Predicting The Impact Of Afforestation Or Deforestation On Recharge Using Only Time Series Soil Moisture and Hydrometeorological Data.

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Abstract: Modelling the impact of afforestation or deforestation on water resources is complex due to factors such as the microclimate, the soils, the underlying geology, the presence of macropores, the species, their age and density. Parameters used in modelling the different processes are traditionally determined individually from laborious measurements. In this study the only input data required are time series precipitation and Penman evapotranspiration. The SHELUC model uses parameters describing interception, evapotranspiration and soil parameters (van Genuchten parameters). The challenging task is to determine the parameters of SHELUC solely from normalized time series soil moisture profiles measured by the neutron method. The model parameter sets derived using an automatic calibration procedure. The SHELUC inverse problem for calibration uses a minimum of parameters to describe the different processes, which renders SHELUC a novel valuable tool to predict scenarios of climate and landuse change.

Keywords: *Recharge; Unsaturated zone; Soil Moisture; Afforestation/ Deforestation; Modelling*

1. INTRODUCTION

Forests cover approximately a quarter of the globe and are constantly being altered. Forests between latitudes 30N and 60N will continue to increase by 70% between 1993 and the 2080s as indicated in modelling studies by Friend *et al.,* (1997). As result of changing climate, forests will grow faster as a result of more favourable temperature, adequate rainfall and nitrogen deposition. This will be enhanced due to the progress of agriculture that permits an increase of production per surface area liberating large surfaces for forests. On the other hand the study predicts that tropical forest will decrease as a result of decreasing rainfall and increasing temperature. Deforestation is also enhanced in the less developed countries caused by an increase in population and a slower development in agriculture.

It is accepted that afforestation and deforestation can dramatically alter the water regime. Predicting the impact of land use change on recharge is very complex; different tree species intercept, evapotranspirate and react differently to stress, but major differences can occur for the same species rooted in different soils, and microclimate. In addition, the rate of recharge under forests is not static and increases/decreases with time. For example younger trees uptake more water then older ones. The root growth could for example cause a sudden decrease in net recharge if the taproots reach the water table or could cause an increase in the recharge by roots causing fractures. Afforestation/deforestation could be the cause of increasing or decreasing recharge.

It has been shown that to determine the impact of afforestation/deforestation one must have a detailed knowledge of the local environment. Controversially the literature tends to show that simpler models which average data from different processes give better results than models which attempt to model processes individually.

This paper describes a research model SHELUC (System Hydrologique European Land Use Change model) which will be the basis for developing simpler models. It computes the recharge for a vegetated area. The understorey is included in the calculation of interception and evapotranspiration. The model takes into account the macropores indirectly due to inverse method techniques that determine most of the parameters solely from time series soil moisture profiles and hydrometeorological data (precipitation and Penman evapotranspiration).

2. STUDY SITE

2.1. Study site

The study sites are situated in the East Midlands of England in Nottinghamshire. This area has got four types of vegetation that were monitored between 12th February 1998 and 23rd April 2002 in order to predict the impact on recharge of doubling the forest area over the next 50 years:

- Grass pasture;
- Heather (dominated by *Calluna vulgaris*) has been the predominant land cover type in this region in the past 500 years;
- The conifer site is a 30-year-old Corsican Pine (*Pinus nigris*) plantation;
- Broadleaf woodland is represented by 62-year-old oak trees (*Quercus robur*).

All sites have an elevation of 90m above sea level +/-5m and have negligible slope. No ponded water was observed on site.

The soils of the 4 monitored sites are sandy soils classified as sandy podzols. They have the particularity of high drainage and low water-holding capacity compared to other type of soils. The grain size distribution reveals a preponderance of sand and very little silt and clay, typically less than 8%. In the profile, layers of pebbles up to 100 mm and marl clay are encountered causing respectively in the soil profile patches of dry and wet zones.

The Sherwood sandstone aquifer was encountered at a depth below 32 meters.

Within the three-year period of study, 1998-2001, there was a dry and wet ‘water’ year. The complete ‘water’ years (October-September) rainfall reached a total of 728, 756 and 901mm respectively in 1998-99, 1999-00 and 2000-01 (the wettest year within the last three decades).

2.2. Experimental design

In order to quantify recharge under the different land uses measurements of soil moisture profiles derived from the neutron methods (to a depth of 9m) were undertaken every 2 weeks. For each land use 5 access tubes have been monitored.

Daily rainfall and evaporation are used as input to the model. Weekly estimates of potential transpiration estimates for short grass have been derived from the Meteorological Office’s MORECS system (Meteorological Office, 1992). Further information on the project can be found (Calder *et al.*, 2001).

3. MODEL DESCRIPTION

3.1. Introducing SHELUC model

This study is devoted to a development of a model, SHELUC, which predicts recharge for different land uses. The model computes interception and evaporation processes for the vegetation cover and the soil water storage and water movement through the unsaturated zone.

SHELUC is the merger of two models, a simple interception and evaporation model HYLUC (Hydrological Land use Change model) which employs the concept of field capacity and SHETRAN (Systeme Hydrologique Europeen TRANsport model) which is a physically-based distributed hydrological modelling system developed in Newcastle (Ewen *et al.*, 2000). SHELUC uses only the 1D Variably-Saturated Subsurface component of SHETRAN. The governing equations for each component are solved using finite-difference methods to solve the unsaturated flow in heterogeneous porous media, based on the Richards equation.

SHELUC uses the whole 9m soil moisture data set and avoids the use of the field capacity concept, as the evaporation regulating function is based on water content rather than soil moisture deficit of the top 2m. The total evapotranspiration is distributed over the rooting depth and the recharge is calculated directly from hydraulic gradients.

3.2. SHELUC flow equation

The 1D water flow in unsaturated heterogeneous soils is described by the Richards' equation. A root extraction term *S* is included:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h).\frac{\partial h}{\partial z} + K(h) \right) - S \qquad (1)$$

where θ is volumetric water content (L^3L^{-3}), t is time (T), C is the differential soil water capacity (L^{-1}) which is equal to the slope $d\theta/dh$ of the soil water retention curve, $h(z,t)$ is soil water pressure head (L), z is gravitational head, as well as the vertical coordinate (L) taken positive upwards, $K(h)$ is the unsaturated hydraulic conductivity ($L\ T^{-1}$), and $S(z,t)$ is soil water extraction rate by plant roots ($L^3L^{-3}T^{-1}$).

The retention curve $\theta(h)$ can be obtained from van Genuchten (1980):

$$Se = \frac{\theta - \theta res}{\theta sat - \theta res} = \frac{1}{\left[1 + (\alpha.h)^n\right]^{1-\frac{1}{n}}} \qquad (2)$$

where Se is the relative saturation. The parameters θres and θsat are residual and saturated water contents respectively, α is related to the inverse of the air entry pressure (L^{-1}), and n is a measure of the pore-size distribution (-).

The unsaturated hydraulic conductivity function can be described by (Van Genuchten, 1980)

$$K(Se) = Ksat.Se^{l}.\left[1-\left(1-Se^{\frac{n}{n-1}}\right)^{1-\frac{1}{n}}\right]^{2} \qquad (3)$$

where *Ksat* is a saturated hydraulic conductivity ($L\ T^{-1}$) and l is a shape factor (-).

3.3. Boundary conditions

The initial conditions for a simulation are for each layer:

$$h(z,0) = h_0(z) \qquad (4)$$

where $h_0(z)$ is a prescribed hydraulic head field. The results were found to be sensitive to the initial conditions although a "run-in" period of about 2 years was included.

During periods of the simulation when no ponded water exists at the ground surface, the flux boundary condition is given by:

$$K(h).\left(\frac{\partial h}{\partial z}+1\right) = Pr - Int \qquad (5)$$

where $Pr(t)$ is precipitation ($L\ T^{-1}$) and *Int* is interception ($L\ T^{-1}$).

If water is ponded then a head is applied given by

$$h(Z_{max},t) = Z_{max} + h_w(t) \qquad (6)$$

where h_w is the depth of the ponded water (L).

For the bottom boundary condition a constant head boundary condition is defined representing the water table level.

$$h(z_{min},t) = h_w(t) \qquad (7)$$

The results where not found to be sensitive to the deep level of the water table.

3.4. Method of solving Richards' equation

The numerical solution of the nonlinear partial-differential Richards equation uses the Newton-Raphson iteration.

3.5. Interception model

SHELUC has incorporated a simple empirical interception model that predicts the daily loss of precipitation by interception (Calder, 1990). The model was developed for coniferous forest in the upland sites in the UK. The equation is:

$$Int = \gamma.\ [1 - \mathrm{Exp}(-\delta.\ Pr)] \qquad (8)$$

γ parameter can be considered to represent the maximum interception loss per day ($L\ T^{-1}$). δ governs the rate of interception loss (-).

For "closed canopy" forests a simplification can be made with little lost of accuracy through the relationship:

$$\delta = 1/\gamma \qquad (9)$$

4. SINK TERM

4.1. Introducing the sink term

The sink term in SHELUC is distributed to the whole root zone and is calculated for each cell:

$$S = \beta.\ PE(t).\ DRY(t).\ RDF(z).\ SMRF(\theta) \qquad (10)$$

where β is the transpiration fraction (-), *DRY* represents the fraction of the day that the canopy could transpire because it is not wet (%), *RDF* is the root density function (%), *SMRF* is the soil moisture regulating function (%) and *PE* is the daily Penman potential transpiration estimated for short grass ($L\ T^{-1}$) with the reflection coefficient equal to 0.25 (rather than 0.05 for water surface).

4.2. Transpiration fraction

It is assumed that the relationship between evapotranspiration from short grass and trees can be simply done by multiplying *PE* by a parameterβ. The values are shown in Table 1.

4.3. Fraction of dryness

DRY represents the fraction of the day that the canopy is dry and is able to transpire ($T\ T^{-1}$). The empirical relation is given by:

$$WET = Int/\ \gamma \qquad (11)$$

$$DRY = 1 - WET \qquad (12)$$

4.4. Root density function

Hoogland *et al.*, (1981) linear RDF model is used for plants with a rooting depth of less than 1m. The % of roots in every cell is given by:

$$\Delta RDF = \gamma.(Z_{up}^{2} - Z_{down}^{2})/ Z_{max}^{2} + \Delta Z\ (1-\gamma)/ Z_{max} \qquad (13)$$

For deeper rooting vegetation, the exponential model of Gale & Gigal (1987) that gives the % of roots for every cell is given by:

$$\Delta RDF = (EC^{[Zdown]} - EC^{[Zup]})\ /\ (1 - EC^{[Zmax]}) \qquad (14)$$

where *Zup, Zdown,* are respectively the depth below ground at the top and bottom of the cell (L). *Zmax* is the maximum depth of the roots (L), and ΔZ is the mesh size (L). *EC* and γ are parameters (-).

4.5. Soil moisture regulating function

Trees transpire less then PE if θ becomes smaller then "wet available water" AW_{wet} (L). When θ becomes smaller then the threshold "dry available water" AW_{dryt} (L) then $PE = 0$. When $AW_{dry} < \theta < AW_{wet}$ then PE is reduced at every depth in the root zone according to the following equation:

$$SMRF=(\theta - AW_{dry}) / (AW_{wet} - AW_{dry}) \qquad (15)$$

5. COMPUTING RECHARGE

The recharge is computed for every land use by computing the differences in the soil moisture as a function of time. The input parameters are retrieved from the inverse modelling procedure.

6. MODELLING APPROACH

6.1. Model set up

A finite-difference grid for SHELUC was set up to correspond to the depths of measuring soil moisture with grid spacing ranging from 0.1m to 0.5m.

Not all potentials of the model have yet been tested in detailed and some parameters have not been optimized:

- One value AW_{wet} was optimized for the whole root zone and AW_{dry} is set to 0;
- The β values are taken from Calder (1990);
- The exponential model was used and was set to $EC=0,96$. The results were found not to be very sensitive to EC.

SHELUC is being calibrated against the normalized time series soil moisture profiles by minimizing the Root Mean Square error (RMSE).

6.2. Reducing the number of parameters to be optimised

From 0 to 9m is divided in 40 layers. Each layer is characterized by 6 soil parameters. There are 5 hydrological parameters: AW_{wet}, γ_{summer}, γ_{winter}, $\beta summer$, $\beta winter$ making a total of 245 parameters to be optimised.

In SHELUC, none of the soil parameters need to be known. Given that the Van Genuchten model has equifinality, the soil parameters are treated as non-physical enabling *n, l, Ksat* to be frozen. This scheme reduces the parameters to be optimised to 125 (Pollacco and Quinn, 2003).

θres for the 40 layers are replaced by 2 parameters θres_{shift}, θres_{mult}. This scheme uses the average observed soil moisture θobs at each layer, hence the number of parameters to be optimised reduced to 87 (Pollacco and Quinn, 2003).

6.3. Difficulties of inverse modelling

In order to predict the impact of afforestation, a set of parameters representing the tree physiology and the modification of the water path in the soils due to its roots need to be determined. After the soils properties of the afforested soils are determined one can predict the impact of afforestation or deforestation on recharge. It is not important for SHELUC, that the retention curve represents equifinality (Pollacco and Quinn, 2003), but it is crucial that the "tree parameters" have the following properties:

- No equifinality (e.g. the parameters representing interception do not take into account the evapotranspiration);
- The values of the optimized parameters are not dependent on the frequency distribution of the data set.

6.4. Equifinality problem

In order to define the total water loss, it is important to separate interception processes from the evapotranspiration. If this is not possible, the most sensitive parameters need to be fixed.

6.5. Dependency on the frequency distribution

A study was conducted to evaluate if the data is sensitive to alternative regulating functions. Different models were tested: Calder *et al.* (1990) and others. It was shown that the RMSE values were independent of the model used. Further analysis showed that the RMSE criterion was biased towards the highest frequency distribution. An elaborate weighted RMSE did not discriminate between the different regulating functions. As also demonstrated by Gupta *et al.* (1998), a good match of a RMSE does not always mean that the physical model depicts well the physical process. This difficult problem needs investigation.

6.6. Minimization search routine

The minimization routine used is an improved downhill simplex method that was extended to include an automated grid search over a bound parameter space.

6.7. Inverse model of 87 parameters: a simple and robust method

In the soil profile it can be shown that some layers are dryer compared to adjacent layers, suggesting the presence of preferential flow. This flow cannot be described well by SHELUC, which employs the Richards equation law making the reproduction of the θobs difficult. A solution is to optimise the 40 layers in a specified order and pattern described in (Pollacco and Quinn, 2003).

7. RESULTS

7.1. Optimisation values

The optimised hydrological parameters are given in Table 1. The optimised soil parameters are not interpreted as being physically based and there values are therefore not given.

Table 1. The hydrological parameters used to describe SHELUC. The transition days between winter and between summer and winter are set as 17th June and 7th November.

Parameters and their units	Grass	Heath	Oak	Pine
AWwet, for the whole 2m. (mm)	179	157	288	173
$\beta summer$	0.88	0.82	0.99	0.76
$\beta winter$	0.98	0.78	0.82	0.89
γ_{summer} (mm d^{-1})	-	2.3	3.0	3.5
γ_{winter} (mm d^{-1})	-	1.4	0.7	4.1

7.2. The interception plot

Pasture grass is assumed to have 0 interception. The simulated optimised interception loss due to evaporation for three vegetation types can be seen in Figure 1. The intercepted loss is reduced to the canopy storage capacity and in general is higher in summer than in winter due to total higher *PE* rate. However in the pine forest, it is interesting to note that the interception loss is higher in winter than in summer. In winter the precipitation is mainly frontal, with generally small raindrops, which can be intercepted by the canopy. Whereas, in summer a larger amount is from convective storms, it is suggested that these generally have larger raindrop sizes and that these raindrops are heavier and produce a greater throughfall.

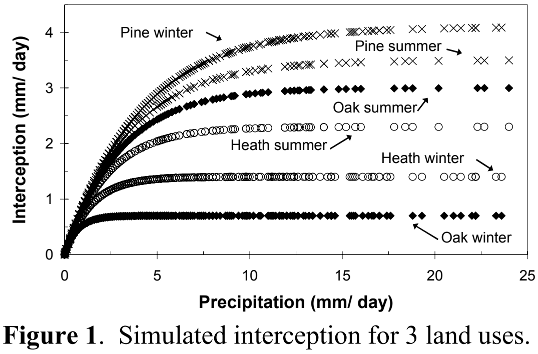

Figure 1. Simulated interception for 3 land uses.

7.3. The soil moisture for each land use

SHELUC simulates the heterogeneity to a satisfactory level for the driest and the wettest periods as shown in Figure 2.

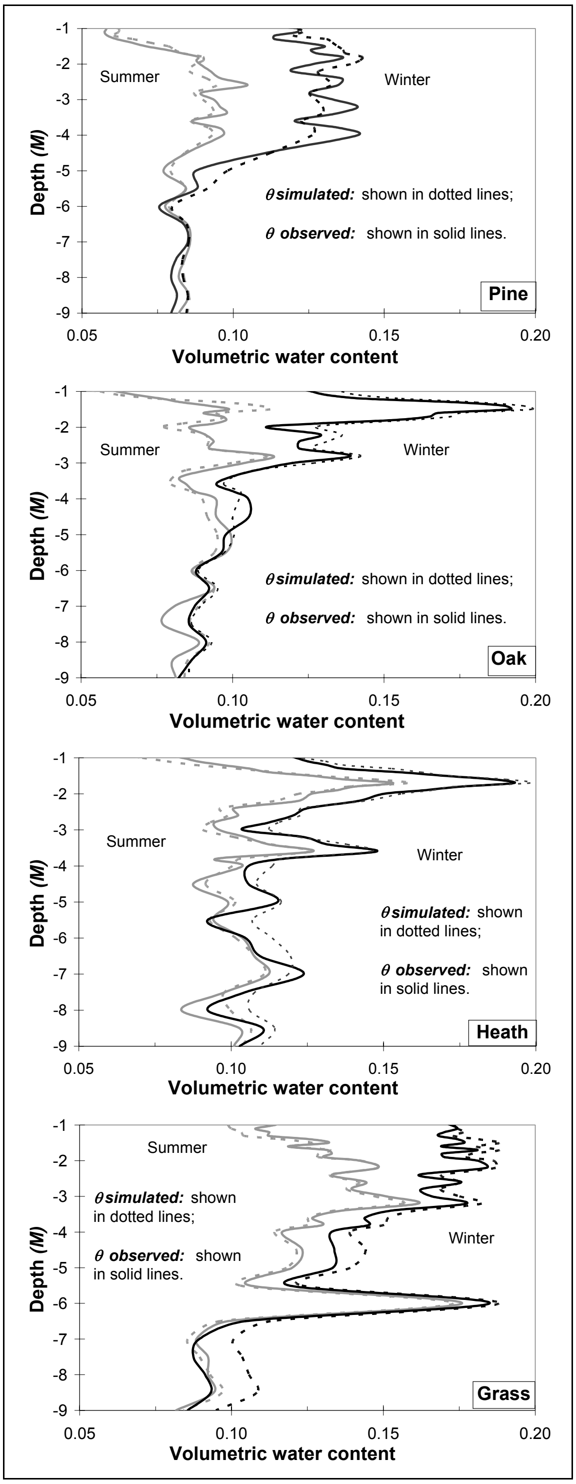

Figure 2. θobs and θsim time shot in the driest and the wettest period respectively for Pine, Oak, Heath, Grass.

7.4. The recharge computed

Figure 3 shows the dynamics of water movements down the profile for the 4 different land uses. Below 15m the flux is almost constant with depth. In summer there is an upward movement of water in the top few metres as a result of water uptake by the root zone.

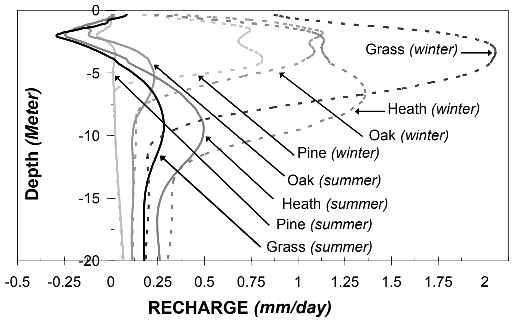

Figure 3. Snap shot of recharge of the 4 different land use, for the summer and winter period.

8. CONCLUSION

A modelling system has been described which can represent the dynamics of water movement through unsaturated soils linked to a parsimonious model of interception and evapotranspiration. The model requires precipitation and potential evapotranspiration time-series as inputs, and uses only soil moisture observations for calibration. The model has been used to provide predictions of recharge under different land uses.

The calibration approach used an optimisation procedure which takes account of the heterogeneity of the soil profiles, and addressed the simulation equifinality by reducing the number of independent model parameters.

For the study site (sandstone aquifer and temperate climate) the sequence of predicted recharge for different land covers is grass (greatest), heath, broadleaf (oak), pine (least).

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