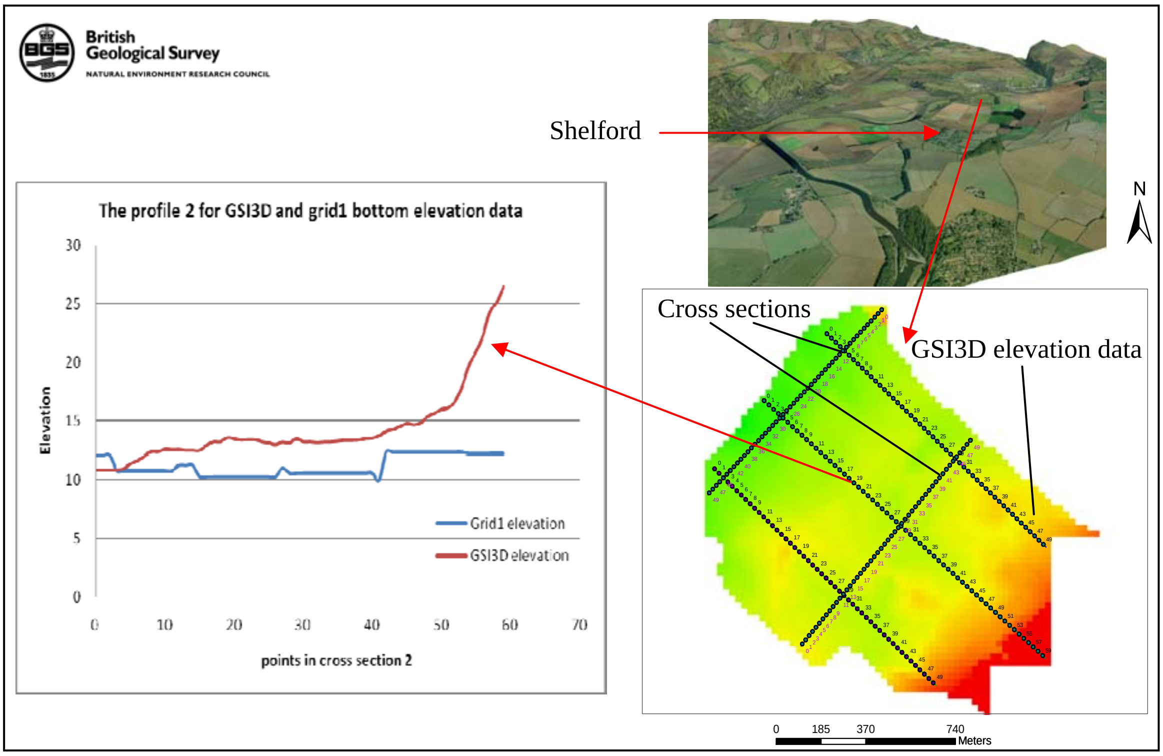
Riverine floodplain groundwater flow modelling – the case of Shelford (UK)

Sustainable Soils Programme

Internal Report IR/09/43



BRITISH GEOLOGICAL SURVEY

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INTERNAL REPORT IR/09/43

Riverine floodplain groundwater flow modelling – the case of Shelford (UK)

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Keywords

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SW corner 455000,322500
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NE corner 485500,361500

Front cover

Cross sections for the comparison of GSI3D and ZOOM Zbase elevations.

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Summary

This report describes a groundwater flow modelling study in the Shelford area, which is located on the riverine floodplain of the Trent Valley. The work was undertaken as part of the BGS Sustainable Soils research programme.

The purpose of this study was to establish a regional groundwater flow model using a ZOOM family of groundwater models for a shallow superficial aquifer lying on the impermeable Triassic bedrocks of the Trent Valley, in order to help understand the groundwater flow processes in riverine floodplains which are prone to groundwater flooding.

This was achieved by setting up a single layer groundwater flow model adopting ZOOMQ3D, and a distributed groundwater recharge model using ZOODRM. The time span of these two models was from 1/1/1970 to 31/12/2007. The groundwater model has three ZOOM grid levels, i.e., grid 1 (250 m × 250 m), grid 2 (50 m × 50 m), and grid 3 (25 m × 25 m). The elevation data of the base of the ZOOM grid was from GSI3D model. Particle tracking was carried out using ZOOPT.

This comprehensive groundwater flow modelling study can be a starting point for (i) understanding the groundwater processes in the study area; (ii) providing a platform for studying contaminant transport in the groundwater regime; and (iii) helping calculate the groundwater flood hazard.

1 Introduction

Groundwater processes in superficial deposits play important roles in groundwater flooding and soluble contaminant transport in low-lying riverine floodplains. However, the effect of superficial deposits on groundwater flooding in low-lying areas is not well understood.

The aim of this project was to carry out a regional comprehensive groundwater flow modelling study at Shelford in the Trent Valley, in order to build up a platform for calculating groundwater flooding hazard, and investigating the transport of nitrate in the riverine floodplain of the study area.

The study area is located in the Trent Valley between Nottingham and Newark (blue rectangle in Figure 1). The River Trent is one of the major rivers in England. From its source in Staffordshire, the river flows through the Midlands until it joins the River Ouse at Trent Falls to form the Humber Estuary, which empties into the North Sea to the south of Hull and Immingham. Situated on the floor of the Trent Valley, Shelford is protected from flooding by comprehensive flood protection.

Groundwater flooding is the result of water rising up from sub-surface permeable strata, and is often characterised by long flood durations. The locations more prone to groundwater flooding are low-lying areas underlain by permeable aquifers. Therefore, it is necessary to set up a groundwater flow model in the Shelford where groundwater flooding is an issue.

In addition to being at risk of groundwater flooding, the Shelford site contains high levels of nitrate in the soil and water. A groundwater sampling study in Shelford shows that nitrate concentrations at most sample locations exceed the 50 mg NO3/l limit of the EU Water Frame Directive (WFD). In order to meet the environmental objectives of the EU WFD by 2015, it is timely to study the complex processes of agricultural diffuse water pollution (ADWP), especially for nitrate, in the phases of source-pathway-target in the shallow riverine superficial deposits where intensive agriculture occurs. This study would provide a valuable platform for carrying out further ADWP investigations for the prevention or remediation of ADWP.

The report has the following structure: the second part of this report describes the conceptual groundwater flow model; the third part presents the regional distributed groundwater recharge estimation using ZOODRM; the fourth part shows the process of regional groundwater flow modelling and particle tracking; the fifth part explains the results; and the last part are conclusions and the suggestions for further study.

2 Conceptual Groundwater Flow Model

2.1 SUPERFICIAL AQUIFER

The geology of an area influences both groundwater and surface water processes. In the study area the geology can be divided into three tiers: bedrock at the bottom, unconsolidated superficial or drift deposits in the middle, and a relatively thin layer of man-made and disturbed material at the surface. The bedrock of the Nottingham area includes a wide variety of sedimentary rocks, ranging from conglomerates, sandstones, siltstones and mudstones to limestone, coal and gypsum. The age of deposition is broad, spanning from the late Carboniferous to the early Jurassic period (Charsley et al., 1990). Superficial deposits recognised in the district include till, sand and gravel, silt, clay and organic material.

The riverine superficial deposits in the Trent Valley form an important local aquifer in the area. Their average depth is 4.8 m, ranging from 1.5 m to 20.5 m. Their relationship to the bedrock in the Trent Valley is shown in Figure 2. Superficial deposits, such as “sand and gravel”, and “clay, silt, sand and gravel”, have much higher hydraulic conductivities than main bedrock formations. Hence the system was modelled as an unconfined shallow superficial aquifer overlaying impermeable bedrock. As all the drift deposits shown in Figure 2 have similar permeability, they were treated as a homogenous unit, with a single hydraulic conductivity value across this one-layer unconfined aquifer. The spatial distribution of superficial deposits in the area is shown in Figure 3.

2.2 HYDROLOGICAL CYCLE

Rainfall is the major water input in groundwater system. The surface water catchment (Figure 3), which is controlled by topography, gathers runoff and interflow to form streams and rivers. The outcrops of regional impermeable bedrock increase the amount of runoff, thus accelerating the water accumulation process in the surface water catchment of the study area. Within this process, water could be lost by evapotranspiration and plant uptake. Meanwhile, water infiltrates vertically into the ground. After filling up the storage spaces in the unsaturated zone, surplus water recharges the groundwater system. To reflect the hydrological cycle in reality, the groundwater recharge calculation needs to be carried out within the whole of the surface water catchment, which is larger than groundwater flow modelling area.

Interactions between river and groundwater occur in the riverine floodplain of the study area because of the comparatively high permeability of the river beds. In dry seasons, groundwater sustains the river in the form of baseflow, and vice versa during wet seasons. Therefore, a groundwater model capable of simulating these interactions should be adopted.

2.3 BOUNDARY CONDITIONS IN GROUNDWATER MODELLING

Since the superficial deposits in this study overly bedrock formations with very low permeability, the water flow between these two can be ignored. It can be assumed that the water recharge to the shallow aquifer will eventually provide baseflow to the river. As the hydraulic gradient in shallow unconfined aquifers tends to be small, the presence of a big river is thought to be an important boundary condition that dominates the water exchange between surface water and groundwater, and the groundwater flow along the Trent Valley can be ignored. Therefore, the river is the only non-zero flow boundary condition in this groundwater modelling study.

3 Estimation of Groundwater Recharge Using ZOODRM

3.1 INTRODUCTION

Groundwater recharge is an important but complex process of the hydrological cycle. It is necessary to spatially and temporally quantify the variability of aquifer recharge in order to improve the understanding of regional and local groundwater flow systems as well as to prevent pollution of aquifers. The main factors that control groundwater recharge are climate, soil, vegetation/land use, and topography (Fayer et al., 1996; Keese et al., 2005). The groundwater recharge calculated in this study was actual groundwater recharge, which is the water that reaches the water table (Lerner et al., 1990).

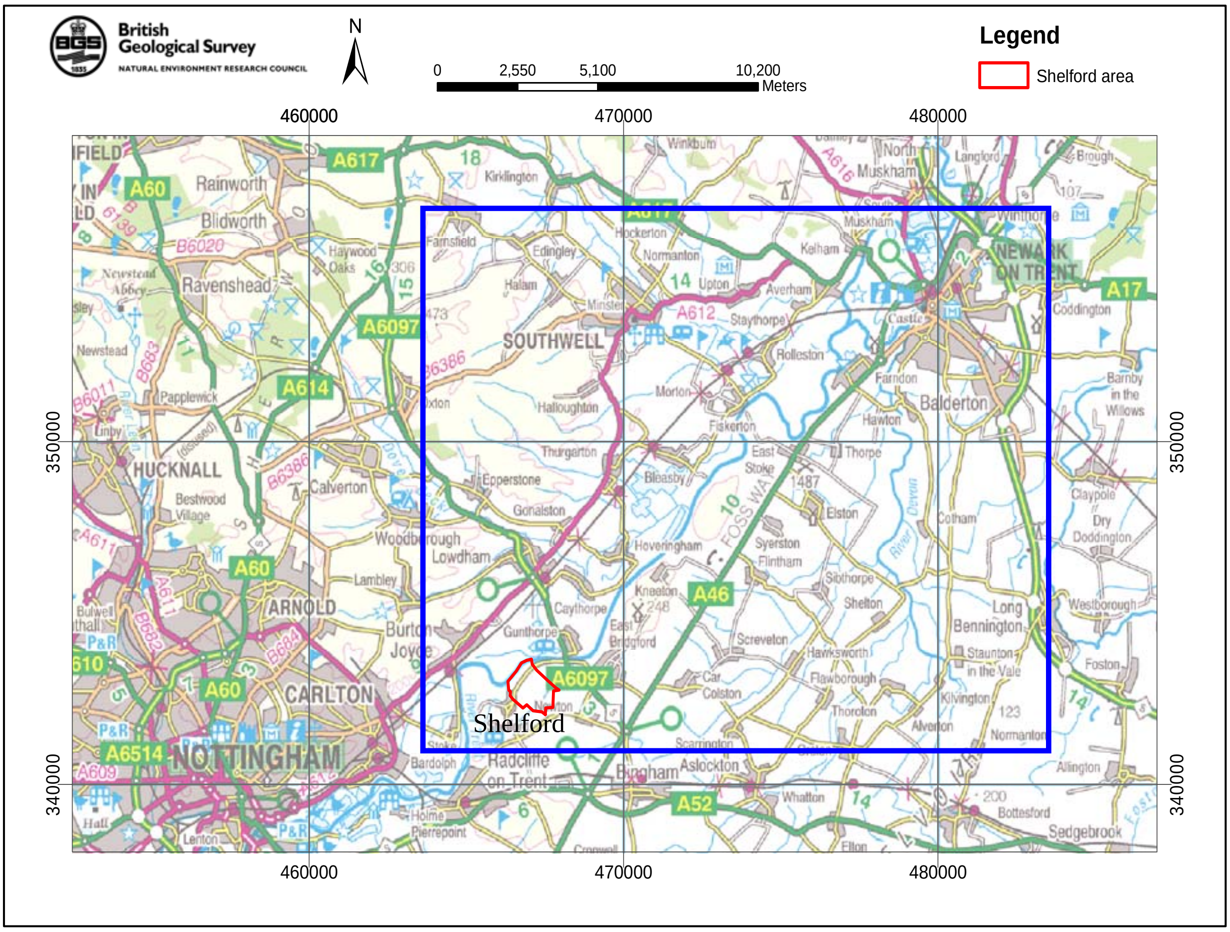

Figure 1. Location of the study area

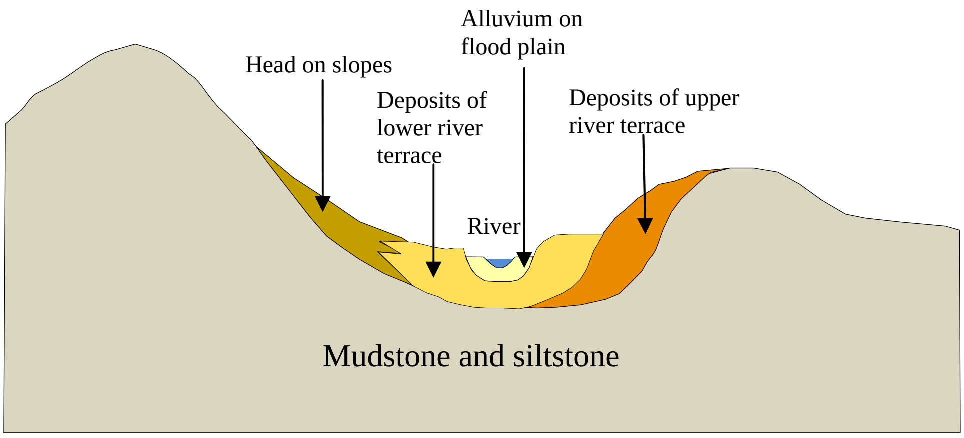

Figure 2. Schematic diagram of geomorphological relationships between drift deposits in the Trent Valley (not to scale)

ZOODRM (Mansour and Hughes, 2004), a distributed object-oriented modelling code, was used to calculate spatial and temporal variations of groundwater recharge. ZOODRM is a member of a ZOOM family of groundwater models, which consists of pre-processor ZETUP, the saturated groundwater flow model ZOOMQ3D, the advective transport particle tracking code ZOOPT, the random walk version of RW_ZOOPT.

ZOODRM is fully compatible with ZOOMQ3D and can be used to produce the time series of groundwater recharge for other groundwater modelling codes. The model applies the soil moisture deficit (SMD) method (Penman, 1948; Grindley, 1967) to calculate the actual evaporation, changes in soil moisture and groundwater recharge.

3.2 DATA SETS

To quantify the complex water cycle in the study area, diverse data sets were collected and entered into the ZOODRM model. These include Digital Elevation Model (DEM) (10 m × 10 m), superficial geology, land cover data LCM2000, surface water catchment boundary, river flow, rainfall data, and the potential evaporation. Aspect and long term average (LTA) rainfall data were derived from the DEM and rainfall data respectively.

3.3 SETTING UP THE GROUNDWATER RECHARGE MODEL

Two 250 m × 250 m cell size ZOOM base grids were created: one for the whole surface water catchment in the area (Figure 3), and one for groundwater catchment covering the superficial deposits of the River Trent only. Both base grids have 50 m × 50 m and 25 m × 25 m refinement grids. The relationship between the grids is shown in Figure 4.

The daily precipitation data of seventeen rainfall gauging stations from 1970 to 2007 were used to calculate the rainfall distribution within the surface water catchment. For missing records, ZOODRM uses a pre-defined substitute gauging station to get the rainfall value at a specified date. The distribution of the LTA rainfall values was calculated from seventeen Theissen polygons generated from the location of the weather stations (Figure 5). Therefore, the daily rainfall at a node is then calculated by multiplying the daily rainfall value at its related gauging station by the ratio of LTA rainfall value, obtained from the map of distributed LTA rainfall values at the node location, to the LTA rainfall at the related gauging station. The average rainfall in the study area is 601 mm/year (1.6 mm/day).

By overlaying the superficial and bedrock maps, seven geological units (both superficial drift and outcrops) were found. The runoff potential of each geology type is assumed to be inversely proportional to its permeability. The values of these runoff potential parameters can be adjusted in calibrating the groundwater recharge model. Table 1 lists the runoff potential for each geological type.

Table 1. The runoff potential for each geological type

Geological type	Runoff potential (%)
Alluvium	10
Diamicton	10
Mudstone, Siltstone, and Sandstone	75
Mudstone, Siltstone, Limestone, and Sandstone	75
Mudstone, Siltstone, Sandstone, Coal, Ironstone , and Ferricrete	75
Sand and Gravel	10
Sandstone and Conglomerate	10

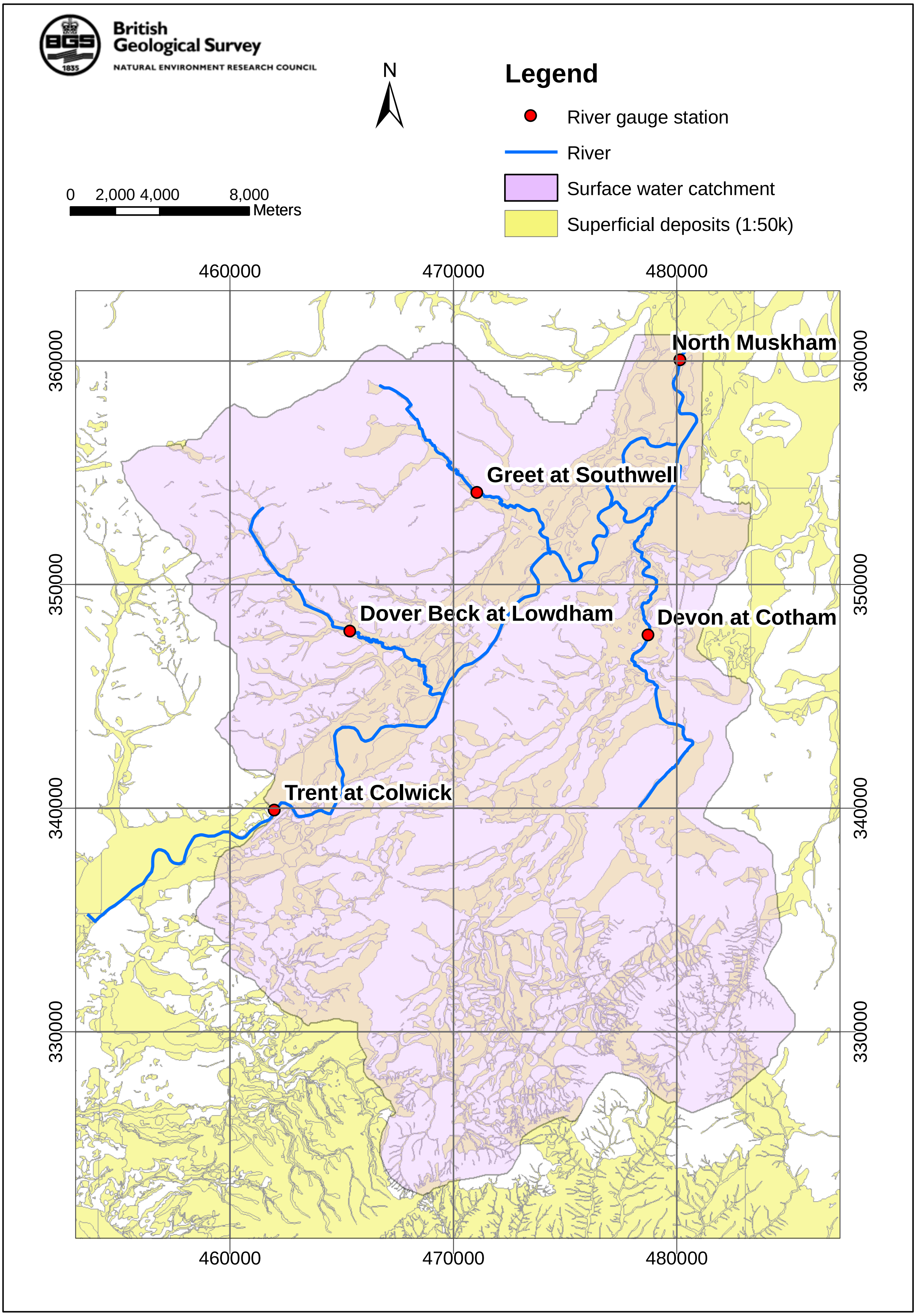

Figure 3. Surface water catchment and superficial deposits distribution in the study area

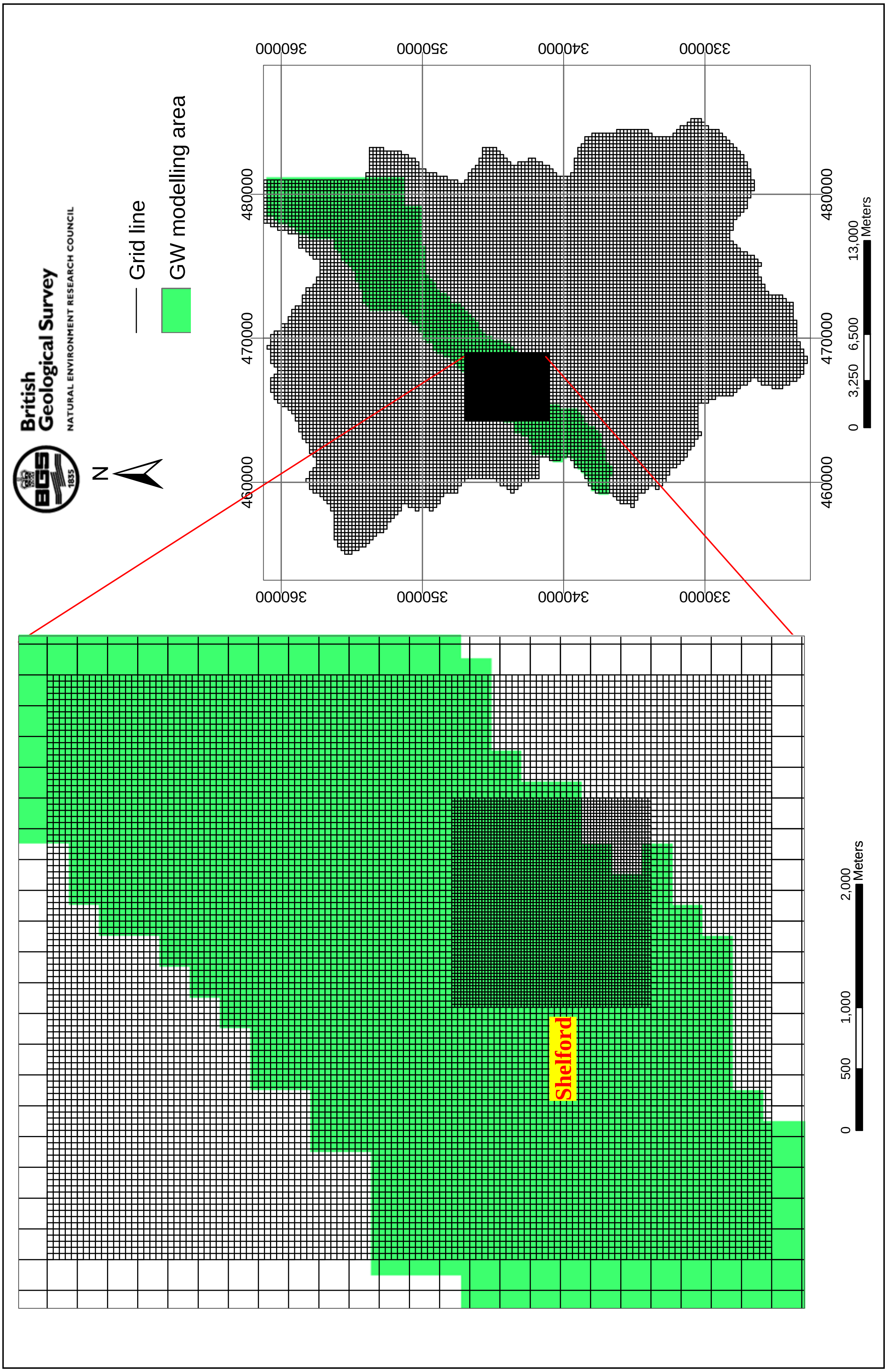

Figure 4. ZOOM grids in the recharge model

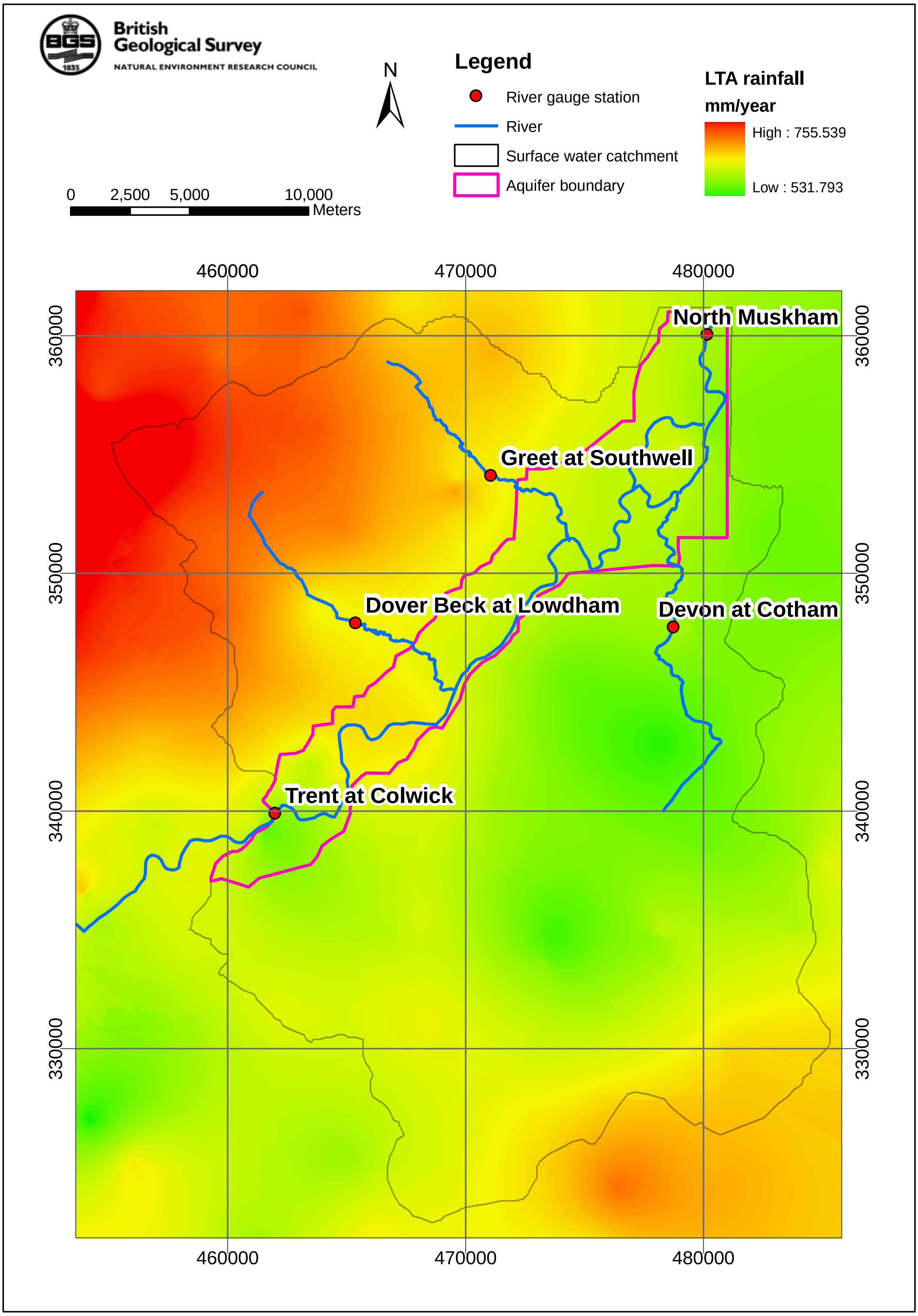

Figure 5. Distribution of the LTA rainfall in the study area

The potential evaporation data between 1970 and 2007 were obtained from the Meteorological Office's MORECS data set for the grids 107, 108, 116, and 117. The average potential evaporation in the study catchment is about 48 mm/month. A 50 m × 50 m aspect raster dataset was generated based on the DEM data (10 m × 10 m). Land use data were from Centre for Ecology & Hydrology (CEH). The values of the root constants (C) and wilting points (D) for the land use types were obtained from Lerner et al. (1990).

The river flows measured at Colwick, Lowdham, Southwell, Cotham, and North Muskham were separated into a groundwater and a surface flow component using the IH low flow method (Gustard et al., 1992). The surface flow component was then used to calibrate the groundwater recharge model by comparing it to the simulated runoff values, and consequently changing the run-off coefficient values until the two datasets match.

The calculated LTA groundwater recharge for the study area is shown in Figure 6. The groundwater recharge for the whole surface catchment is low (between 0 and 7.1 mm/day) except for the comparatively high groundwater recharge value in streams outside of the groundwater modelling boundary. The average value of the LTA groundwater recharge in the groundwater modelling area is 0.26 mm/day ranging from 0 to 2.7 mm/day. The monthly distributions of groundwater recharge between 1970 and 2007, calculated using ZOODRM, can be directly used in ZOOMQ3D for groundwater flow modelling.

4 Groundwater Flow Modelling

4.1 SETTING UP THE GROUNDWATER MODEL

The object-oriented groundwater flow numerical model ZOOMQ3D (Jackson and Spink, 2004), was used in this study. The boundary in the x-y plan was from the extent of superficial deposits in the Trent Valley based on the 1:50 k superficial geological map of BGS. River shape and river stage data were obtained using aerial photographs from BGS and DEM (10 m × 10 m) in ArcGIS. Three levels of ZOOM grids and rivers were created for the one-layer aquifer using ZETUP, namely, ZOOM grid1 (250 m × 250 m; bottom left: 455500, 334750; top right: 481000, 361000), ZOOM grid2 (50 m × 50 m; bottom left: 464250, 341000, top right: 469000, 347000), and ZOOM grid3 (25 m × 25 m; bottom left: 466300, 342000, top right: 468000, 343650). The groundwater model extends over an area of 115.25 km^2, covering the superficial deposits along the Trent Valley for 32.9 km from Colwick in Nottingham to North Muskham near Warwick. The average width of superficial deposits is 3.2 km (Figure 5). The hydraulic conductivity value of this one-layer superficial deposit was set to 20 m/day.

The depth of the alluvial deposits was obtained from the BGS national depth of alluvial deposit inventory. This was used to create the aquifer bottom elevation. In general, the higher the spatial resolution of a raster dataset, the more precise the data are. Since the river stage data were derived from DEM with resolution 10 m × 10 m, while the resolution of the ZOOM base grid is 250 m × 250 m, the aquifer bottom elevation could be above the river stage if the aquifer bottom elevation is created by subtracting the depth of superficial deposits from the original DEM data. To solve this problem, an artificial DEM dataset was generated by interpolating the river stage data using the Kriging method in ArcGIS.

In order to improve the accuracy of groundwater flow modelling in the Shelford area (ZOOM grid3), the detailed Shelford 3D superficial deposit model (1.48 km^2) built using Geological Surveying and Investigation in 3 Dimensions (GSI3D) (Kessler et al., in press) was introduced. A dummy ZOOM grid (25 m × 25 m) was created to convert the Shelford GSI3D to ZOOM format. The geological layers ALV-SACL, HEAD-DMTN, HEAD-SAND, and HPSG-SAGR, were exported from GSI3D to ZOOM models.

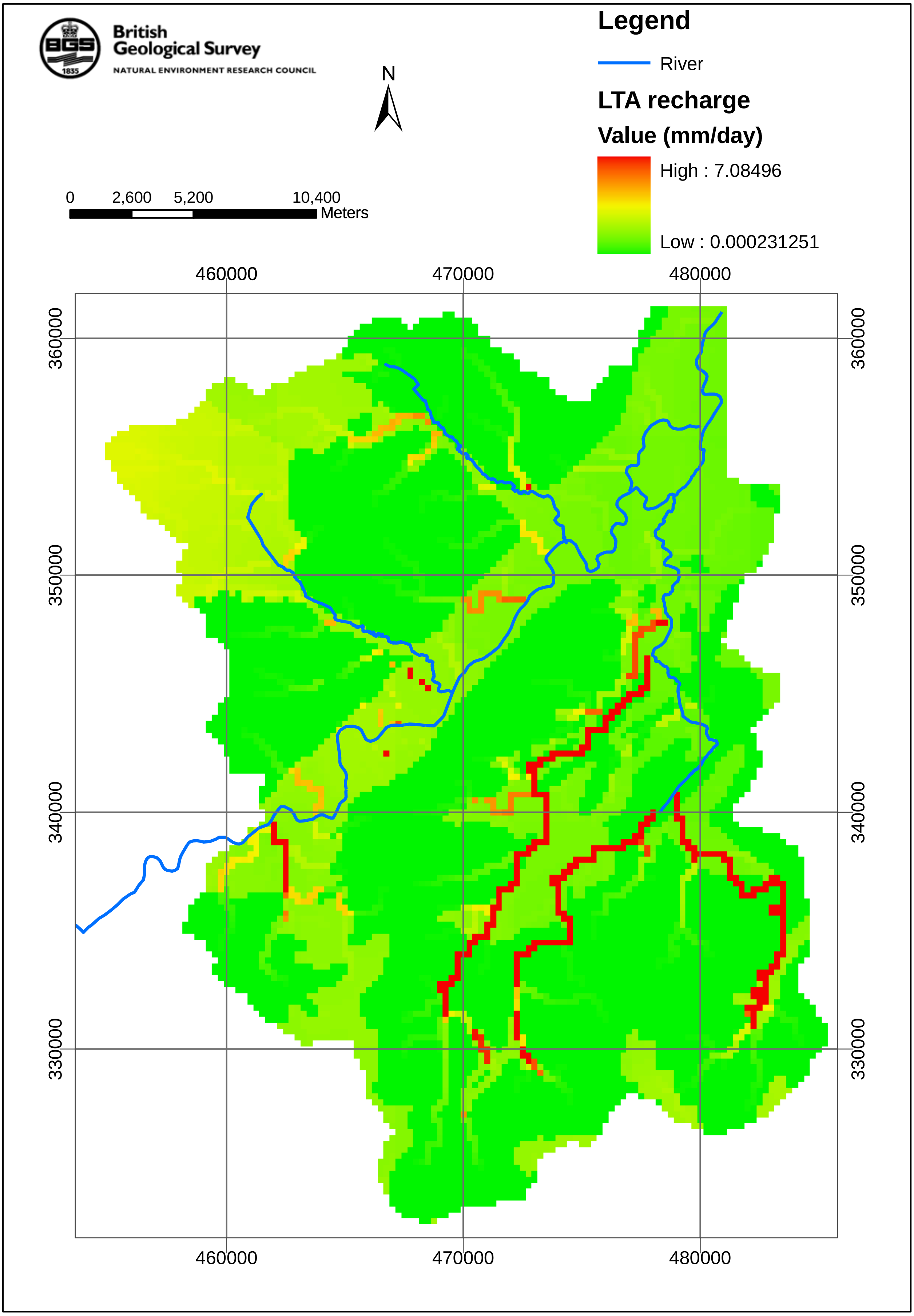

Figure 6. Calculated LTA groundwater recharge in the study area

The GSI3D data was compared with the bottom elevation of the base grid (Zbase) (Figure 7). The GSI3D elevation is more detailed than the Zbase data. It is higher and steeper to the south-east of the grid3 area, and is lower to the north-west of 3D model area. Coupling these two data sets caused two problems: firstly there are gaps (No data) between them because of the limited lateral extent of the GSI3D model; secondly elevation values differ. If two datasets were integrated directly, there would be a high contrast in elevation at the mosaic boundary. Therefore, the “No data” areas between these two datasets were interpolated to allow the gradual changing of elevation values between these two datasets.

4.2 BOUNDARY CONDITIONS

The rivers in such highly permeable shallow superficial deposit are expected to have significant impacts on surface water and groundwater. Intensive interactions between these two through the high permeable sand and gravel river beds are assumed. Therefore, the base and sides of this groundwater model were thought to be comparatively impermeable, and were given no-flow boundary conditions, as explained in 2.3.

The surface water catchment is larger than the groundwater modelling boundary. The runoff accumulation process is considered in ZOODRM. The groundwater recharge calculated using ZOODRM is the water entering the groundwater system from the upstream of the model boundary as baseflow. All river flows simulated by ZOOMQ3D are baseflows.

4.3 PARTICLE TRACKING

ZOOPT was used for particle tracking to indentify the groundwater flow characteristics in the study area, thus helping the understanding of contaminant pathways in the groundwater system. ZOOPT is the particle tracking code associated with the groundwater flow model ZOOMQ3D. The code enables the definition of steady-state and time-variant path lines in three dimensions (Jackson, 2004). The porosity value of the superficial deposits was set to 0.25 in this study. A particle was generated for each cell in the ZOOM grid2.

5 Results

5.1 HYDROGRAPHS

The monthly groundwater recharge values from 1970 to 2007 were used in groundwater flow modelling. In order to compare the simulated and monitored hydraulic heads, the 14 observation boreholes in Shelford were added to the groundwater flow model. Figure 8 shows the distribution of hydraulic heads at the end of 2007. The heads gradually decrease from southwest to northeast, and are strongly influenced by river stage. In ZOOM grid3 (25 m × 25 m), dewatering occurs to the southeast and to a few cells to the north due to the high bottom elevation of the aquifer.

The groundwater flow model was run with two specific yield (S_y) values, 0.1 and 0.2. The hydrographs from the run using $S_y = 0.2$ fluctuate less and match the observed data better than those obtained with $S_y = 0.1$. Figure 9 shows that the simulated heads in borehole 4 and 5 are close to monitored head values.

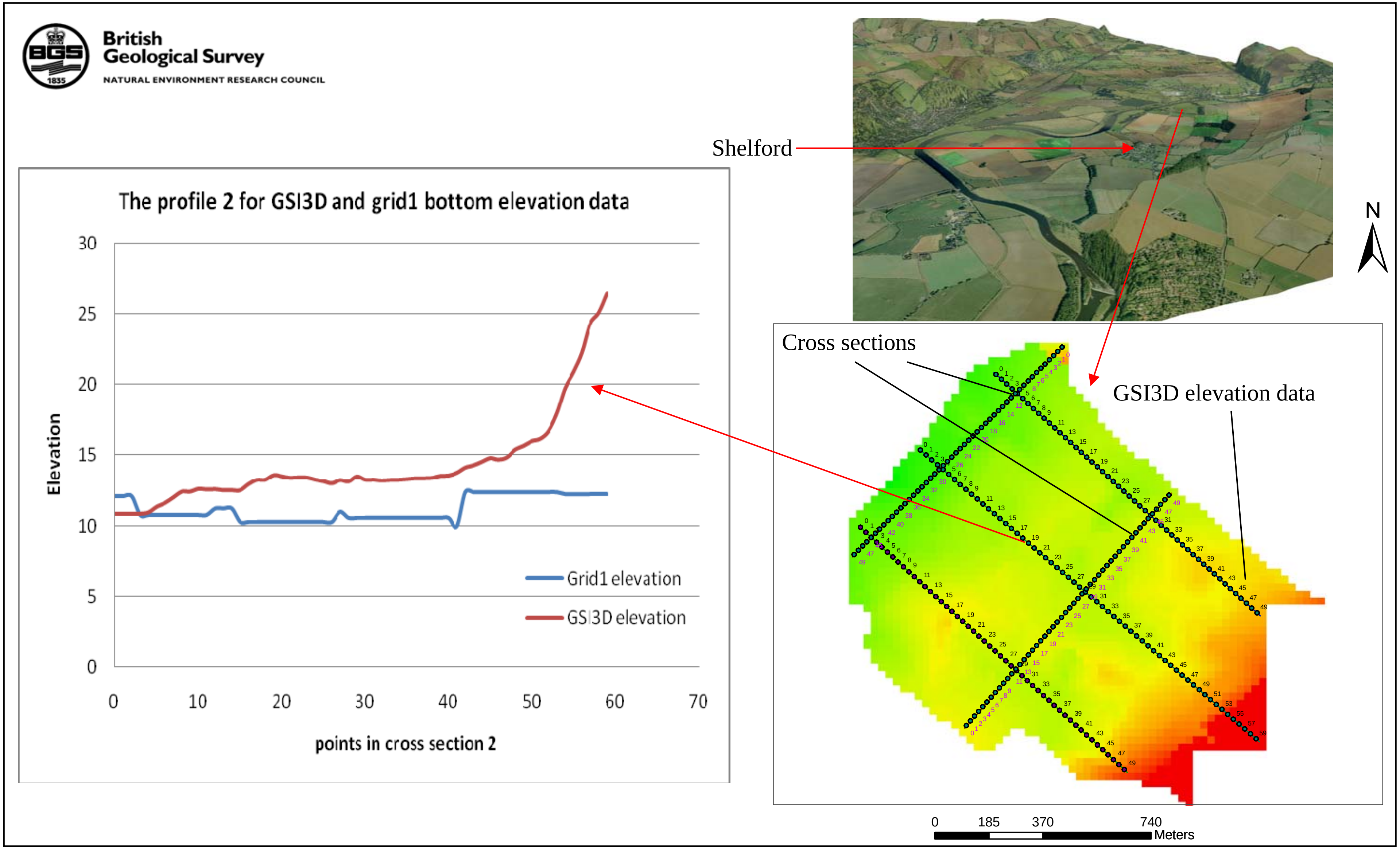

Figure 7. Cross sections of GSI3D and ZOOM Zbase elevations

5.2 PARTICLE TRACKING

Particle tacking was carried out for three periods: 2 years, 10 years, and 20 years. The results show that if contaminants were present in groundwater, they would move towards the river at an overall slow speed (Figure 10 Figure 11) even though the particles near the river move to river comparatively quicker than particles that are far from river. The results also show that the speed of contaminant movement in groundwater is inversely proportional to their distance from river.

5.3 GROUNDWATER FLOODING HAZARD

Flooding adversely affects the Trent Valley. The groundwater flooding hazard in Shelford was calculated based on the simulated hydraulic heads and the elevation of the ground surface. The assumption in this process is that there are no low permeability soil layers above the superficial deposit aquifer.

The groundwater level in the study area was highest on 31/12/2000 and 31/07/2007 (Figure 12). Therefore, the groundwater flooding hazards on these two dates were calculated. In 2000 the areas around Shelford were flooded, especially where subsidence occurs due to coal mining, such as in the northwest of Shelford. The village itself however was not affected by flooding. Figure 13 shows the groundwater flooding hazard on 31/12/2000. The groundwater flood hazard in Shelford itself is low (about 0.5 above the ground surface), while in the area around the stream to the northwest of Shelford it is high (about 3.8 m above the ground surface). It is important to clarify that a positive value of flooding depth does not necessary correspond to an occurrence of groundwater flooding. For example, in Shelford, the superficial deposits are covered by 0.5 m clay layer, which could stop the water reaching to the ground surface to some extent. Figure 14 shows that Shelford town and the surrounding areas had a low groundwater flooding hazard on 31/07/2007 (about 0.5m above the ground surface) except for rivers, streams, and ditches around Shelford with 2.5 m above the bed of river / stream / ditch. The model predicts that groundwater entered the surface water cycle in the form of baseflow on 31/07/2007, and that the rise in river stage could subsequently have resulted in fluvial flooding in some areas.

6 Conclusions and Suggestions

6.1 CONCLUSIONS

The groundwater flow model set up using the ZOOM family of models covers the whole hydrological cycle in the study area, thus helping our understanding of the groundwater system in shallow superficial deposits overlaying impermeable bedrocks in the Trent Valley.

The spatial-temporal groundwater recharge time series calculated using ZOODRM shows that the average value of the LTA groundwater recharge in the groundwater modelling area is 0.26 mm/day with a range of 0 – 2.7 mm/day between 1970 and 2007.

The particle tracking results indicate that soluble pollutants travel towards the river at an overall slow speed; the speed of particles is inversely proportional to their distance to the river.

The groundwater flow model set up in this study can be used for groundwater flooding hazard calculation. The groundwater flooding hazard results show the possibilities of groundwater flooding when groundwater level is high.

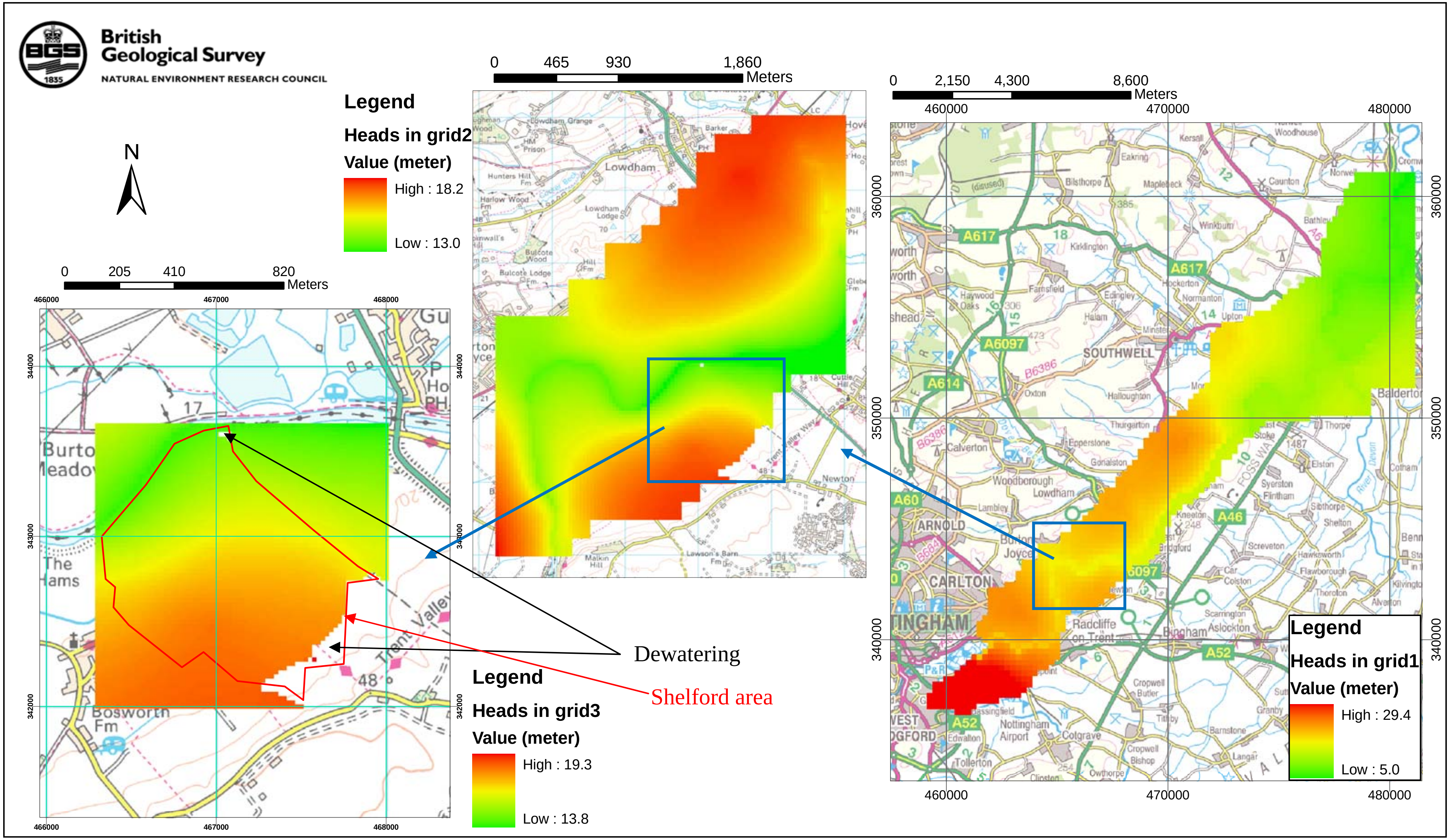

Figure 8. Distribution of simulated hydraulic heads at the end of 2007 using ZOOMQ3D

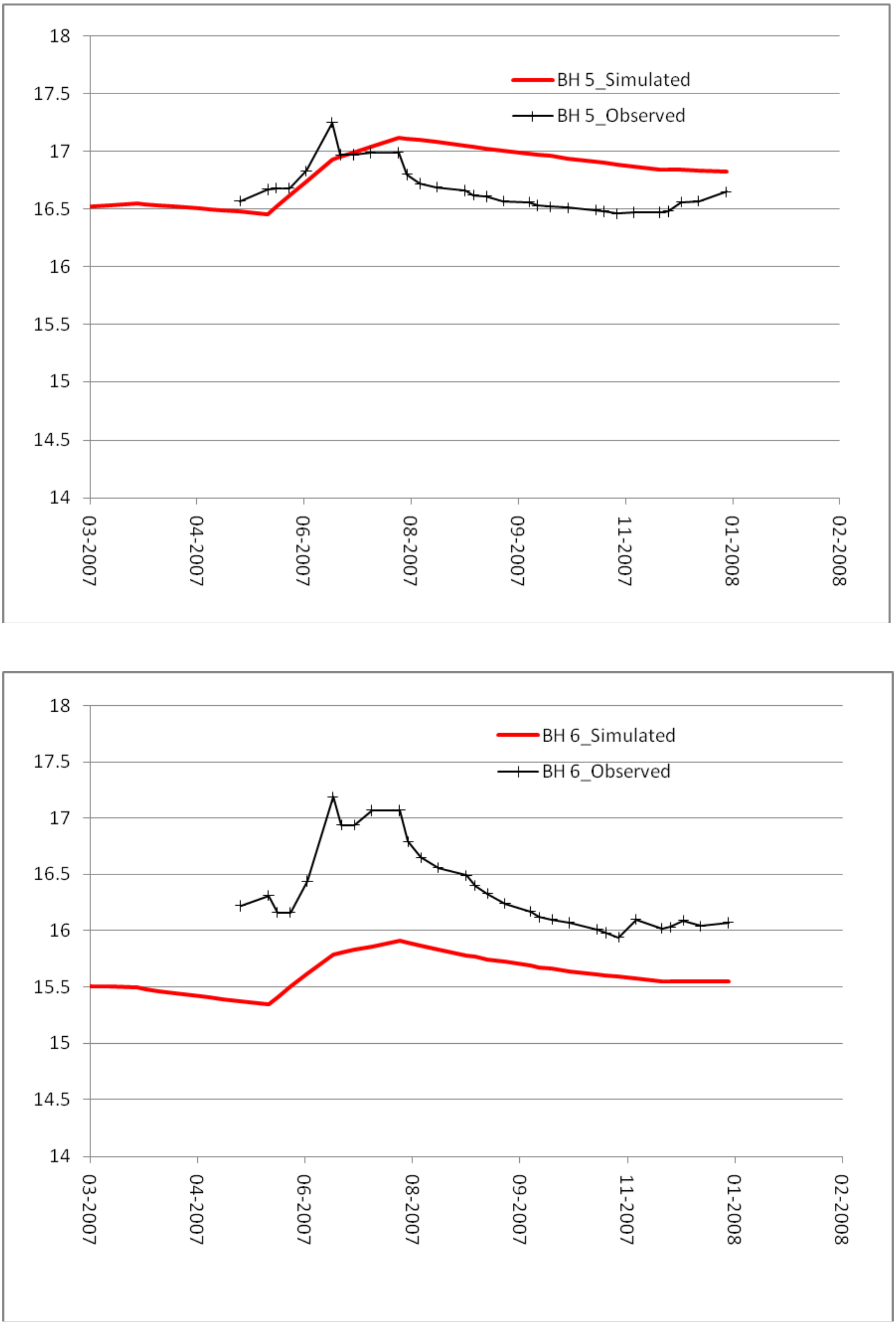

Figure 9. Comparison between simulated and observed hydrographs at borehole five and six

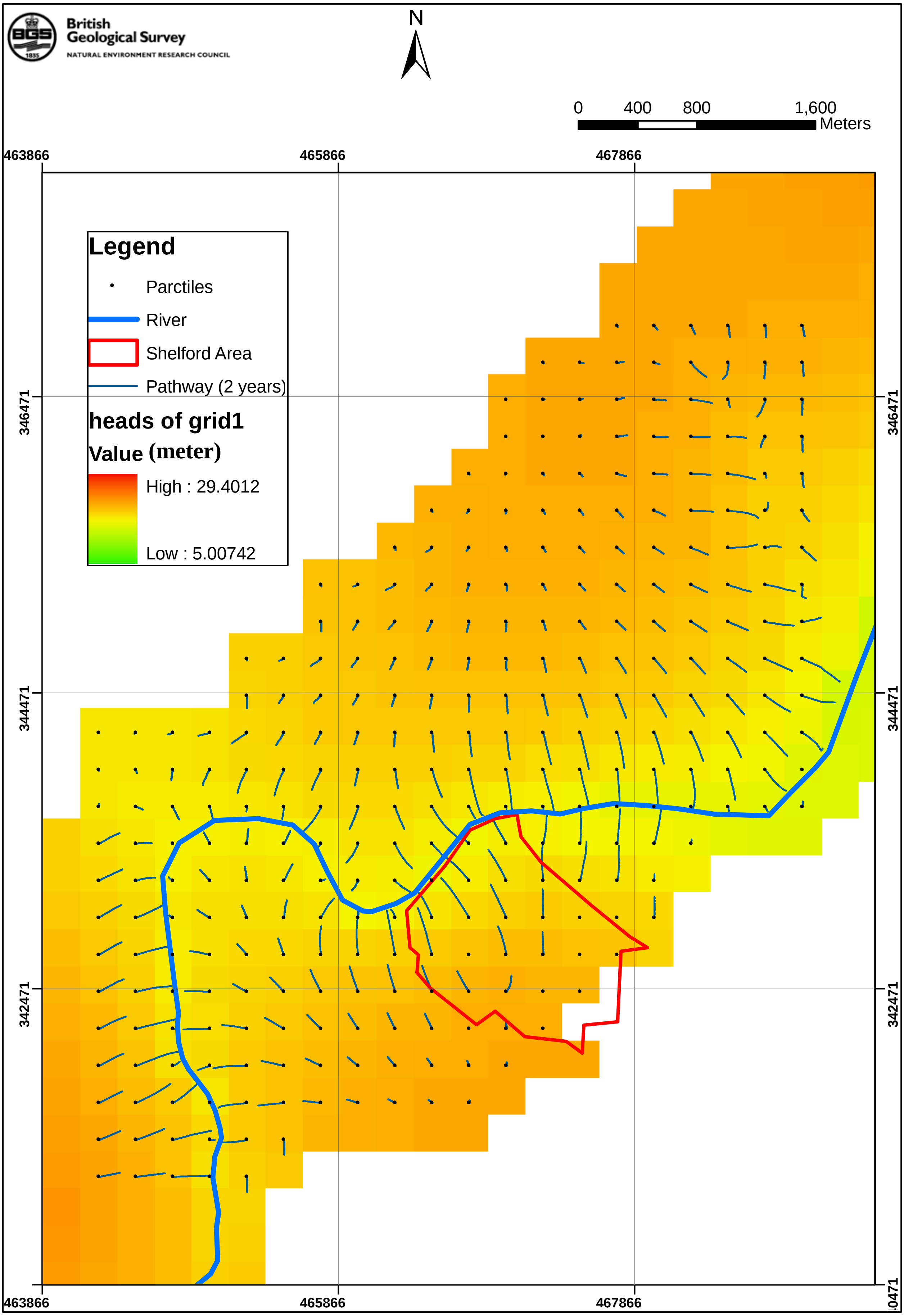

Figure 10. Two-year particle tracking result using ZOOPT

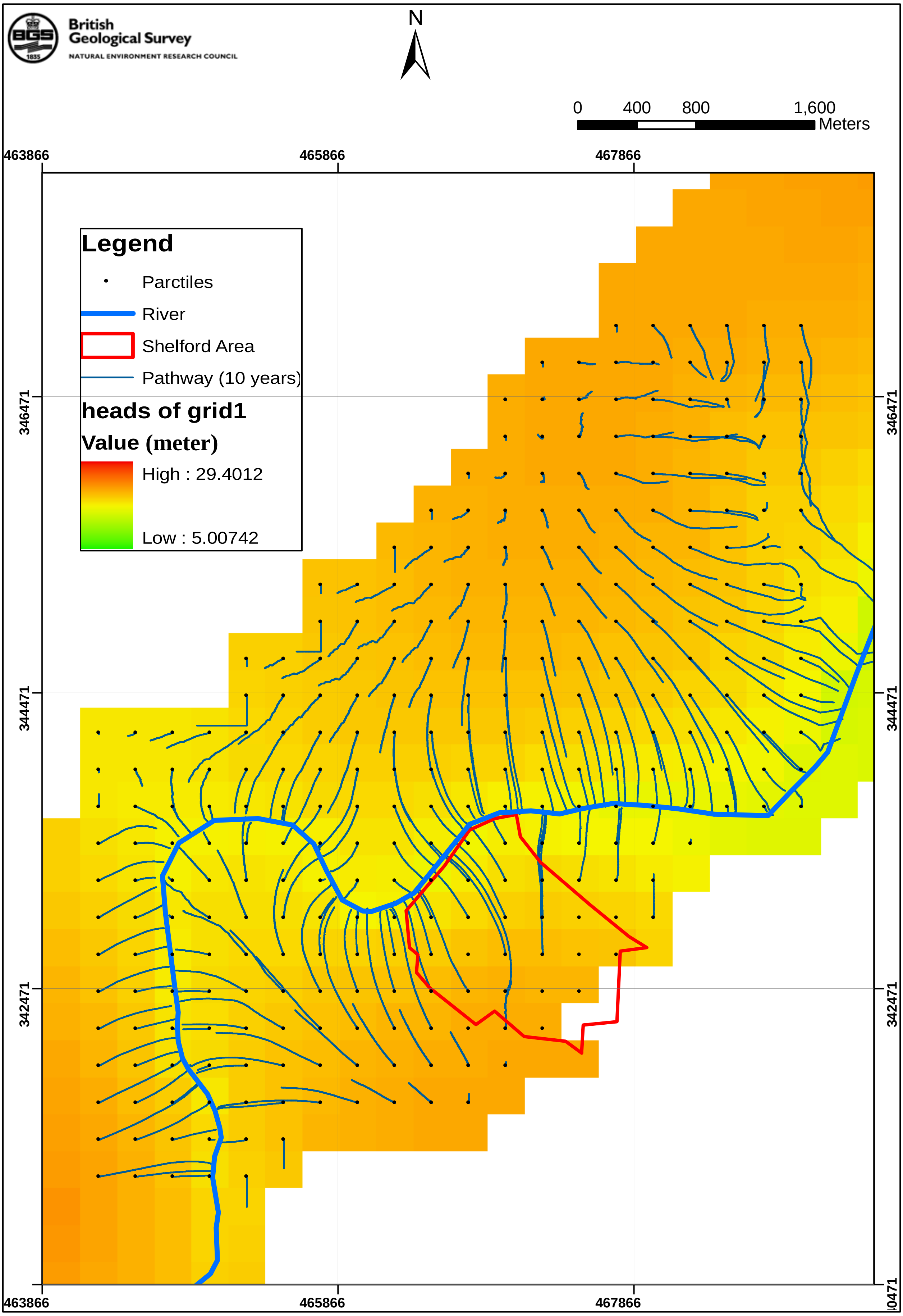

Figure 11. Ten-year particle tracking result using ZOOPT

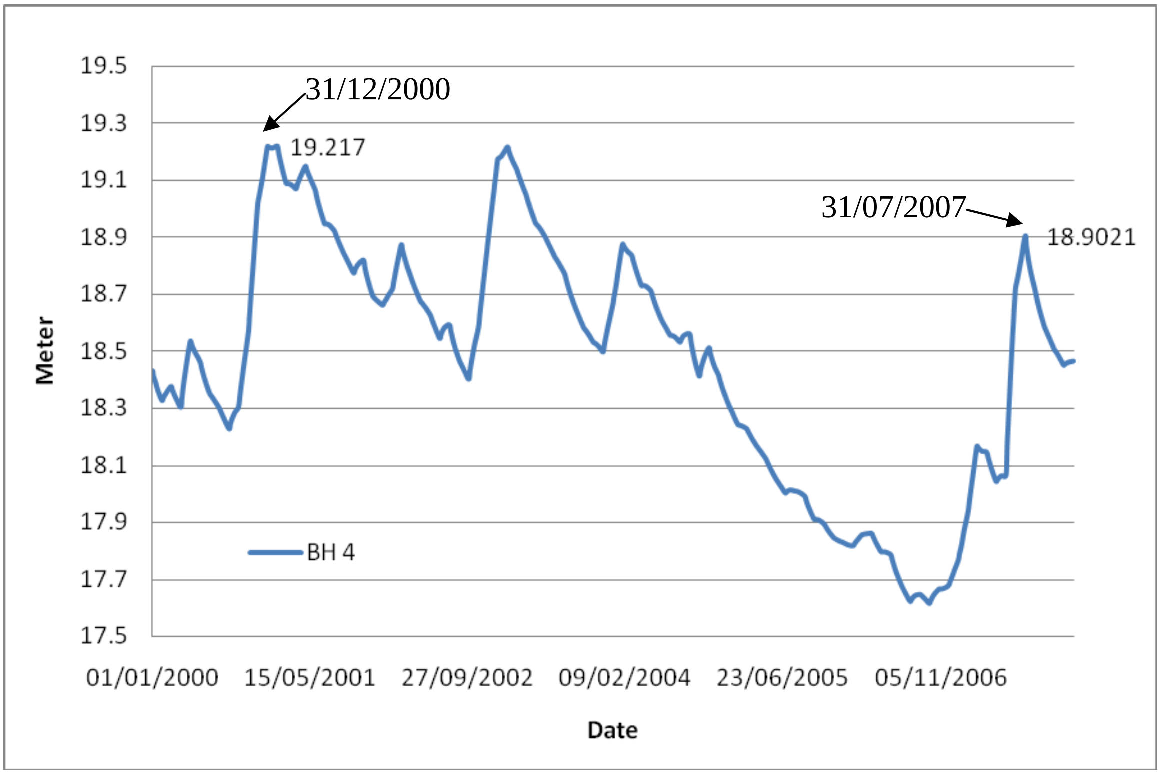

Figure 12. The groundwater hydrograph of borehole four

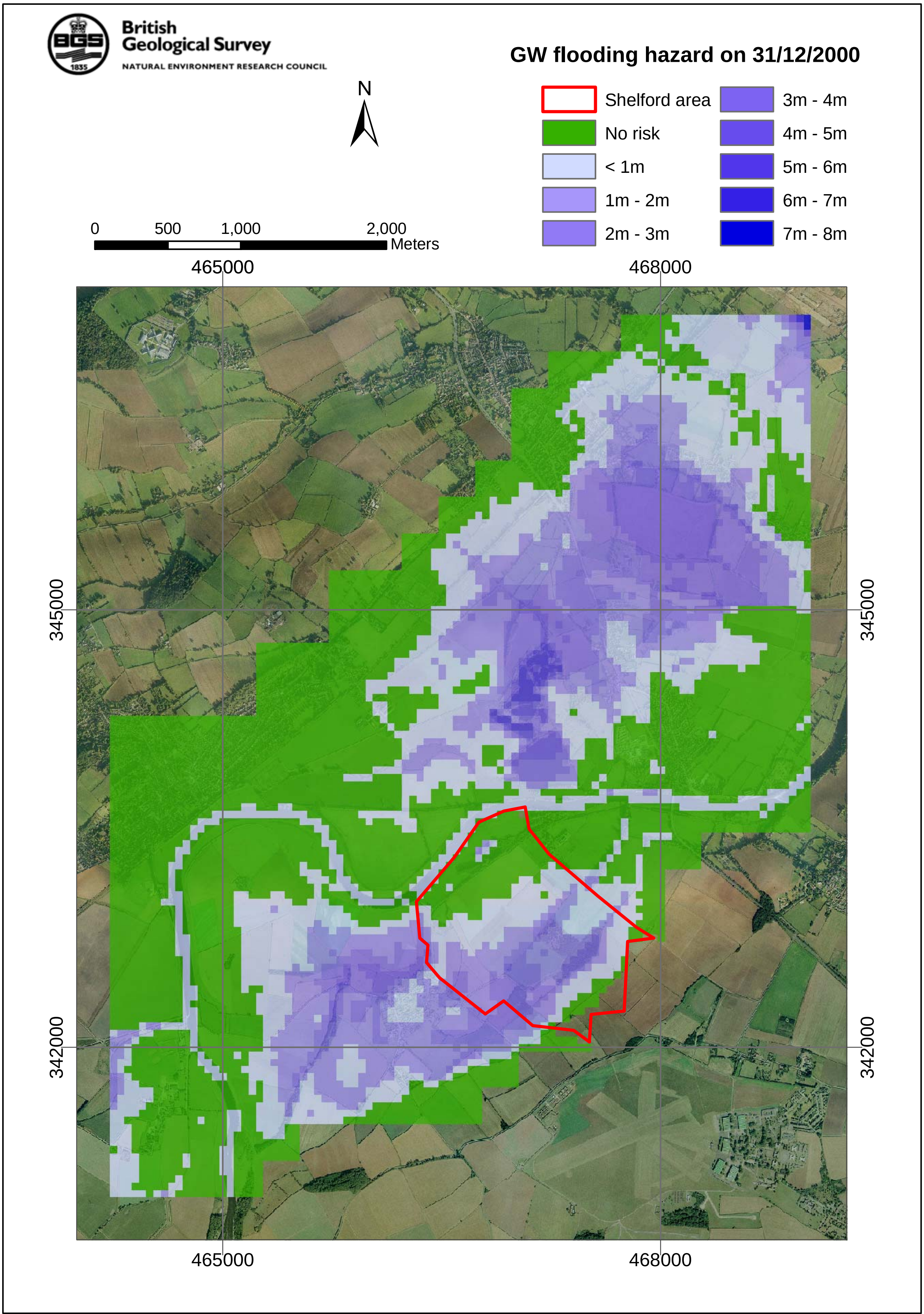

Figure 13. Estimated groundwater hazard on 31/12/2000

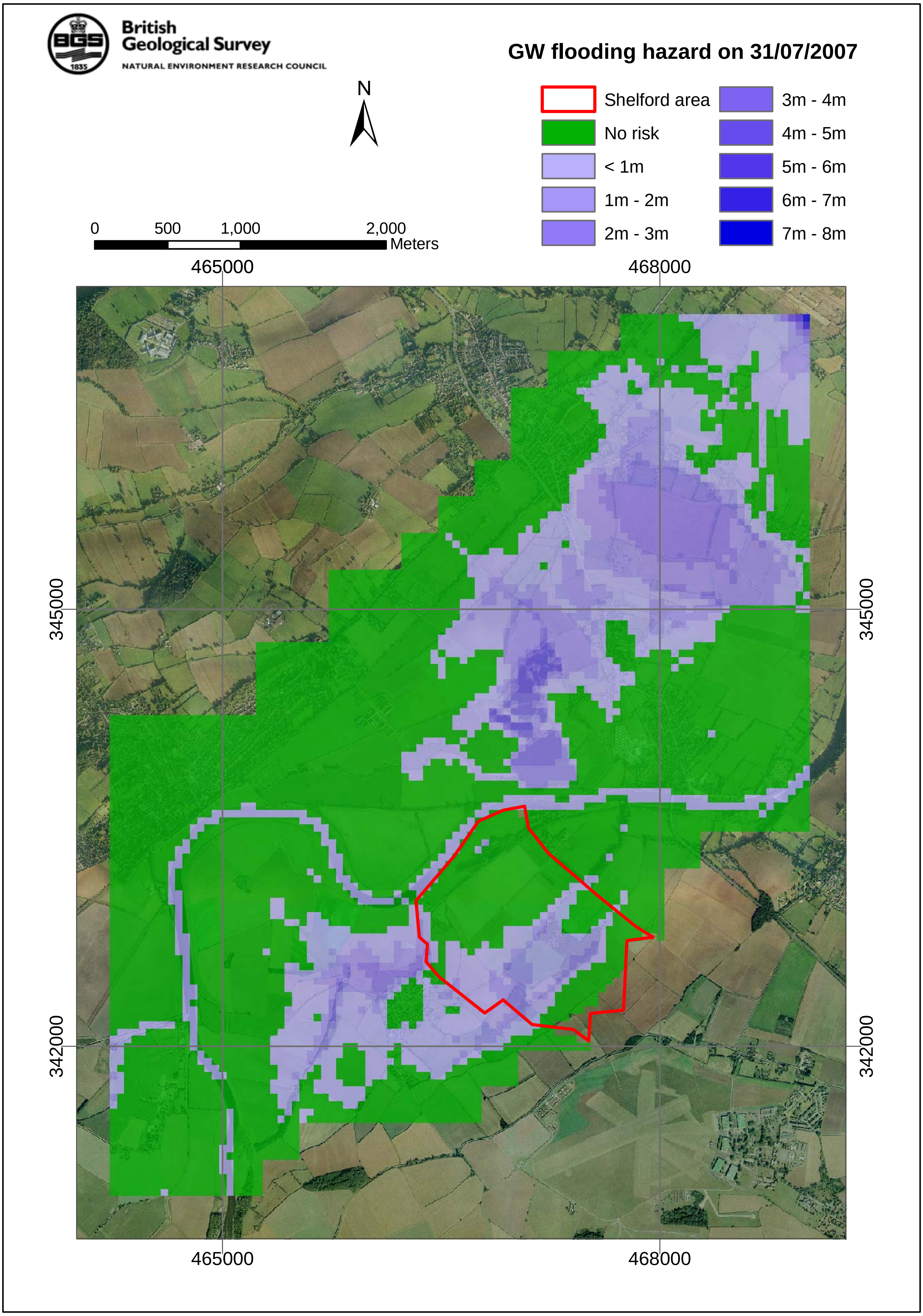

Figure 14. Estimated groundwater hazard on 31/07/2007

6.2 SUGGESTIONS FOR FUTURE WORK

Water abstraction in the Trent Valley is one of the important components in the whole hydrological cycle in the area. It is necessary to get accurate abstraction data in the study area from the Environment Agency (EA) for the water balance calculation for more detailed groundwater recharge model calibration.

Currently, the groundwater level data from boreholes in the small area around Shelford, cover a short period of time, from the middle of 2006 to 2008. In order to verify the groundwater flow model over its entire duration from 1970 to 2007, the regional groundwater level data with longer monitoring history are required for further study.

Since the river stage data used were from DEM data of a single year, the river boundary condition is a static one. Time variable river stage data are necessary for more accurate groundwater flow simulation.

Agricultural activities are major sources for groundwater nitrate pollution in the shallow unconfined aquifers of the Trent Valley. The groundwater nitrate pollution hazard maps could be generated using an index method.

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