Hydrological Modelling of the Tarrawarra Catchment: Use of Soil Moisture Patterns

Andrew W. Western[1], Timothy R. Green[2] and Rodger B. Grayson[1]
[1]Centre for Environmental Applied Hydrology and CRCCH, University of Melbourne
[2]CSIRO Land and Water, Perth, Western Australia 6014

Abstract Thirteen detailed soil moisture patterns are available for the 10.5 ha Tarrawarra catchment in southern Victoria, Australia. These patterns along with surface runoff and meteorological data are used in applications of the Thales and VIC models at Tarrawarra. Thales is a process based distributed parameter hydrologic model which explicitly simulates the spatial pattern of soil moisture while VIC uses a distribution approach to model the spatial statistics of soil moisture storage. Both models simulate saturation excess runoff and are forced by rainfall and potential evapotranspiration. Following calibration of the models to observed runoff at the catchment outlet, internal validation is achieved by comparison of predicted and observed spatial patterns for the Thales model and of predicted and observed saturation deficit distributions for the VIC model. Thales is able to predict the seasonal changes in soil moisture pattern with limited calibration. Detailed examination of the errors in the simulated patterns allowed identification of structural problems in the model, thus illustrating the value of detailed spatial data for testing spatially distributed hydrologic models. For the VIC model, spatially averaged internal state variables were consistent with observations. However the statistical distribution of saturation deficit assumed in the model differed from that observed. The maximum deficit (i.e., storage) averaged over the catchment required adjustment due to limited temporal sampling, such that the most extreme dry state was not sampled. Each model was able to approximate the internal soil moisture "patterns" relevant to its formulation (spatially distributed for Thales and statistically lumped for VIC) from available rainfall and runoff data.

1. INTRODUCTION

Soil moisture is a key control on a range of hydrologic processes such as runoff generation and evapotranspiration. It is also highly variable in space and time; however, the characteristics of this variation are not well understood at present. Adequate representation of the spatial and temporal behaviour of soil moisture in hydrologic models is important for obtaining reliable simulations at both the catchment scale and at smaller scales. Soil moisture is also one of the key state variables that potentially can be used to verify the internal predictions of spatially distributed hydrologic models; a critical step if the predictions from these models are to be used to predict other processes such as erosion and nutrient generation.

This paper examines the extent to which the Thales model [Grayson et al., 1995] and the VIC model [Wood et al.,1992; Sivapalan and Woods, 1995] are able to represent the spatial and temporal variability of soil moisture in the 10.5 ha Tarrawarra catchment. Thirteen patterns, each based on approximately 500 point measurements of soil moisture in the top 30 cm of the soil profile, are used together with soil moisture profile data from 20 sites. Western et al. [this issue] provide details of the field experiments at Tarrawarra and Western et al. [this issue] Figure 1 shows the topography and location of soil moisture profile monitoring sites at Tarrawarra.

The two models used here take different approaches to representing the spatial variability of soil moisture. The VIC model uses a statistical distribution to characterise the spatial variation in soil moisture storage. This distribution is selected on the basis of the simulated average soil moisture. Thales is a fully distributed model in that it explicitly represents each point in a numerical mesh using a deterministic approach. Thus, Thales makes predictions of the soil moisture storage and surface and subsurface fluxes of water at many points in the landscape while VIC predicts the spatial variability within the simulated area but not the actual pattern of soil moisture. Predictions from Thales can potentially be used as input to models of other processes (e.g., erosion). Initial internal validation results are presented for both models.

2. MODEL STRUCTURE

2.1 Thales

Thales is a distributed parameter rainfall-runoff model which uses an element network based on topographic contours and stream lines. This allows complex terrain to be represented using one-dimensional equations of flow and continuity. The original version of Thales is an event model which has been applied to research catchments in Australia (Wagga Wagga) and the United States of America [Moore and Grayson, 1991; Grayson et al., 1992a,b, 1995]. A modified version of Thales is used here. This model uses a water balance to simulate soil moisture for each element. Inputs of water to an element are rainfall, subsurface flow from upslope and surface flow (with runon infiltration) from upslope. Outputs of water are evapotranspiration, subsurface flow to downslope, and surface flow to downslope. Exfiltration is possible. Surface flow is generated when an element is saturated and is routed using mass continuity.

In Thales, the vertical soil moisture profile is assumed to be uniform when the average moisture is below field capacity, θ_{fcp}. When the moisture is above θ_{fcp}, a water table is allowed to form. It is assumed that soil moisture is at saturation, θ_{sat}, below this water table and at θ_{fcp} above the water table. These soil moisture profile approximations are likely to be invalid for deep soils where the dynamics of the unsaturated zone are important. The soil profile is assumed to consist of two layers. These layers can loosely be thought of as soil horizons. Lateral subsurface flow is allowed when part or all of the upper soil layer is saturated. This flow is simulated dynamically using a kinematic wave description and Darcy flow. The depth of the upper layer is assumed to coincide with the relatively high transmissivity surface soil horizons (often the A horizon). The lower soil layer provides additional storage which is active during dry periods. Lateral flow is assumed to be insignificant in this layer.

Evapotransiration is assumed to occur at the potential rate when the soil moisture exceeds a stress threshold, θ_{stress}, and below θ_{stress} it decreases linearly to zero at the permanent wilting point, θ_{pwp}.

2.2 VIC

The VIC (Variable Infiltration Capacity) Model of Wood et al. (1992) assumes that scaled infiltration (i.e., storage) capacity is a random variable with its cumulative distribution function given by the Xinanjiang distribution (Zhao et al., 1980). The concept of assigning some distribution function to infiltration capacity has been used in other statistical-dynamical models such as the Stanford Watershed Model (Crawford and Linsley, 1966). It allows runoff generation and evapotranspiration to vary within an area (lumped catchment). Here, we apply the modified distribution function (Kalma et al., 1995) which includes a minimum storage level for the initiation of surface runoff. The cumulative distribution of the maximum saturation deficit, s, is given by:

$$s = 1 - (1-s_{min})(1-A_s)^{1/\beta} \qquad (1)$$

where A_s is physically the fraction of saturated catchment area, s_{min} is the minimum scaled storage for overland flow, and β is the model parameter giving a convex up shape for values less than one or concave up for values greater than one. Kalma et al. (1995) specified all of the functional relationships between a scaled storage level v (equals s at saturation), the catchment average storage level w, and the fraction of saturated area A_s. The model assumes that any rain falling on the saturated area generates surface runoff immediately (within the model time step), while the remaining rainfall infiltrates and fills some of the available storage under the s curve.

The ratio of actual to potential evapotranspiration is computed with a distribution function of the same form as the storage capacity. Baseflow is a linear function of the scaled total soil-water storage, w. Wood et al. (1992) assumed uniform rainfall over the lumped area. Subsequently, Sivapalan and Woods (1995) modified the model to include "patchy" rainfall given by an exponential distribution of the area. We used the code written by Sivapalan and Woods, but elected to use uniform rainfall. This is generally consistent with the rainfall data over the 10.5 ha experimental catchment at Tarrawarra at a daily time step.

Spatial variability is treated in a statistical manner without any spatial correlation. There is no allowance for deep drainage or other subsurface water to exit the catchment, except by baseflow. Thus, any deep drainage is lumped with the computed evapotranspiration as the residual between measured rainfall and streamflow.

3. METHODS

3.1 Thales Simulations

For this research Thales was run with a daily time-step. Results are based on the period 1 December 1995 to 30 November 1996. Simulations were started three months earlier to remove the effects of the assumed initial soil moisture pattern. Potential evapotranspiration (PET) was calculated using the Penman-Montieth model [Smith, 1992] with net radiation, temperature, humidity and wind data from the weather station at Tarrawarra. No adjustment was made to the estimated PET values in Thales. Spatially uniform values of all model parameters (θ_{sat} = 50%, θ_{fcp} = 35%, θ_{pwp} = 12% and θ_{stress} =30%, and saturated hydraulic conductivity, k_{sat} = 100 mm/hr) and soil depths of 300 mm and 180 mm for the upper (laterally transmissive) and lower (storage only) soil layers repectively, were used. Some manual adjustments of k_{sat}, θ_{fcp}, θ_{pwp}, and θ_{stress} were made but a comprehensive calibration was not performed. Rainfall and potential evapotranspiration were also assumed to be spatially uniform. Since spatially uniform parameters and soil depths are used for these simulations, the only source of spatial variation in soil moisture is the topography.

Thales simulates soil moisture on a network of contours and stream tubes. These were interpolated onto the regular grid used for field sampling. The simulated soil moisture was then adjusted, using the moisture profiles assumed in the model, to represent the moisture in the top 30 cm of the soil moisture profile. Finally, maps of the residual between the simulated and observed patterns were calculated.

3.2 VIC Simulations

The same daily data used to drive Thales (rainfall and potential evaporation) also drives the VIC model. However, simulations were started on 1 January 1996 when no runoff was being generated. The initial condition was set to zero available soil water storage (i.e., maximum simulated saturation deficit). Other parameters that were set prior to the calibration included the conceptual maximum soil depth for active soil water movement (D_{max} = 550 mm), the effective porosity ($\Delta\theta = 0.40$ m^3/m^3), and the height of the capillary fringe divided by D_{max} (0.15 m/m). Note that $\Delta\theta \cdot D_{max} = 220$ mm which exceeds the maximum saturation deficit estimated from field data (174 mm). This is consistent with the likelihood of experiencing drier periods and positions than sampled. Any over-estimation of these two parameters may be compensated for in the model by increasing the value of s_{min}. Finally, the capillary fringe parameter affects the actual evaporation as formulated by Sivapalan and Woods (1995).

3.3 Saturation Deficit Estimation

The VIC model uses distributions of saturation deficit to determine the runoff. These distributions are inferred from the runoff hydrograph. We also estimate these distributions from the observed soil moisture data using a three-step procedure:

1) The soil moisture profiles measured at 20 sites (see Western et al. [this issue], Figure 1) were used to estimate the soil moisture deficit for depths greater than 30 cm. It was assumed that the wettest measurement at each site represented saturated conditions below 30cm. These were then interpolated onto the sampling grid used for the TDR sampling (454 sample points per date were used in these analyses).
2) TDR soil moisture maps were used to estimate the saturation deficit in the top 30cm of the soil moisture profile. A porosity of 50% was assumed.
3) The saturation deficits estimated for the upper and lower soil layers were then combined.

These estimates will be affected by errors in the interpolation of the saturation deficit in the lower soil layer (step 1) and by the assumption of a spatially uniform porosity of 50% in the upper soil layer (step 2), as well as by measurement errors. There is also an implicit assumption that saturation occurs from the bottom of the soil profile up, or that there is no perching within the soil profile.

Figure 1a shows cumulative distributions of the scaled saturation deficits over the catchment at 8 sampling dates ranging from very dry conditions in February to very wet in September 1996. Each value in space and time is scaled by the maximum estimated value during the driest sample date. All of the scaled values may be biased by a factor due to the difference between the maximum recorded (estimated) and the maximum possible value.

One question that arises when considering the catchment response to an average soil wetness is how the distribution of soil moisture (and its deficit) changes with the mean saturation (deficit). Figure 1b shows the standard deviation (a measure of the spatial variation) of saturation deficit versus the mean values for 11 sample dates in 1996. When the catchment is relatively dry (high mean saturation deficit), the distribution scales uniformly by the mean, resulting in a constant spatial variance in the drier range of Figure 1b. This is also

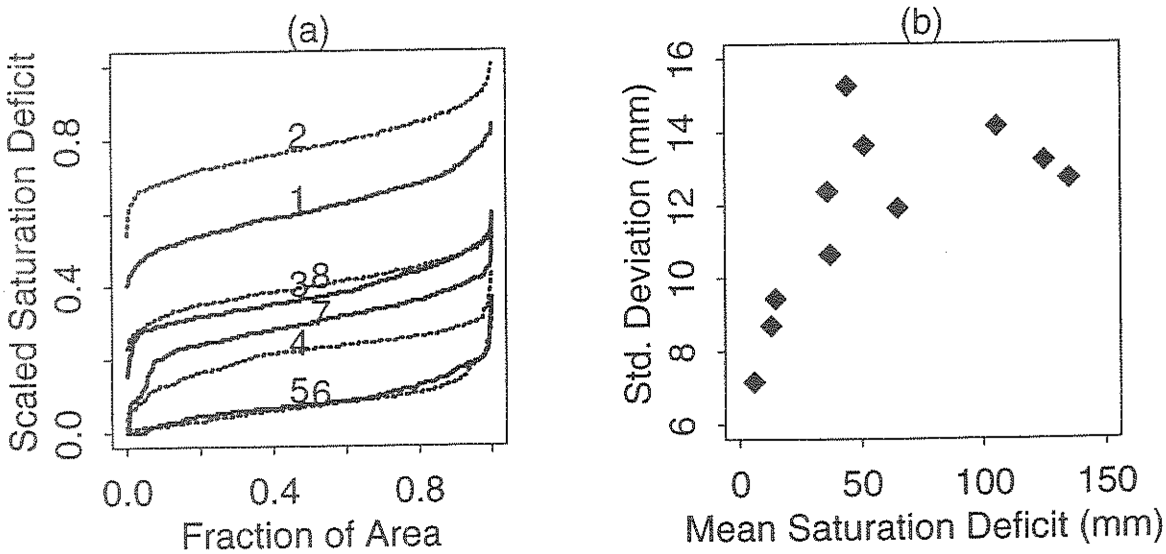

Figure 1. Saturation deficits estimated from field measurements in 1996: (a) cumulative distributions for eight dates as indicated (1 = 14 Feb; 2 = 23 Feb; 3 = 13 Apr; 4 = 22 Apr; 5 = 3 Jul; 6 = 20 Sep; 7 = 25 Oct; 8 = 10 Nov), and (b) standard deviation versus the mean saturation deficit at all 11 sample dates in 1996 (c.f. Figures 2-4).

manifested as a simple translation up or down in Figure 1a between the first three dates. As the catchment wets up, a fraction of the area (and sample sites) becomes saturated. This physical constraint skews the distribution and reduces the variance.

There is a subtle difference in interpretation of the saturation deficit distributions estimated from the soil moisture data and those to be inferred from the VIC model. Those estimated from the data take no account of the spatial arrangement of the soil moisture deficit. Therefore the possibility of runon infiltration downslope is ignored. Those inferred from the VIC model account for any runon infiltration effects since the hydrograph only contains information about runoff form source areas connected to the catchment outlet. That is, the saturation deficit distributions inferred from the runoff are effective distributions rather than actual distributions. Furthermore, it is physically possible for one location to have higher and lower than average moisture storage (or deficit) from wet to dry seasons. Both run-on infiltration and subsurface lateral flow may account for this. These mechanisms are explicitly and implicitly accounted for in Thales and VIC, respectively.

4. MODELLING RESULTS

4.1 Runoff Simulations

The purpose of this paper is to relate observed and simulated runoff to the relevant distributions of soil moisture. It is not to compare model performance by any particular measures. Even if an appropriate performance measure was decided upon, these simulations cannot be compared directly due to different levels of model parameterisation and different calibration efforts. The simulation results are presented with this in mind.

The observed hydrograph and simulated hydrograph for Thales are shown in Figure 2. Thales predicted an annual runoff (1 Dec 1995 – 30 Nov 1996) of 209 mm compared to the 170 mm observed. Much of this over

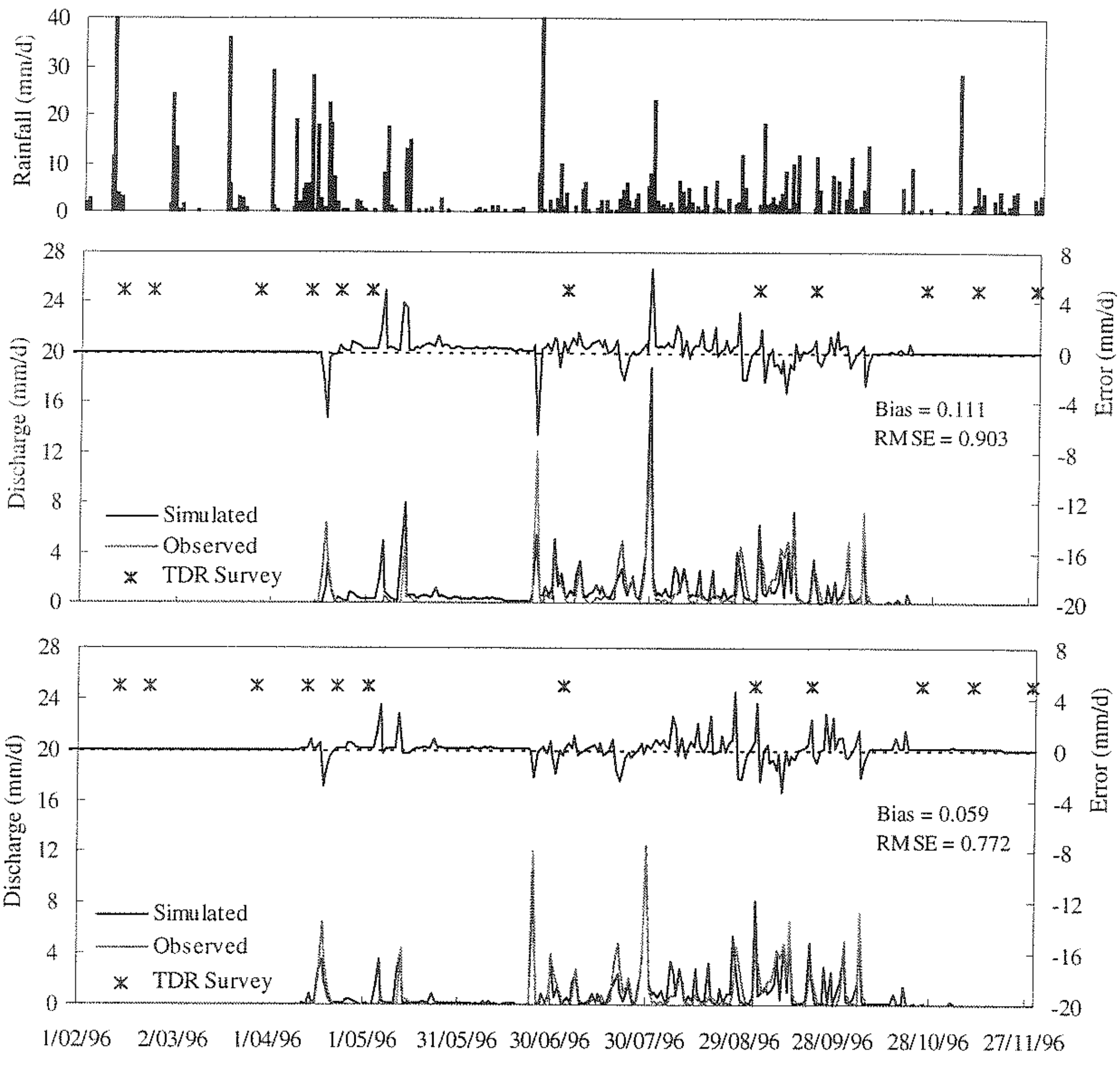

Figure 2: Daily values of measured rainfall (top panel), daily observed runoff with runoff simulated by Thales (middle panel), and daily observed runoff with runoff simulated by VIC (lower panel).

estimate of 23% is likely to be due to underestimation of evapotranspiration. An error of 5-10% in PET, which is not unreasonable, could account for this simulation error. Also it should be noted that the peak flows for 3 events between 17 and 20 April 1996 were estimated due to flow bypassing the flume. Runoff may have been underestimated for these events. Another potential source of error is the assumption of zero deep seepage. Varying θ_{stress} and θ_{pwp} between reasonable limits led to a 12% range in simulated annual runoff.

Thales tends to underestimate runoff for individual events early in a wet period (eg. 17-19 April, 25 June, Fig1) and overestimate peak flows during runoff events later in a wet period. This indicates that the temporal dynamics of the saturated areas is not being correctly simulated. It also overestimates baseflows during wet conditions.

The VIC model is much simpler and less physically based than Thales. VIC has four main parameters affecting the storage distribution curve (β and s_{min}), baseflow recession and actual evaporation. These were thoroughly calibrated. The storage parameters β and s_{min} most notably affect the high and low flow peaks, respectively. The evaporation parameter and the baseflow coefficient both affect the mean bias through removing water from storage, with subsequent effects on moisture levels and saturated areas.

Figure 2 shows the rainfall and runoff time series (trimmed to highlight the active runoff periods) for the VIC simulation. The fit to data is measured by the root mean squared error (RMSE) and mean bias, both shown in Figure 2. The bias shown corresponds to a 13 percent over-estimation of the recorded runoff. As above, this "error" is indistinguishable between model and data uncertainty. After calibration, the modified VIC model (Kalma et al., 1995) was able to reproduce the general temporal pattern of little or no runoff during the summer, despite significant rainfall events, and rapid runoff responses in the wetter season. This is consistent with the "switching" phenomenon described by Grayson et al. [in press] and Western et al. [this issue].

4.2 Saturation Deficit Distribution Estimation

In addition to time series of runoff, VIC simulates the spatially averaged soil water storage, and the fraction of catchment area that is saturated (i.e., zero saturation deficit and infiltration capacity). Figure 3 shows predictions of the scaled average storage over the catchment, w_{vic}, and the saturated area, A_s. Values of storage, wo, estimated from the soil moisture data are also shown. These have been scaled by the maximum observed saturation deficit, S_{obs}. Clearly the VIC predictions are biased low. While both dry and wet conditions were sampled, it is unlikely that either the driest or wettest of these samples represent the most extreme conditions occurring in the catchment during the study period. Therefore the maximum saturation deficit was increased by an amount, f, and the observed data was scaled using S_{obs}+f. These adjusted scaled storage values are shown as w^* in Figure 3. The resulting agreement between the temporal characteristics of the simulated and observed mean storage is very good. This gives us some confidence in the statistical distribution approach for simulating runoff generation from the Tarrawarra catchment.

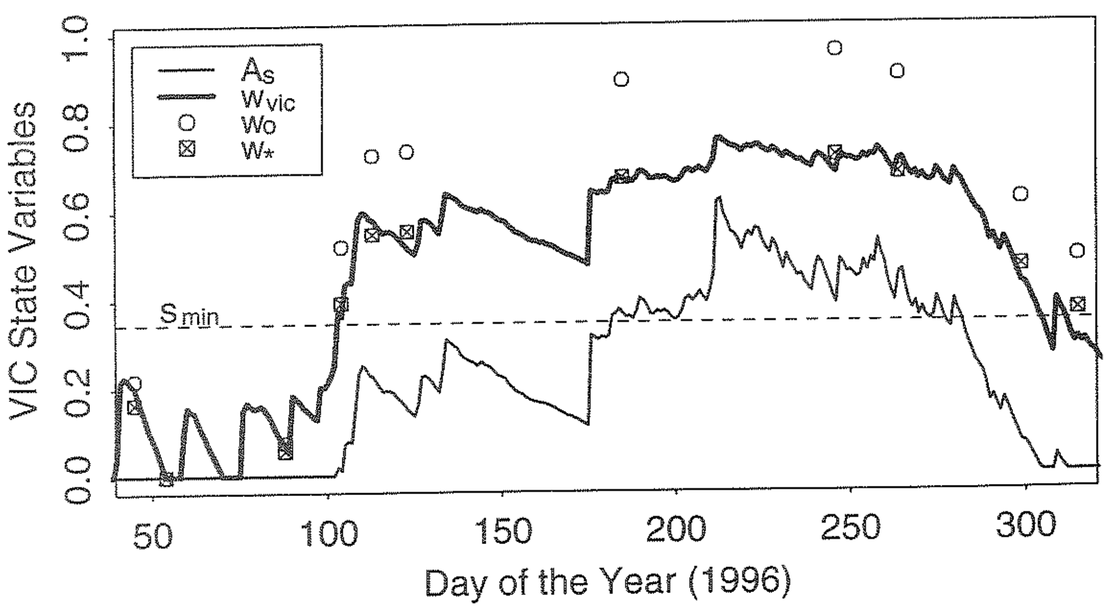

Figure 3: Time series of VIC state variables compared with measured soil moisture states. All values are scaled by the maximum infiltration capacity (storage) possible in the catchment: A_s = fraction of area saturated, w_{vic} =total storage over the catchment (simulated), wo = value of w estimated from raw data assuming the data includes the wettest and driest possible states, and w^* = an adjusted estimate obtained by adding a constant storage term to the estimated maximum storage which scales all of the w estimates.

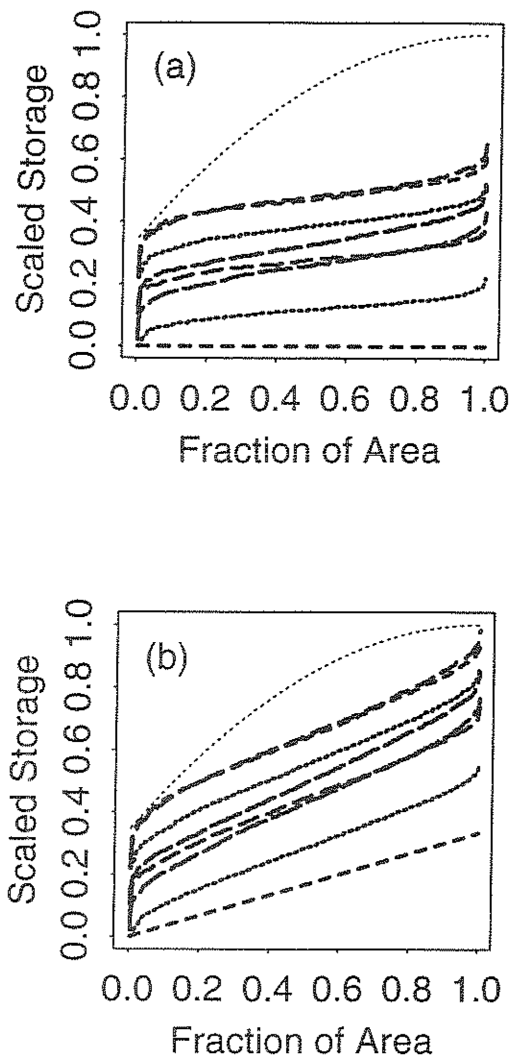

Figure 4. Scaled and sorted distributions of measured soil water storage (8 dates given in Fig. 1) relative to the VIC distribution of scaled storage.

Because the absolute values of the distribution of stored water are not possible to estimate, even from a detailed database like that at Tarrawarra, it is very difficult to estimate the distribution function for scaled soil water storage used in VIC. This presents a major impediment to using VIC in a predictive mode (without some calibration). Thus, it was necessary to first calibrate β, and the cumulative storage distribution, then use the calibrated s curve along with the field estimates of saturation deficit to predict runoff.

VIC assumes that storage within the catchment is given by Equation 1 for saturated areas and is uniform in unsaturated areas. In Figure 4a, the cumulative spatial distribution of scaled storage is shown. The storage is estimated from the observed data and is relative to the driest observations. It is scaled by the same factor (S_{obs}+f) used to estimate w*. The VIC model assumption implies a cumulative distribution that follows Equation 1 (upper dashed line) for the fraction of area less than the saturated area and is horizontal for the fraction of area greater than the saturated area. Figure 4b is similar to 4a except that additional storage has been added to the storage estimated in 4a. This additional storage is equivalent to f. It was assumed that the cumulative distribution for this distribution was linear (uniform pdf, with zero lower limit and mean f). It is clear from Figure 4 that the spatial cumulative distribution of storage assumed in VIC is different from that observed. For a given saturated area, the storage in the catchment is actually greater, or the average saturation deficit less, than that assumed by VIC. This provides some additional explanation of the bias observed in simulated storage (see Figure 3). It is likely that calibration of the model compensates for many of the errors introduced by the incorrect assumption relating to the spatial distribution of saturation deficit.

4.3 Soil Moisture Pattern Simulation

Figure 5 shows patterns of soil moisture simulated by Thales and Figure 6 shows patterns of residuals between the simulated and observed soil moisture (mid grey is a correct prediction). Comparing Figure 5 with the observed patterns [Western et al., this issue, Figure 3], it is apparent that Thales simulates the general seasonal variation in soil moisture pattern well. There are however, differences between the simulated and observed patterns, some of which indicate potential problems with the model structure. The simulated patterns are much smoother than the observed patterns. There are two reasons for this. First, the simulations presented here have spatially uniform soils, whereas spatial variation in soils is expected in nature. Second, the field observations are affected by measurement errors (estimated to be 1.7% V/V standard deviation). It should also be noted that Thales has an average element size of 140 m^2 while the TDR measurements are essentially point measurements. Thus, we need to account for the effects of spatial averaging in Thales.

The maps of residuals indicate some other problems with the model structure. On several occasions there is a noticeable relationship between aspect and the error in the simulated soil moisture pattern, with moisture on northerly slopes being overestimated. This indicates that PET is likely to be spatially variable, which would be expected due to topographic variation in solar radiation. While the model generally over-estimated soil moisture on 13 April 1996, soil moisture levels in areas of high topographic convergence (e.g,. the head of the eastern drainage line) were underestimated, indicating that more topographic redistribution had occurred than was predicted by the model. This accounts in part for the underestimation of runoff during the subsequent events and the overestimation of soil moisture on 22 April, 1996. It suggests that some lateral redistribution may be occurring under unsaturated conditions which is not allowed for in the present model structure.

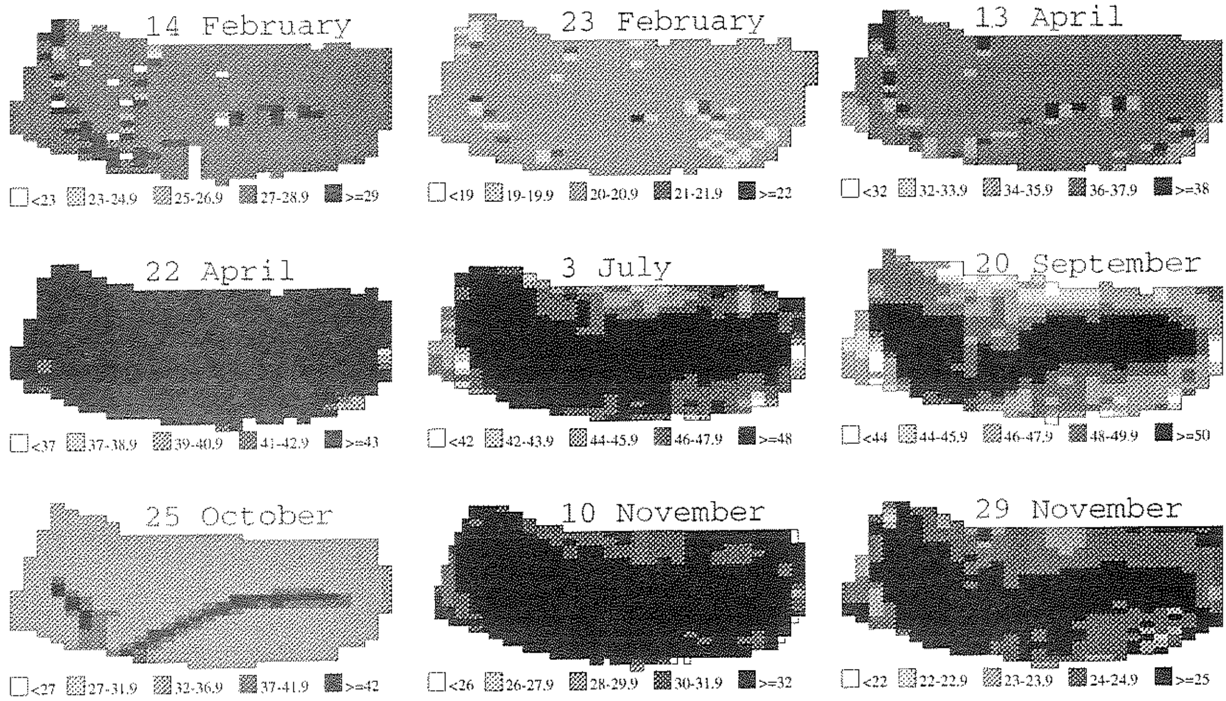

Figure 5: Soil moisture patterns simulated by Thales. Units are percent volumetric.

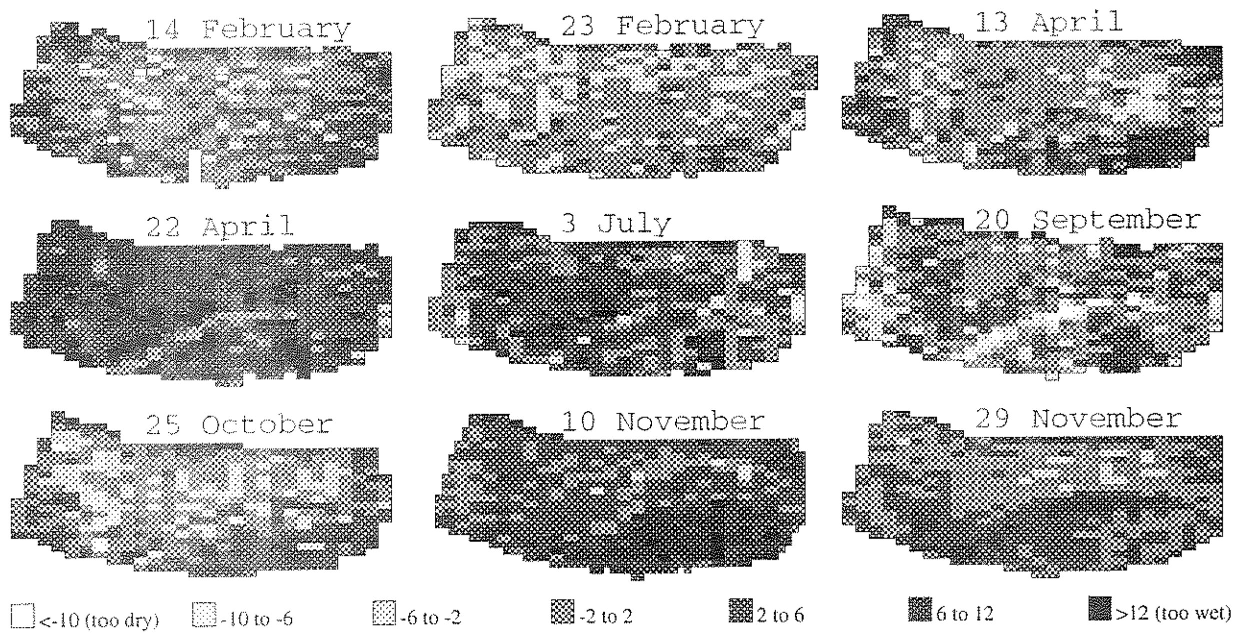

Figure 6: Errors in soil moisture patterns simulated by Thales. Units are percent volumetric.

5. Discussion

Hydrologic models can be used either in a predictive mode (to provide design or management information) or in an investigative mode as they are used here. The simulations of soil moisture patterns at Tarrawarra using Thales indicate that saturation excess is the dominant runoff process and that extensive saturation excess runoff occurs on the hillslopes as well as in the drainage lines. These simulations are consistent with observations of spatial patterns of soil moisture. These conditions also make application of the VIC model appropriate. The simulated behaviour is consistent with the concept of preferred states in soil moisture patterns [see Grayson et al., in press; Western et al., issue].

A major problem with distributed models has been that different process descriptions often led to very similar outflow hydrographs. The use of patterns to validate internal model predictions should significantly reduce this problem. To date the Thales simulations, or rather the errors in the simulated patterns, have suggested that unsaturated lateral redistribution may be important when the landscape is wetting up. While some hint of a problem may have been gained from the outflow hydrograph, the internal testing of model predictions was essential for identifying the specific cause of the simulation errors. The patterns also allowed problems in the spatial simulation of evapotranspiration to be identified.

From a modelling perspective, an interesting example of the value of patterns is in identification of dominant runoff processes. At Tarrawarra it is possible to reproduce the daily hydrograph with similar levels of accuracy using k_{sat} values of 100 and 2000 mm/h. With k_{sat} = 2000 mm/h, the model essentially predicts subsurface storm flow on the hillslopes while with k_{sat} = 100 mm/h it predicts saturation excess on the hillslopes. When the patterns are compared it is clear that k_{sat} = 2000 mm/h leads to unrealistically rapid drainage. For larger catchments, the problem of process identification using the runoff hydrograph becomes even more difficult due to greater amounts of spatial and temporal averaging in the observed data.

6. Conclusions and Future Work

The Thales model satisfactorily reproduced observed soil moisture patterns and the seasonal variations in these patterns, and the VIC model approximated the observed cumulative distributions. The use of the observed patterns to validate the models has enabled the identification of dominant runoff processes in the Tarrawarra catchment with much greater confidence than if the hydrograph were the only available testing data. The comparison of observed and simulated patterns has helped identify two modifications to Thales which will be made in the future. These are: inclusion of topographic variation in evapotranspiration; and modification of the subsurface redistribution process description to include unsaturated redistribution. Other modifications to the model will include incorporating spatial soil data that has been collected at Tarrawarra. Application of a multidimensional variably saturated flow model is also planned to further our understanding of lateral unsaturated flow dynamics.

From a methodological perspective efforts will be made to find methods for quantitative pattern comparison which can provide hydrologically useful information. VIC is suited to applications requiring an efficient model based on calibration to runoff data. There appears to be more scope for incorporating internal state variables (soil moisture status) into the calibration and validation procedures, and for identifying and improving landscape evapotranspiration schemes. Thales will be used to estimate a spatially distributed water balance and thus quantify the relative importance of different process at different points in the landscape.

7. Acknowledgements

The Tarrawarra catchment is owned by the Cistercian Monks (Tarrawarra) who have provided free access to their land and willing cooperation throughout this project. Funding was provided by the Australian Research Council (project A39531077), the Cooperative Research Centre for Catchment Hydrology, The Department of Science Industry and Tourism (International Science and Technology Program), the Oesterreichische Nationalbank, Vienna (project 5309) and the University of Melbourne. Ross Woods graciously provided the modified VIC code, now called 'Patchy'. CSIRO priority funding for climate variability and impacts research provided partial support to the second author in collaboration with Bryson Bates.

8. References

Grayson, R. B., I. D. Moore, and T. A. McMahon, Physically based hydrologic modeling 1. A terrain-based model for investigative purposes, *Water Resour. Res,*, *28*, 2639-2658, 1992a.

Grayson, R. B., I. D. Moore, and T. A. McMahon., Physically Based Hydrologic Modelling 2. Is the concept realistic?, *Water Resour. Res,*, *28*, 2659-2666, 1992b.

Grayson, R. B., G. Blöschl, and I. D. Moore, Distributed parameter hydrologic modelling using vector elevation data: Thales and TAPES-C, in *Computer models of watershed hydrology*, (V. P. Singh ed.), pp. 669-695, Water Resources Pub., Highlands Ranch, Colorardo, 1995.

Grayson, R. B., A. W. Western, F. H. S. Chiew, and G. Blöschl, Preferred states in spatial soil moisture patterns: Local and non-local controls, *Water Resour. Res.,* in press.

Kalma, J.D., B.C. Bates and R.A. Woods, Predicting catchment-scale soil moisture status with limited field measurements, *Hydrol. Process.*, 9, 445-467, 1995.

Moore, I. D., and R. B. Grayson, Terrain-based catchment partitioning and runoff prediction using vector elevation data, *Water Resour. Res.*, *27*, 1177-1191, 1991.

Sivapalan, M. and R.A. Woods, Evaluation of the effects of general circulation models' subgrid variability and patchiness of rainfall and soil moisture on land surface water balance fluxes, in *Advances in Hydrol. Process.*, Scale Issues in Hydrological Modelling, edited by J.D. Kalma and M. Sivapalan, 453-473, Wiley, Chichester 1995.

Smith, M., R. Allen, J. L. Monteith, A. Perrier, L. Santos Pereira, and A. Segeren, *Expert consultation on revision of FAO methodologies for crop water requirements*, Land and Water Development Division, Food and Agriculture Organization of the United Nations, 1992.

Western, A. W., R. B. Grayson, G, G. Willgoose, and T. McMahon, The Tarrawarra Project: High resolution spatial measurement and analysis of hydrological response, *MODSIM 97*, Hobart, Tasmania, 8-11 Dec. 1997, this issue.

Wood, E.F., D.P. Lettenmaier and V.G. Zartarian, A land-surface hydrology parameterization with subgrid variability for general circulation models, J. Geophys. Resear., 97(D3), 2717-2728, 1992.