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2.16 USE OF SOIL PROPERTY DATA IN THE DERIVATION OF CONCEPTUAL RAINFALL-RUNOFF MODEL PARAMETERS

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1. INTRODUCTION

Parameters for conceptual models such as the Sacramento Soil Moisture Accounting model (SAC-SMA, the National Weather Service operational model [Burnash, 1995]) can be derived from input/output data analysis using automatic or manual calibration procedures, but are not readily derived from physical basin characteristics. While soil property data are available now for the entire country as high resolution gridded files (e.g., STATSGO), they are used mostly as qualitative information, restricting application of these models (e.g., ungaged basins, semi-distributed versions, etc.) significantly. This study is focused on developing a procedure to derive SAC-SMA model parameters based on STASGO soil texture data in 11 soil layers. Analytical relationships were derived for 11 of 16 SAC-SMA model parameters. Preliminary tests were performed on a few river basins in different regions of the U.S.

2. SAC-SMA MODEL STRUCTURE AND PARAMETERS

The basic design of the SAC-SMA model incorporates a two soil layer structure. Each layer consists of tension and free water storages that interact to generate soil moisture states and five runoff components. The free water storage of the lower zone is divided into two sub-storages which control supplemental (fast) and primary (slow) groundwater flows. Partitioning of rainfall into surface runoff and infiltration into the lower zone storages depends on an available storage of tension and free water in the upper zone. The rainfall above the tension water capacity of the upper zone, ***UZTWM*,** becomes the excess rainfall, and the excess rainfall above the free water capacity, ***UZFWM*,** becomes surface runoff. After the upper zone storages are filled, a runoff rate depends on deficiencies of the lower zone reservoirs, the tension water, ***LZTWM***, and free water, ***LZFSM*** and ***LZFPM*,** capacities. Each free water reservoir can generate runoff depending on a depletion coefficient of the reservoir, namely ***UZK*** coefficient for the upper zone, and ***LZSK*** and ***LZPK*** for the lower free water storages. A percolation rate into the lower zone is a nonlinear function of deficiencies of the lower and upper reservoirs that includes two parameters, the maximum rate of percolation, ***ZPERC***, and an exponent value, ***REXP***. Percolated water into the lower zone is divided among three storages. A constant ***PFREE*** is used to express the fractional split between tension and free water storages. There are five minor parameters that control impermeable area runoff and evapotranspiration. Although there are strong physical arguments to support the model, 16 model parameters can not be measured, and have to be calibrated using historical hydrometeorological data.

3. SOIL TEXTURE AND SAC-SMA MODEL PARAMETER RELATIONSHIPS

To quantify relationships of model parameters with soil properties, the assumption was made that the SAC-SMA tension water storages relate to an available soil water, and that the free water storages relate to gravitational soil water. Porosity, θ_{max}, field capacity, θ_{fld}, and wilting point, θ_{wlt}, derived from STATSGO dominant soil texture for eleven layers were used in estimating available and gravitational water storages. STATSGO soil data are available at 1x1 km grids. The total depth of the upper and lower layers is assumed to be equal the soil profile depth, Z_{max}. A concept of an initial rain abstraction [Linsley et al., 1958] is used to estimate the thickness of the upper layer. It is assumed that under average soil moisture conditions the free water reservoir of the upper zone is empty and an initial rain abstraction should satisfy the capacity of this storage. The Soil Conservation Service (SCS, now is NRCS) developed an approach of estimating an initial rain abstraction based on soil type, vegetation, and soil moisture conditions [McCuen, 1982]. The upper zone thickness, Z_{up}, can be calculated then based on a SCS curve number, CN, for each soil profile:

$$Z_{up} = 50.8 \frac{\frac{1000}{CN} - 10}{\theta_{max} - \theta_{fld}}, \ mm \quad (1)$$

The SAC-SMA storages can be estimated then based on the schematic in Figure 1:

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

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

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

$$LZFWM = LZFSM + LZFPM =$$

$$(\theta_{max} - \theta_{fld}) (Z_{max} - Z_{up}) \quad (5)$$

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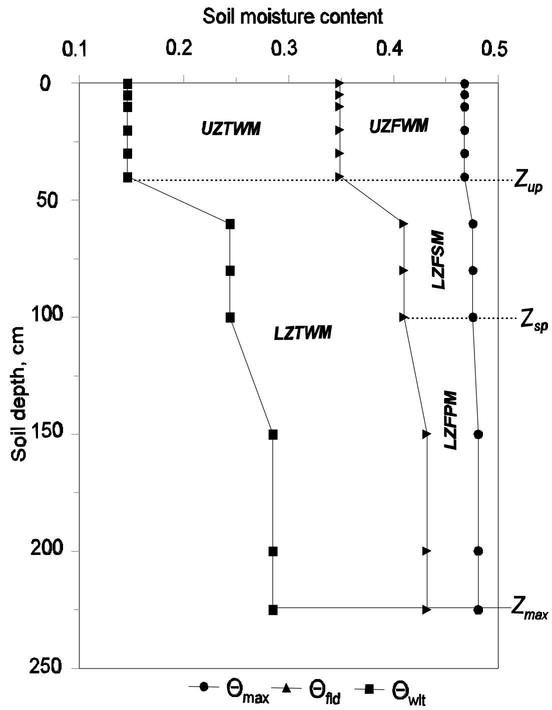

Figure 1. Schematic of SAC-SMA parameter definition based on soil profile properties.

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 wilting point of a soil can be used as an index of how heavy a soil is:

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

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

Empirical relationships were derived to estimate runoff depletion coefficients. Interflow rate is calculated as a ratio of the free water content:

$$UZK = 1 - \left(\frac{\theta_{fld}}{\theta_{max}}\right)^{n_1} \qquad (7)$$

Armstrong [1978] suggested a formula to calculate the supplemental flow rate:

$$LZSK = \frac{UZK}{1 + 2(1 - \theta_{wlt})} \qquad (8)$$

The primary flow rate can be obtained from a solution of Darcy's equation for an unconfined homogeneous aquifer [Dingman, 1993]:

$$LZPK = 1 - \exp\left[-\frac{\pi^2 K_s (Z_{max} - Z_{up}) D_s^2}{4\mu}\right] \qquad (9)$$

where K_s is the saturated hydraulic conductivity, D_s is a stream channel density, and μ is the specific yield of soil. An empirical relationship was derived using data from Linsley et al. [1958] and Armstrong [1978]:

$$\mu = 3.5(\theta_{max} - \theta_{fld})^{1.66} \qquad (10)$$

The maximum percolation rate can be calculated from parameters already estimated

$$ZPERC = \frac{LZTWM + LZFSM(1 - LZSK)}{LZFSM * LZSK + LZFPM * LZPK} + \frac{LZFPM(1 - LZPK)}{LZFSM * LZSK + LZFPM * LZPK} \qquad (11)$$

The ***REXP*** parameter, which defines the shape of the percolation curve, can be associated with the soil type. The minimum permissible value of 1.0 would indicate an almost constant decrease of percolation as the lower zone deficiency decreases and would be associated with sand. A large value would indicate a rapid decrease of percolation as the zones become saturated such as is expected in a clay. A reasonable approximation of recommended values (from calibration results) is

$$REXP = \left(\frac{\theta_{wlt}}{\theta_{wlt,sand} - 0.001}\right)^{0.5} \qquad (12)$$

The ***PFREE*** parameter relates to the water that follows paths through cracks, faults, etc. to escape the capillary demands of the soil. One can expect that clay type soils may have more cracks to recharge baseflow, and should have higher values of the parameter. A wilting point ratio is a good index to represent this feature:

$$PFREE = \left(\frac{\theta_{wlt}}{\theta_{max}}\right)^{n_1} \qquad (13)$$

These derived relationships cannot account for some specific local conditions of river basins. Therefore, estimated parameters should be adjusted using calibration if there are observed rainfall/discharge data. The main objective of these relationships is to give reasonable initial values, and to reduce uncertainties in parameter ranges. Another benefit is that these relationships are based on available physical properties of soils and can be used on ungaged basins. They also allow a reduction in the number of calibrated parameters. Changing just a curve number *CN* can redefine all other model parameters. It is possible also to adjust/calibrate just four well defined characteristics of soil properties, θ_{max}, θ_{fld}, θ_{wlt}, Z_{max}, to get better estimates of 11 model parameters. This is very important for semi-distributed approach when measured discharges are only available at the entire basin outlet.

4. APPLICATION TO HEADWATER BASINS

The approach was used for a few river basins in different climatic regions (Arkansas-Red river basin, Des Moines basin, Conasauga river, Georgia). Manually calibrated parameter sets were available for these basins. Soil characteristics for each soil class were calculated using the Campbell [1974] function for the matric water potential and regression equations from Cosby et al. [1984] to estimate parameters of this function. SCS curve number values were defined for four hydrologic soil groups [McCuen, 1982] under average soil moisture conditions: 80 mm for group A covered soil classes 1-3; 33 mm for group B covered classes 4-6; 20 mm for group C covered the 7-th class; 13 mm for group D covered classes 8-12. SAC-SMA parameters calculated from Eqs. 1-13 were compared to calibrated parameters for selected river basins. Calibrated and estimated from soil texture parameters are plotted in Figure 2 for the Illinois river,

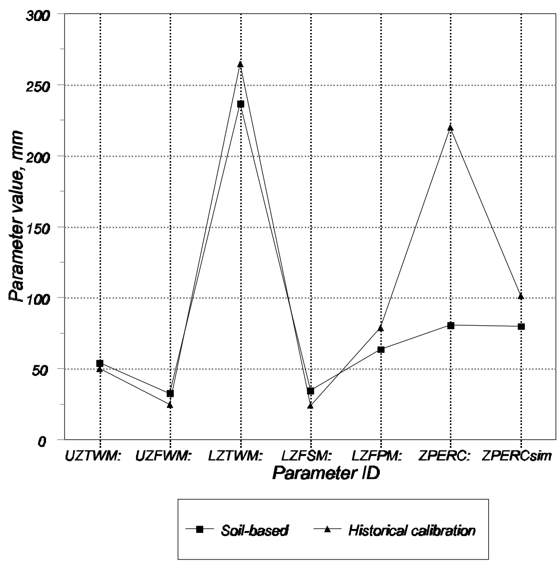

Figure 2a. Calibrated and soil derived SAC-SMA parameters for the Illinois river (WTTO2), Oklahoma.

Oklahoma. Overall, most derived parameters agreed reasonably well with calibrated parameters. The biggest difference can be seen in the ***ZPERC*** parameter. By SAC-SMA model definition, ***ZPERC*** can be calculated from Eq. 11 using other calibrated parameters. Calculated ***ZPERC*** values (parameter $\boldsymbol{ZPERC_{sim}}$ in Figure 2a) were much closer to values estimated from soil properties. It suggests that the calibrated ***ZPERC*** does not agree with physics defined in the SAC-SMA model. Significant differences were seen between calibrated and soil-based lower zone free water storages for some basins. The lower zone free water storages can relate for deep ground water reservoirs which were not accounted in the soil-based approach. More analysis should be done regarding this effect using additional information such as an outlet hydrograph.

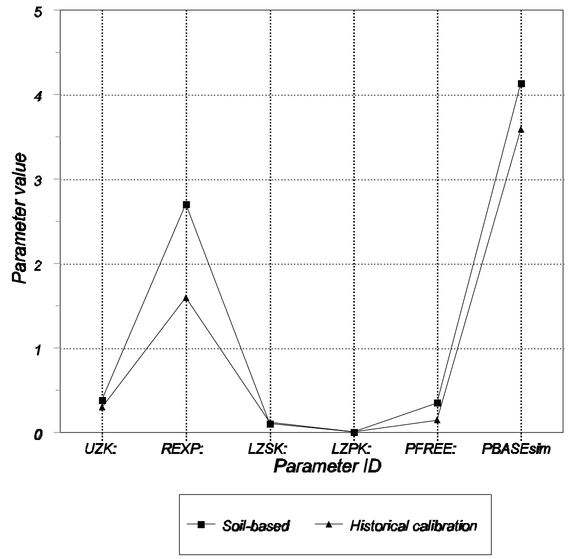

Figure 2b. Calibrated and soil derived SAC-SMA parameters for the Illinois river (WTTO2), Oklahoma.

Calibrated parameters were obtained using manual calibration package which is based on visual fitting of simulated and observed hydrographs, and comparing different statistics. This is a subjective procedure and an 'optimal' parameter set can vary widely if calibrated by different hydrologists. Comparison of calibrated and soil derived parameters only can not provide conclusive information. Accuracy statistics of hydrographs simulated using calibrated and soil derived parameters were also calculated and are presented in Table 1. As seen in Table 1, calibrated parameters usually produce higher accuracy although the gain is not significant as compared to use of soil derived parameters. If parameters were not properly calibrated or regional parameters were used, soil derived parameters produced better statistics, e.g., Tilton basin (TLNG1 in Table 1) in Georgia.

5. SUMMARY

Soil data provide valuable information in estimating conceptual model parameters. Soil derived SAC-SMA parameters are very reasonable initial approximation that can be improved by manual or automatic calibration if input/output data are available. This approach is helpful in semi-distributed modeling when model parameters should be defined over many ungaged small sub-basins. More analysis of soil derived parameters should be done in different climatic regions. Land use and land cover data can be useful in addition to soil texture.

6. REFERENCES

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Table 1. Accuracy statistics of hydrographs simulated using calibrated/regional and soil derived SAC-SMA parameters

Basin ID/RFC	Calibrated/regional parameters				Soil derived parameters			
	DRMS	MRMS	R^2	BIAS, %	DRMS	MRMS	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

Notes: DRMS is a root mean square error of daily discharges, cms; MRMS is a root mean square error of monthly runoff, mm; R is a correlation coefficient of daily discharges; BIAS is a runoff bias for the entire simulation period.