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Towards an upscaled model of aquifer recharge through glacial drift deposits, Shropshire, UK

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Abstract Recharge through the glacial drift, which covers significant areas of the United Kingdom's aquifers, is a potentially important component of the groundwater inflows to the underlying aquifers. However, its estimation has largely been based on rather crude assumptions based on the available drift maps, which present few data on the thickness or variability of these materials. Invasive and non-invasive field investigations in Shropshire UK, have shown the significance of the lateral and vertical variability of the glacial drift in the vicinity of the Potford Brook and Platt Brook catchments. The gathered data have been used to develop conceptual models of the heterogeneity of the drift materials and these have formed the basis for numerical models to assess the impact of the heterogeneity of the drift formations on the recharge to the underlying Triassic Sandstone. Interference between the vegetated soil layer and the underlying clay materials leads to marked differences in the recharge estimates for the alternative conceptual models. Recharge rates are found to vary between 0.9 and 200 mm year^{-1} for the materials mapped as the same type in the current drift mapping. The numerical results are providing valuable information on the required form of an upscaled recharge model.

Keywords electrical resistance tomography; glacial drift; numerical modelling; recharge; Triassic Sandstone; UK; upscaling

INTRODUCTION

Glacial drift covers significant areas of the major and minor aquifers of the United Kingdom. Drift maps, readily available from the British Geological Survey, provide evidence of the extent of the glacial drift cover and to some extent the vertical thickness, although the latter is of lower accuracy. The composition of the formations is not well characterized by the mapping and the spatial variation of the recharge that enters the underlying aquifers has received little attention. Simplified recharge models based on estimates of the hydraulic conductivity of the predominantly clay materials and the presumption that a unit hydraulic gradient exists vertically through the clays have been typically employed to predict the annual recharge rates (Mackay *et al*., 2001). The resulting recharge has been improved through calibration of this component of the water balance of the underlying groundwater systems. However, this approach may not prove to be robust for predictive modelling of the groundwater system response to climate change or land use change impacts. A study, funded by the UK Natural Environment Research Council, is underway to explore the possibility of developing an improved methodology for the determination of drift recharge. The strategy for the study is based on successive scale refinement through field investigations, coupled with successive refinement of the conceptual models of the glacial drift structure. The study is working progressively from the kilometre scale using relatively broad-brush survey techniques, through to the decimetre scale requiring detailed experimental methods and analyses. Each phase of refinement is supported by a simulation programme to interrogate the alternative conceptual models identified from the data, which describe the structure of the drift in the study area and its implications for recharge. The preliminary recharge results presented here are applicable to the intermediate stage of refinement at the hectare scale and are derived from detailed electrical resistance tomographic data. These results are being used to define the required form of the upscaled modelling for use with a regional groundwater model.

THE STUDY AREA

The study area comprises the surface water catchment of the Potford and Platt Brooks, tributaries of the River Tern in Shropshire, UK, to above a gauging station at Sandyford Bridge (National Grid Reference: SY 635 222). The location of the study area and the mapped drift areas are shown in Fig. 1. It is a lowland catchment covering 22.5 km^2 with low relief and undulating terrain underlain predominantly by a Permo-Triassic sandstone aquifer with a covering of drift (superficial deposits) generally less than 10 m thick. The drift is dominated by glacial and glacio-fluvial deposits laid down near the southern limit of the Late Devensian ice sheet (Thomas, 1989), but glacio-lacustrine clays, post-glacial head (solifluxion deposits), river terrace deposits and alluvium are also present in the catchment. Numerous small ponds are observed on the main areas of glacial till and are probably due to historical extraction of clay as a building material.

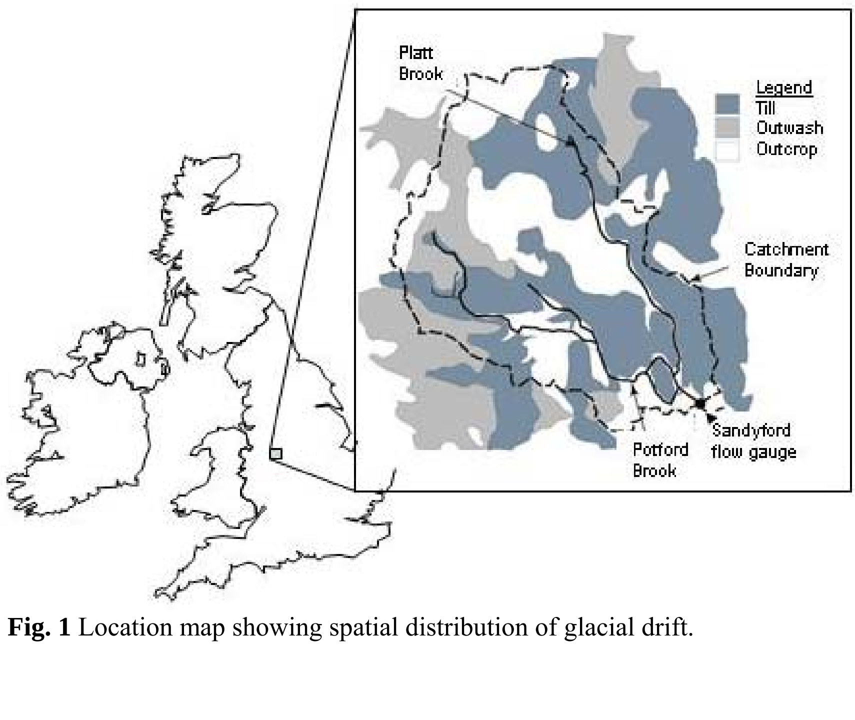

Fig. 1 Location map showing spatial distribution of glacial drift.

The Permo-Triassic sandstone forms an important regional aquifer in the area and underlies the whole of the Potford Brook catchment. Groundwater levels in the sandstone lie between 4 and 10 m below ground level and have seasonal fluctuations of around 0.5 to 1.5 m. Where groundwater levels are monitored within both the sandstone and the drift, the hydrographs indicate that, in some places, the till can effectively isolate overlying sands from the underlying aquifer. In other areas the degree of hydraulic connection between the drift and the sandstone is greater. In some places, pond water levels are highly variable indicating seasonal vertical drainage and refilling, whereas in other areas seasonal fluctuations are much smaller and are likely to be controlled by the balance of evaporation and rainfall/runoff inputs.

DATA COLLECTION AND CONCEPTUAL MODELLING

Characterization of the drift has been undertaken using data from borehole and shallow auger logs and supplemented by detailed investigation of particular features using electrical resistivity tomography (ERT). Inversions from ERT surveys are shown in Fig. 2, which illustrate the local scale variability of the drift. Undisturbed materials have been recovered and subjected to hydraulic, textural and electrical laboratory tests.

The till was deposited by sub-glacial lodgement processes and can reach a thickness of around 8 m. In some places it overlies significant thicknesses of older outwash deposits (Fig. 2(a)) but more often lies directly on top of weathered bedrock. The till comprises silt and clay with sand and gravel contents of 40% to 60% and 0% to 20% by mass respectively, based on analysis of 65 samples. The internal structure of the till is apparently relatively homogeneous on the scale of tens to hundreds of metres with no evidence of significant sand lenses or other discontinuities (Fig. 2(b)). Till covers at least 50% of the catchment but in some areas is only a thin patchy cover (Fig. 2(a)). Data from trial pits and cores indicate that weathering of the till has commonly resulted in oxidation and fissuring in the top 2 to 3 m.

Areas of glacio-fluvial outwash deposits cover around 15% of the catchment. Over much of the area only a thin covering is present, sitting in hollows on the irregular till surface (Fig. 2(b) and (c)) and masking the till surface topography. However, thicknesses in excess of 5 m are found in in-filled channels (Fig. 2(d) and (e)). The outwash deposits vary in lithology from fine sands to coarse gravely sands reflecting complex facies distributions controlled by variations in lateral and distal proximity to the meltwater source through time (Anderson, 1989). Less areally extensive glacio-lacustrine deposits have also been observed in the catchment comprising clean laminated silty clays.

Simplified conceptual models of the possible pathways for flow through the drift sequences are illustrated in Fig. 3, based on the typical features identified from the ERT inversions. These have been used as the basis for two-dimensional flow modelling in the unsaturated zone using the code FAT3D_UNSAT developed and tested at Birmingham University (Ash, 2004).

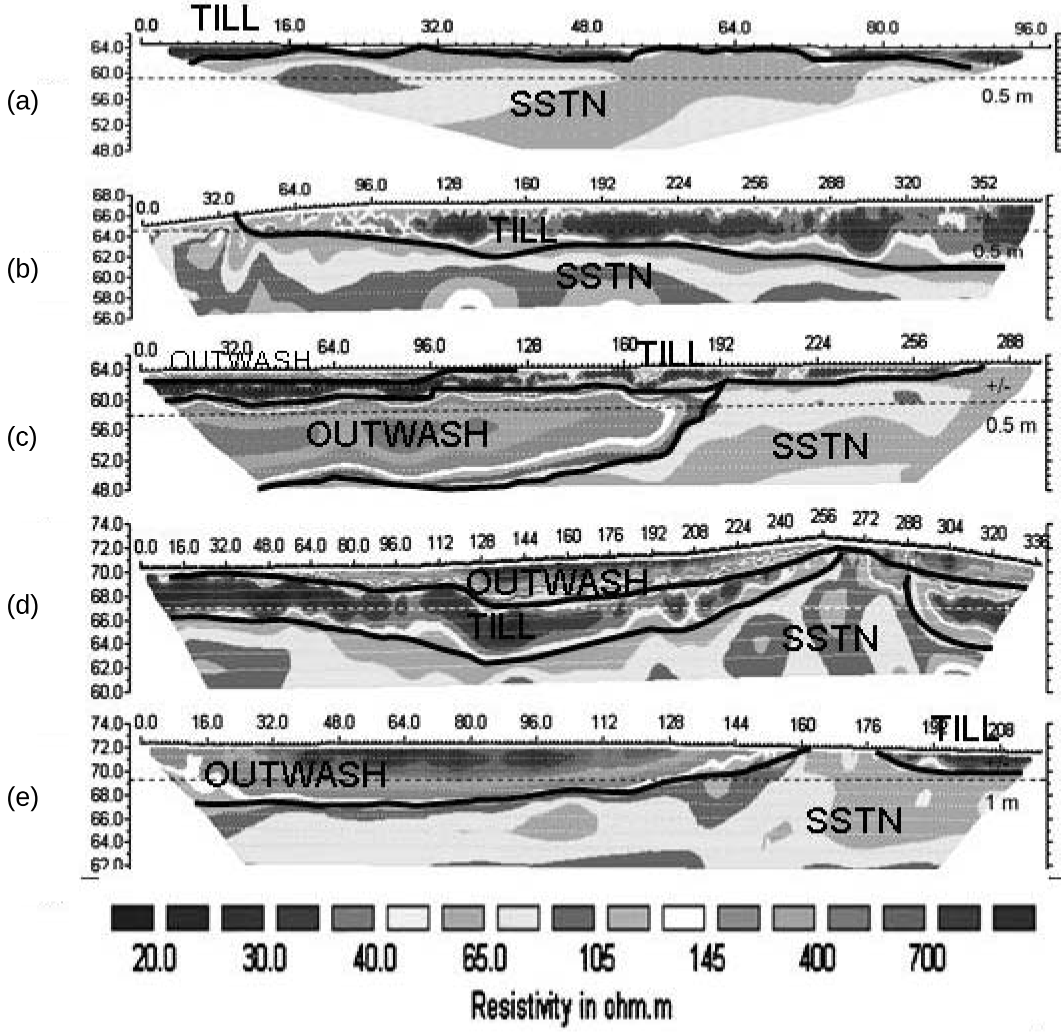

Fig. 2 ERT inversions illustrating drift lithological variations.

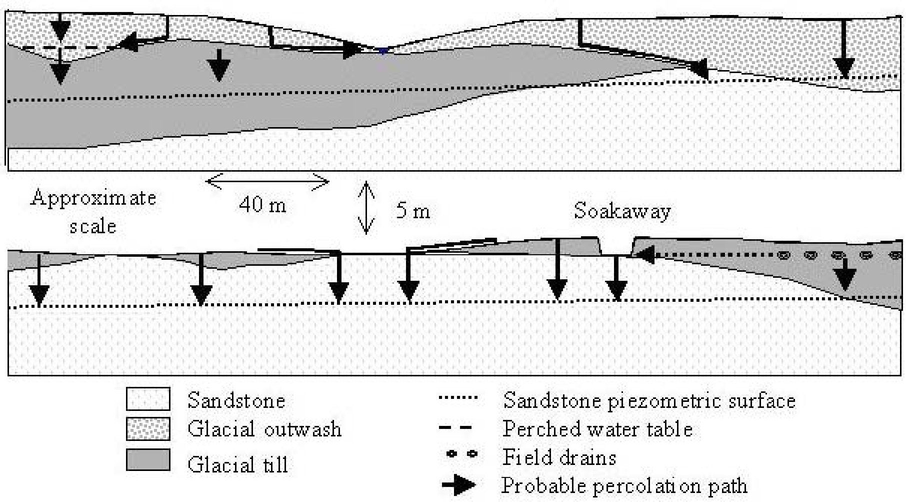

Fig. 3 Conceptual flow paths through the drift unsaturated zone.

THE NUMERICAL MODEL FAT3D_UNSAT

FAT3D_UNSAT is a finite difference numerical model that solves Richards' equation in three dimensions. It employs the soil moisture characteristic equations, (equations (1) and (2)) based on the work of Van Genuchten that are used in Tanji & Neeltje (2003):

$$K(S) = K_{sat} S^{1/2} \left(1 - \left(1 - S^{n/(n-1)}\right)^{(n-1)/n}\right)^2 \tag{1}$$

$$\psi(S) = \frac{\left(S^{-1/m} - 1\right)^{1/n}}{\alpha} \tag{2}$$

where K_{sat} is saturated hydraulic conductivity [L T^{-1}], n is the Van Genuchten shape parameter [–] and S is the degree of saturation [–], $\psi(S)$ is the tension characteristic [L], $m = (n - 1)/n$ [–] and α is the Van Genuchten scale parameter.

Bottom boundary conditions may be fixed flow or fixed pressure. Top boundary conditions permit the inclusion of direct precipitation and actual evaporation based on a surface soil pressure (suction) limit and root uptake based on a distributed root zone model in which evaporative demand is balanced over the root zone. For the present modelling AE = PE ($\theta_{soil} \geq 0.18$), AE = 0.1PE ($0.18 > \theta_{soil} \geq 0.06$), AE = 0 ($\theta_{soil} < 0.06$) Time stepping is automatically defined according to the nonlinearity of the problem being tackled.

SIMULATION RESULTS

FAT3D_UNSAT has been used to model a large range of two-dimensional 100-m long transects of the near surface deposits to examine the impact of variations in the pattern of lodgement till and glacial outwash on the apparent recharge. Figure 4 shows one of the transects that has been examined in detail. It is illustrative of the pattern of variation observed in the field. For simplicity, the ground level has been assumed to be horizontal, but as described in the next section, this decision may not be appropriate for the full upscaling calculations. The recharge responses that have been determined for this transect illustrate the main features affecting the recharge rate. The spatial distribution of effective rainfall (net deep percolation) and the pattern of recharge to groundwater are shown on Fig. 5. Two cases are shown in which the aquifer piezometric level is fixed at 4 and 10 m depth below ground level. To perform the simulations, a 1-year climate record from a weather station in the catchment has been used to generate the rainfall (R) and potential evaporation (PE) distribution (July–June). The annual rainfall of 760 mm and PE of 880 mm are typical for the area. The simulations were carried out using a 3-year cyclical period to remove any impact of unrealistic initial conditions. The last year's data were output at daily intervals for comparison. Figure 6 shows the daily variation of R, Actual Evaporation (AE), and G/W recharge (GR) for the transect for 1 year.

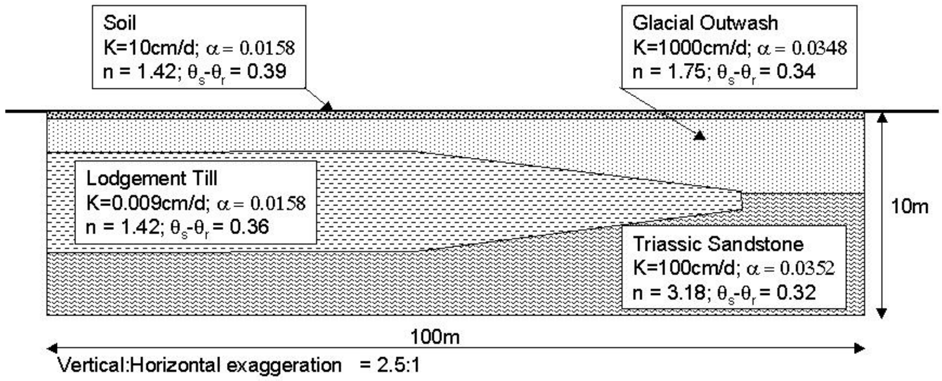

Fig. 4 Schematic of the transect.

(a) (b)

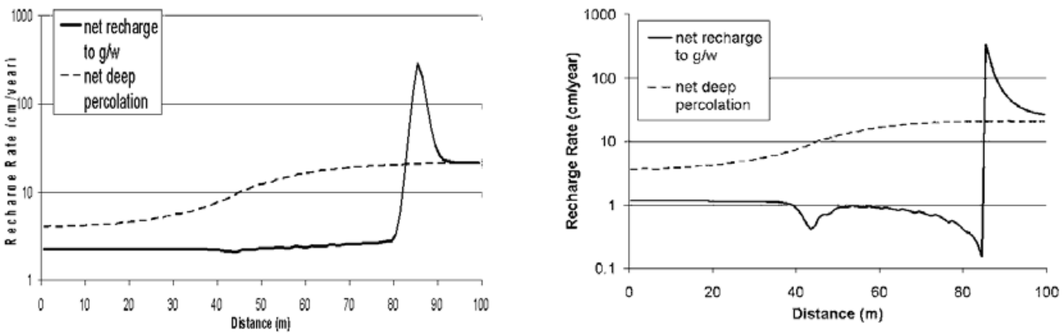

Fig. 5 Annual recharge for aquifer potentiometric heads at (a) 4 m and (b) 10 m.

(a) (b)

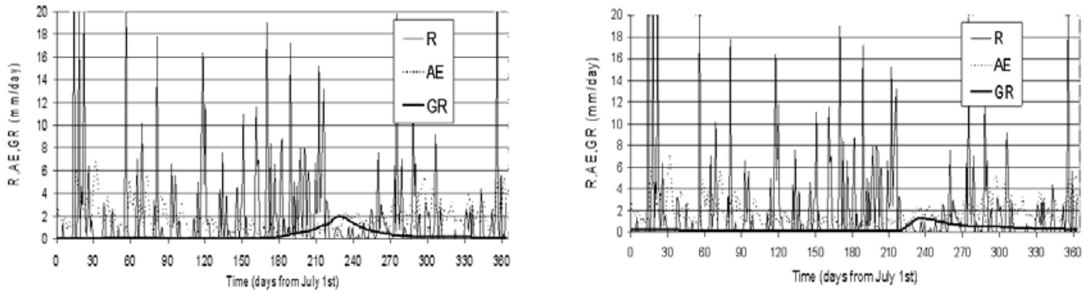

Fig. 6 Rainfall (R), Actual Evaporation (AE) and Groundwater Recharge (GR) over 1 year for aquifer potentiometric heads at (a) 4 m and (b) 10 m.

DISCUSSION AND CONCLUSIONS

The results presented in Figs 5 and 6 show several features that are worth noting and are influential in defining an appropriate upscaling model for recharge. The depth to the potentiometric surface does not significantly affect the total annual recharge in the range 4 to 10 m but the pattern of recharge throughout the year is significantly affected. A much longer tail is observed for the deeper water table, indicative of the retention of the percolating water in the deeper unsaturated zone, with a consequent decrease and a delay in the peak recharge rate. The spatial pattern of recharge within the transect depends heavily on lateral flows above the lodgement till. Lateral flows affect the moisture near the surface in the soil zone and correspondingly the actual evaporation from the surface. If the till is laterally horizontal and persistent, then recharge is reduced to less than 1 mm year^{-1}. Land surface slopes and breaks in the till can be expected to play a pivotal role in controlling the subsurface recharge where outwash deposits overly lodgement tills. Considering all the simulations, a range of recharge from 1 to 200 mm year^{-1} is observed depending on the underlying structure of the till and outwash deposits. The link between the near surface and deeper geological regime provides strong evidence that a soil moisture deficit-based recharge model can not be appropriate to model recharge over till and, equally, a model based solely on the configuration of the drift geology is inappropriate. A combination model linking the properties of both domains is now being sought. In summary, the present study has provided useful evidence of the recharge behaviour that may be expected for thin glacial drift sequences and has provided insights into the model form that will be needed to construct a stochastic upscaled model for drift-controlled recharge in the Tern catchment. The next step is to expand the Monte Carlo upscaling calculations and to develop the final averaged model result.

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