The use of soil moisture in hydrological forecasting

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Abstract

Soil moisture data generated by a land-surface scheme within a meteorological model are used to replace soil moisture estimates of a calibrated hydrological model for simulating river flows in the Thames basin. It is found that the land-surface soil moisture has to be adjusted to correspond to the soil moisture required by the hydrological model. This is done by comparing the soil moisture from the two models and linearly transforming the land-surface soil moisture. No advantage is found in using the land-surface soil moisture (even after adjustment) over the soil moisture intrinsic to the hydrological model.

The other issue explored is how much information can be obtained about soil moisture, or about soil characteristics, from river flow (i.e. the inverse problem). The study identifies that the ratio of base to surface flow is significantly sensitive to the hydraulic properties of the upstream soils, as well as to parameters in the rainfall-runoff model. This ratio can be inferred using standard statistical analysis of the river flow records.

1. Introduction

Soil moisture is included in meteorological and hydrological models and in some way represents a link between the disciplines of meteorology and hydrology. In a meteorological model the soil moisture control and limit on evaporation is of prime interest, whereas in hydrological models, the soil moisture control on runoff generated at the surface is of greater concern. As a result, the models have been tuned to be sensitive to the soil moisture in different ways, with meteorological models highlighting the area-average evaporative control and hydrological models focussing on the small fraction of the area that reaches saturation and produces runoff.

The main part of this paper summarises work done to quantify the added value to flood forecasting that use of ELDAS (European Land Data Assimilation System) soil moisture could make. This represents the soil moisture as interpreted by a Meteorological Land Surface Scheme, as opposed to a Hydrological Forecast model, given observed data. The trial has been undertaken using observations and model outputs for the year 2000. This period was chosen to include the Autumn 2000 floods in the UK, which were particularly severe and may well have been unprecedented in duration and extent since records began. The last previous flooding on this scale occurred in 1947 but direct comparisons are difficult as many flood defences have been built since then, and so too have many more properties. The flooding was the result of one of the wettest autumns since records began in the 1700s; soils were considered to be saturated so excess water from heavy rainfall ran straight into rivers.

The use of river flow to inform the land surface model upstream is discussed in the last part of the paper.

2. Use of ELDAS soil moisture for flood forecasting

The methodological approach is tested using data from the Autumn 2000 floods in the Thames basin. A comparison of information about the soil-moisture in the catchment given by the observed river flow and by the satellite-derived products of ELDAS is made. The comparison involves a type of rainfall-runoff model used worldwide for operational flood forecasting. The probability soil moisture modelling approach is used in models such as the PDM (Moore, 1985, 1999) and the ARNO model (Todini, 1996) and the former representation is used here.

The methodology is as follows:

- The PDM is calibrated to three catchments with flow observations in the Thames basin and run in simulation mode, without correction using flow observations. Data from 1 January to 31 December 2000 are used; this period incorporates the Autumn 2000 floods.
- The time-series of modelled soil moisture from the PDM is compared to soil moisture information from ELDAS models.

The land-surface scheme Tessel (Tiled ECMWF Scheme for Surface Exchanges over Land), described in Viterbo and Beljaars (1995) and Van Den Hurk (2000), has been used to provide soil-moisture values at a 20 minute interval on a lat-long grid (~40km) covering the Thames basin. Tessel currently assumes a single medium-textured soil-type everywhere.

A time-series of Tessel soil moisture estimates for a single gridbox, for the four individual layers, is presented in Figure 1. The values shown are for the Tessel grid-cell that lies closest to the catchment draining to the Mole at Kinnersley Manor. The graph indicates greater responsiveness from the upper layers (layers 1 and 2), than for the deeper soil layers, particularly layer 4. The deeper soil layers also have a lagged response to rainfall compared to the surface layers, as would be expected.

The structure of the PDM (Probability Distributed Model) is described fully in Moore (1985, 1999). The model inputs are rainfall and potential evaporation over the catchment and the output is river flow (or level) at the catchment outlet. Moisture store capacity of the soil and vegetation is expected to vary across the catchment. Thus, the PDM assumes a *distribution of store depths* across the catchment, with depths ranging from a minimum depth c_{min} to a maximum depth, c_{max}.

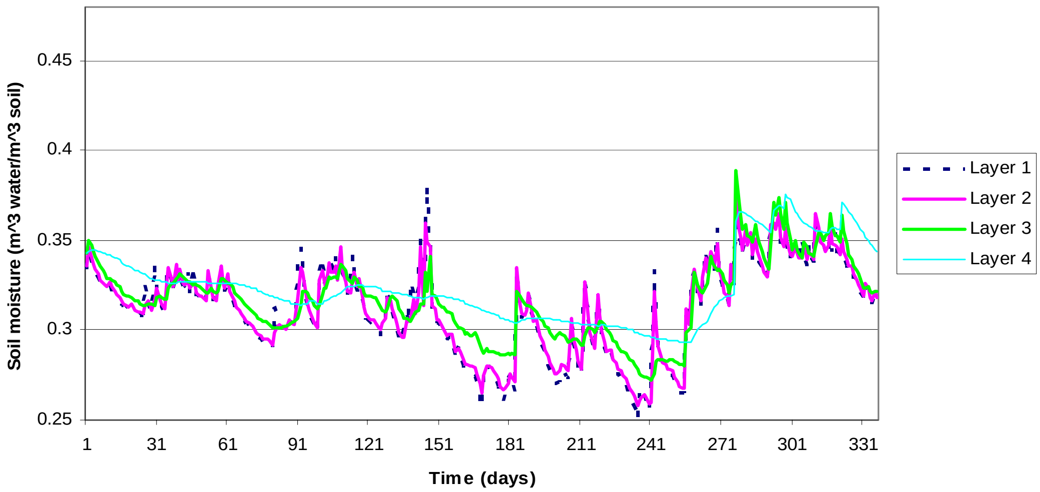

Figure 1: Time-series of ELDAS daily soil moisture estimates for four soil layers. The dashed line indicates the level of soil moisture saturation.

The PDM parameters (eg storage time constants, soil store maximum depth and shape distribution) are usually tuned to an individual catchment by comparing model and observed river flow, and adjusting the parameters to achieve the best possible agreement.

3. Comparison of ELDAS and PDM estimates of soil moisture

In order to evaluate the utility of ELDAS soil-moisture estimates to flood forecasting, values of the soil water fraction from Tessel are compared to soil-moisture values calculated by the PDM. Three catchments in the Thames basin have been selected for study: the Mole at Kinnersley Manor (142km^2), the Roding at Redbridge (301km^2), and the Silkstream at Colindeep Lane (29km^2).

Raingauge data at an interval of 15 minutes are available for all three catchments, and can be compared to Tessel values of rainfall, which are available at a 20 minute interval. Tessel rainfall values are provided by a network of daily raingauges and radar data are used to disaggregate rainfall data from daily to three-hourly values. In areas without observations, ERA-40 fields have been blended. The rainfall hyetographs (not shown here) indicate a reasonable agreement between the Tessel and raingauge observations of rainfall.

In order to compare PDM-derived soil-moisture estimates with those from Tessel, the maximum depth of soil-store of the PDM is varied. The PDM has been calibrated for layers 1 to 3 using these values of c_{max}. The time-series of this PDM modelled soil-moisture deficit are shown alongside the Tessel values in Figure 2 for the Mole catchment. This indicates that there is some relation between the two estimates of soil moisture. However, the PDM soil moisture estimates are the more variable indicating that the soil dries out more quickly in the PDM than in the Tessel model. Figure 3 shows a scatter plot of the PDM and Tessel estimates of relative soil moisture for soil layer 1. There is clearly a linear relationship between the two sets of values, although it is not a 1:1 relation. A best fit straight line has been superimposed on the scatter plot with an R^2 of 0.78. Very similar results are observed for two other catchments: the Roding and the Silkstream.

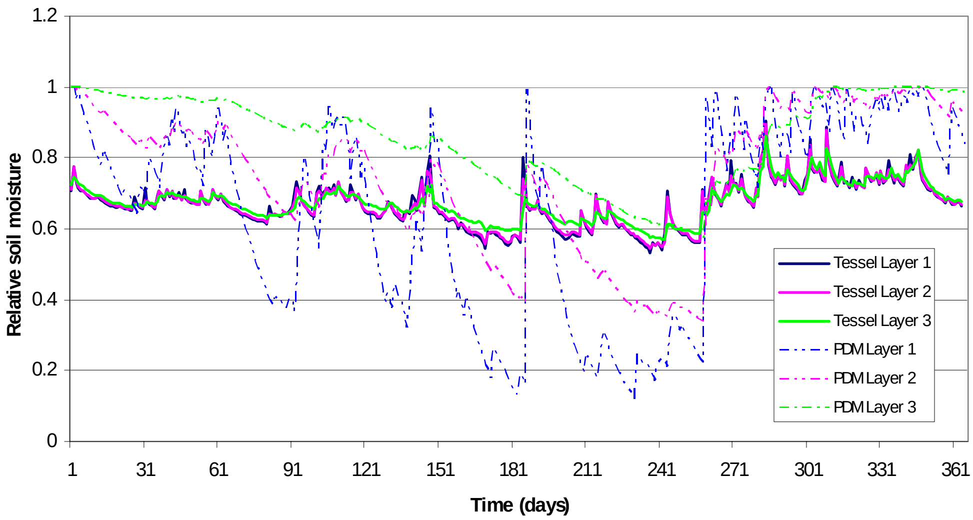

Figure 2: Relative soil moisture estimated by the PDM and Tessel for the Mole: 2 January to 31 December 2000.

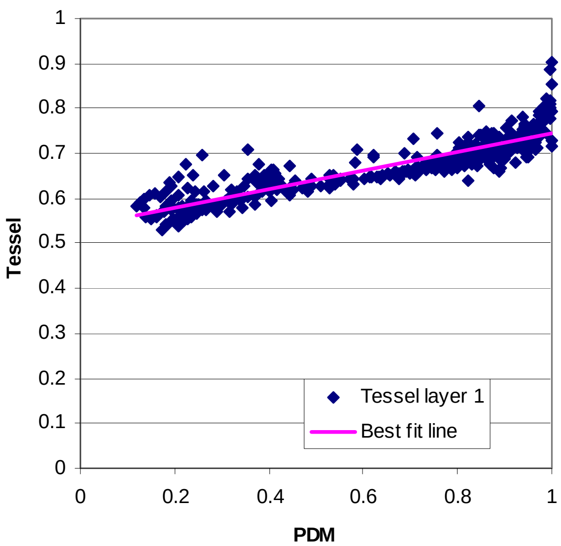

Figure 3: Scatter plot of PDM and Tessel estimates of relative soil moisture for the Mole.

4. Use of Tessel soil moisture for river flow simulation

In order to quantify any added value to flood forecasting that Tessel soil moisture could make, soil moisture information from Tessel has been incorporated in the PDM rainfall-runoff model, and the simulated river flow compared to observations. The trial has been undertaken using observations and model output for the year 2000. This period was chosen to include the Autumn 2000 UK floods, which were particularly severe and may well have been unprecedented in duration and extent for at least a century.

Three PDM flow simulations obtained using alternative sources of soil-moisture estimates have been compared to flow observations. These sources are:

1. soil moisture calculated internally by the PDM
2. “raw” soil moisture from Tessel (layer 1),
3. “transformed” soil moisture from Tessel (layer 1)

Where Tessel soil moisture, S_T, has been used with the PDM, it has been incorporated as a full state-correction at the start of each model time-step, such that

$$S^{*} = S + G(S_T - S),$$

where S is the PDM soil moisture prior to correction, S^* the value after correction and G a gain parameter. For the flow simulations done here, a full state-correction has been invoked and the gain coefficient set to unity, ie, $G = 1$. This has the effect of completely replacing the soil moisture calculated internally by PDM by the Tessel estimated value.

Flow estimates were compared over the period 2 January to 31 December 2000. The accuracy of the model flow simulations have been compared using the R^2 statistic. Results are presented in Table 1. In each case the PDM parameters have not been adjusted: the only difference between the simulations is the source of soil-moisture values. For all catchments the best flow simulations are obtained when PDM uses the soil moisture it has calculated internally using a probability distribution of soil store depths. The PDM performs least well using “raw” Tessel soil moisture values. However there is improvement in model performance for two of the three catchments if the Tessel soil moisture values undergo a linear transformation.

Catchment	PDM – soil moisture calculated internally	“Raw” Tessel soil moisture values	“Transformed” Tessel soil moisture
Silkstream	0.766	0.553	0.544
Mole	0.821	0.545	0.748
Roding	0.865	0.463	0.566

Table 1 Comparison of R^2 values from PDM simulations using different sources of soil moisture estimate: 2 January to 31 December 2000

5. Use of river flow to inform soil characteristics

It is well established that catchments containing different soil types generate different monthly and annual river flow; catchments containing permeable soils generate a more even distribution of river flow but a lower annual total than catchments containing impermeable soils. The potential of harnessing this information to calibrate land surface schemes for atmospheric models is considered here.

By driving the model with observed meteorological data from a point, it can be demonstrated (Blyth, 2001) that the representation of vertical soil water processes can significantly affect the water balance. The partition of rainfall into evaporation, surface runoff and drainage is strongly affected by the soil type chosen:

fine soils support less evaporation than coarse soils and they have little or no drainage, while coarse soils have little or no surface runoff.

This partitioning (evaporation/runoff and surface/subsurface runoff) affects different aspects of the water balance. The monthly river flow represents the runoff aspect of the model and the annual river flow represents the evaporation aspect provided annual carryover of aquifer storage is negligible. The routing component of the model affects the flow at finer timescales – expressing the delay and attenuation between runoff generation and river flow at the catchment outlet. The actual timescale depends on the size of the catchment.

6. Conclusions

1. The land surface model generated soil moisture data (Tessel) are much less variable than the hydrological soil moisture estimates (PDM), and seldom reach saturation, even during the autumn 2000 floods in the UK which were thought to be due to heavy rainfall on saturated ground.
2. The soil moisture information from Tessel was incorporated into a PDM simulation of river flow for three catchments in the Thames basin. A comparison with observed river flow indicates that direct incorporation of the “raw” Tessel soil-moisture estimates into the PDM leads to poor model performance. However, once a linear transformation is applied to the “raw” Tessel soil moisture values to better equate them to PDM values, the resulting flow simulations are improved. For selected flow events the resulting flow simulations can sometimes be better than those obtained from the PDM alone. However, results are variable, and when model performance is evaluated for the whole of the year 2000, the PDM with internally calculated soil moisture is found to be best.
3. River flow statistics could be used to characterise soil types upstream as well as rainfall-runoff model parameters.

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