The Sensitivity of a Catchment Model to Soil Hydraulic Properties Obtained by using Different Measurement Techniques.

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Sensitivity tests of the physically based catchment model Topog_dynamic have identified saturated hydraulic conductivity (Ksat) to be a key model input parameter (Vertessy et al., 1993). Ksat represents one of the most difficult soil hydraulic properties to measure in heterogeneous field soils owing to the contribution of soil structural features to hydraulic behaviour under saturated conditions. To date, no tests have been carried out to identify the sensitivity of predicted catchment discharge produced by Topog_dynamic to Ksat data obtained from a range of different techniques.

The work presented in this paper is a component of a larger study which focused on the identification of the best methodology to quantify soil hydraulic data for the application of the physically based catchment model Topog_dynamic to forest catchment. A constant head well permeameter, small cores (73 x 63 mm) and large cores (223 x 300 mm) were used to measure saturated hydraulic conductivity within a 100 x 100 m plot. The comparative experimental work demonstrated significant variation within and between techniques.

Results indicate that present state of the art methods for measuring soil hydraulic properties fail to quantify, adequately, hydraulic properties in a highly heterogeneous forest soil. As a result of these limitations, model output data may be strongly influenced by the technique used to quantify the soil hydraulic input data. We conclude that, in highly heterogeneous field conditions, techniques to quantify soil hydraulic properties are of limited use for modelling applications. This work highlights the need for caution when applying soil hydraulic measurements to catchment scale models.

INTRODUCTION

It is well recognised that in order to test and refine the present generation of physically based catchment models accurate input data are required. To date, our ability to develop complex computer models has progressed more rapidly than our ability to accurately measure soil hydraulic properties in the field (Hillel, 1991). These problems are most pronounced in the measurement of saturated hydraulic conductivity (Ksat) of a field soil owing to the heterogeneous and anisotropic nature of many soils, and the contribution of soil structural features to water movement under saturated conditions. In addition, the spatial distribution of soil hydraulic properties makes catchment wide parameterisation difficult. Some authors have argued that difficulties in accounting for spatial variation limit the utility of physically based catchment models (Loague and Freeze, 1985).

Moreover, there is considerable debate in the literature regarding the validity of extrapolating point measurements to the element scale used in physically based models (Beven 1989; Grayson et al., 1991). However, this approach remains the most common method of parameterising such models, and therefore warrants investigation.

Comparative studies of methods to measure soil hydraulic properties have demonstrated that different techniques may produce significantly different Ksat data (Paige and Hillel, 1993; Lee et al., 1985). Moreover, even in the event of consistent methods, the scale of measurement may have a significant impact on measured Ksat (Lauren et al., 1988). The disparity between results generated by different techniques is a function of both the theoretical basis of a method, and the scale at which that method is applied. To date, however, little attention has been directed toward the implications of these problems when the soil hydraulic data are used as input parameters for physically based catchment models.

The major aim of this study is to investigate the implications of using Ksat data obtained by three different methods as input data for the physically based catchment model Topog_dynamic. Ksat was chosen as the key soil hydraulic parameter to investigate because: it is difficult to measure in heterogeneous soils because of soil structural features such as macropores which may contribute significantly to the soil hydraulic properties. Further, previous sensitivity tests (Vertessy et al., 1993) have identified Ksat as a key input parameter to the physically based catchment model Topog_dynamic.

Topog_dynamic

Topog_dynamic is a collection of modelling routines developed to simulate the processes of water movement through a catchment. The model requires digital elevation data, climate, vegetation and soil parameters. A full description of these input parameters is presented by Vertessy et al. (1993).

Water flux is calculated at an element level, with the elements defined by contour spacing, and flow trajectories which are calculated by a contour-based terrain analysis routine in the model.

The model computes groundwater and soil water dynamics and evapotranspiration on a daily timestep. A detailed description of the soil water dynamics component is presented below. A detailed description of the way in which Topog_dynamic models the other processes is presented in Vertessy et al. (1993).

Vertical unsaturated flow is calculated using an implicit numerical solution of the Richards equation. Saturated flow is modelled in both the vertical and horizontal dimension. Under saturated conditions, water is routed downslope using Darcy's Law. Subsurface lateral flow for a given element is expressed as

$$q\ (\mathrm{out}) = K_s\, bmh \qquad (1)$$

where b is the element width, m is the element slope and h is the thickness of the saturated layer.

Overland flow is allowed to develop on any element when the rainfall intensity exceeds infiltration rate, when an element is saturated; or if an element receives flux from upslope that exceeds the transmission capacity of the soil.

THE STUDY SITE

The model was applied to a 0.32 km^2 experimental catchment, Myrtle II (latitude (°S): 37 ° 35.3': longitude (°E) 145° 36.8') . The catchment is one of fourteen experimental catchments in the North Maroondah area, located in the central highlands of Victoria, 70 km north east of Melbourne. The North Maroondah area is a component of the water supply system for the City of Melbourne .

Catchment elevations range between 590 and 790 m above mean sea level, slopes are generally between 25 and 35 %. The catchment has a predominantly south-facing aspect. Myrtle II was clear-felled in 1984; modelling simulations presented in this study were conducted for the period 1972 until 1979 when the catchment was in an undisturbed mature forest state. During this period 78 % of Myrtle II was vegetated with mature (215 - 230 year old) Mountain ash (*Eucalyptus regnans* F. Muell.) forest, with the remainder of the catchment vegetation comprised of a temperate rainforest community.

Average annual precipitation for Myrtle II is 1600 mm with a slight bias toward a winter/spring rainfall regime. Summer and winter mean monthly temperatures range between 16 - 17 °C and 3 -5 °C respectively.

The geology North Maroondah experimental area is comprised of a Mesozoic peneplain composed of resistant Devonian volcanics. The present landform is the result of stream dissection following uplift during the Pliocene and Pleistocene. Present valley form and drainage patterns are the result of differential erosion.

The soils of the Myrtle II catchment, described in detail by Vertessy et al., (1991), are approximately 4 - 5 m deep and may be described as deep red brown earths. The upper 50 cm of the soil profile is well structured dark brown organic clay loam, with abundant macropores. Between 50 and 300 cm the soil graded from a well structured red brown loamy clay to a light clay. Below 300 cm the soil typically changes to a yellow brown incompletely weathered soil with a light to medium clay texture. Bedrock or saprolite was generally evident at 400 to 500 cm. This soil depth is substantially less than the 10 - 15 m reported by Langford and O'Shaughnessy (1977) for the North Maroondah experimental area.

Saturated Hydraulic Conductivity Data.

The Ksat data generated during a comparative study of measurement techniques were used for input data to the model sensitivity tests presented in this paper.

Three methods, small cores (7.3 x 6.3 cm), large cores (23 x 30 cm), and constant head well permeameter (borehole diameter 10 cm), were used to measure Ksat at a 100 x 100 m ridge top experimental site on Black Spur, approximately 1 km south east of the Myrtle II catchment. The constant head well permeameter is an *in situ* technique. Constant head methods were used to measure Ksat on the small cores (Klute and Dirksen, 1986) and large cores (McKenzie and Jaquier, 1996) in the laboratory. A full account of the methods is described by Davis et al. (1996).

The transfer of the Ksat data obtained at the Black Spur site to the Myrtle II model sensitivity tests is based on the assumption that variation in measured Ksat was greater between measurement methods than any variation between the Myrtle II catchment and the Ksat experimental plot. The Myrtle II catchment and the Ksat experimental site share common geology, ecology and climate. It is reasonable to conclude therefore, that pedogenic processes at each site are comparable. Soil surveys at both the Myrtle II and Black Spur site support this assumption, as both sites exhibit a gradational soil profile with abundant macropores in the upper 50 cm of the soil profile. Moreover, field measurement of Ksat in the Myrtle II catchment using the constant head well permeameter carried out by Vertessy et al., (1991) reported values consistent with those measured at the Black Spur site with the same method.

The Ksat measurement study demonstrated statistically significant differences between Ksat values obtained by each of the three techniques, with large cores generally producing Ksat values 1 - 3 orders of magnitude greater than the small core or constant head well permeameter techniques. Moreover, the results indicated the presence of a two-layer soil, with significantly higher Ksat values obtained in the upper horizon (0 - 50 cm), and consistent Ksat values between 50 and 500 cm soil depth.

Median, lower fourth and upper fourth Ksat values for each of the techniques are presented in Table 1. Lower and upper fourth values correspond, approximately, to the 25 th and 75 th percentile. The median upper and lower fourth values allow the expression of central tendency and spread of data, between the upper and lower forth values, using exploratory data analysis (EDA) (Hoaglin, 1983). EDA was used in preference to traditional summary statistical methods as it allows investigation of a batch of data without relying on an assumed distribution, or being significantly influenced by outlying data points.

Table 1: Ksat data (cm/day) measured at the Black Spur site. Superscript number denotes soil layer.

Method	n	Lower fourth	Median	Upper fourth
CHWP ^{1}	12	106.3	180.5	340.5
Small core^1	20	7	35	78
Large core^1	7	1118	5500	8800
CHWP^2	65	5	9	21
Small core^2	35	4	9	26
Large core^2	10	31	160	366

Parameterisation of Topog_dynamic

The Myrtle II catchment has been used previously for model sensitivity tests by Vertessy et al. (1993). These sensitivity tests were conducted by a systematic variation in a range of input parameters. The work presented in this paper builds upon this earlier sensitivity analysis by assessing sensitivity of the model to a range of Ksat data obtained as a result of different experimental methods. The input parameters are therefore, consistent with those presented by Vertessy et al., (1993). During this study, Ksat was the only input parameter data varied between model runs.

Simulations were run over a 7 year period. K, Ψ, Θ relationships required to solve the Richards equation were obtained using a least-squares optimisation method on experimental $\Psi(\Theta)$ data measured on small cores from the Black Spur site. The Broadbridge and White (1988) soil hydraulic model was fit to the experimental data, and used to predicted the $K(\Theta)$ function.

A two layer soil was modelled with the surface layer extending from 0 - 50 cm, and layer 2 from 50 to 500 cm. Representative K, Θ, Ψ functions were chosen for each of the soil layers. As the Ksat comparative study was conducted on a single experimental plot at a ridge top site, spatial distribution of Ksat properties was not identified.

Owing to the absence of information about spatial distribution of Ksat, soil hydraulic properties were applied uniformly through the catchment. This simplification is not considered to be a major limitation of the sensitivity test, as Ksat surveys conducted in the North Maroondah experimental area have failed to provide any evidence of a spatial structure in the distribution of Ksat using a sampling interval of 20 m (Lorieri, in prep). It is possible, however, that a spatial structure exists at a smaller scale than was sampled (eg: Loague and Gander, 1990).

RESULTS AND DISCUSSION

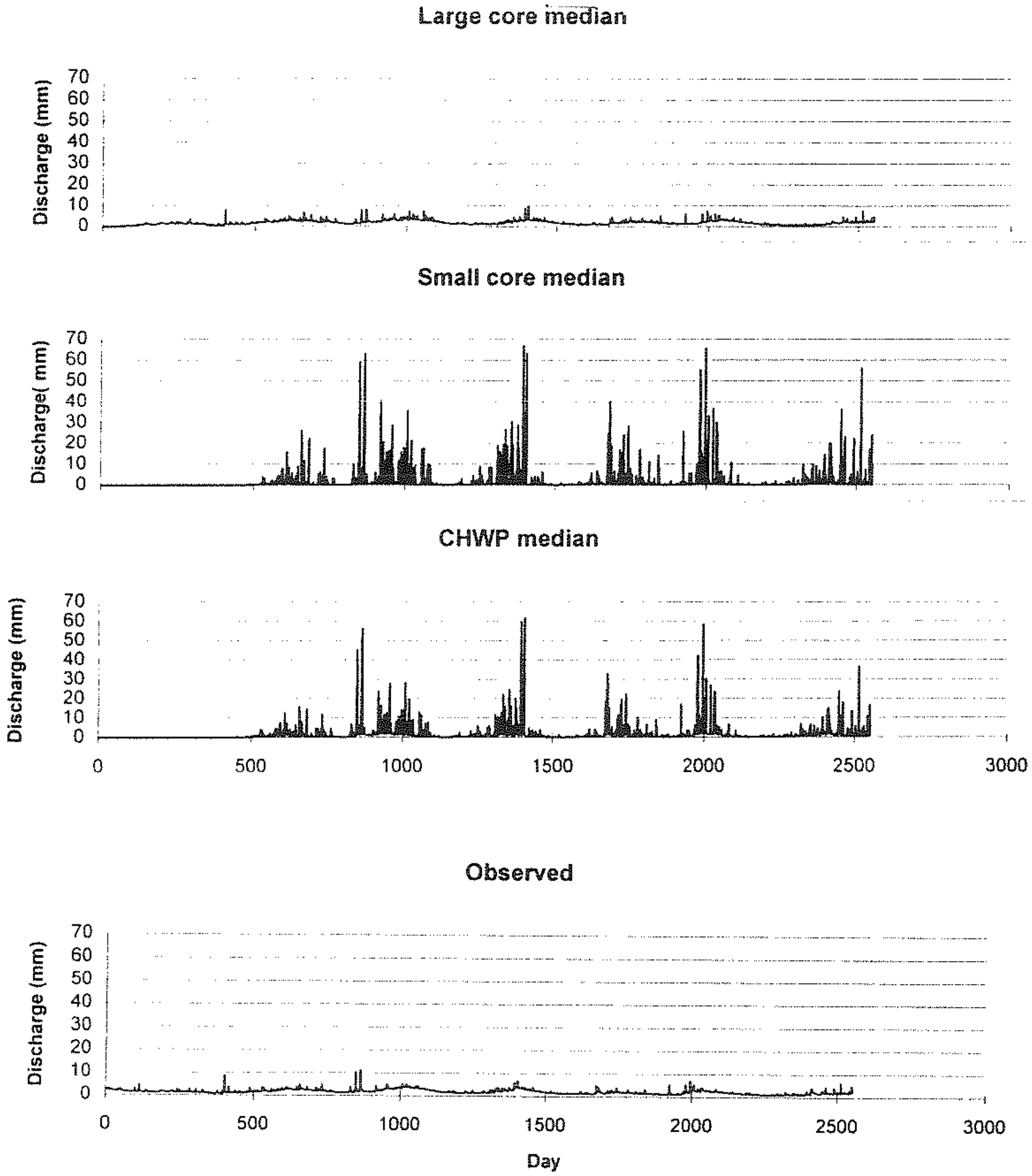
The results of the model sensitivity tests are presented in Figure 1 together with the observed data. The results demonstrate that there is considerable disparity between the hydrographs generated by the model. The simulation using the large core median Ksat data produced daily discharge values significantly lower than model simulations using the constant head well permeameter and small core Ksat data . However, the results produced by the small core and constant head well permeameter data are similar.

Figure 1 illustrates that the model simulations using small core or constant head well permeameter Ksat data produced hydrographs with unrealistically high estimates of daily catchment discharge compared with the observed catchment discharge. The simulations using the large core data, however, produced excellent estimated hydrographs when compared to observed data as illustrated in the observed - simulated plot presented in Figure 2.

The cause of the significant disparity between predicted hydrographs generated by the range of Ksat data is believed to be the underestimation of lateral movement in the saturated zone of the hillslope, resulting from unrealistically low Ksat values produced by the small core and constant head well permeameter for layer 2 of the soil profile. In the upper 50 cm of the soil profile (layer 1) there was an order of magnitude difference between the small core and constant head well permeameter data. However, in layer 2 the median and fourth spread values were essentially the same.

We believe that the Ksat value of layer 2 was the dominant control on the form of the hydrograph. Water table data from the model (Figures 3 and 4) illustrate that for both the small core and constant head well permeameter simulations, the water table ranged between 69 and 78 cm below the soil surface for the entire catchment.

Studies of water table depth in other experimental catchments in the North Maroondah area report water table depths in excess of 10 m at catchment ridgetops (Campbell, in prep) indicating the water table plots presented in Figures 3 and 4 underestimate water table depth in the upper regions of the catchment. Moreover, no catchment discharge was predicted from either simulation during the first 400 days of the model run. During this period of time each of the elements within the model were simply filling up with water. The capacity of the element to transport water laterally down


Large core median

Small core median

CHWP median

Observed

Figure 1: Predicted and Observed hydrographs

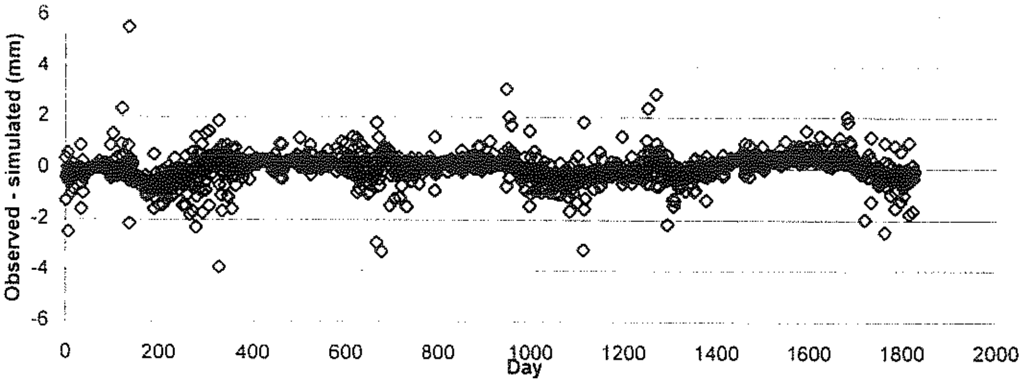


Figure 2:Plot of observed - simulated runoff

the hillslope was so limited that catchment discharge was not predicted until the elements were saturated, and overland flow became the dominant flow process. This is reflected in the extremely peaky nature of the hydrographs.

The considerably higher estimates of Ksat obtained for layer 2 from the large cores (160 cm/day) produced excellent predictions of catchment discharge. Moreover, the simulation provided a more realistic distribution of water table depth through the catchment (Figure 5), than the small cores and constant head well permeameter. The water table depth, predicted by the large core Ksat simulations, ranged between less than 1.22 m in the gullies to deeper than 4.28 m on the ridgetops.

The reason for the superior results produced by the large core simulations is believed to be a function of the performance of the measurement technique in the subsoil. Although large cores performed poorly in the upper 50 cm of the soil profile, owing to the abundance of macropores, the simulation results suggest cores removed from deeper than 50 cm provided more realistic estimates of Ksat for modelling applications. The poor performance of the technique, in the upper 50 cm of the soil profile, is of limited significance as the lateral saturated flow processes occur predominantly in layer 2 of the soil profile. Accurate measurement of the Ksat properties of a heterogeneous field soil is intrinsically difficult owing to the significance of scale in the measurement process. The results of the simple sensitivity tests presented in this study illustrate that the choice of measurement technique can have a significant impact upon model results.

Small core and constant head well permeameter methods to measure Ksat produced input data which resulted in inaccurate predictions of water movement

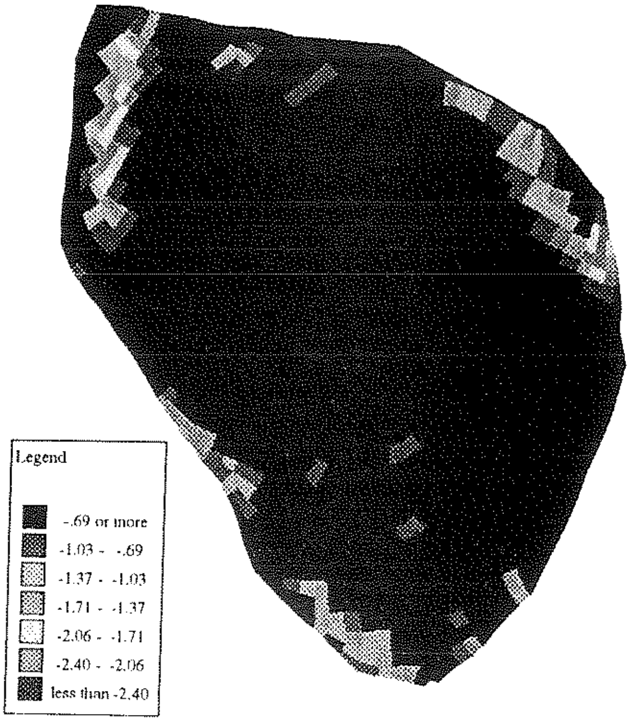


Figure 4: Plot of predicted water table for day 700 using the small core Ksat data

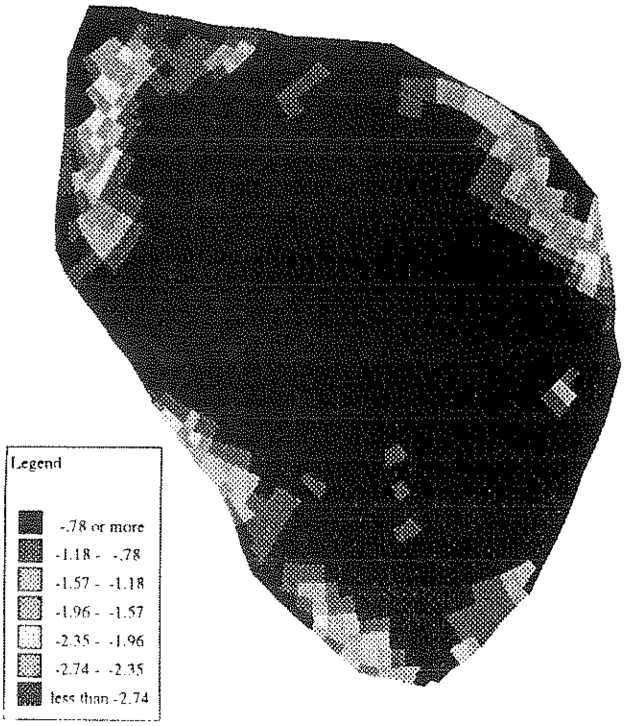


Figure 3: Plot of predicted water table day 700 using constant head well permeameter Ksat data

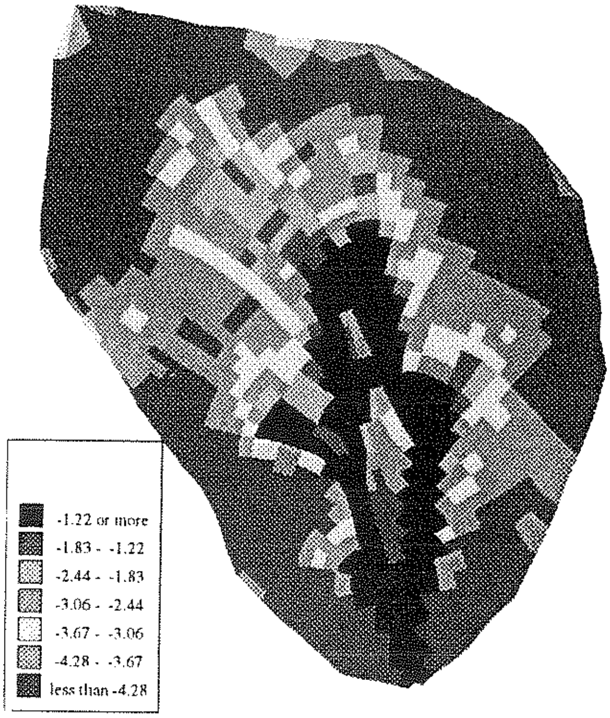


Figure 5: Plot of predicted water table for day 700 using large core Ksat data.

through the catchment, illustrated by the poor predictions of water table depth and catchment discharge.

Conclusions and Recommendations

It is not possible to make conclusive statements about which technique may provide the best input data for model applications because the performance of each technique is a function of the soil type being considered. This is not only a site specific factor but also a function of the composition of the soil profile. The results of this study indicate that lateral water movement through the hillslope is the dominant flow process in the catchment modelled. Therefore, accurate approximations of the hydraulic properties of the subsoil was essential to obtain the best model results. This may not be the case in catchments where other flow processes may be significant.

Further work to assess the effect of stochastic distribution of the experimental data set may provide additional information on the relative performance of each technique.

The results in this study show that use of experimentally measured Ksat data may produce dramatically different model output depending on the measurement technique used. In situations where insufficient resources exist to adequately investigate Ksat for model applications, it may be more expedient to view Ksat as a calibration parameter, and focus attention on obtaining the most complete data set of physical input parameters which are less problematic to measure.

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