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SMAP - A SIMPLIFIED HYDROLOGIC MODEL

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ABSTRACT

In developing nations the scarcity of hydrologic information poses a difficult problem to the hydrologist who is interested in the generation of streamflow series through the use of a sophisticated rainfall-runoff model. The difficulty is mainly related to the time interval required for the calculations in detailed conceptual models. In general the time interval used in these models is the hour or even a fraction of the hour. The availability of information in such detail is extremely rare and most of the time daily streamflow records are the finest time interval operationally available to the hydrologist.

This paper presents a simplified rainfall-runoff model whose parameters are related to the physical characteristics of the watershed. The model works on a daily basis which is consistent with the availability of data in less developed countries. The number of parameters that depends on the calibration procedure is kept to a minimum to avoid problems associated with the short length of the streamflow records that are generally available.

The model uses the concept of curve numbers from the Soil Conservation Service procedure to define the soil retention capacity of the unsaturated zone. Moisture accounting is continously performed from initial conditions given to the model. At each day moisture updating of the unsaturated zone is done by computing infiltration through the SCS runoff equation. Recharge to the saturated zone is done using the concept of field capacity. The advantage of the model is that the parameters involved in the updating procedure are easily defined in terms of the soil and vegetation cover characteristics alone.

An application is described for three rural watersheds of different characteristics located in southern Brazil. The results have indicated that the methodology is adequate. The error in terms of annual and monthly volumes for the calibration period of 4 years was in the range of 20 percent. The model was applied to watersheds with drainage areas smaller than 3,500 square kilometers.

INTRODUCTION

In recent years the hydrologic community has been flooded by a countless number of hydrologic continous simulation models. In general these models have two basic disadvantagens when applied to less developed countries. The first is their complexity which requires a large number of parameters to be estimated from a small record of observed flows and the second is the time step (hour or fraction of the hour) used in the computations which is not easily found in operational form. Some sophisticated models poses both problems (Crawford and Linsley, 1966; U.S. Army, 1972, EPA, 1971), others less sophisticated in terms of time steps still have many parameters (Mero, 1969). Kraeger (1971) proposed a method to deal with the problem of small time steps through disaggregation of daily precipitation into hourly amounts. This statistical procedure gives good results when precipitation is relatively homogeneous as in the case of temperate climates. In the tropics, however, the predominance of convective rainfall poses some difficulties in the application of the approach.

In this paper is presented an alternative hydrologic model which has a relatively simple structure and operates with daily rainfall and mean monthly potential evapotranspiration inputs. The model was developed in such a way to minimize the subjectivity in the calibration process. Actually there is just one parameter that does not have a direct physical estimator. This parameter is associated with the groundwater recharge and some indications for a first guess are shown in the case study presented at the end of the paper.

The model utilizes a soil moisture accounting procedure that is based on two linear reservoirs representing the unsaturated and saturated zones. Infiltration is taken into account by the Soil Conservation Service (SCS) runoff equation. In the following sections a brief review of the SCS method is presented together with a description of the accounting procedure. Finally, three applications of the proposed model to rural watersheds in the State of São Paulo, Brazil are discussed.

MODEL DEVELOPMENT

The Soil Conservation Service Technique

The Soil Conservation Service (SCS) runoff curve number technique allows the obtaining of runoff volumes from the equation below (Soil Conservation Service, 1975):

$$Q = (P - IA)^2/(P - IA + S) \tag{1}$$

where Q is the direct runoff, P is precipitation, IA is the initial abstraction and S is the potential abstraction, all in milimeters.

Potential abstraction (in mm) is calculated by

$$S = 25.4 \left[(1{,}000/CN) - 10\right] \tag{2}$$

with CN defined as the curve number, related to the soil, vegetation, cover and antecedent moisture conditions of the watershed. Estimates of CN can be obtained for different antecedent soil moisture conditions (dry, normal and wet), through the use of tables (Soil Conservation Service, 1975). Setzer and Porto (1979) in a recent study for the State of São Paulo, Brazil has adapted those tables for the semi-tropical conditions of watersheds of this part of the world. Initial abstraction depends on the land cover conditions and estimates for different situations are easily found elsewhere (e.g. Haan, 1976).

For a given precipitation over the watershed the use of the SCS runoff curve number technique produces direct runoff volumes. This method is event based, restricted to three basic soil moisture conditions and to obtain the event hydrograph one has to add the base flow component. Despite these limitations, it has been used worldwide with acceptable results. Its simplicity and suitability for application to practical problems suggests the use of the SCS concepts to generate direct runoff in hydrologic continuous simulation models. To calculate base flow and update soil moisture conditions the soil and groundwater components have to be simulated.

Soil Moisture Accounting Procedure

Continuous hydrologic simulation models are usually a combination of transfer functions and reservoirs that simulates the natural phenomena. They differ in the transfer functions and (or) the number or type (linear, non linear) of reservoirs. In this paper, the choice was to use three linear reservoirs representing the surface, soil and aquifer retention characteristics (Figure 1). Transfer functions are treated preferentially as linear functions to save computer time whenever the assumption of linearity is acceptable.

A fraction of precipitation (P) is conveyed as direct runoff (DR) by the SCS runoff curve numbers technique (equation 1), to a linear reservoir that routes this water to the basin outlet (RDR). The remaining water depth (P - DR) is depleted at the potential evapotranspiration rate (PE). Excess water (P - DR - PE) enters a linear reservoir representing the upper soil horizon (unsaturated zone). Moisture is lost from this zone at an evapotranspiration rate (AE) proportional to the rate of filling (RF) of the reservoir (actual level divided by the maximum level) times the potential evapotranspiration (PE).

The output from this reservoir is the recharge to the groundwater reservoir. The concept of field capacity (FC) is used in this transfer function. If the actual level (RSOIL) of the soil reservoir is higher than field capacity, recharge (REC) occurs and is equal to:

$$REC = (RSOIL - FC) \times RF \times CREC \tag{3}$$

where RF = RSOIL/SAT is the rate of filling of the soil reservoir, SAT is the maximum soil water content (saturation capacity) and CREC is a recharge coefficient, an input parameter representing the rate of depletion of the soil reservoir. Water transferred to the aquifer below is regulated by this parameter.

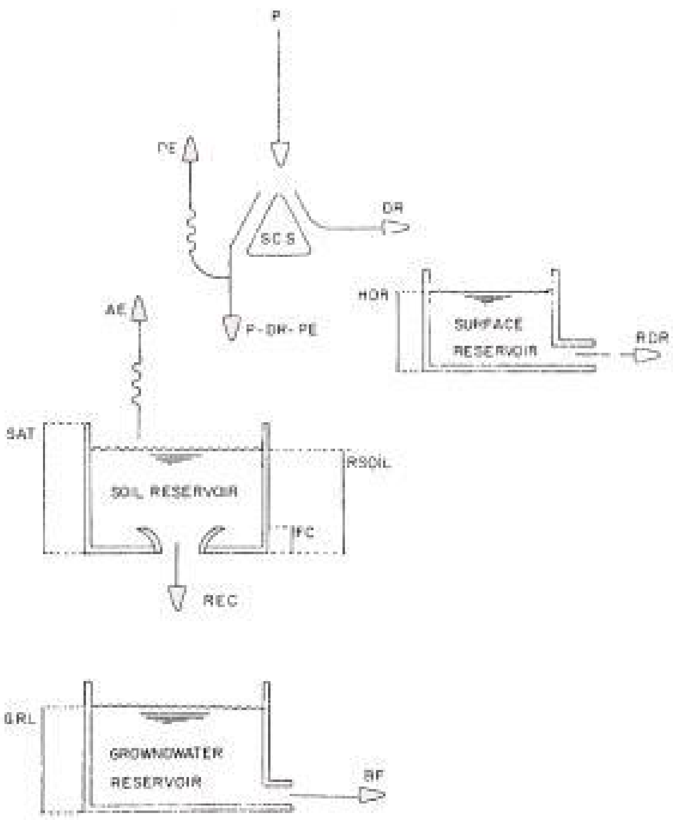

Figure 1. The Soil Moisture Accounting Model.

The groundwater reservoir is another linear reservoir whose depletion characteristic is that of the observed base flow hydrograph. Discharge is obtained as the addition of the routed direct runoff and the base flow component (BF) (output of the groundwater reservoir).

Following the above procedure the levels in each reservoir are continuously updated for each time step.

This updating enables the use of a variable potential abstraction (S) in Equation 1. Accordingly, S is computed by substracting from the saturation capacity the actual soil reservoir level at the time step being considered (Eq. 4). It should be noticed that RSOIL is the actual reservoir level that is used to calculate the potential abstraction (S) for the next time interval.

MODEL PARAMETERS AND OPERATION

As daily data is the most frequent available hydrological information, specially in less developed countries, the model was structured in such a way that the computations are performed on a daily basis. Basic input data to the model are daily precipitation, mean monthly evapotranspiration by month and daily streamflow for the calibration period.

The following ten parameters used in the model are either obtainable directly from data or based on watershed characteristics described below.

AREA (SqKm) - drainage area of the watershed

PCOF - rainfall weighting coefficient relating point rainfall to watershed rainfall, obtainable from Thiessen or isoietal maps.

CN - Soil Conservation Service (SCS) runoff curve number estimated from watershed soil and land cover characteristics and soil moisture condition at the starting time of simulation (obtainable from tables: SCS, 1975: Setzer and Porto, 1979)

IA (mm) - initial abstraction, as defined in Equation 1, is a function of watershed land cover type, including interception and surface retention losses.

FC (percentage) - field capacity of the upper soil horizon,estimated for the whole basin. Can be determined experimentaly from soil characteristics.

CREC - recharge coefficient. A parameter related to the movement of water in the unsaturated soil zone, and therefore a function of soil type, determined during calibration through successive approximations.

K1 (1/day) - base flow recession constant determined from hydrograph analysis (Linsley et al., 1975, pp. 225 - 230).

K2 (1/day) - direct runoff recession constant obtainable from hydrograph separation (Linsley et al., 1975, pp. 225 - 230).

SOLIN (percentage) - initial soil moisture content.

BASIN (CMS) - base flow at starting time of simulation.

As mentioned before the model is composed of three linear reservoirs with separation of direct runoff and infiltration performed by the SCS runoff curve number technique (Equation 1), with S being updated at each time interval by:

$$S = SAT - RSOIL \tag{4}$$

SAT is the soil saturation capacity. This constant is calculated once for all at the beginning of simulation. At this time RSOIL is exactly equal to SOLIN (the initial soil moisture in percentage) times SAT and S is directly obtained from CN (input parameter) by using Equation 2. From Equation 4 above the saturation capacity (SAT) is obtained by dividing S by (1 - SOLIN). The value of SAT thus obtained is used throughout the simulation as a constant.

Depletion of direct runoff reservoir (RDR) will occur as

$$RDR = (1 - K2) \times HDR \tag{5}$$

where K2 is the direct runoff recession constant and HDR is the actual level of the surface reservoir. The same procedure is used to deplete the groundwater reservoir, substituting K2 by K1 and HDR by GRL (see Figure 1). The initial groundwater reservoir level (GRL) is obtained through the conversion of the initial base flow input (BASIN) to depth in milimeters as

$$GRL = 86.4 \times BASIN/\left[A\ (1 - K1)\right] \tag{6}$$

where BASIN is the given initial base flow in CMS, A is the drainage area in Square meters and K1 is the base flow recession constant.

The model was designed to continuously simulate the daily mean flow but can also be used as an event based model. It was developed to run on small to medium size computers and the present FORTRAN IV version of the model requires 32 K bytes of core storage.

MODEL APPLICATION

The model was applied to three watersheds of the State of São Paulo, Brazil: the Pinheirinho river basin with 113 km^2, the Camanducaia river basin with 928 km^2 and the Jaguari river basin with 3,399 km^2. Figure 2 shows schematically the shape and location of the hydrologic gage stations. Available data are daily precipitation, mean daily flows and class A pan evaporation records. Input data for the calibration period is daily rainfall, average daily streamflow and mean monthly evapotranspiration by month. Table 1 shows the details of the hydrologic gage stations used in the simulation.

Vegetation cover of the watersheds is mainly grassland and the soil type is classified as groups A and B according to the Soil Conservation Service tables given by Setzer (1979). Hydrometeorological factors show marked seasonality, with dry winter (June, July) and rainy summer (December, January, February). Mean annual potential evapotranspiration varies from 1250 mm (Camanducaia and Jaguari river basin) to 1550 mm (Pinheirinho river basin). The minimum mean monthly evapotranspiration is around 2 mm by day (Camanducaia and Jaguari) in September and the

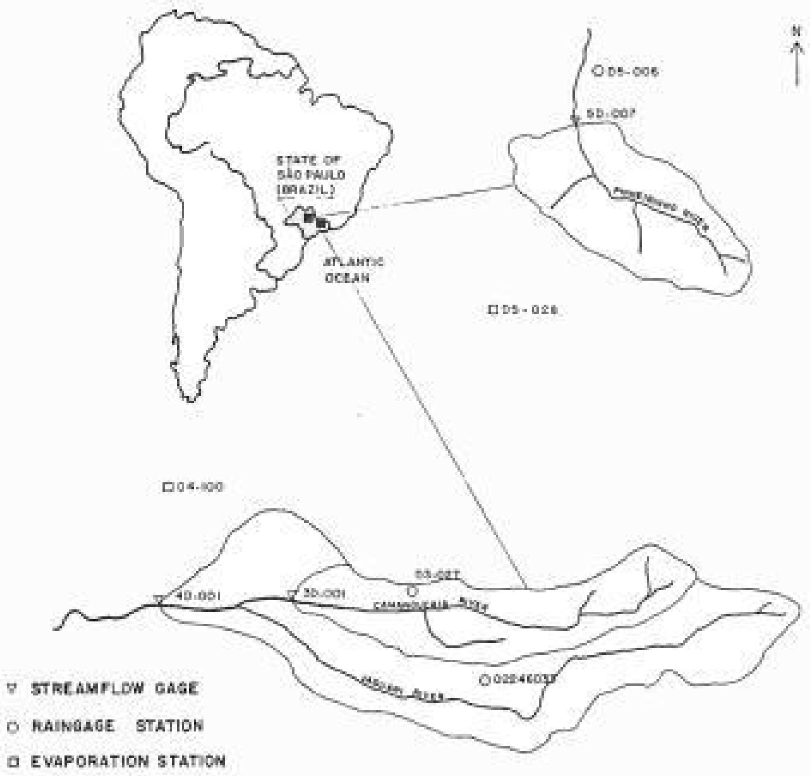

Figure 2. Location of the Watersheds Used in Simulation Runs.

TABLE 1 - Gage Stations Used in the Simulation Runs

Streamflow	Precipitation	Evaporation (Class A)	Drainage Area (km^2)	Calibration period
3D-001 (Camanducaia at Fazenda Barra)	D3-027 (Monte Alegre do Sul)	D4-100 (Campininha)	928	Oct, 1963 to Sept, 1968
4D-001 (Jaguari at Usina Ester)	02246033 (Bragança Paulista)	D4-100 (Campininha)	3,400	Oct, 1958 to Sept, 1963
5D-007 (Pinheirinho at Usina Três Saltos)	D5-006 (Torrinha at Usina Três Saltos)	D5-028 (Barra Bonita)	113	Oct, 1940 to Sept, 1947

maximum mean is about 6,0 mm by day (Pinheirinho) in February. Average annual rainfall is about 1400 mm for the Camanducaia River Basin and for the Jaguari River basin and 1300 mm for the Pinheirinho River basin. In a rainy month the total rainfall can amount to more than 450 mm and in a dry month it could be zero.

Calibration of model parameters is done according to the description given in the previous section. The set of parameters that gave the best results for the calibration period are given in Table 2.

TABLE 2 - Final Model Parameters Used in Simulation

River Basin Station Code	3D-001	4D-001	5D-007
Rain Gauge Station Code	D3-027	02246033	D5-006
Pan Evaporation Station Code	D4-100	D4-100	D5-028
Rain Coefficient (PCOF)	1.0	1.0	1.0
Drainage Area (Area-sgkm)	928.	3399.	113.
SCS Curve Number (CN)	42.	45.	45.
Initial Abstraction (IA-mm)	5.	5.	5.
Field Capacity (FC-%)	0.35	0.40	0.35
Recharge Coefficient (CREC)	0.012	0.009	0.013
Base flow recession (K1-1/day)	0.992	0.993	0.993
Direct runoff recession (K2-1/day)	0.800	0.800	0.700
Initial soil moisture (SOLIN-%)	0.37	0.42	0.38
Initial base flow (BASIN-cumecs)	3.70	33.0	1.00

Results are presented in Figures 3, 4 and 5 in the form of mean monthly flows for the calibration period. Most of the differences between monthly observed and simulated flows do not depart more than 20 percent, which is almost the usual level of dispersion found in basic hydrological data in developing countries. Daily flows have greater discrepancies despite the good agreement in the recession part of the hydrograph between observed and simulated flows, and some peak flows hydrographs that are well close to the observed. The most important factor that explains these discrepancies is the non representativeness of the spatial rainfall over the watershed for many high flows events. Spatial rainfall variability is significant in this area of the world, due to the characteristics of the weather, with cold fronts and convective effects. Since the model uses just one precipitation station the best results were those from the Pinheirinho River Basin which is the smallest one (113 km^2).

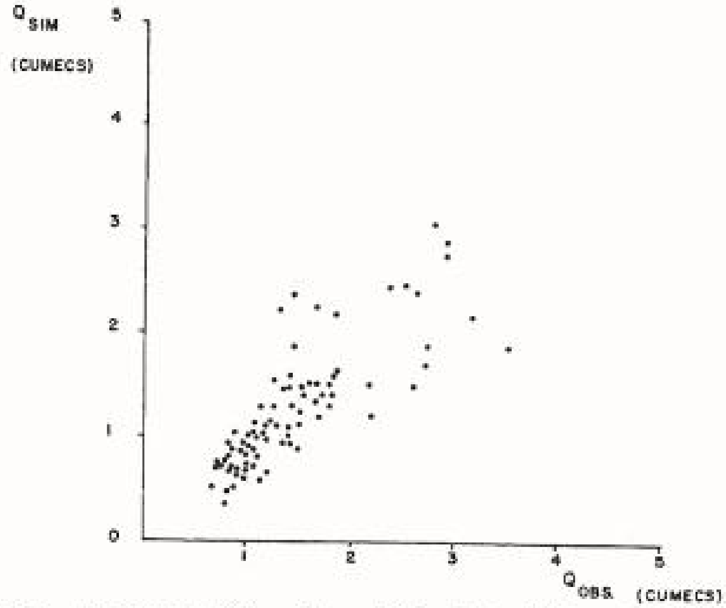

Figure 3. Observed (Q_{OBS}) and Simulated (Q_{SIM}) Mean Monthly Flows for the Pinheirinho River (A = 113 km^2).

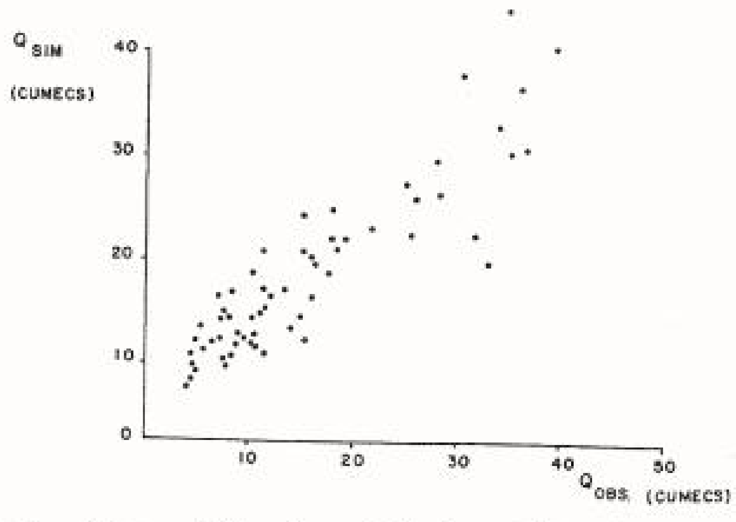

Figure 4. Observed (Q_{OBS}) and Simulated (Q_{SIM}) Mean Monthly Flows for the Camanducaia River (A = 928 km^2).

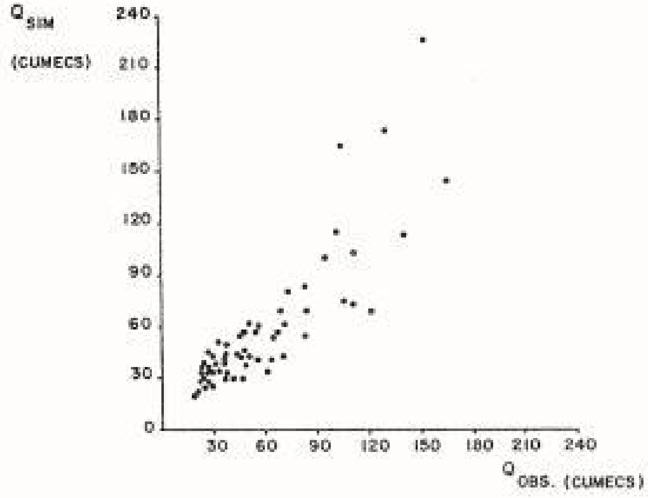

Figure 5. Observed (Q_{OBS}) and Simulated (Q_{SIM}) Mean Monthly Flows for the Jaguari River ($A = 3,400\ km^2$).

Figure 6 shows the results for the Pinheirinho River Basin in terms of mean daily flows for a typical year of the simulation period. It can be observed that the model is adequate and even the peak flows are well represented.

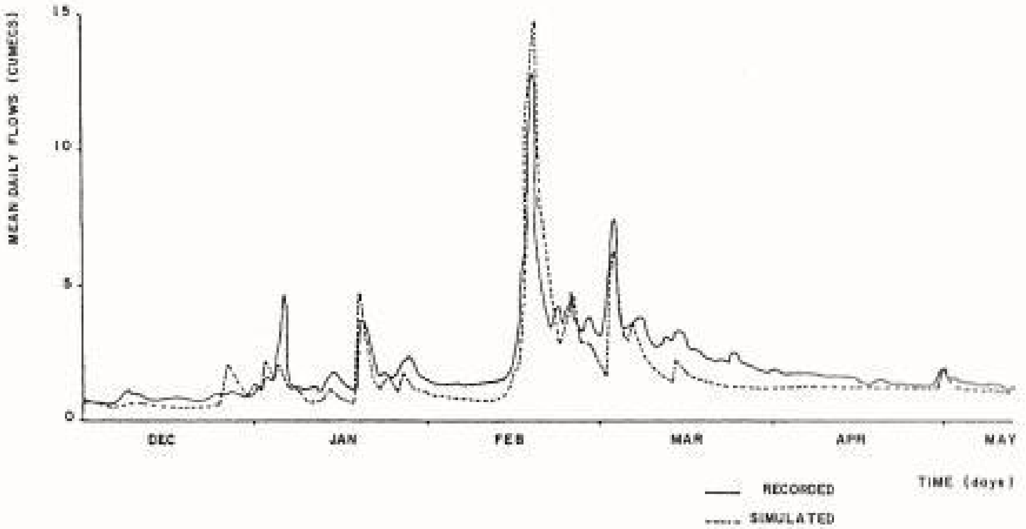

Figure 6. Observed and Simulated Mean Daily Flows for the Pinheirinho River from Dec, 1946 to May, 1947.

CONCLUSIONS

A model has been developed that is suitable for application when hydrologic data is scarce. The scarcity of data seriously limits the application of complex rainfall - runoff models to watersheds in less developed countries. The model presented here can successfully simulate daily flows from daily precipitation and monthly potential evapotranspiration. The hydrologic data used in the applications come from regular stations of the hydrologic network of the State of São Paulo, Brazil. This was done to avoid using experimental basins that are well measured and in general are not representative of the natural environment found in practical engineering applications.

Although no extensive sensitivity analysis has been developed, from the case study presented, it can be seen that the spatial variability of rainfall will limit direct applications of the model to small watersheds (up to 900 km^2). This limitation can be circunvemted, however, by subdividing the watershed into small segments and then apply a convenient routing procedure to route the flows from one segment to the other.

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