Identifying Evapotranspiration relationships for Input into Rainfall-Runoff Models using the SWIM model

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Abstract: Accurate estimates of evapotranspiration are often an essential input for rainfall-runoff modelling and water balance calculations. Present methods for estimating evapotranspiration rely either on mass balance or climatic data measuring wind, humidity, solar radiation and temperature. This paper presents an alternative method for estimating evapotranspiration for input into semi-distributed rainfall-runoff models. Three different vegetation types were tested on a range of soil types within a catchment using the Soil Water Infiltration and Movement (SWIM) model. The results for wheat are presented in this paper. The relationship between available soil water and evapotranspiration was then identified for each soil type. This relationship was then used to estimate the distributed evapotranspiration pattern for a catchment over time based on particular land-use and rainfall patterns. Preliminary results and the advantages of using such a meta-model approach in semi-distributed hydrological modelling are presented.

Keywords: *Evapotranspiration; Soil water; Vegetation; Rainfall-runoff models; Regionalisation; Scale*

1.INTRODUCTION

Evapotranspiration is an important component in hydrology models. Without accurate and reasonable methods for estimating plant transpiration, it is difficult to model land use change affects on catchment hydrology. There is a need to accurately estimate evapotranspiration for a variety of vegetation types growing in various soils. Many of the current methods of estimating evapotranspiration require complex and difficult to measure input data (Van den Berg and Driessen, 2002; Zhang et al., 1999; Monteith, 1981; Verburg et al., 1996). Other methods are based on calibrated parameters that rely on dubious assumptions, or limit modellers to gauged catchments.

Although the relationship between available water and transpiration is well known, rarely are the relationships determined for soil and vegetation types, used to drive evapotranspiration in catchment hydrology modelling. This paper investigates the use of SWIM (Soil Water Infiltration Model)(Ross, 1990) to provide simulations and the relationships between soil profile water and transpiration for input into a semi-distributed catchment hydrology model. SWIM gives estimates of drainage, crop water use, evaporation and plant available water. The SWIM model simulates the soil water balance using simultaneous numerical solutions of differential soil water flow equations (Verburg, 1995). Obviously running the SWIM model within the framework of a distributed catchment hydrology model for each soil and vegetation case would be tedious. However if the relationships are defined prior to modelling then the complexity of a mechanistic model like SWIM can be avoided. It may be said that soil suction transpiration curves have been developed. These curves however, do not take into account changes in soil texture with depth. Also the reaction of the plant is different under wetting conditions compared to drying conditions.

The relationship between soil profile moisture and evapotranspiration will be used in the catchment hydrology model for defining evapotranspiration rates following rain and the subsequent reduction in transpiration during days with no precipitation. The aim therefore is simply to determine the maximum transpiration rate and the equation which most accurately depicts the drying curve for each case tested.

2.TRANSPIRATION MODELS

The methods used to estimate plant transpiration in models are extensive. The choice of which transpiration model or method to use is often determined by the availability and accuracy of data, and the scale of modelling. For instance the estimation of transpiration for a single or small group of plants can be determined using sap flow measurements (Slavich et al., 1999a), but such methods are not appropriate at the catchment scale. Other methods include the use of isotopes of water. Brunel et al. (1997) describe the use of stable isotopes of water to partition evapotranspiration. These methods rely on accurate sampling of isotopic water vapour and analysis from plants and soil.

Zhang et al. (1999) found that simulations of evapotranspiration and soil water by a soil-vegetation atmosphere transfer model (SVAT) called WAVES compared favourably to measurements by isotope studies and lysimeters. SVAT models are complex and have a large number of parameters which are often difficult to measure (Slavich et al., 1999b). For instance WAVES relies on accurate measurements of net radiation budget for input into Beer's Law and the Penman-Monteith equation (Monteith, 1981). A study by Meiresonne et al. (2003) makes use of eddy covariance, which measures atmospheric water fluxes. This method has been shown to have problems relating atmospheric flux with ecosystem water exchange due to many assumptions. Eddy covariance has also been shown to be unreliable on days with rainfall.

Most physically based evapotranspiration models fall into two categories. Models in which the plant system drives water exchange with the atmosphere and models such as SWIM, which use soil to drive the water exchange with the atmosphere. The plant system models transpiration by imitating water vapour exchange through stomata leaf surfaces. This can then be related to Leaf Area Index (LAI). Plant water exchange models are seen as advantageous due to the differentiation between plant transpiration and interception evaporation (Meiresonne et al., 2003).

This advantage is lessened however when comparisons between the two modelling approaches are based on total evapotranspiration. This is because although evaporation of intercepted water reduces transpiration, the final calculation of evapotranspiration is similar between soil and plant water exchange models. Plant driven water exchange models can also under estimate transpiration when a duplex soil is encounted. The presence of a clay layer can increase plant available water in the root zone and therefore transpiration (Meiresonne et al., 2003).

A simple method for estimating evapotranspiration as a function of potential evapotranspiration and soil moisture storage (defined by a single variable) in the unsaturated zone is described by Keig and McAlpine (1974). Such models however fail to take the heterogeneous nature of soil profiles into account.

3. THE SWIM MODEL

The SWIM model works on a one-dimensional heterogeneous vertical soil profile that is assumed to be homogenous in the horizontal. The model efficiently solves Richards' (1931) equation for water flow in porous media.

Richards' equation in the SWIM model takes the form

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(k\frac{\partial\psi}{\partial z}) + S$$

where θ is the soil volumetric water content (cm^3/cm^3), t is time (h), z is depth (cm), K is hydraulic conductivity (cm/h), ψ is soil water potential and S is a source or sink of water ($cm^3/cm^3/h$). The Richards' equation used is a combination of the Darcy flow law

$$q = -k\frac{\partial\psi}{\partial z}$$

(where q is water flux (cm/h)), and the equation of continuity

$$\frac{\partial\theta}{\partial t} = \frac{\partial q}{\partial z} + S$$

The SWIM model is able to simulate runoff, infiltration, transpiration, evaporation, deep drainage and solute transport. The vegetation inputs required for soil water modelling by SWIM are properties such as root length and xylem potential and fraction of potential evapotranspiration for each vegetation type. Other inputs include soil hydrological properties for each layer, pan evaporation and precipitation (Verburg, 1995).

The SWIM model can model single crops, intercropping and mixed species such as trees and grass. Electrical circuit analogies are used to determine root water uptake for each soil layer (Verburg, 1995). Van den Berg et al. (2002) investigated the use of such a electrical analogue model and determined that the theoretical nature of such models improved understanding of complex processes. Poor performance in the model investigated by Van den Berg et al. (2002) was seen to be due to the use of a one layered soil profile.

Soil evaporation and plant transpiration water supply and demand are handled in the SWIM model in relation to the potential rate. Plant transpiration takes place at the potential rate when water supply meets demand. When supply falls below demand an iterative procedure determines the actual water that can be transpired. Similarly soil evaporation takes place at the potential rate, when the soil surface is wet and water meets evaporative demand, otherwise soil evaporation is determined by the soil's ability to supply water to the surface (Verburg, 1995). A more detailed description of the SWIM model can be found in Verburg (1995).

4. SWIM MODEL ACCURACY

One important limitation of the SWIM model related to research conducted here should be noted. Vegetation representations in the model do not account for the plant becoming stressed. Once the plant has grown it will not diminish in times of drought or water stress. Instead it ceases to transpire and begins again at a normal rate when water becomes available. The SWIM model is also only as accurate as the equations that describe it. As the model assumes horizontal equilibrium, care needs to be taken in applying results at a field scale. Another potential problem is that the model does not take into account changes in soil properties during the simulation period.

Despite the above limitations the SWIM model has been shown to be very successful in predicting soil water content and plant transpiration with limited data input. The use of soil profile partitioning in SWIM is seen as advantageous when compared to one layer profile models. Models that used one soil compartment to simulate the root zone assume water is spread evenly over the entire root zone. This can result in water being consumed in a shorter time span than in models that compartmentalize soil into a number of layers. These layered models allow for differences in water content with depth and account for most of the water being contained in surface layers (Van den Berg et al., 2002).

Van den Berg et al. (2002) found that one layer models are inappropriate for modelling water uptake in soils, subject to irregular cycles of drying and wetting. Soil compartments, each with its own soil water uptake properties, were seen to be more successful in simulating water uptake under dryland agriculture.

In one extensive study the SWIM model is compared to another soil water model called SoilWat (Verburg, 1995). SoilWat is a multi-layer, cascading water balance module and the flow processes are calculated consecutively as apposed to simultaneously in SWIM. In the Verburg (1995) study the SWIM model was found be be more accurate than SoilWat in predicting soil evaporation compared to measured data.

SWIM also performed better in predicting water fluxes measured using a bromide pulse. For this study the relative fluxes may not be as important, as comparisons are being made between profile moisture and transpiration. Strong correlations have been found between transpiration and the total amount of soil water (Van den Berg and Driessen, 2002).

The use by SWIM of Richards' equation can make SWIM seem more complex than models like SoilWat that use parameter optimization. The development of pedo-transfer functions however, has reduced this complexity somewhat (Smettem et al., 1999; Bristow et al., 1995). The SWIM model is also reliant on accurate vegetation parameters for correct estimates of transpiration. For instance a study by Slavich et al. (1999a) found that low transpiration rates were associated with low leaf area index.

5. TRANSPIRATION AND SOIL MOISTURE CURVES

The SWIM model is being used here to investigate the relationship between soil profile moisture and transpiration for use in a semi-distributed catchment hydrology model. The SWIM model itself will not be used in the catchment hydrology model, but simply the mathematical relationships that SWIM determines for different vegetation on various soils. For the purposes of this paper many assumptions have been made. The intention is to simply illustrate how and to what extent the relationship between soil profile moisture and transpiration may be utilized in a catchment hydrology model.

It was assumed the vegetation types being modelled are fully grown for the duration of the SWIM simulation so as to imitate native grasses which exhibit similar root properties to winter wheat (Russell, 1988). Future model research will imitate changes in transpiration due to crop growth. During SWIM simulations pan evaporation rate was kept constant at 10 mm/day so that profile moisture could be changed based on one variable (i.e. rainfall). The use of these transpiration relationships in catchment hydrology models relies on SWIM model accuracy as shown by Verburg (1995) and Smettem et al. (1999). One important aspect of the transpiration relationships derived by the SWIM model will be their effectiveness at the catchment scale. Future research will look at what level of modelling is needed at the plot scale for application at the field scale. Remote sensing would be utilized to identify vegetation types and apply the appropriate transpiration relationship dependent on a soil moisture deficit.

To run the model various scenarios were developed. The model was tested on four different soil types namely a sand, a loam, a clay and a duplex soil. The soil properties for this study were obtained using typical sand, loam, clay and duplex profile information and pedo-transfer equations described in Smettem et al. (1999). For each soil a wheat crop was used as the reference crop with vegetation parameters being taken from a previous study by Smettem et al. (1999). All soil properties were assumed to be uniform within the profile except in the duplex soil which imitated a sand changing to a clay at 50cm. The total profile depth was 1.5m.

The subsequent transpiration curves are seen here as a simple and reasonable method to estimate plant transpiration in a semi-distributed rainfall-runoff, recharge-discharge model previously described in Carlile et al. (2002). The use of the transpiration curves will allow a simple conceptual water balance model to account for changes between vegetation types in a catchment. The success of such an approach will be determined following extensive testing including catchment hydrology model simulations of stream flow versus observed flow.

Figure 1 shows both the wetting and drying curves for a sandy soil with wheat, as simulated by the SWIM model. In this example rain was applied at a rate of 10 mm/day for 500 days and then allowed to dry out. Because the model has been set up assuming the plant is fully grown at the beginning of the simulation, the wetting curve (solid line) quickly jumps to the potential transpiration rate. The drying curve (dashed line), however, is more gradual. This response is then replicated in the model, by ensuring that transpiration jumps to the potential rate for a particular vegetation type following periods of sufficient rainfall. Transpiration then drops according to the drying relationship identified.

The original estimation of evapotranspiration in the model assumed an exponential decay for evapotranspiration. This was found not to be the case however when the drying curves for a sand, loam, clay and duplex soil under a wheat crop (solid line - Figure 2) were fitted exponentially. The best fit to the drying curves a cubic relationship (dashed line - Figure 2). However, the form that this relationship will take may be different at the sub-catchment scale.

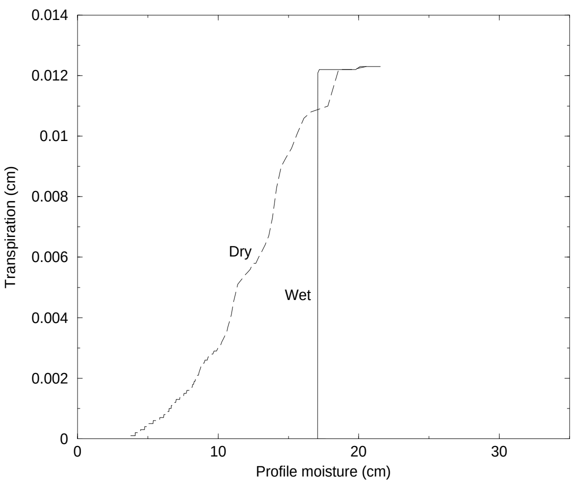

Figure 1: The wetting and drying transpiration curves simulated for wheat on a sandy soil

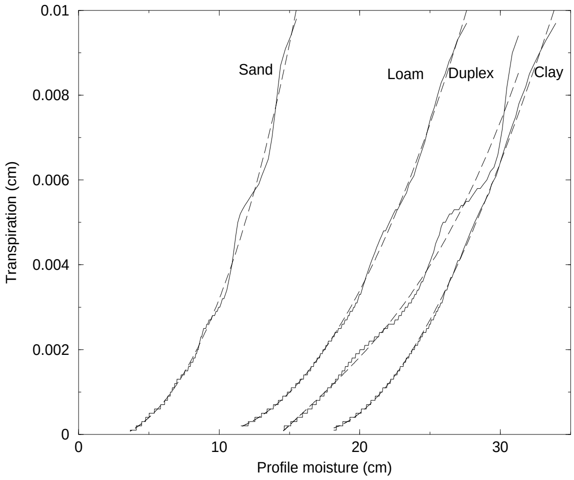

Figure 2: Transpiration drying curves fitted with a cubic on four soil types

The cubic equation coefficients were determined by regression (Table 1) for the relationship between soil profile moisture and transpiration once the profile is allowed to dry.

Table 1: Coefficients determined for cubic fit ($y = a + bx + cx^2 + dx^3$)

Soil	a	b	c	d
Sand	-0.0001	-6.344e-5	2.696e-5	1.251e-6
Loam	0.0022	-0.0005	2.46e-5	9.823e-8
Clay	0.0151	-0.0019	7.207e-5	-5.598e-7
Duplex	-0.0079	0.001	-4.171e-5	8.813e-7

It is these equations that are utilized whenever wheat is encounted on a sand, loam, clay or duplex soil. As can be seen in Figure 2 soil moisture increases with changes in soil texture. Also the rate at which transpiration decreases is less in a clay compared to the loamy soil, and less again compared to a sandy soil. As expected the duplex soil shows properties of a sand a clay. These curves are similar and related to transpiration versus soil suction curves (Russell, 1988). As soil suction increases (reduction in soil water) transpiration decreases, with actual transpiration falling below the potential rate at the top of the curve.

6. INCORPORATING THE META-MODEL IN CATCHMENT HYDROLOGY MODELS

The original formulation for evapotranspiration in the envisaged catchment hydrology model IHACRES (Jakeman and Hornberger, 1993; Croke et al., 2002; Carlile et al., 2002), uses a simple relationship between temperature and evapotranspiration defined as:

$$E_k = c_1 T_k exp(-c_2 CMD_k)$$

where T is temperature, CMD_k is a catchment moisture deficit at time step k and $c_1$and $c_2$are parameters. In this formulation ET is directly proportional to temperature and decreases exponentially as CMD increases. Higher temperatures result in larger ET losses provided there is sufficient soil moisture (Evans and Jakeman, 1998).

This method relied on accurate estimates of temperature and did not take into account changes in vegetation and soil, which in turn made it difficult to apply in a distributed model. The use of transpiration curves overcomes these restrictions by estimating transpiration, which can in turn be used to estimate effective rainfall using a mass balance approach for each subcatchment or hydrologic response unit (Carlile et al., 2002).

Recharge would be estimated in a similar way as that used by Cook et al. (2001). They used the approach that the time for deep drainage to reach the water table is dependent on the deep drainage rate, the initial water table depth and the soil water content within the unsaturated zone. The storage is calculated daily and deep drainage is said to occur when the storage is exceeded. Drainage would not be estimated using SWIM because of the assumption by SWIM that the soil profile is homogeneous in the horizontal.

The application of a plot scale model to the field scale has problems related to transpiration rates for single plants compared to crops or forests. It is envisaged that vegetation distributions and Leaf Area Index (LAI) determined using satellite imagery would be used to distribute the plot scale model to the field scale. Andersen et al. (2002) investigated the use of remotely sensed estimates of leaf area index (LAI) and precipitation in a distributed hydrological model. LAI was used to estimate root length of annual vegetation, using the relationship between root growth and LAI changes. This relationship was described by

$$Rd_i = Rd_{max} \frac{LAI_i}{LAI_{max}}$$

where Rd_i is the root depth on day i, LAI_i is the corresponding LAI and LAI_{max} and Rd_{max} are the maximum LAI and root depth for a given vegetation class for the period. Andersen et al. (2002) found considerable improvements in discharge simulations when using remotely sensed LAI.

The final distributed model will not try to imitate the many physical processes present in catchment hydrology. It will however use simplified principles, with the aim of distributing physical processes. Van den Berg and Driessen (2002) considered that ”simplified theoretical descriptions based on physical laws have their merits.” They found that models suited to rain fed conditions need a conceptual view of the soil profile where wet and dry parts of the soil are represented. It was also suggested that relationships between transpiration and soil water can be obtained by logistic equations over the entire range of available water.

7. DISCUSSION AND CONCLUSION

This paper has suggested a meta-model approach based on the physical SWIM model for estimating transpiration in conceptual catchment hydrology models such as IHACRES. If the subsequent transpiration relationships are kept as signatures describing transpiration for various plants on different soils, the need to run physical models prior to catchment hydrology modelling is reduced. The distributed model simply calls upon the appropriate transpiration relationship for each vegetation-soil combination present. The proposed meta-model is then able to better describe the evapotranspiration response of a hydrologic unit or sub-catchment.

The advantages of using the above approach in catchment hydrology modelling may become more pronounced with the advances in remote sensing. There has been little success in directly measuring transpiration using remote sensing. However, there have been considerable advances made in determining plant species and health. If physical models such as SWIM accurately depict the transpiration behaviour of plants under different profile moisture conditions then remote sensing can be used to distribute it.

The inclusion of actual estimates of evapotranspiration in catchment hydrology models makes investigating the effects of land use change easier. These estimates also have potential for setting parameter values using observable quantities (e.g. vegetation cover, soil properties and topography). Conceptual models have calibrated parameters describing the evapotranspiration rate. In the case of the rainfall-runoff model IHACRES, temperature and a catchment moisture deficit are used in a exponential relationship to determine evapotranspiration. This makes investigations of the effects of land use change on hydrology difficult. The method suggested here is seen as advantageous because changes in evapotranspiration are directly linked to changes in vegetation and soil type.

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