Estimating direct groundwater recharge using a simple water balance model – sensitivity to land surface parameters

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Abstract

Periods of below average rainfall in the UK have emphasised the need for reliable estimates of groundwater recharge. Simple water balance models are often used to estimate direct groundwater recharge, but a significant effort is required to determine the land surface parameters. This paper describes a sensitivity analysis of such a model to determine the parameters having the greatest influence on estimates of recharge. The results of varying the vegetation canopy parameters for forest, and permanent and annual short vegetation, were analysed, in addition to varying the parameters of the soil moisture model. There were significant differences between the three land cover types but recharge estimates were relatively insensitive to the vegetation canopy parameters for short vegetation. However, principally due to the inclusion of a model of rainfall interception, recharge estimates were sensitive to the forest canopy parameters. Sensitivity to the parameters of the soil moisture model, particularly the rooting depth, and fractional available water content and fractional field drainable water, was found to be very high.

Keywords: Modelling; Recharge; Sensitivity analysis; Water balance

1. Introduction

The UK rainfall between 1988 and 1992 (Marsh et al., 1994) was markedly less than usual. This, and the subsequent dry period from 1995 to 1997, has highlighted the vulnerability of groundwater resources to variations in recharge. One of the principles for controlling groundwater abstraction within England and Wales is that “total abstraction from any groundwater resource area does not exceed the long-term annual average rate of replenishment” (National Rivers Authority, 1992). This low rainfall, coupled with an increasing demand for water, means that the total abstraction in many groundwater resource units is approaching the limits of sustainable yield. Thus there is an urgent need to improve the accuracy and reliability of groundwater recharge calculations.

Simple water balance models, such as those described by Grindley (1969) and Hough and Jones (1998) have been widely used for estimating groundwater recharge in the UK. These models combine a model of evaporation with a model of soil moisture. This approach has the advantage that it can be used to provide time series estimates of direct groundwater recharge from readily available meteorological data and that a real estimates of recharge can be produced from these estimates by applying simple procedures for spatial aggregation, either directly (Rushton and Ward, 1979) or as part of a full catchment water balance model (Wilby et al., 1994).

Although the driving variables required by simple water balance models are readily available, the same cannot necessarily be said of the land surface parameters. These require information on the vegetation
canopy and the soil hydraulic properties. Although the required parameters may be available from point measurements, these values may not be representative of the large areas generating groundwater recharge.

Given the uncertainties in the land surface parameters of simple water balance models, it is important to understand how sensitive the estimates of direct groundwater recharge are to these parameters. Howard and Lloyd (1979) investigated the sensitivity of the parameters in the Penman–Grindley model, but concentrated their analysis on the driving variables rather than the land surface parameters. Nevertheless, they concluded that substantial changes in the soil water model parameters could result in large differences in the estimation of summer recharge. Beven (1979) investigated the sensitivity of actual evaporation estimated by the Penman–Monteith equation (Monteith, 1965) to variations in input parameters and demonstrated a strong dependence on the aerodynamic and canopy resistances, which are used to parameterise the vegetation canopy in this model. In particular, the evaporation estimates for forest canopies were very sensitive to the values of canopy resistance, which will have an impact on estimates of groundwater recharge.

This paper describes a study of the sensitivity to variations in land surface parameters of estimates of direct groundwater recharge derived from a simple water balance model. The effort in obtaining values for operational applications can then be concentrated on the parameters to which the model is most sensitive.

2. The model

Direct recharge is calculated using a simple daily water balance equation, for day $i$:

$$ P_i = E_a_i + I_i + R_i + B_i + \Delta S_i $$

where $P_i$ is precipitation (in mm), $E_a_i$ is evaporation (mm), $I_i$ is canopy interception loss (mm), $R_i$ is runoff (mm), $B_i$ is flow bypassing the soil water store (mm) and $\Delta S_i$ is change in soil water (mm).

Recharge is the sum of positive values of $\Delta S$, once the soil water content exceeds the field capacity of the soil. and $B$. Negative values $\Delta S$ of represent an increase in soil moisture deficit. It is implicit in this statement that there is no upward movement of water from groundwater to the soil store, i.e. the water table is at depth.

The Penman–Monteith model (see Allen et al., 1994) is used to calculate evaporation, coupled to a simple soil water model (Ragab et al., 1997). An interception model (Gash et al., 1995) is included for forest canopies. The Penman–Monteith model is gaining wide acceptance for estimating evaporation for operational hydrology. It combines a physically based approach with a pragmatic requirement for data.

The Penman–Monteith model was implemented in the form for daily meteorological data given by Allen et al. (1994):

$$ \lambda E = \frac{\Delta(R_n - G) + 86.4 \rho c_p ((e_a - e_d)/r_a)}{\Delta + \gamma (1 + (r_a/r_d))} \tag{2} $$

where $E$ is evaporation (in kg m$^{-2}$ d$^{-1}$), $G$ is soil heat flux (MJ m$^{-2}$ d$^{-1}$); $R_n$ is the net radiation flux density at the surface (MJ m$^{-2}$ d$^{-1}$), $c_p$ is the specific heat of moist air (kJ kg$^{-1}$ °C$^{-1}$), $e_a$ is the saturation vapour pressure (kPa), $e_d$ is the saturation vapour pressure computed at dew point (kPa), $r_a$ is the aerodynamic resistance (s m$^{-1}$), $r_d$ is the bulk surface resistance of the vegetation canopy (s m$^{-1}$), $\Delta C$ is the latent heat of vaporisation (MJ kg$^{-1}$), $\lambda$ is the latent heat of vaporisation (MJ kg$^{-1}$), $\gamma$ psychrometric constant (kPa °C$^{-1}$) and $\rho$ is the atmospheric density (kg m$^{-3}$).

The parameters which involve the land surface, i.e. the vegetation canopy, are the aerodynamic resistance and the bulk surface resistance. The aerodynamic resistance is given by:

$$ r_a = \frac{\ln((z_m - d)/z_{om}) \ln((z_h - d)/z_{oh})}{k^2 U_z} \tag{3} $$

where $U_z$ is mean wind speed at height $z$ (m s$^{-1}$), $d$ is zero plane displacement of wind profile (m), $k$ is the von Karman constant, $z_h$ is the height of air temperature and humidity measurements (m), $z_{om}$ is the height of wind speed measurement (m), $z_{oh}$ is the roughness parameter for heat and water vapour (m) and $z_{om}$ is the roughness parameter for momentum (m); $d$ is taken to be $2/3h_c$, where $h_c$ is the mean vegetation height.

The roughness lengths are given by Monteith and Unsworth (1990) as:

$$ z_{om} = 0.123h_c \tag{4} $$

$$ z_{oh} = 0.1z_{om} \tag{5} $$
The bulk canopy resistance is:
\[
 r_s = \frac{r_t}{0.5LAI}
\]
where \( r_t \) is stomatal resistance of a single leaf (s m\(^{-1}\)) and \( LAI \) is leaf area index (dimensionless).

The soil water model of Ragab et al. (1997) is a compromise between a rigorous representation of the processes and the likely availability of input parameters. The root zone is divided into four layers. The decision to use four layers is a pragmatic solution as the model approximates the continuous distribution of roots with depth as a series of discrete layers. It achieves a reasonable representation of physical conditions whilst avoiding unnecessary complexity: \( W \), water movement between layers is based on a capacity approach. If the inflow to the first layer exceeds its field capacity then the excess water drains downwards into each layer of the bottom layer is considered available for groundwater recharge. The effective rainfall, \( P_e \) is taken as the inflow to the top layer. It is defined as (Martin et al., 1990)
\[
P_e = P - R - B - I
\]
where \( P \) is daily rainfall (mm), \( P_e \) the minimum rainfall required before surface runoff or bypass flow occur (mm), \( P_e \) is the effective rainfall (mm), \( a \) is the fractional proportion of rainfall assigned to surface runoff and \( b \) is the fractional proportion of rainfall that bypasses the soil store.

Plant roots take up water at the rate given by Eq. (2) as long as there is no water stress, i.e. the water content is equal to the field capacity. The ratio between the current and the maximum available water is considered as a stress factor, \( S \), and used to reduce the potential water uptake rate to actual uptake rate for each layer:
\[
 S_j = \frac{(\theta_j - \theta_{wp,j})Z_j}{A_j}, \quad \theta_{wp,j} < \theta_j < \theta_{fc,j}
\]
\[
 S_j = 0, \quad \theta_j \leq \theta_{wp,j}
\]
\[
 S_j = 1, \quad \theta_j \geq \theta_{fc,j}
\]
\[
 E_{a,j} = E_pS_jC_j
\]
where \( A_j \) is fractional maximum available soil water content for the \( j \)th layer (dimensionless), \( E_{a,j} \) the actual root water uptake for the \( j \)th layer (mm), \( E_p \) the potential total root water uptake (mm), \( Z_j \) the layer thickness for the \( j \)th layer (mm), \( C_j \) the fractional proportion of roots in the \( j \)th layer (dimensionless), \( \theta_j \) the current fractional soil water content for the \( j \)th layer (dimensionless), \( \theta_{fc,j} \) the fractional soil water content at field capacity for the \( j \)th layer (dimensionless) and \( \theta_{wp,j} \) is the fractional soil water content at wilting point for the \( j \)th layer (dimensionless).

The maximum available water for plant water uptake is the difference between the soil moisture content at field capacity and wilting point:
\[
 A_j = \theta_{fc,j} - \theta_{wp,j}
\]

The contribution of each soil layer to the total root water uptake, and hence the actual evaporation, depends on its root density. The distribution of active roots in a normal soil is approximately triangular in shape, the greater concentration being near the surface (Hansen et al., 1979a).

The flow of water, \( F_j \), downwards into each layer of the soil model is can then be calculated as
\[
 F_j = P_e \quad j = 1
\]
\[
 F_j = F_{j-1} - (\theta_{fc,j-1} - \theta_{j-1})Z_{j-1} \quad j > 1
\]
\[
 F_j = 0 \quad F_{j-1} < (\theta_{fc,j-1} - \theta_{j-1})Z_{j-1}
\]

Thus the potential direct groundwater recharge is the influx to the fifth layer.

Runoff is calculated as a function of the soil water content of the first layer:
\[
 R = P_e - Z_1(\theta_s,1 - \theta_1) \quad P_e > Z_1(\theta_s,1 - \theta_1)
\]
\[
 R = 0 \quad P_e < Z_1(\theta_s,1 - \theta_1)
\]

where \( \theta_s,1 \) is fractional saturated water content of the first layer (dimensionless).

The flow bypassing the soil store and going directly to recharge, \( B \), is estimated using the method of Rushston and Ward (1979):
\[
 B = aP_e \quad P_e > P_e
\]
where \( B \) is daily bypass flow (mm), \( P_e \) the daily effective rainfall (mm), \( P_e \) the minimum rainfall required
before bypass flow can occur (mm) and \(a\) is the fractional proportion of rainfall assigned to bypass flow.

The model of canopy rainfall interception described by Gash et al. (1995) has been included when the land cover is forest. This is an analytical interception model for forests which is comparable to the evaporation and soil models in its degree of rigour. It considers that for any storm there are a series of distinct phases, beginning with a period when the rainfall is less than a threshold value necessary to saturate the canopy. This is followed by a period of saturation and then a period of drying out after rainfall ceases. For a small storm, insufficient to saturate the canopy, the interception, \(I\), is calculated as:

\[
I = cP_G
\]  

(19)

where \(c\) is canopy cover (dimensionless) and \(P_G\) is storm rainfall (mm).

For a storm which saturates the canopy the interception is:

\[
I = cP_G' - cC_e + (c\bar{E}_c/R)(P_GP_G') + T
\]  

(20)

where \(C_e\) is canopy capacity per unit area of cover (mm), \(\bar{E}_c\) the mean evaporation rate during rainfall (mm \(d^{-1}\)), \(P_G'\) the threshold rainfall necessary to saturate the canopy (mm), \(R\) the mean rainfall rate (mm \(d^{-1}\)) and \(T\) is the evaporation from trunks (mm).

The evaporation from trunks for storms which saturate the trunks is:

\[
T = S_t
\]  

(21)

where \(S_t\) is the trunk storage capacity (mm); and for storms which do not:

\[
T = p_tP_G
\]  

(22)

where \(p_t\) is the proportion of rainfall diverted to stemflow.

It is assumed that only one storm occurs per day and so \(P_G\) is equal to the daily rainfall.

Seasonal variations in vegetation are simulated by calendar date (Hough and Jones (1998). For crops, fixed dates are assumed for germination, emergence, maximum leaf area and harvest. The root development is simulated by changing the contribution made from each layer. This is achieved by assuming that the rooting depth increases linearly starting from zero on the date of germination until the date of maximum leaf area is attained. No growth is assumed between 1st December and a date in early spring for crops sown in the autumn. The proportion of roots in layer \(j\), \(F_j\), for a rooting depth \(D\), is:

\[
F_j = 0 \quad \sum_{n=1}^{j-1} Z_n > D
\]  

(23)

\[
F_j = F \max_j \quad \sum_{n=1}^{j} Z_n < D - Z_{j+1} - Z_{j+2}
\]  

(24)

\[
F_j = F \max_j + (1 - \sum_{n=1}^{j} F_n)(1 - \sum_{n=1}^{j} Z_n)/Z_{j+1}
\]  

(25)

\[
F_j = 1 - \sum_{n=1}^{j} F_n \quad \sum_{n=1}^{j-1} Z_n < D < \sum_{n=1}^{j} Z_n
\]  

(26)

where \(F \max_j\) is the proportion of roots in layer \(j\) at full development.

For the case when \(D < Z_1\) the proportion for the first layer is set to 1 and for all other layers to 0. The leaf area index and canopy height are assumed to increase linearly from the date of emergence until the date of maximum leaf area. At harvest the parameters are set to zero.

The parameters required for the soil water component of the water balance model are the proportions of rainfall diverted to bypass flow, the rainfall threshold above which bypass flow occurs, the rooting depth, the proportion of roots in each of the four layers, and the fractional soil water moisture content at wilting point and and field capacity of each layer and the fractional soil water content of the first layer at saturation. The soil moisture content at wilting point is effectively a constant against which the soil moisture contents are calculated and so it is simpler to consider the wilting point and field capacity together in the form of the maximum available water content, i.e. the difference between these parameters. Similarly, in calculating the runoff, the field capacity and saturated water content of the first layer are considered together as the maximum field drainable water.

The vegetation canopy is parameterised by three variables;
the mean canopy height, the stomatal resistance of a single leaf and the leaf area index. Four additional parameters, the canopy cover, canopy capacity, stem storage capacity and proportion of rainfall diverted to stemflow, are required for forest. For seasonal vegetation the dates of emergence, full leaf area and harvest are required.

<table>
<thead>
<tr>
<th>Canopy ‘reference’ parameters</th>
<th>Permanent short vegetation</th>
<th>Annual short vegetation</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomatal resistance, ( r_l ) (s m(^{-1}))</td>
<td>100</td>
<td>100</td>
<td>142</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>2.88</td>
<td>4.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Canopy height (m)</td>
<td>0.12</td>
<td>0.8</td>
<td>16.0</td>
</tr>
<tr>
<td>Rooting depth (m)</td>
<td>0.8</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Root proportions</td>
<td>0.75,0.15,0.1,0.05</td>
<td>0.75,0.15,0.1,0.05</td>
<td>0.75,0.15,0.1,0.05</td>
</tr>
<tr>
<td>Growing season (days)</td>
<td>154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canopy cover</td>
<td></td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Canopy capacity (mm)</td>
<td></td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Stem storage (mm)</td>
<td></td>
<td></td>
<td>0.014</td>
</tr>
<tr>
<td>Proportion of stemflow</td>
<td></td>
<td></td>
<td>0.016</td>
</tr>
</tbody>
</table>

3. Sensitivity experiment

3.1. Parameters and meteorological data

Three types of land cover have been considered: permanent short vegetation, annual short vegetation and coniferous forest. Permanent short vegetation is generally accepted as the standard land cover, e.g. Allen et al. (1989), but the situation of an annual crop must also be considered as this has a period of bare soil followed by a period of increasing canopy development up to a maximum which then remains constant until harvest. For short vegetation, the increase in evaporation resulting from rainfall interception by the canopy is generally taken to be negligible, but this cannot be accepted for forest and so the inclusion of this process is necessary.

A set of ‘reference’ parameters for each land cover type were defined. For permanent and annual short vegetation the values were those given by Allen et al. (1994) except for the growing period for the annual vegetation when the function and values given by Thompson et al. (1981) for the area of the meteorological station were used. For forest, the values used were those given by Gash (1979) and Gash and Stewart (1975) for pine forest. These are summarised in Table 1.

A set of soil parameters were defined which are intended to represent a simple standard soil. The proportion of rainfall diverted to bypass flow and surface runoff was set to 0.1, and the rainfall threshold to 5 mm, representing a free draining soil on subdued topography (Rushton and Ward, 1979; Bishop and...
Rushton, 1993). The fractional maximum available water content was set to a value of 0.15, typical of free draining soils (Beer, 1990), and the maximum available water in each layer of the soil moisture model has been assumed to be equal in order to simplify the analysis. A value of 0.15 was used for the fractional field drainable water content. The range over which each parameter was varied was selected to encompass all values that might reasonably be expected, Table 2. All parameters were varied linearly over the range selected. The exception was the proportion of roots in each layer, $d_i$. This was defined in terms of a factor $x$ as:

$$d_4 = 0.25^x$$

$$d_3 = 0.5^x - d_4$$

$$d_2 = 0.75^x - d_3 - d_4$$

$$d_1 = 1 - d_2 - d_3 - d_4$$

When $x$ is set to 1 the proportions of roots in each layer are equal. The effect of increasing $x$ is to increase the proportion of roots in the upper two layers and decrease it in the lower two.

### 3.2. Meteorological data

The model was driven using daily meteorological data for the period 1972 to 1995 from the station near Wallingford (51°36′9″N, 1°6′34″W, 48 m AOD); long enough to reflect the inter-annual variability. The mean annual rainfall during this period was 587 (95) mm and the Penman (1948) potential evaporation 601 (46) mm. An albedo of 0.25 was used for short vegetation and a value 0.13 for forest to calculate the net radiation. The wind speed above the forest canopy was calculated from the measured wind speed using the method of Rutter et al. (1975).

#### 3.3. Measures

Six measures were used to assess the recharge. These were the means and standard deviations of the annual recharge, the number of days on which recharge took place and the daily recharge on these days when recharge took place. The results for the ‘reference’ parameters are given in Table 3.

To facilitate comparisons of the sensitivity of the predicted recharge to variations in a parameter, the results of the model runs were plotted as ratios of these ‘reference’ conditions and it is these graphs that are presented in this paper. In addition, to allow a simple comparison between the parameters, the percentage change in a parameter from the ‘reference’ value required to produce a 1% and 5% variation in the mean annual groundwater recharge were computed.

### 4. Results

It was found that there was very little variation in the annual mean and standard deviation of the daily recharge. The annual recharge and the number of recharge days were strongly correlated, typical correlation coefficient of 0.99, so that the presentation of the analysis is limited to a consideration of the mean of the annual recharge. This has the additional advantage that the mean annual recharge is commonly used as a measure to control abstraction from aquifers.

Table 3
Measures of direct groundwater recharge for the three land cover types; standard deviations are given in parentheses

<table>
<thead>
<tr>
<th></th>
<th>Permanent short vegetation (mm)</th>
<th>Annual short vegetation (mm)</th>
<th>Forest (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual potential evaporation</td>
<td>519.8 (43.6)</td>
<td>587.5 (95.1)</td>
<td>467.8 (66.8)</td>
</tr>
<tr>
<td>Mean annual recharge</td>
<td>176.7 (71.4)</td>
<td>290.5 (75.8)</td>
<td>96.4 (42.9)</td>
</tr>
<tr>
<td>Mean daily recharge</td>
<td>2.98 (3.94)</td>
<td>2.99 (4.00)</td>
<td>2.02 (2.73)</td>
</tr>
<tr>
<td>Mean number of recharge days</td>
<td>59.2 (16.43)</td>
<td>97.2 (19.3)</td>
<td>47.8 (12.13)</td>
</tr>
</tbody>
</table>
4.1. Sensitivity to soil parameters

Fig. 1 shows the effects on the mean annual groundwater recharge of variations in the soil water model parameters. The sensitivity to soil parameters does not depend on evaporation, with the result that all land covers behave the same. The results are therefore presented for short permanent vegetation. Increasing the rooting depth decreases the amount of groundwater recharge, as larger soil moisture deficits can develop which must be replenished before recharge can take place. This effect also results from varying
the maximum available water (Table 4). The relationship is non-linear as the effect increases rapidly with decreasing maximum available water, though it tends to linearity at higher values. There is an inverse relationship between the fractional field drainable water content with decreasing runoff resulting in increasing recharge.

The estimated mean annual groundwater recharge is very insensitive to the value assigned to the rainfall threshold which must be exceeded before bypass flow or surface runoff occurs, but is more sensitive to the proportion of rainfall that bypasses the soil store. The mean annual groundwater recharge increases slowly as bypass flow increases, as this water is not available to reduce the soil moisture deficit and so recharge through the soil matrix is reduced. The relative proportions of roots in each layer has little effect.

4.2. Vegetation canopy parameters

4.2.1. Short vegetation

The sensitivity of direct groundwater recharge to the vegetation canopy parameters is shown in Fig. 2. Only one set of graphs is presented as the parameters

![Fig. 2. Variation in normalised mean annual groundwater recharge with canopy parameters for short vegetation.](image-url)
Fig. 3. Variation in normalised mean annual groundwater recharge with canopy parameters for forest.
for permanent and annual short vegetation overlap. Variations in the canopy height have a negligible effect on the estimate of groundwater recharge. Variations in the leaf area index are more important, but only at the lower values when the effect rises rapidly. Estimates are relatively insensitive to variations around the ‘reference’, which might be considered typical of a permanent grassland (Table 5). The effect of varying stomatal resistance is essentially linear and can be considered to have a moderate effect as a change in the stomatal resistance of 28.2% will result in a change in 5% in the estimate of mean annual groundwater recharge.

There is an inverse relationship between the length of the growing season and the mean annual groundwater recharge, which is essentially linear.

### 4.2.2. Forest

The sensitivity to variations in leaf area index and stomatal resistance for forest is greater than for short vegetation (see Table 6). As is the case with short vegetation, variations in the canopy height have little effect on the mean annual groundwater recharge. Fig. 3.

Estimates of groundwater recharge are comparatively sensitive to the values used for the interception model with the exception of stem storage and the proportion of stemflow. For all the parameters the relationship between the parameter and the mean annual groundwater recharge is approximately linear with increases in the parameter value resulting in decreases in the estimates of recharge. This is because increases in any of the parameters result in increased interception with the result that the rainfall is not available to reduce soil moisture deficits.

### Table 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change in recharge of 1%</th>
<th>Change in recharge of 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf area index</td>
<td>5.8</td>
<td>29.3</td>
</tr>
<tr>
<td>Stomatal resistance</td>
<td>5.6</td>
<td>28.2</td>
</tr>
<tr>
<td>Canopy height</td>
<td>19</td>
<td>99</td>
</tr>
<tr>
<td>Growing season</td>
<td>5.6</td>
<td>28</td>
</tr>
</tbody>
</table>

### 5. Discussion

The results of the sensitivity analysis, shown in Table 3, predict clear differences in the mean annual groundwater recharge under the same soil due to differences in the vegetation canopy type. Recharge is highest under annual short vegetation due to the period of reduced canopy that occurs during the winter when recharge is happening, despite this being the period when evaporation from permanent short vegetation is also low because of the net radiation and air temperature being low. Recharge is least under forest due to the high rainfall losses caused by evaporation being a combination of canopy interception and transpiration. Thus it is important to distinguish between these three land cover types, but this can be achieved relatively easily.

When considering the relative importance of the soil and vegetation canopy parameters, it is clear that the estimates of the groundwater recharge derived from simple water balance models are most sensitive to the soil parameters. Recharge predominantly occurs when the soil moisture content exceeds field capacity, i.e. during the winter months. During this period rainfall significantly exceeds evaporation and so the recharge is not particularly sensitive to the evaporation rates. During the summer, once a soil moisture deficit has developed, significant recharge does not take place through the soil matrix. The crucial parameter then becomes the maximum soil moisture deficit at the end of the summer as it is this deficit which must be replenished before recharge can
The larger the deficit the longer it will be before recharge occurs and the shorter the winter period of recharge will be. This is confirmed by the observation above that there is little variation in the mean daily recharge with any of the parameter variations. Rather, increases in the mean annual groundwater recharge are a result of an increase in the number of days on which recharge occurs.

5.1. Vegetation canopy parameters

For each of the land cover types, estimates of groundwater recharge are relatively insensitive to the mean canopy height, but are more sensitive to the stomatal resistance and the leaf area index. Values for leaf area index are readily determined, Pearcy et al. (1989). Estimating the appropriate value for the stomatal resistance does raise problems although values are cited in the literature, e.g. Hatfield (1994); Lindroth (1993); Rochette et al. (1991); Wallace et al. (1981). The reduction in evaporation due to soil moisture deficits should be expressed through increasing the stomatal resistance (Kim and Verma, 1991; Stewart, 1988; Huntingford and Cox, 1997) in the Penman–Monteith equation. This equation should be used with hourly, or more frequent, values of the driving variables because the stomatal resistance varies throughout the day (Choudhury and Idso, 1985; Bischoe et al., 1976; Leach, 1979) as a function of some of the driving variables. This is rarely practicable in operational use as measurements of the driving variables on a time scale more frequent than a day are not commonly made although this will be less of a problem in the future with the change from manual meteorological observations to automatic systems. At present, the only solution is to assume a single value for each land cover type, as is done in the Met. Office Rainfall Evaporation Calculation System, MORECS, (Hough and Jones (1998). However, there are relatively few published values for use with daily meteorological data (e.g. Szeicz and Long, 1969). And so there is a need for more determinations of stomatal resistance to be used with daily data for different vegetation types and to investigate the variation within one type.

Estimates of groundwater recharge are sensitive to the length of the growing season for annual short vegetation but acquiring this information is difficult.

In MORECS (Hough and Jones (1998) the planting, emergence, full canopy development and harvest dates for each crop are assumed not to change from year to year and this is probably the best that can be currently done for regional studies although it may be possible to collect these data when carrying out local studies. Vegetation growth models, e.g. Kaduk and Heimann (1996), are one possible method for obtaining the necessary information, though this may be a case of moving the problem of obtaining data from the water balance model to the growth model. An alternative may be Earth Observation data which is used in agricultural monitoring (Ellen, 1993; Clevers et al., 1994).

Interception is a significant component of the water balance for forest, as the rainfall intercepted is not available for recharge. However, the parameters relating to the stems are not particularly important because stemflow normally represents a small part of rainfall interception losses. Determinations of the necessary parameters have been reported, e.g. Pearce and Rowe (1981); Dolman and Gregory (1992) and Hutjes et al. (1990), but more determinations are required to understand how these parameters vary between different types of forest.

5.2. Soil parameters

The proportion of rainfall bypassing the soil store is not easily determined but, as the estimates of groundwater recharge are not particularly sensitive to this parameter, it is probably sufficient to determine whether the process is occurring and then arbitrarily select a realistic value based on similar situations described in the literature or from an analysis of hydrographs from boreholes. For example a value of around 15% seems to have been accepted for soils on the Chalk (Smith et al., 1970) in the UK when this process occurs.

The crucial parameters for the soil water model are the fractional field drainable water content, fractional maximum available water content and the rooting depth. The variation in these parameters between various soil types is illustrated in Table 7. Both parameters show a significant range of values with the variation in maximum available water content being mainly a function of the silt content and the variation
in maximum field drainable water dominated by the sand content.

Most determinations of the field drainable water and maximum available water contents are made using functions relating texture etc. and to soil hydraulic properties (Clapp and Hamberger, 1978; Brooks and Corey, 1964). However, soils with similar texture measures can have different soil hydraulic properties; and also the commonly accepted definition of field capacity as the water content at a matric potential of $-33 \, \text{kPa}$ may not apply to all soils (Webster and Beckett, 1972). Despite these reservations, estimates of these parameters can generally be obtained.

Determining the rooting depth is not so easily achieved. Canadell et al. (1996) give a very useful compilation of the maximum rooting depths for a wide range of vegetation types but the maximum values may not be appropriate in many situations. The presence of a shallow, hard strata may limit the depth to which roots can develop, although under these conditions direct groundwater recharge is unlikely to be important. There is evidence that water may be drawn up from depths significantly deeper than the rooting depth. For example, Gregory (1989) reported that water was drawn up from as deep as 3 m by cereal crops grown on a thin soil overlying Chalk. It may be possible to handle this type of situation in the water balance models by simply treating the rooting depth as an effective depth, defined as the depth above which water can be lost by evaporation, and not worry about whether roots actually attain this depth. However, further research is required into the processes involved and how they can be simply represented in a model.

### 6. Conclusions

This study has shown that the most crucial land surface parameters required by simple water balance models for estimating groundwater recharge are those required by the soil water component of the model. In particular, it is field drainable water, maximum available water, and the rooting depth which have a major impact on estimates of direct groundwater recharge. Most effort needs to be expended in obtaining reliable estimates of these values. Information about the rooting depth is probably the most difficult to obtain and there is a need to both obtain values for the rooting depth and to carry out research into the definition of this term and the definition of this depth.

The predominantly linear behaviour of the relationships between estimates of potential direct groundwater recharge and the model soil parameters is encouraging in terms of scaling up from point to a real estimates. It suggests that the use of simple averaging procedures, to accommodate spatial heterogeneity, will be sufficient to produce reliable predictions.

Estimates of groundwater recharge are relatively

<table>
<thead>
<tr>
<th>Soil type</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Fractional maximum available water</th>
<th>Fractional field drainable water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>92</td>
<td>3</td>
<td>5</td>
<td>0.109</td>
<td>0.190</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>82</td>
<td>12</td>
<td>6</td>
<td>0.130</td>
<td>0.177</td>
</tr>
<tr>
<td>Sandy clayey loam</td>
<td>65</td>
<td>26</td>
<td>9</td>
<td>0.165</td>
<td>0.157</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>60</td>
<td>12</td>
<td>28</td>
<td>0.134</td>
<td>0.177</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>40</td>
<td>42</td>
<td>18</td>
<td>0.212</td>
<td>0.135</td>
</tr>
<tr>
<td>Clayey loam</td>
<td>35</td>
<td>30</td>
<td>35</td>
<td>0.190</td>
<td>0.120</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>35</td>
<td>22</td>
<td>43</td>
<td>0.175</td>
<td>0.103</td>
</tr>
<tr>
<td>Silty clayey loam</td>
<td>20</td>
<td>65</td>
<td>15</td>
<td>0.284</td>
<td>0.078</td>
</tr>
<tr>
<td>Clayey loam</td>
<td>20</td>
<td>20</td>
<td>60</td>
<td>0.181</td>
<td>0.016</td>
</tr>
<tr>
<td>Silty clay</td>
<td>10</td>
<td>55</td>
<td>35</td>
<td>0.255</td>
<td>0.074</td>
</tr>
<tr>
<td>Clay</td>
<td>8</td>
<td>47</td>
<td>45</td>
<td>0.235</td>
<td>0.045</td>
</tr>
</tbody>
</table>
insensitive to the vegetation canopy parameterisation, although there is a need to distinguish between permanent and annual short vegetation and forest. However, estimates of the canopy development are important for annual short vegetation, as are the parameters for the interception model used for forest. If the proportion of forest planted in the UK increases significantly in the areas where groundwater recharge occurs there will be an impact on groundwater resources. Similarly, changes in types of annual short vegetation or the conversion from annual to permanent short vegetation could also have an effect.

It should be noted that these conclusions may only apply to the climatic conditions typified by the meteorological data used. It should also be noted that they apply to the use of water balance models for estimating direct groundwater recharge. The results of a similar study for other applications, e.g. meteorological forecast models, might well be different. This is because it is the energy fluxes that would have the dominant effect on a meteorological model and so it is the daily variations that are important.

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