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MODELLING RECHARGE
IN THE UNSATURATED ZONE

IH Project T05051Y5 Report

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CONTENTS

1 AIMS

2 MODELLING

3 CONCLUSIONS

1 AIMS

1.1 AIM OF PROJECT

The project aims to determine recharge to the saturated groundwater zone, including spatial and temporal variability. This is seen as an aid to groundwater resource management without groundwater 'mining', and is of relevance to streamflow maintenance concerns. A 'top-down' approach (whereby recharge is calculated from the path taken by infiltrating rainfall) is to be adopted, as opposed to a 'bottom-up' approach (recharge derived from saturated zone behaviour), capitalising on IH's spatial data sets.

A short demonstration project was set up as a feasibility study and as a basis for seeking future funding. WBW suggested a test site, the Black Wood area of Hampshire, 12 km north-northeast of Winchester. This is an Upper Chalk area with some in-house soil-base drainage data available for use.

The modelling methodology aims to be general, and the input and results are to be GIS-presented.

1.2 AIM OF REPORT

This report covers work to date on the modelling of the unsaturated zone from the base of the soil (and plant water uptake zone) down to the regional saturated zone. Its purpose is to record experience for a full understanding of the current work for those involved in both scientific and marketing aspects, and to serve as a starting point for future extensions as and when appropriate.

In the interests of expediency, a literature review of recharge methodologies and the specific site is not included: a general familiarity with these aspects is assumed.

2 MODELLING

2.1 MODELLING: AIMS AND BACKGROUND

The requirement was for a simple model because

i) short run times were required because of repeated use under a wide variety of spatial circumstances at a 1 km^2 scale, and possible future embedding within a GIS for on-line calculation

ii) comprehensive suites of parameters are not available for the deep unsaturated zone, nor likely to become so in the near future.

A considerable degree of physical basis was preferred if possible because

i) of compatibility with the nature of the present evapotranspiration and soil uptake models and their (improved) future versions

ii) some *simple* physical parameters are to some degree available, particularly in terms of guidelines as to reasonable ranges of values.

The general types of models therefore include lags, storages, transfer functions and combinations of these.

2.2 MODELLING: METHODOLOGY

The approach decided on in the first instance, and seen below to provide some useful preliminary results, is as follows.

The input is the drainage from the base of the soil as provided by RJH and following the methodology described in the report 'Hydrological Impacts of Broadleaf Woodland' No 115/02/ST (DoE, NRA).

Water can traverse the unsaturated zone via two routes, a 'slow' route representing matrix flow and a 'fast' route representing fissure or macropore flow. The proportion of water entering the routes can vary but, once started in a route, continues in that route down to the saturated zone. The fast and slow velocities can be varied. A running mean is introduced to represent, in a very general way, the diffusion during travel: a seasonal 5-month running mean is currently in use. Data are handled on a monthly basis to pick up seasonal variation without excessive computation.

Three parameters are therefore involved by this stage, namely the fast velocity of travel, the slow velocity and the proportioning between the routes.

Low values of the slow velocity require drainage inputs some considerable time in the past. The drainage record was therefore extended back in time using mean annual drainage distributed over the year in sine wave form. In practice, the particular parameter values presented below do not call on this facility.

2.3 MODELLING: CALIBRATION

Experience suggests that in practice many, or indeed most, physically based models require calibration to some degree. It is particularly the case here since soil drainage was not fully validated prior to its use as input. It will of course be appreciated that, in the absence of extreme changes in unsaturated zone storage, this input soil drainage term determines the overall amount of recharge, whilst subsequent unsaturated zone processes determine the distribution of times of arrival at the saturated zone.

Calibration of the recharge model was undertaken against groundwater level, for expediency at a single borehole.

At the Black Wood site (BGS unpublished archive site SU54/81), NRA water level readings are taken only rarely and on an irregular time basis. No nearby wells are featured in the BGS groundwater level database. NRA Southern hold a number of records in the area, access to which was made possible by the Winchester office. A frequency of at least monthly data was required, and preferably a duration of record in excess of 20 years. Minimal artificial perturbation was sought, particularly with respect to groundwater regulation schemes to the southeast of Black Wood.

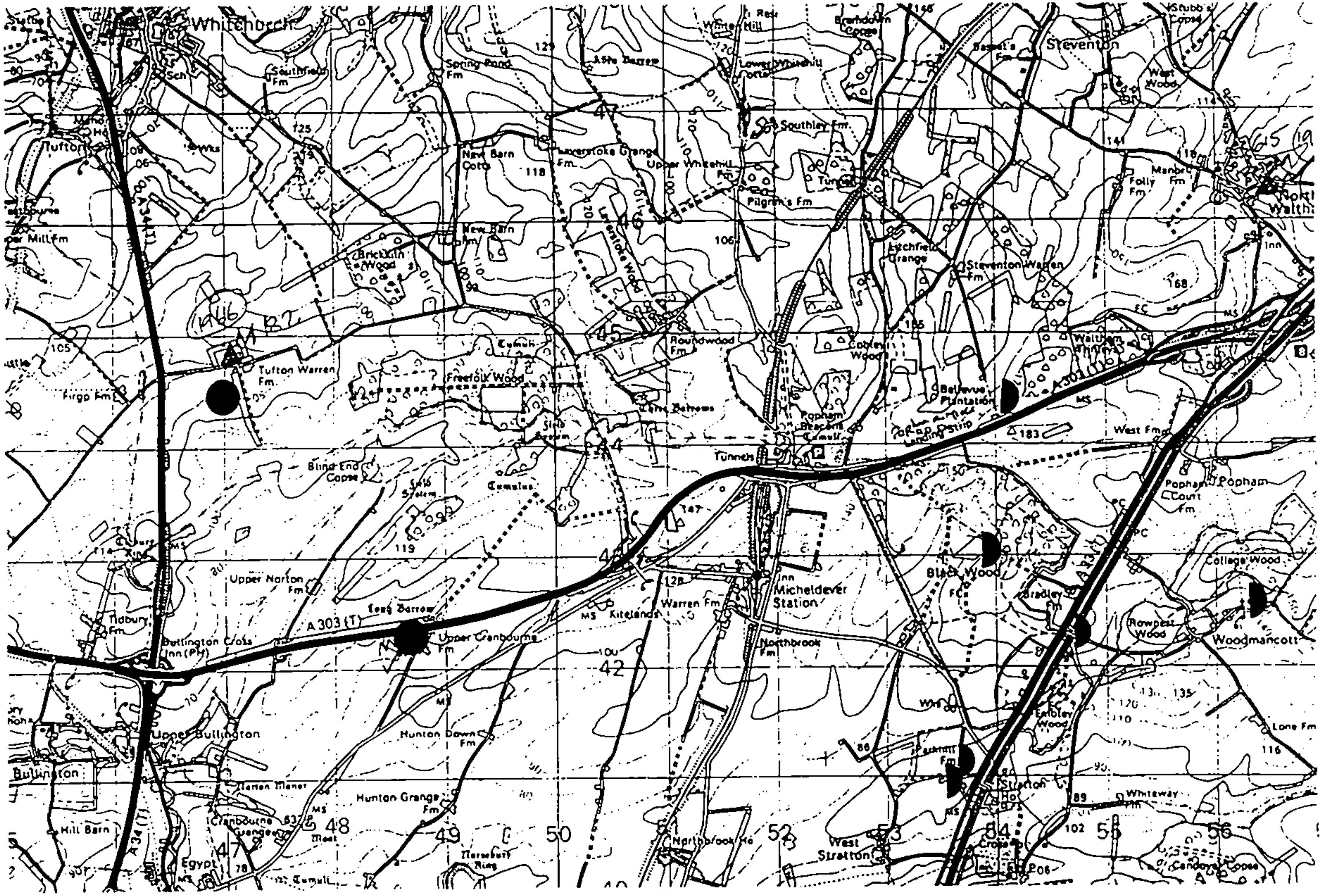

Figure 1. Soil drainage and saturated zone modelling sites

(extract from O.S. 1:50,000 sheet 185)

These requirements were met by the Upper Cranbourne Farm bore (SU 487423, figure 1), 4.5 km west of Black Wood. The depth to the saturated zone is 20 m (based on October 1973 data presented on the Hampshire and Isle of Wight hydrogeological map (IGS and SWA)). The land use is arable.

Comparison of recharge with water levels, relative or absolute, is not of course possible without recognition of other inflows and outflows at that aquifer location, that is, the integrated behaviour of the saturated zone over time at that location. The test area is one of a gentle watertable gradient to the southwest.

Areal saturated zone modelling is the obvious option for the conversion of recharge to water level but is demanding of time. Simple options were therefore considered for the *net* removal of water from the saturated zone at a site, that is, its integrated behaviour. These were
i) net saturated zone removal from the site at the mean recharge rate over the record length
ii) net saturated flow at the mean recharge rate over each year
iii) net saturated flow at twice the mean recharge rate over half the yearly cycle (the falling limb of the recharge cycle).
On each of these options a variation about the value of ± 10% was allowed. Some experimentation, though not exhaustive, suggested

option (ii) above to be sensible and general.

Water level updates were made at each time step: the depth of unsaturated zone travel was not concomitantly adjusted because of complex continuity considerations and, more importantly, because this information would not be known when modelling the unsaturated zone without reference to underlying saturated zone behaviour, as is the case in many 'production' runs of the model.

In converting recharge to water levels we have, therefore, introduced two further parameters, first, a storage or specific yield term converting inflow to saturated volume and, second, a flow term integrating saturated zone behaviour in terms of net loss in the saturated zone from the site as a proportion of annual recharge.

For operator independence, the five model parameters were optimised automatically. Use was made, on the IBM mainframe, of the NAG routine E04CCF which employs a robust simplex method for parameter optimisation. The error function used was the root mean square error between observed and predicted water levels at monthly intervals. A monthly predicted water level was assessed against variable time-base observations if the latter occurred in the calendar month. If there was more than one such observation, the mean of those within the calendar month was used.

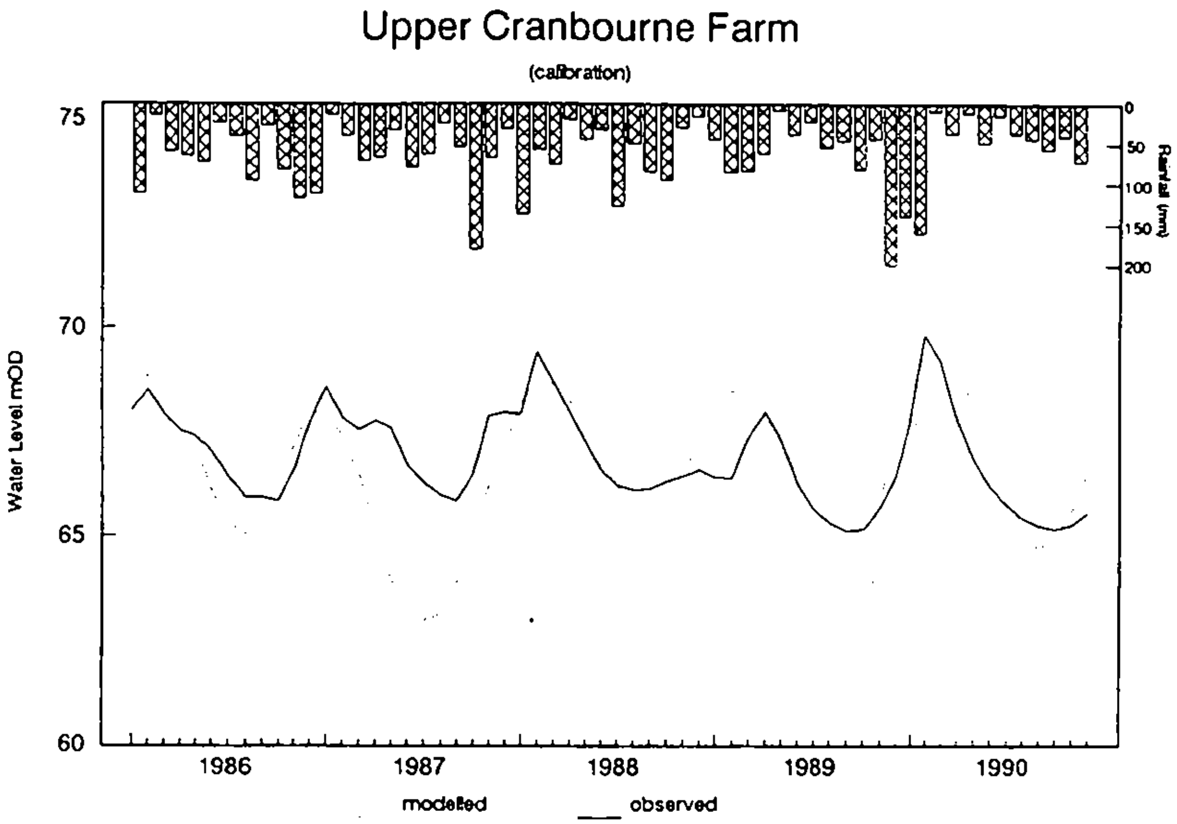

Figure 2. Unsaturated zone calibration results

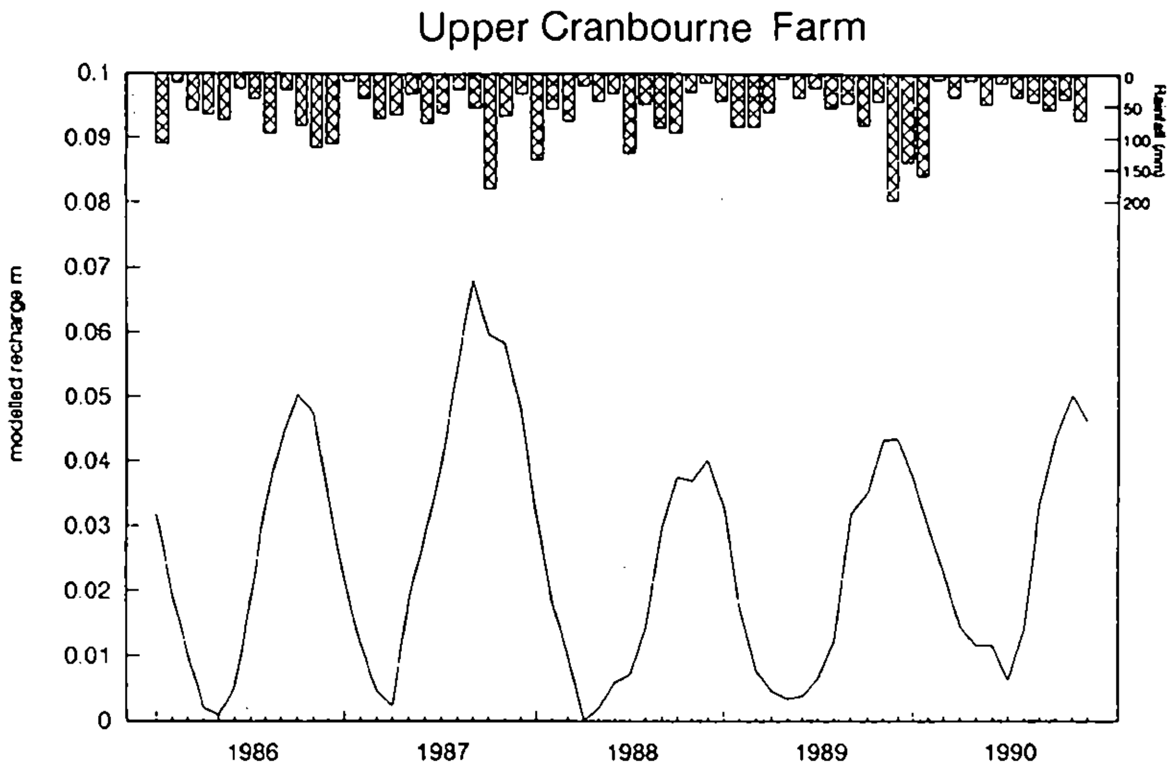

Figure 3. Predicted recharge

Visual inspection of optimised predictions against observed levels suggested a minor but possibly significant improvement could be made in terms of peak and trough timings by slightly reducing the fast velocity. This was implemented, despite operator-dependence, recognising that, if time permitted, a more sophisticated peak-time-orientated error function could be employed. (It is suggested that a somewhat low water leveltrough and a high peak were responsible for the automatically-optimised determination.)

The resultant values were as follows: fast velocity 28.2 m yr^{-1}, slow velocity 1.1 m yr^{-1}, proportion via fast route 0.31, net saturated flow at 1.02 times annual recharge.

Figure 2 shows the calibrated model output versus observed water levels for Upper Cranbourne Farm for 1986-1990, and figure 3 shows the associated recharge to the saturated zone.

2.4 MODELLING: VALIDATION

Time constraints meant that validation was necessarily cursory, but it was nevertheless seen as important to conduct. The Tufton

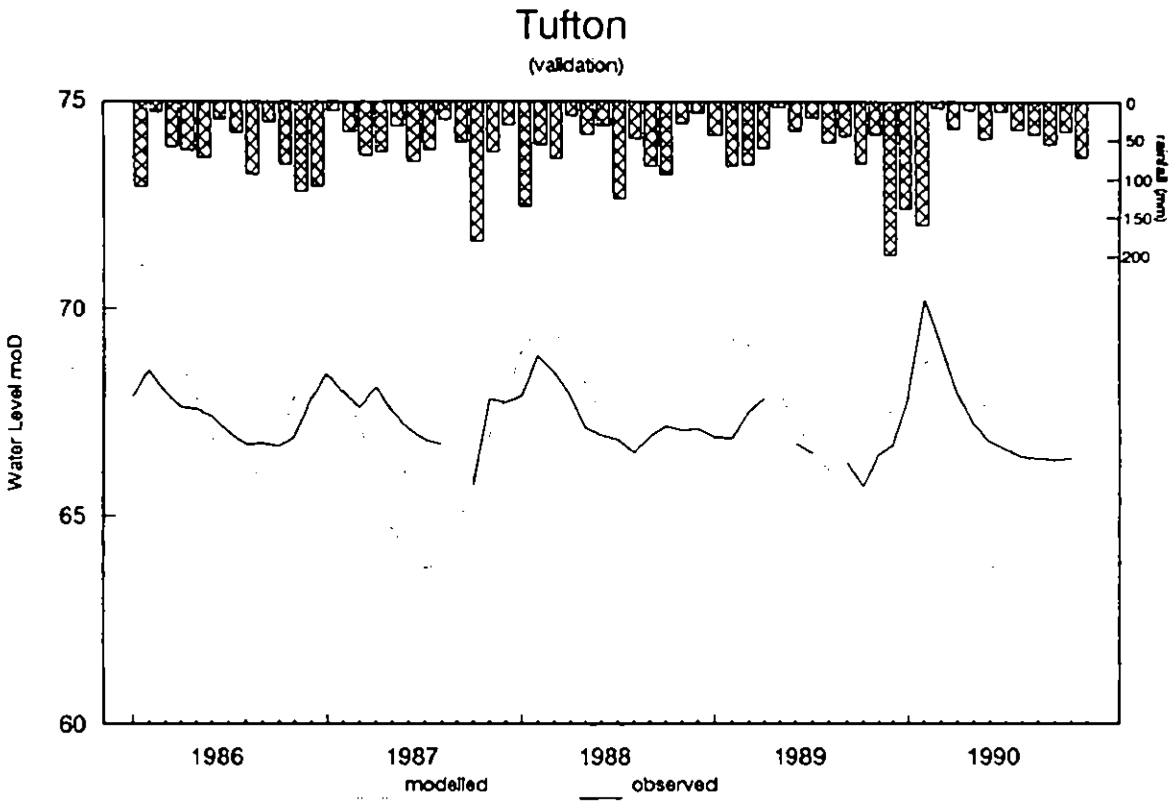

Figure 4. Unsaturated zone validation results

Warren bore (SU 472448, figure 1 above) was used as a validation site. The depth to saturated zone is 15 m, the distance from Upper Cranbourne Farm is 3.5 km, and the land use is arable.

The carrying across of fast and slow velocities from Upper Cranbourne Farm to Tufton was found in practice to be less satisfactory than to carry across their associated lags, namely 0.7 year and 18.9 years for the two routes. The values of the three other parameters were carried across directly.

Figure 4 shows the validation results, that is, the modelled and observed water levels at Tufton Warren.

2.5 MODELLING: ROUTINE FOR GIS

Soil drainage data had been provided by RJH for five classes of land use - grass, wheat, ash, beech and conifers. The respective mean annual totals (1967-1990) for drainage are 272, 361, 350, 323 and 177 mm. (We note in passing a Mott MacDonald / NRA value of 280 mm yr^{-1} recharge derived from optimisation of a version of Stanford Watershed Model against surface flow in the Andover region.) The current modelling used grass drainages because of their reported greater reliability over wheat values. Drainage data were provided for three conjectural climatic regimes in addition to the present regime at Overton (SU 515495). These regimes were

i) 10% less winter (October - March) rainfall
ii) 10% less rainfall all year
iii) 10% more rainfall all year

Only rainfall variations were considered at this stage, not associated variations in other climatic variables.

JWF provided 55 land use class types with respect to proportion of each of four vegetation classes - grass, cereal, coniferous and broadleaf woodland. The latter was interpreted as half ash and half beech.

The unsaturated zone model was run for the 55 land use classes under each of the four climatic regimes, producing 220 time series of recharge for incorporation into a GIS display. Because of the uncertainty noted above regarding use of lags versus travel velocities, the unsaturated zone was, in this demonstration, kept at 15-20 m. Obviously this issue is to be pursued and the depth varied in the future.

3 CONCLUSIONS

3.1 GENERAL

Given the severe time constraints and the uncertainty regarding input soil drainage data, the recharge results were deemed acceptable at this demonstration stage of the work. It is fair to point out that there may be a large error attached to predictions, especially in conditions different from the calibration and validation sites. The magnitude and direction of that error are difficult to specify and, indeed, the error of the *input* to this specific part of the modelling is unknown at present.

3.2 NEAR-SURFACE MODELLING

RJH considers likely some improvement of soil drainage modelling under non-forest land uses. MORECS data are not favoured by RJH because of inappropriate handling of chalk soils. Validation of the soil model as a separate component is recommended and can only benefit subsequent modelling of the deeper unsaturated zone.

Future provision must be made for conditions with a near-surface runoff term or lateral transfer of water, whether throughflow or surface runoff.

3.3 UNSATURATED ZONE MODELLING

The unsaturated zone modelling at present arguably suffers from a degree of ill-conditioning in its consideration of two parallel components if used without independent *a priori* establishment of parameter values. Against this is set its scope for considering fast and slow travel routes representing generally recognised processes and, indeed, ones which different authorities favour to differing degrees.

The storage value is arguably high, even for the Upper Chalk and accommodating a measure of fissure storage. This may imply that drainage terms are somewhat high and/or that aquifer outflow should be handled differently.

Numerical experimentation with use of various hydrologically reasonable parameters without optimisation, and with various constraints on optimisation, produced no marked improvements in results, though experimentation in the available time was plainly not exhaustive. The experiments also included an alternative representation working from *raw* rainfall with an overall (evapotranspiration) loss parameter. Choices to be made between similar, but not excellent, outcomes reflect an aspect of ill-conditioning.

3.4 SATURATED ZONE VALIDATION

Direct validation of the behaviour or modelling of the unsaturated zone, arguably one of the least accessible parts of the hydrological cycle, is difficult. It is not completely satisfactory, albeit conceptually and computationally concise, to have a single parameter to represent saturated zone behaviour. In practice saturated zone measurements and/or modelling provide a promising approach to validation, albeit a time-consuming one. Certainly, a close inspection of groundwater level data, and the rate of change over time, in relation to rainfall (or drainage if available) is likely to form a large part of future work. Procedures must be set up for more complex saturated zone situations, including channel-aquifer interactions. If one embarks on extensive saturated groundwater modelling one should consider whether in fact top-down recharge assessments may be of value over bottom-up determinations, which is, of course, the favoured approach of many.

3.5 SUMMARY

In summary, we have a framework of a working procedure for representing variable recharge. The pilot project has raised details to be met on a number of issues. We should refine the soil model and validate it, refine the unsaturated zone procedure after the inputs are validated, and if possible offer some accompanying measure of the uncertainty of predictions. Resultant recharges should be validated against saturated zone behaviour, at a minimum in type sites and in particularly sensitive sites with respect to environmental and/or economic issues.

ACKNOWLEDGEMENTS

There has been useful general discussion amongst a number of IH staff: details of approach and GIS setting have been discussed with Jon Finch. I am also grateful to Nicola Hasnip for data and diagram preparation, and to Peter Midgley and Sally Wright of NRA Southern for access to groundwater level data.

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