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Toward improved parameter estimation of land surface hydrology models through the Model Parameter Estimation Experiment (MOPEX)

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Abstract A key issue in land surface modelling is to estimate model parameters that vary spatially and are unique to each computational element. An international Model Parameter Estimation Experiment (MOPEX) was established to develop techniques for the *a priori* estimation of the parameters used in land surface parameterization schemes of atmospheric models and in hydrological models. The major effort to achieve this goal is to assemble a large number of high quality historical hydrometeorological and river basin characteristics data sets for a wide range of intermediate-scale river basins (500–10 000 km^2) throughout the world. Data sets from Phase I of MOPEX are available via the Internet. MOPEX Phase II activities will collect additional data from the USA as well as data for basins from other countries. During the next three years, the scientific community will use the available MOPEX data sets to estimate basin parameters and to relate them to basin characteristics. This paper presents the MOPEX science strategy, describes the MOPEX data sets, and illustrates the execution of MOPEX strategy with an example based on the Sacramento Soil Moisture Accounting model (SAC-SMA) used by US National Weather Service for river and flood forecasting.

Key words hydrological models; parameter estimation; model calibration; parameter regionalization; MOPEX

INTRODUCTION

A major scientific objective of the Global Energy and Water Cycle Experiment (GEWEX) is to develop and validate macroscale hydrological models, related high-resolution atmospheric models and coupled hydrological–atmospheric models. A critical element in making progress on this objective is improving the representation of land surface components in these models. A key step in applying land surface parameterization schemes to specific locations is to estimate the model parameters. These parameters are inherent in every scheme. They vary spatially so they are unique to each grid location. Parameters of some schemes may also vary seasonally as well as spatially. Therefore, to estimate these parameters, *a priori* relationships are needed between the model parameters and soils, vegetation, topographic and climatic characteristics.

It is well known that hydrologists use model calibration to estimate parameters for the conceptual hydrological models used in river forecasting, because parameters of conceptual models generally are not directly observable. Even if parameters of conceptual models could be estimated *a priori*, river forecast applications would still require fine tuning of the *a priori* parameters where there are sufficient data to support model calibration. To calibrate model parameters, many years of historical hydrometeorological data, including precipitation, streamflow discharge, and potential evaporation must be available.

Most land surface models (LSMs) used in atmospheric models are physically-based models (PBMs) that have parameters related to observable physical properties and they can be estimated using assumed *a priori* relationships between model parameters and land surface characteristics. The estimation of LSM parameters in global atmospheric models presents a different challenge than that of conceptual models. First, there does not exist a hydrometeorological database to conduct model calibration globally. Second, even where data exist, there are not enough to use calibration techniques to estimate parameters for every grid cell. Therefore, alternative procedures to specify parameters *a priori* for each cell must be used.

Presently *a priori* relationships linking model parameters and land surface characteristics such as soil and vegetation classes are available for many LSMs, but these relationships have not been fully validated through rigorous testing using retrospective hydrometeorological data and corresponding land surface characteristics data. This is partly because of insufficient data for such testing. Moreover, generally available information about soils (e.g. texture) and vegetation (e.g. type or vegetation index) only indirectly relates to model parameters such as hydraulic properties of soils and rooting depths of vegetation. Also, it is not clear how heterogeneity associated with spatial land surface characteristics data affects those characteristics at the scale of a model grid cell. Consequently, there is a considerable degree of uncertainty associated with the parameters given by existing *a priori* procedures. Recent studies have illustrated that these procedures do not necessarily produce proper parameter values and that improper model parameters result in poor model performance (see Liston *et al.*, 1994; Duan *et al.*, 1995). The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(c) represented the first PILPS effort to allow participating LSMs to utilize streamflow data to estimate some model parameters (Wood *et al.*, 1998). Their results indicated that the LSMs that used streamflow data to calibrate model parameters had better overall performance in both water balance and energy balance simulations. Still, there is a wide range of results and much of this variability can be accounted for by uncertainty in the values of the best parameters to use in each model.

Because of the high sensitivity of model performance to model parameters, improved *a priori* procedures for parameter estimation are needed. Also, existing model calibration techniques tend to produce "noisy" parameter estimates because many combinations of model parameters produce very similar model response. Therefore, improved *a priori* estimation procedures might be used not only to provide initial parameter estimates, but also to provide uncertainty limits during model calibration.

The primary goal of the Model Parameter Estimation Experiment (MOPEX) is to develop techniques for the *a priori* estimation of the parameters used in land surface parameterization schemes of atmospheric models and in hydrological models. These parameter estimation schemes would likely be unique to each model and would relate model parameters to soils, vegetation, topographic and climatic characteristics. This paper presents the MOPEX science strategy, describes the MOPEX data sets, and illustrates the execution of MOPEX strategy with an example based on the Sacramento Soil Moisture Accounting Model (SAC-SMA) used by the US National Weather Service (NWS) for river and flood forecasting.

MOPEX STRATEGY

The goal of the MOPEX parameter estimation strategy is to develop techniques for *a priori* estimation of parameters that can be applied globally. The first step of the strategy is to develop the necessary data sets and then to use these data to study individual models using three parallel paths. The first path is to make control runs with model parameters estimated using existing *a priori* parameter estimation procedures. The second path is to make model runs using calibrated or tuned values of selected model parameters. Then, relationships would be developed between the calibrated parameters and basin climate, soils, vegetation and topographic characteristics. These relationships are used to define the new *a priori* parameters. The third path is to make new model runs using the new *a priori* parameter estimates. Achievement of the parameter estimation goal is then established in two steps. The first is to measure how much of the potential improvement in model performance when operated in calibration path is obtained when the model is operated using new *a priori* parameters. This step uses the same data sets as were used to develop the new *a priori* parameter estimates. The second step is to demonstrate that new *a priori* techniques produce better model results than existing *a priori* techniques for basins not used to develop the new *a priori* techniques.

DEVELOPMENT OF MOPEX DATA SETS

Historical data are needed for many years for around 200 test basins which have the minimum observations and basin physical characteristics data and which cover a wide range of climate, soils and vegetation characteristics. The main types of required historical data are: hourly and daily gauged precipitation; daily maximum, minimum and average temperature; surface meteorological observations and daily average stream discharges. Supporting basin boundary, stream and land characteristics data relating to topography, soils and vegetation are also needed.

The data collection is to be executed in two phases. The primary focus of Phase I was to create an initial database primarily using data from the USA. Some 2000 USA basins with substantially unmodified streamflow were examined. The majority of these were too small to qualify as an intermediate scale (ISA) basin, or were found to have insufficient precipitation data to adequately represent these key forcing data. To date around 70 basins have been selected in the Mississippi River basin for which daily average basin precipitation and discharge data have been computed. Currently, hourly precipitation data are being prepared. It is planned to have average hourly precipitation and daily streamflow data available for around 200 ISA basins covering the entire USA. The initial Mississippi 70 basin data set is available now via the Internet at: ftp://www.nws.noaa.gov/oh/gcip/mopex/.

The purpose of MOPEX Phase II is to collect additional data from the USA and from other countries as well. The additional USA data will include both additional basins and additional data for the existing basins, including hourly gauge-based precipitation data for all USA basins and distributed, hourly, gauge + radar multisensor data for selected basins. Data from other countries would include basins in North and South America, Europe and Australasia. Data from Asia and Africa also will be obtained and initial steps have been taken to do this, but the basic data collection strategy being used in MOPEX is to seek the most readily available and highest quality data first.

TESTING OF THE MOPEX STRATEGY USING THE SAC-SMA MODEL

This section illustrates how the MOPEX strategy as outlined above can be implemented. Koren *et al.* (2000) developed an *a priori* parameter estimation procedure for the SAC-SMA. The SAC-SMA model is an operational model used by the NWS for river and flood forecasts throughout the USA. A detailed description of SAC-SMA is available in the literature (see Burnash *et al.*, 1973). The estimation of SAC-SMA parameters is very difficult and this has been demonstrated by previous studies (Brazil, 1988).

To develop *a priori* parameters for SAC-SMA, it is assumed that SAC-SMA parameters are related to local soil properties. The 1-km STATSGO soil database developed by Miller & White (1999) was used to determine the soil texture properties. Regional equations were established for 11 of SAC-SMA parameters. For illustration purposes, five of the equations related to soil water storage capacities are presented below.

Estimation of soil water storage capacity parameters in SAC-SMA

To quantify relationships between soil water storage capacity parameters of the SAC-SMA and soil properties, assumptions were made that tension water storages are related to available soil water, and that free water storages are related to gravitational soil water. Available soil water and gravitational soil water can be estimated from soil properties such as porosity, θ_{max}, field capacity, θ_{fld}, and wilting point, θ_{wlt}. The combined depth of the upper and lower layers is assumed to be equal to the soil profile depth, Z_{max}. A concept of an initial rain abstraction (McCuen, 1982) is used to estimate the thickness of the upper layer. The Soil Conservation Service (SCS) developed an approach to estimate the initial rain abstraction based on soil and vegetation type, as well as on soil moisture conditions (McCuen, 1982). Under the average soil moisture conditions stipulated by SCS, one can assume that the upper tension water storage is full and the free water storage is empty. In this case, the initial rain abstraction should satisfy upper free water storage capacity. The upper layer thickness, Z_{up}, (mm) can then be calculated based on an SCS curve number, CN, for each soil profile:

$$Z_{up} = 5.08 \times \frac{1000/CN - 10}{\theta_{max} - \theta_{fld}} \quad (1)$$

Then the SAC-SMA storages can be estimated based on:

$$UZTWM = (\theta_{\text{fld}} - \theta_{\text{wlt}})Z_{\text{up}} \tag{2}$$

$$UZFWM = (\theta_{\max} - \theta_{\text{fld}})Z_{\text{up}} \tag{3}$$

$$LZTWM = (\theta_{\text{fld}} - \theta_{\text{wlt}})(Z_{\max} - Z_{\text{up}}) \tag{4}$$

$$LZFWM = LZFSM + LZFPM = (\theta_{\max} - \theta_{\text{fld}})(Z_{\max} - Z_{\text{up}}) \tag{5}$$

where *UZTWM*, *UZFWM*, *LZTWM*, *LZFSM* and *LZFPM* are the SAC-SMA storage capacities; *LZFWM* is the sum of *LZFSM* and *LZFPM*.

To split the total free water storage of the lower zone into two components, one can assume that lighter soils (with a higher percentage of sand) have less supplemental storage/runoff than heavier soils. The soil wilting point can be used as an index of how heavy a soil is:

$$LZFSM = LZFWM\left(\frac{\theta_{\text{wlt}}}{\theta_{\max}}\right)^{n_1} \tag{6}$$

A value of 1.6 for n_1 was used in this analysis to keep an average ratio between supplemental and primary storage capacities close to 1:3.

Additional assumptions were made to derive other SAC-SMA parameters. For a description of the procedures used to derive other SAC-SMA parameters, see Koren *et al.* (2000).

Comparison of calibrated parameters and regional parameters

Calibrated parameters were obtained for six test basins using a manual calibration package available in NWS River Forecast System (NWSRFS). Calibrated parameters and those estimated from basin physical properties (regionalized parameters) are plotted in Fig. 1(a) and (b) for the Illinois River, Oklahoma, USA. Overall, most regionalized parameters agreed reasonably well with calibrated parameters. The biggest difference was seen in the percolation parameter, *ZPERC*. This difference is due to the fact that *ZPERC* was treated as an independent parameter in calibration and could take on any value over a wide range, subject to the objective function used. On the other hand, *ZPERC* was computed as a function of other SAC-SMA parameters in the regional equation and its values are determined by local soil properties. Noticeable differences were seen between calibrated and soil-based lower zone free water storages for basins with significant baseflow contribution from deep aquifers. This is because the soil-based approach is restricted to the top 2.5 m of the soil layer and cannot account for deep groundwater storage. Future research may deal with this limitation by utilizing additional information such as outlet hydrographs.

Model performance statistics of hydrographs simulated using calibrated and regionalized parameters are presented in Table 1. As shown in the table, calibrated parameters usually produce higher accuracy than regional parameters although the gain is not significant. However, if parameters were not properly calibrated, regional parameters actually produced better statistics (e.g. see Table 1, Tilton basin (TLNG1)).

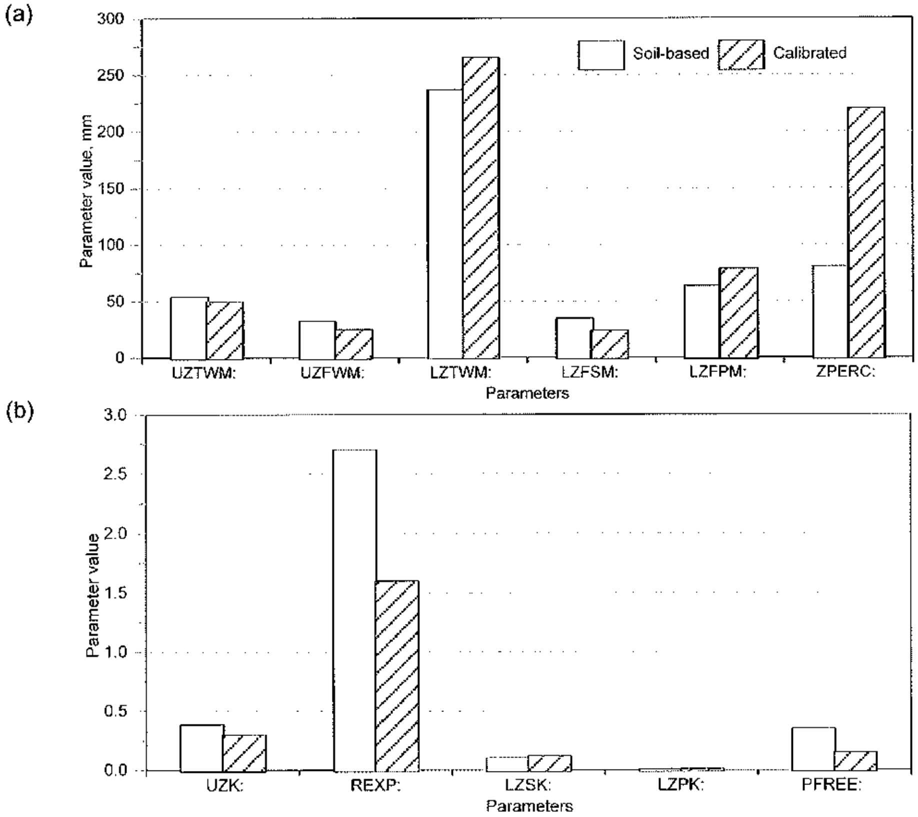

Fig. 1 Comparison of calibrated and regionalized parameters for Illinois River (WTTO2), Oklahoma, USA: (a) storage and capacity parameters, and (b) rate and exponent parameters.

Table 1 Performance statistics of simulated hydrographs using calibrated and regional parameters.

Basin ID/RFC	Calibrated/regional parameters:				Soil derived parameters:			
	DRMS	*MVRMS*	R^2	Bias (%)	*DRMS*	*MVRMS*	R^2	Bias (%)
WTTO2/ABRFC, calibrated	16.2	10.8	0.92	10.9	21.1	11.7	0.89	12.8
TIFM7/ABRFC, calibrated	22.3	8.7	0.91	−2.8	25.0	13.0	0.87	−21.8
BSSI4/NCRFC, calibrated	13.6	12.4	0.84	12.7	13.4	11.3	0.84	12.4
DLLI4/NCRFC, calibrated	13.3	11.3	0.84	3.1	13.1	13.2	0.81	−1.1
TLNG1/SERFC, calibrated	18.0	8.3	0.95	1.1	26.5	11.3	0.92	4.5
TLNG1/SERFC, regional	34.2	24.9	0.85	22.5	26.5	11.3	0.92	4.5

DRMS: daily root mean square error; *MVRMS*: monthly volume root mean square error.

SUMMARY AND CONCLUSIONS

A priori estimates of LSM parameters are needed to apply these models over large regions, or globally, where sufficient data do not exist to permit calibration of those model parameters that vary spatially. The international Model Parameter Estimation Experiment (MOPEX) is developing data sets and techniques for data analysis that should lead to improved *a priori* estimation of those LSM parameters that can be inferred by analysing differences between observed and simulated streamflow variables. An initial database has been developed for MOPEX and additional data sets are being added. These data sets have been made available via the Internet to the general scientific community. A MOPEX strategy has been outlined in this paper. This strategy was successfully implemented using the SAC-SMA model. It is hoped that this strategy will be used by other researchers to develop parameter estimates unique to their own LSMs and the results of their developments will be discussed during a number of workshops and symposia that would be organized by MOPEX.

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