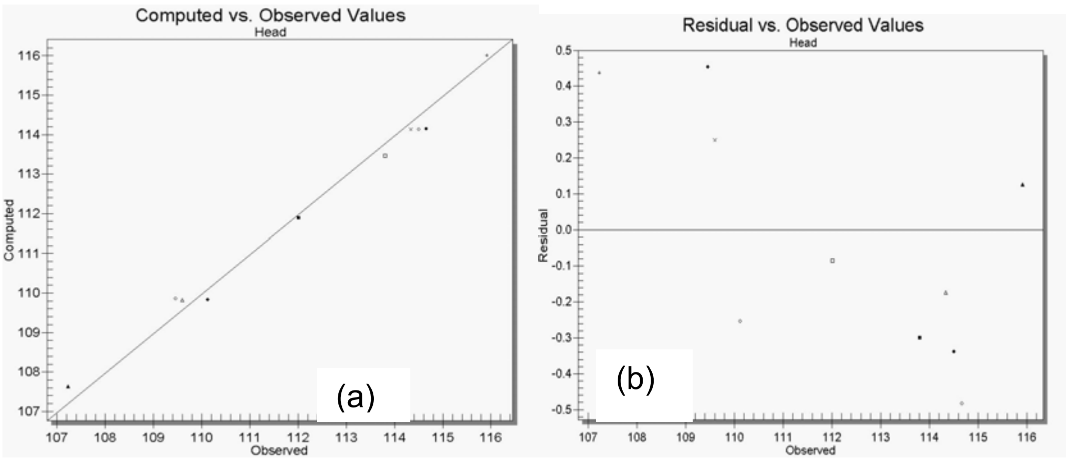

Figure 2: Steady state calibration showing (a) computed versus observed groundwater heads (mAOD) and (b) residual versus observed groundwater heads (mAOD)

Transient groundwater model

Following successful calibration of the steady state groundwater model, a transient model was developed to study changes in the groundwater system over time. Ideally, for calibration purposes, this requires a year of observed data, both groundwater and surface water levels, but due to the unavailability of this data it was decided to reproduce the extreme recharge events of Summer 2004, for which substantial quantities of data are available. Particularly high rainfall during the month of August resulted in a rise in groundwater levels of up to one metre across the modelled area. As in the steady state model, recharge was taken to be 10% rainfall but, during the period of extreme rainfall in August, recharge had to be increased to 40% that of rainfall in order to achieve a successful calibration. Similarly, the boundary conditions were altered during August, with the specified head and general head boundaries both increasing, according to the observed changes in groundwater levels. This allowed for an increased supply of water into the model from beyond the model boundaries. River levels, in the River Wear, Eels Beck and Bradley Beck, were also increased during this period. In addition, a specific yield of 10%, typical of a sand and gravel aquifer (Anderson & Woessner, 1992), was found to produce the best calibration.

Since the steady state model was calibrated to observed groundwater levels on 4th June, the transient model was calibrated over the period June to September in order to use the calibrated steady state model to provide the starting heads for the transient simulation. Although the model does not reproduce the observed groundwater levels in August (i.e. the worst case scenario) to the same degree of accuracy as in the steady state model, it is felt that the results are acceptable given such an extreme recharge event. On the other hand, the model compares favourably with the observed groundwater levels in June, July and September. Figure 3 shows examples of time series of groundwater heads for two boreholes. The time series in (a) is for a borehole which is located close to the confluence of the Eels Beck and River Wear (Figure 1) and shows a good correlation, with the groundwater level remaining within the calibration targets at all times. Conversely, the time series given in (b), for a borehole also located close to the River Wear, between its confluences with the Bradley Beck and Eels Beck, shows how the groundwater level becomes very close to the lower calibration target during August and falls beneath the target for several days. However, in both figures it can be seen that the model is capable of reproducing the timing and amplitude of the observed recharge peak.

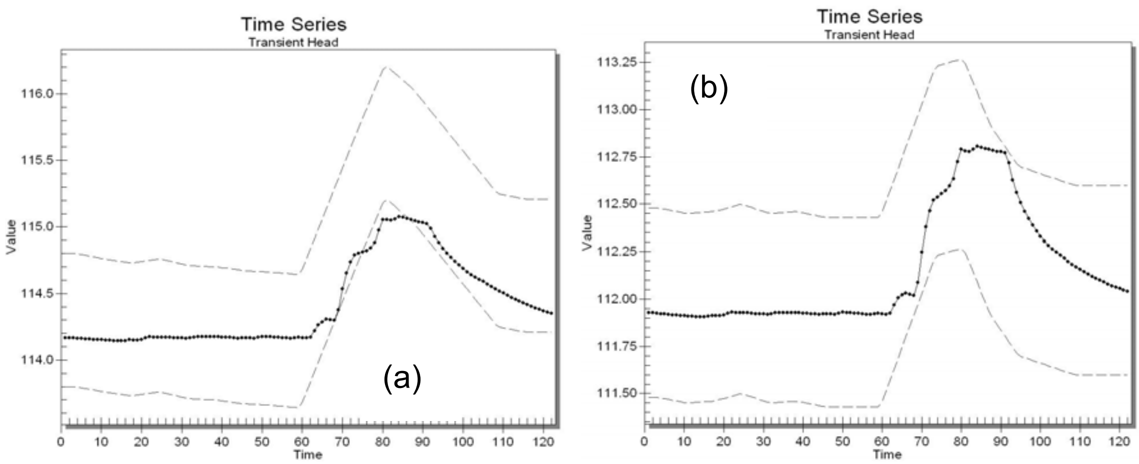

Figure 3: Time series for groundwater heads in borehole 5 (a) and borehole 9 (b) (mAOD) during transient simulation, showing calibration targets

Predictive groundwater model

In order to predict the likely behaviour of future pit lakes in hydraulic continuity with groundwater, a predictive model was developed, using the calibrated transient model to generate the starting heads. The model was set up to begin in October and to run for 12 month periods, with recharge entered as monthly averages as opposed to the daily rates entered in the transient model. To calculate changes in recharge over a 12 month period, average monthly recharge rates (as 10% rainfall) were calculated for 20 years, from 1985 to 2004. This reveals a relatively constant recharge over much of the year, with a maximum rate of $2.9x10^{-4}$ m/d calculated for December and a minimum rate of $1.6x10^{-4}$ m/d calculated for May. The predictive model was used to calculate required pumping rates for well point dewatering of each extraction phase but its main task was to predict groundwater rebound levels following cessation of dewatering and restoration of the pit lakes.

A detailed literature review has revealed very little work to have been carried out on the hydrogeology of flooded sand and gravel pits. However, research by Morgan-Jones *et al*. (1984) and Gandy *et al*. (2004) has shown that, following groundwater rebound, the water level in a flooded pit will attain a level midway between the groundwater levels that existed at the upstream and downstream ends of the pit before the gravel was extracted. To satisfy this condition, groundwater levels must fall up-gradient of the pit and rise down-gradient of it (Morgan-Jones *et al*., 1984). Therefore, if the pre-extraction water table profile is compared with the long-term profile once a pit lake is established, it will be found that the latter is steeper than the pre-mining water table immediately up-gradient from the pit lake and gentler down-gradient of it (Figure 4). According to Darcy's Law, the steeper water table feeding into the pit lake means that a greater volume of water feeds into that zone of the aquifer than before mining, thereby creating a zone of 'infinite permeability' and high unit storativity (Younger *et al*., 2002).

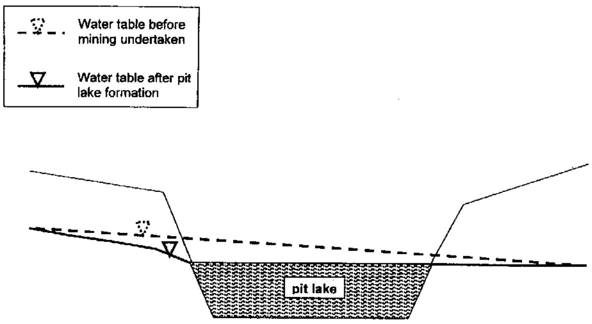

Figure 4: Pre-extraction and post-pit lake formation water table profiles around a pit lake in flooded sand and gravel workings (after Younger *et al*., 2002)

The predictive model was used to enable groundwater levels to be analysed following the cessation of dewatering and the flooding of the pit lakes. Groundwater levels up-gradient and down-gradient of the proposed extraction areas were studied and it was possible to predict the likely fluctuations in lake levels to reflect seasonal variations. It is essential when planning the final form of pit lakes and wetlands to know the height to which groundwater will rebound in each pit lake in order to determine the volume of soil to be backfilled to support the reed beds. Also, controls may have to be implemented to prevent flooding of the reed beds during periods of high rainfall. The greatest fluctuation in water level within the flooded pit lakes throughout the year was predicted to be approximately 80 cm.

It was also possible from the predictive model to investigate any adverse effects of the proposed sand and gravel quarry on the River Wear. It was assumed for this that all the extraction areas had been allowed to flood and groundwater rebound was complete. The restored lakes were represented by zones of higher hydraulic conductivity, with a value of 1000 m/d used for each (compared to 100 m/d for the sand and gravel aquifer), as well as higher specific yield (20%) to account for the increased storage capacity. In addition, evaporation from the flooded pit lakes was considered, with an average open water evaporation rate of 500 mm/yr used for this purpose. This equated to an average daily evaporation rate from each lake ranging from approximately 3 to 19 m^3/d, depending on its surface area. Since the restored lakes will be effectively part of the groundwater system (i.e. 'through-flow' lakes), they were modelled by a series of wells around the perimeter of each, to represent losses due to evaporation. The results of this predictive simulation revealed that the planned development will have very little effect on the local groundwater system and the River Wear, with only a slight depletion in groundwater levels evident following restoration.

CONCLUSIONS

Through the development of a series of groundwater flow models, successfully calibrated to observed data, it has been possible to not only characterise the present hydrological functioning of a pristine floodplain in Northern England, but to predict the likely comportment of future pit lakes, following the working of sand and gravel deposits, in hydraulic continuity with groundwater. The final form of these pit lakes and wetlands has been deliberately planned with avian ecology in mind in a move away from historic attitudes whereby pit lake creation has simply proceeded according to the demands of gravel winning. This is not only feasible but encourages the development of wetland habitats for waterfowl, in an attempt to replace the recent loss of such habitats throughout Europe.

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