Part 2: A Preliminary Report on Hydrogeological Modelling.

This report is a draft of the Hydrogeological modelling for the 'Where Rivers Meet' project. This report will be superseded by the final report, which will contain more details on the application of the numerical model, once calculations are complete (M.S.R).

1. Introduction

The focus area lies to the east of the A38 between Burton upon Trent and Alrewas, and is situated within a meander of the river Trent extending from Wychnor to Walton-on-Trent (Figure 16). The area is divided into two along a north-northeast axis by the Cross Country Main Line railway line that connects Birmingham and Burton upon Trent. The railway divides and crosses the Trent at Wychnor Viaduct, approximately 1 km southeast of Wychnor Bridges. The River Tame flows into the Trent at Wychnor Viaduct and the River Mease joins the resulting augmented river about 400 m further downstream, i.e. to the east. The area is also bounded by the Trent and Mersey canal, which runs largely parallel to the A38 and which crosses the Trent between Wychnor and Alrewas.

West of the railway line the land is largely devoted to arable farming, whereas land use to the east is dominated by the extraction of high-grade sand and gravel by Hanson Aggregates UK. Exploitation of the gravel resource to the east of the railway line started in 1980 in the north of the area and has been progressing southwards. The present workings are now approaching the southern end of the area and the operator plans to exploit the deposits on the western side of the railway line following the exhaustion of the current workings. It is expected that the land on the western side of the railway will provide sand and gravel for at least 25 years. The proposed extension of the gravel extraction is an area of considerable archaeological interest, which is discussed elsewhere.

The gravel deposits form a shallow alluvial aquifer from which the site operators pump water in order to drain the deposit prior to excavation. The proposed extension of the area of gravel extraction may provide opportunities to the archaeological community through this dewatering as well as posing threats to important ancient sites. The purpose of this hydrogeological study is to develop an understanding of the groundwater system and to investigate how it is likely to be affected by the future dewatering process. The study has been conducted in three stages. During the summer of 2003 an MSc Hydrogeology student from the School of Geography, Earth and Environmental Sciences at the University of Birmingham conducted an investigation into the hydrogeology of the study and focus areas (Guidon, 2003). On top of this, two undergraduate students undertook a localised field investigation into the hydraulic connection between the Trent and the groundwater system (Pardoe, 2003; Adams, 2003), and two further undergraduates explored recharge to the system through a combination of surface geophysics and water balance calculations (Goodier, 2003; Goodenough, 2003). Starting in October 2003, a further desk study was carried out by the Hydrogeology Research Group at the University of Birmingham as part of the current project. The understanding of the groundwater system developed in these studies has led to a conceptual model of the system described later in this report. Subsequently, that conceptual model has been realised in the form or a numerical model, which has been used to quantify and test the conceptual model and which will form the basis for predictions of water table lowering due to dewatering in the future.

This is an unusual groundwater study in that predictions of water levels must take into account the staged removal of the aquifer material.

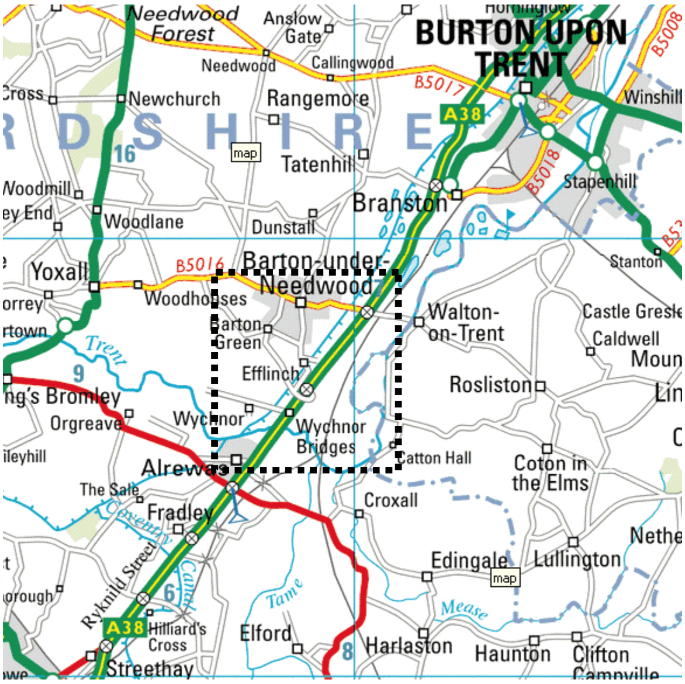

FIGURE 16 - Map of the study region featuring the confluence of the rivers Tame and Mease with the river Trent. The Environment agency monitors river levels and discharge at Yoxall on the Trent (west) and Elford on the Tame (south) upstream of the confluence. The dashed box highlights the focus area.

2. Background

REGIONAL SETTING

The Trent in this region is bordered by broad alluvial flats (Barrow *et al*., 1919) that give way to relatively steep valley-sides. Locally, these slopes are cut down through Mercia Mudstone that outcrops adjacent to the valley. This underlies the area and provides resistant, obtrusive punctuation to the generally flat landscape. Beneath the surface the Mercia Mudstone acts as an aquitard between the two main water bearing rocks in the regional succession: the Triassic Sherwood sandstone of the Bromsgrove Formation at depth; and the post-Pleistocene glacio-fluvial sands and gravels of the valley fill above. The upper aquifer forms the focus of this study.

Within the focus area, the thickness of the aquifer ranges between 5 and 8 metres. The aquifer widens and thickens to 16.5 m at Burton upon Trent (Downing *et al*., 1970; Riches 1994). Local breweries in Burton upon Trent are the chief abstractors of water from the aquifer (Riches, 1994) although there are many individual licensees permitted to abstract privately for such activities as farmland irrigation (Downing *et al*., 1970; Environment Agency Data, 2003). The only abstraction licence within the focus area is held by Hanson Aggregates UK for excavation dewatering.

GEOLOGICAL SETTING

<u>*Regional geology*</u>

The creation of the Trent valley as a drainage system was brought about by regional tectonic uplift to the south (Gibbard & Lewin, 2003). Subsequent abrasion by successive glacial advances and retreats, and associated glacio-fluvial discharge, carved and incised the valley into an embryonic form of its present configuration by the late Pleistocene (Davies, 2004). However, these processes denuded, reworked and redeposited underlying strata producing considerable stratigraphic variability along the length of the valley. A general regional summary stratigraphy is outlined in table 4.

Geological Period	Age	Geological Unit	Subset/Description
Quaternary	Pleistocene and recent	Peat & alluvium	Peat, clay, silt and sand
		River Terrace Deposits	Sand and gravel with clay lenses and organics
		Glacial Sand and Gravel	Sand and gravel with local clays
		Glacial Till	Stiff, pebbly, sandy clay
Mesozoic	Triassic	Rhaetic	
		Mercia Mudstone Group	Red & green calcareous mudstone with occasional gypsum
		Bromsgrove Sandstone Formation	Pink and red sandstones with mudstone bands
		Cannock Chase Formation	Red/brown sandstones with conglomerate layers
		Hopwas Breccia	Soft sandstone with angular pebble clasts
Palaeozoic	Carboniferous	Keele Formation	Red mudstones, siltstones and sandstones
		Halesowen Formation	Red and grey sandstones
		Etruria Marl Formation	Purple mudstones
		Productive Coal Measures	Mudstones, sandstones and coals

***TABLE 4**. (After: Downing et al., 1970 and adapted according to modern nomenclature, where known, regarding names of the geological units set down by the BGS).*

Local lithology

Much of the summary succession is absent in the vicinity of the study area, where it is dominated by two unconformities. These act to effectively separate two distinct aquifer strata; at least 105 metres (Barrow *et al*., 1919) of the Triassic Bromsgrove Sandstone, and the relatively thin superficial Quaternary deposits above. Between them lies an unusually thin layer (52 metres) of the Mercia Mudstone (Barrow *et al*., 1919) and more specifically, a unit formerly known as the Tea Green Marl (Downing *et al*., 1970). A map of solid geology and superficial deposits is presented in Figure 17.

The Mercia Mudstone is the most persistent stratum associated with the Trent Valley, ever-present throughout the valley succession. It is a well-consolidated, fine-grained calcareous mudstone, which, at its base, is intercalated with dolomitic sandstones exhibiting pseudomorphs of salt. It has a low permeability although it can yield water, mostly by flow through fractures and cavities created by dissolution of gypsum (Downing *et al*., 1970). It acts as a confining layer to the extensive Sherwood Sandstone aquifer - the UK's second most important groundwater resource (Goodman, 1999).

The superficial deposits in the focus area consist of two glacial sand and gravel terraces, the lower being approximately four metres thick and the upper, less well-developed terrace approximately two metres thick. The lower terrace is composed of relatively well-sorted, coarse but otherwise texturally mature quartzitic gravel. Clasts can reach up to 18 cm along the long axis but are generally of medium to large pebble grade (16-32 mm). This terrace represents the more attractive aggregate resource as it contains little interstitial silt, fine sand or lignite and few clay lenses. By contrast, the upper terrace is more poorly sorted and contains frequent clayey or lignite-rich lenses and impersistent pebble lenses. Compositional and textural analyses confirm that the main source of material was reworked Lower Triassic Bunter Pebble Beds, although the significant proportion of flint is thought to have been sourced from the east by the river Mease (Barrow *et al*., 1919).

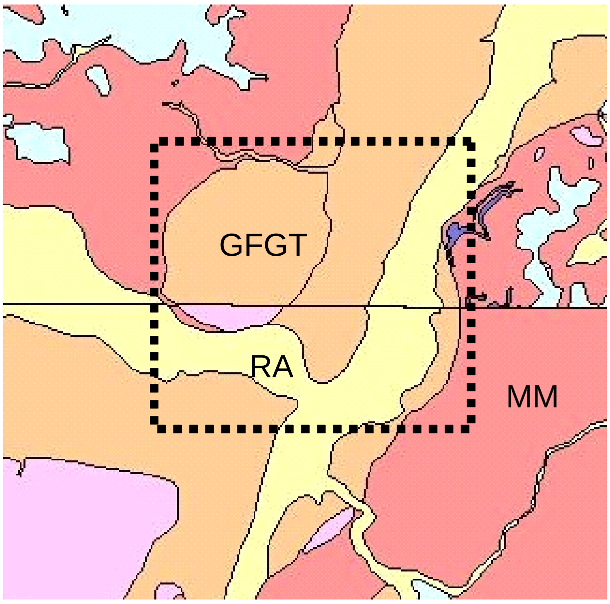

***FIGURE 17** - Map of the regional geology showing both superficial and solid rock outcrop. Mercia Mudstone (MM) appears in red. Orange and pink are glacio-fluvial gravel terraces (GFGT). Yellow bodies represent more recent alluvium (RA) and identify the three river courses of the Trent (west to northeast), the Tame (from the south) and the Mease (from the southeast). The focus area is highlighted by the dashed box.*

The lower terrace is generally unbedded, sheet-like and laterally homogenous. The upper terrace contains many more discrete channel forms containing finer sands with basal pebble lags and both planar and trough cross-bedding. This contrast can be attributed to two markedly different discharge styles during deposition. The lower terrace is likely to have been deposited in a high energy environment, when the stream was high and persistent, and able to carry coarse clasts considerable distances, probably in extensive braid networks. The upper terrace architecture implies that these deposits were laid down when the flow velocity had diminished. Only large flood events were able to mobilise anything larger than granule to gravel clast size.

Although similar in appearance, the terraces are delineated by the presence of epigenetic 'frost' cones near the top of the lower terrace that appear truncated against the base of the upper terrace. These are sediment fill features that indicate a repeated cycle of freeze and thaw within the sediments when exposed that confirm the influence of glacial processes in their distribution. Similar features are recorded in deposits at a sand and gravel quarry downstream near Hoveringham, northeast of Nottingham (Goodman, 1999).

In the focus area, the aquifer is covered by between 0.5 and 1.8 m of soil. Although the soil is clay and organic rich, it is commonly pervaded by silt and stray pebbles probably derived from the aquifer beneath. The soil is thought not to significantly impede the infiltration of direct recharge from precipitation.

HYDROGEOLOGICAL SETTING

The aquifer unit in the study area affected by dewatering, which is formed by the shallow sand and gravel deposits (Figure 17). These are underlain by approximately 50m of the Mercia Mudstone formation, which forms a major aquitard significantly limiting the interchange of water between the upper, minor aquifer and the lower, major sandstone aquifer.

Studies by MSc and undergraduate students in the summer of 2003, centred on the riparian area immediately to the west of Wychnor viaduct on set-aside land, confirmed there is a strong hydraulic connectivity between water levels in the river and the aquifer.

Annual rainfall in the focus area was 765 mm in 2001 (Hedges, pers. comm.) and 783 mm in 2002 (Environment Agency).

The Barton East Quarry, which lies to the east of the railway line in the focus area, is operated by Hanson Aggregates UK. The operators are licensed by the Environment Agency to abstract up to 1.5 Mm^3 per year at a nominal location within the site for dewatering purposes. Abstraction is concentrated primarily in the 6 – 8 driest months of the year to dewater the more valuable lower terrace gravels. During the wettest part of the year when the lower terrace is prone to flooding, quarrying activity is scaled down and is moved to the higher upper terrace. Anecdotal evidence from the site operators suggests that their primary workings are flooded at least three times a year, between the months of October and March.

Other than the dewatering activities in the study area, the only major abstraction from the superficial aquifer is used by the brewing industry at Burton upon Trent. Riches (1994) reported that brewers had become concerned at a drop in water levels possibly due to an upstream gravel extraction scheme. Active dewatering at a gravel extraction site south of Burton, but north of the focus area (Riches, 1994) generated a groundwater divide just south of the town. The backfilling of restored pits with Pulverized Fuel Ash (PFA) was a cause for further concern for fear that a return to the natural groundwater flow regime might bring contamination towards Burton. Riches concluded that in fact, the connection between the river Trent and the groundwater levels in the aquifer was so good that, gravel extraction dewatering was likely to be drawing a significant amount of artificial recharge from the river itself. Riches predicted that any contaminants would probably be preferentially discharged to the river should pumping cease.

Many standing water bodies are apparent but LiDAR data (Figure 18) indicate that their surfaces rest at differing elevations. These data have also been precise enough to detect the elevation of running surface water in the river Trent. Water bodies and pits created by the gravel extraction process change quite rapidly. Those shown on the LiDAR data (collected on February 19th, 2003) vary significantly from those shown on the local Ordnance Survey maps, and have now been further extended.

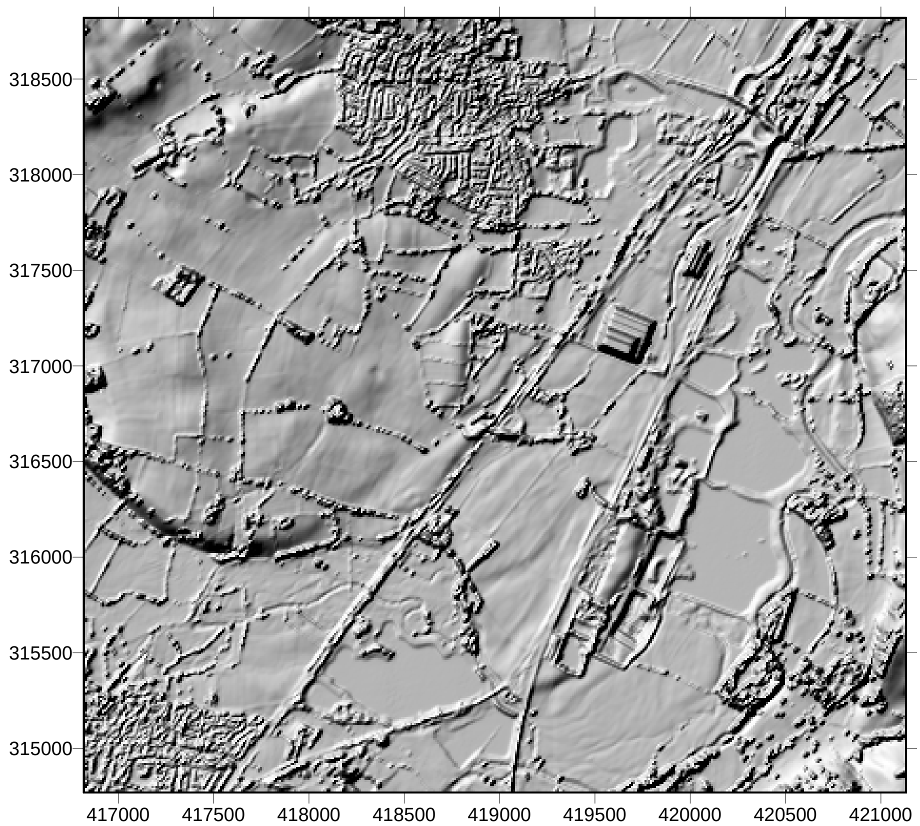

***FIGURE 18** - A shaded relief map of the study area obtained from LiDAR data. The A-38 and Cross-Country Railway Line can be seen to divide the focus area with approximate North-northeast trends.*

QUARRYING PRACTICE AT BARTON EAST QUARRY

In 1980 Hanson Aggregates UK began exploiting the glacial gravels north of the meander loop, adjacent to Catholme. Quarrying has been staged in order to ameliorate the impact on the local groundwater flow regime. Once worked-out, many pits have been restored to allow natural infilling in order that groundwater can re-establish a natural flow path towards the river. Ultimately the site has been designated as a water sports and leisure park.

Typical approach

The working of a gravel pit proceeds as follows:

- Overburden is stripped away and stockpiled along with any clay- and silt-rich alluvium.
- A working gravel face is established that is cut down to the impermeable Mercia Mudstone basement. A peripheral system of passive drainage ditches is cut around the target gravel, which is drained by pumping, developing shallow water seepage faces of 50-60cm above basement.
- Once all gravel is removed, either a cycle of backfilling and landscaping takes place, or a pit is left to refill naturally by direct recharge and groundwater seepage. Pit banks are landscaped and toughened. Both options utilise the overburden stockpile and uneconomic gravel fraction i.e. the very coarse cobble to boulder grade.
- A new pit is sited adjacent to the last worked-out area.

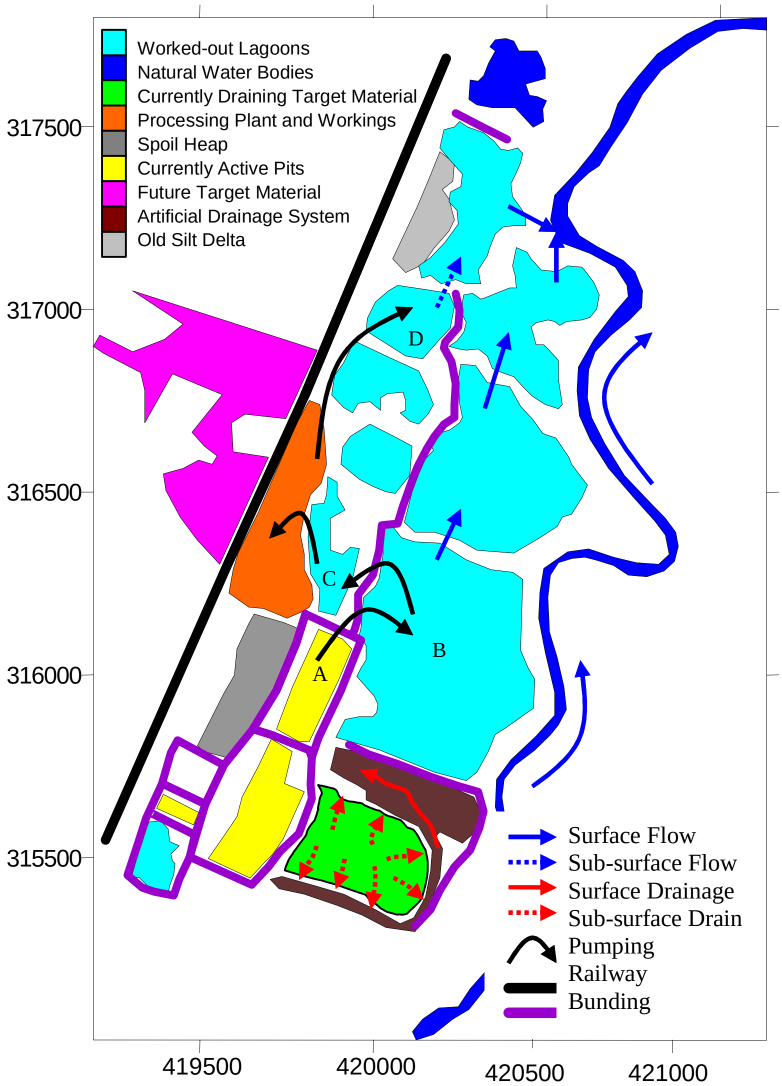

FIGURE 19 *- Simplified map of the Barton East Quarry workings*

The system employed at Barton East is common practice and is seen at other sites along the Trent (Goodman, 1999). The system of breaking the extraction up into a series of smaller cells with the long axis of the workings made to lie perpendicular to the regional groundwater gradient is practice recommended by Goodman (1999) as the best option for minimising the impact on the natural groundwater flow regime.

The specific system employed at Barton East segregates the worked pits into two designated functions. Those lagoons that lie adjacent to the river Trent exist primarily as a buffer to flood water from the river. They are in continuity with the groundwater and are designed to cascade floodwater northwards and into the Trent once past the site. The smaller lagoons, situated close to the main processing plant, are used in pre- and post-processing of the extracted gravels.

Once extracted, the gravels are washed and sorted before being left exposed to dry. The newest working gravel pits to the south are drained by an extensive drainage system that delivers water to lagoon A (Figure 19) which is pumped into the first of the flood lagoons (lagoon B). Water is then pumped from here into the lagoon that supplies the bulk of water to the processing plant for gravel washing (lagoon C). Of this pumped washing water, up to 10% is thought to be lost by evaporation in the drying process. The remaining 90% is pumped northwards to the active siltation lagoon (lagoon D) where the water is discharged and solid particles are allowed to settle. The currently active siltation lagoon is the second dedicated such lagoon in the lifetime of quarry activity here, the former situated immediately adjacent to the north. The LiDAR elevation data picks out the broad silt delta protruding into the older lagoon, away from the source of the pumped water.

3. Hydrogeological modelling

CONCEPTUAL MODEL

The aim of the hydrogeological model is to allow estimation of the water levels in the gravel deposits as a result of the dewatering activities required by the mineral extraction process. Flow from the underlying Triassic Sandstone through the Merica Mudstone is assumed to be negligible for the purpose of this investigation.

The River Trent, the Trent and Mersey canal and two areas to the southwest and northeast of the domain (figure 20) provide lateral boundary conditions imposed upon the modelled domain. The study by Guidon (2003) shows that the river is a dominant control on riparian water levels in the gravel. The boundary with the river is, therefore represented as a prescribed water level in the river connected to the water in the gravel by a high conductance, effectively transferring the head in the river directly to that in the aquifer.

The effect of the Trent and Mersey canal is less well understood, but it is clear that the canal provides an important boundary to the west. Geological maps show the gravel deposits extending westwards beyond the A38 and terminating against the Mercia Mudstone outcrop (Figure 20). Detailed information on the thickness of the gravel deposits in the area to the west is limited, but it is thought that they thin towards the mudstone outcrop, probably never achieving a thickness greater than 2 metres. Under natural circumstances it would be expected that subsurface drainage in this area would follow features in the base of gravel, which might be assumed to be represented reasonably by the surface topography. However, since the gravels are shallow and the canal is probably engineered to key into the mudstone wherever possible, it is likely that the canal acts as a significant control on drainage to the valley floor by intercepting drainage from the hillside, dispersing and redistributing it. Since the water level in the canal is well regulated by the locks at Wychnor Bridges and at Barton Turn, the canal is assumed to provide a prescribed head boundary to the model domain. Although the degree of hydraulic connectivity between it and the gravels is uncertain, it is unlikely that the canal provides large quantities of water to the aquifer, and so the conductance term between the canal and aquifer has been set low initially.

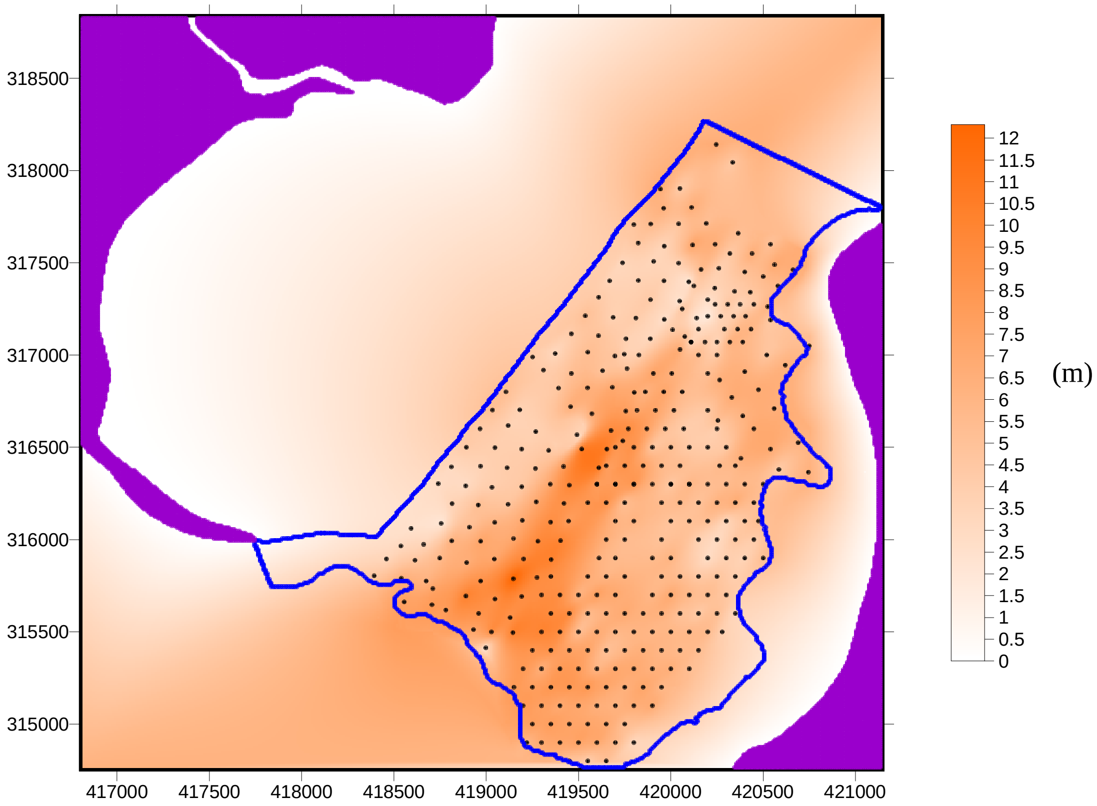

FIGURE 20 *- Image map showing the thickness of gravel within the model domain. The model boundary is shown in blue and surrounds the location of borehole data. The purple area represents outcrop of the Mercia Mudstone.*

The short boundary of the model domain to the far west and that to the northeast are taken to be general head boundaries and have been formed by interpolating water levels between the river, canal and standing water bodies. The conductance between these water levels and those in the gravel has been set low initially.

The elevation of the land surface in the study area is well-known from the LiDAR data. The top and base of the gravel deposits have been determined from site investigation borehole data supplied by Hanson Aggregates UK. The borehole data cover the area of the present extractions to the east of the railway line and those proposed to the west (Figure 20). Continuous surfaces for the top and base of the gravels have been estimated geostatistically using kriging. To avoid the problem of unreal intersections between these two surfaces, rather than estimating them independently, the thickness of the gravels and the soil layer have been estimated from the borehole data and the absolute elevation of the surfaces determined relative to the LiDAR ground surface data.

There are no measured values of the hydraulic properties of the deposits. The hydraulic conductivity of the gravels and soils is assumed to be homogeneous and isotropic in the horizontal. A vertical to horizontal anisotropy is considered in both materials. Specific yield is assumed to be homogeneous. Typical values for hydraulic conductivity and specific yield for the gravels have been used initially based on the results of extensive testing in similar river terrace deposits, namely those carried out at Hoveringham Quarry, Nottinghamshire by Goodman (1999), and on other relevant studies (Wilson, 1983; Riches, 1994; Spang, 1995). An essential element of the drainage system at the quarry is the presence of lower permeability bunds, emplaced to restrict water movement to drained, working areas. The hydraulic conductivity of the material comprising these structures is difficult to determine *a priori*, and have been estimated by model calibration.

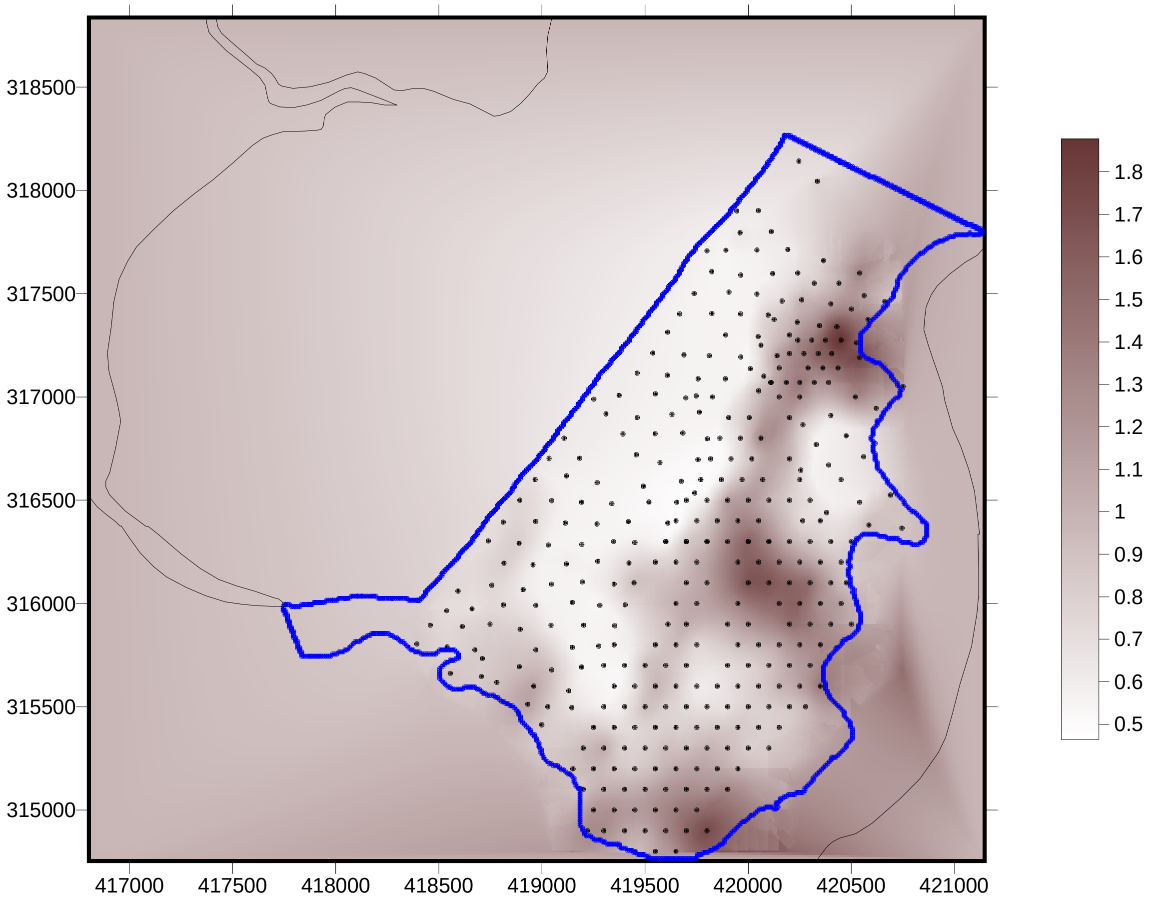

FIGURE 21 *- Image map showing the thickness of soil (metres) within the model domain. The model boundary is shown in blue and surrounds the location of borehole data. An outline of the outcrop of Mercia Mudstone is also shown.*

Potential evapotranspiration measured at the nearby Cherry Holme coppice (Read, 2003) was estimated as 45 mm per year. The total direct recharge from rainfall is estimated to have been between 0.752 mm per day and 0.914 mm per day calculated using the Penman and Grindley soil moisture accounting method. Crop coefficients used were those recommended by the Food Agriculture Organization of the United Nations (FAO) to represent simple grassland, trees and urban areas. Three years of rainfall data are available from the Cherry Holme Coppice site in addition to the data provided for Lichfield in 2002-2003 by the Environment Agency.

Abstraction from the aquifer is taken to be up to the licensed 1.5 Mm^3 per year, and its location has been determined by the current dewatering arrangements at Barton East Quarry.

There are no long-term monitored boreholes in the gravels within or close to the study area, and so water level data has had to be taken from the LiDAR data, which gives only a snapshot on one day. There is a lot of standing water in the area and the river level is readily discernible. River level data are available at Yoxall and Drakelow for 2002 and 2003.

NUMERICAL MODEL

The numerical model representing conceptual model is based upon a finite difference modelling package using a preconditioned conjugate gradient solver. Since the model has to account for steep changes in elevation, a relatively small grid size of 10 m × 10 m has been employed. The model has two separate layers representing the gravel deposits and the overlying soil (where it exists). The ground surface elevation was determined by averaging the LiDAR data locally on each grid cell and removing non-topographic surface features.

NUMERICAL MODELLING ACTIVITY TO DATE AND FURTHER INVESTIGATIONS

Accurate calibration of the model has been made difficult by the lack of recorded water level data. However, the aquifer is thin, which provides well-defined limits to the water levels, and the levels to which the site is dewatered under the current pumping and drainage regime are well known at specific locations. Furthermore, the existence of a large number of standing water bodies allows some calibration albeit only at one point in time. At present, a pseudo steady state model has been produced and is being calibrated using the present dewatering scenario. An example of the water level distribution predicted by the model is shown in figure 22. The effect of dewatering pumping and the low permeability bunds can be seen clearly.

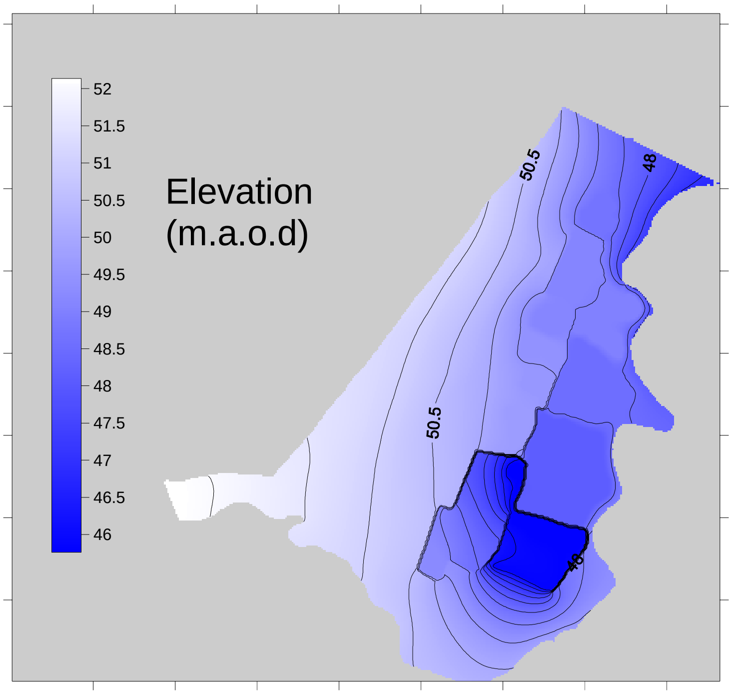

***FIGURE 22** - Groundwater level distribution predicted by the current model under steady-state conditions.*

Data preparation for the model has been organised so that the dewatering regime can be changed relatively easily and that the excavated areas can be augmented. A number of possible future dewatering scenarios will be simulated to demonstrate how the model could be used in the planning of further excavation and archaeological investigation. Full results of the model calibration and modelled scenarios will be included in the final project report.

Acknowledgements

The authors would like to thank Hanson Aggregates UK for allowing access to site investigation borehole records, and particularly to Bob Woodbridge for invaluable help and allowing access to the site and to Roy Bishop for sharing his unparalleled knowledge of the day to day operation of Barton Quarry. Thanks are also due to Dr Peter Hedges and Katy Read of the University of Aston for supplying meteorological data from the experimental weather station at Cherry Holme, and to Andy Malliber for allowing undergraduate students to work on his land during the summer of 2003.

APPENDIX: Data CD Contents:

- Digital geological maps – shape files and images
- Digital representation of base of gravel deposits determined from extensive borehole data
- Digital representation of top of gravel deposits from borehole data
- Digital representation of ground surface
- Rainfall records for Lichfield during 2002
- River level records for the Trent at Yoxall during 2002
- Evapotranspiration records for Cherry Holme coppice during 2002
- Estimated, spatially distributed, recharge data for the year 2002
- Licensed abstraction from Barton East Quarry
- Current internal (intra lagoon etc) pumping regime at Barton East Quarry