II.3-SAC-SMA CONCEPTUALIZATION OF THE SACRAMENTO SOIL MOISTURE ACCOUNTING MODEL

Introduction

The development of rainfall-runoff relationships has gone through a sequence of methodologies. Early in this development, the goal was to focus on storm runoff using procedures such as the Antecedent Index. As the limitations of such procedures became apparent and computer methodology developed, there was a continuing attempt to define additional elements of the hydrologic cycle through increasingly complex formulations. Many of these attempts to simulate runoff and resultant streamflow continued to focus on the streamflow simulation, with little consideration of the soil moisture characteristics which are responsible for streamflow production. The Sacramento model represents an attempt to parameterize soil moisture characteristics in a manner that would:

- logically distribute applied moisture in various depths and energy states in the soil
- have rational percolation characteristics
- allow an effective simulation of streamflow

As the system developed, there was concern that the logic which allows such an approach would become so complex that many users of such a system would inadvertently employ it as a black box technique with little consideration for the physical significance of the basic parameters used within the system. Subsequently, statisticians and hydrologists alike have confirmed the concern through interpretations of results or of the system's parameters in a manner which overlooks or misinterprets the conceptual basis and/or data limitations associated with streamflow simulations. Proper use of this system requires interpretations of the primary mechanisms (precipitation, evapotranspiration and soil moisture) in a physically reasonable manner. A distortion in any of these characteristics will produce a compensating distortion in another element. Such distortion may appear to produce an effective streamflow simulation during the fitting period, but can destroy the system's effectiveness during extremes of dryness or wetness not represented in the original fitting.

It is essential that system components be utilized to fit their intended purpose. Great care must be exercised to insure that they are not inadvertently applied in a manner which results in compensating errors rather than physically realistic considerations. It is for this reason that those utilizing a conceptual runoff simulation process, such as the Sacramento model, should understand the physical significance of each parameter and use it for its intended purpose.

Definition of Tension Water and Free Water

The simplest way to visualize the basic components of the Sacramento model is to start not with streamflow, but with the soil mantle. If we were to examine a block of the soil mantel which we had carefully isolated in a convenient container, we could observe some important characteristics as the soil block went through successive cycles of drying and being rewetted. If the soil vegetation in the box were allowed to dry naturally, we would end up with a certain weight of material within our imaginary container. This material would contain a small amount of residual moisture. We would find it virtually impossible to remove the remaining moisture in any ordinary atmospheric condition and would satisfy ourselves that a small level of residual moisture was natural to any particular environment. This level represents a lower limit of moisture. This moisture is so tightly bound to the soil molecules that it is generally unavailable for plant use or for evaporation into the atmosphere. In terms of soil moisture accounting, this moisture can be considered as permanently resident in the soil and, as such, need not be included in an accounting of those components which do vary with time.

If we were to slowly add moisture to our soil block, we would observe a substantial capability of absorption without any leakage from the block. This volume of water generally is something in the order of magnitude of 15 percent by weight, although it will vary depending upon soil types. This additional volume represents that moisture which is attracted to moisture-deficient soil particles so strongly that it can be removed only by evaporation or evapotranspiration. In the Sacramento model, as in most soil analysis, this volume is identified as tension water. However, once all tension water demands of the soil have been met, if we looked carefully within our soil box, we would find many voids in the interstices between soil particles which could temporarily be filled with water which, unless artificially obstructed, would eventually drain out of the box. The volume of water not bound to the soil molecules, but which would fit within our imaginary soil box, is identified as free water. These components, tension water and free water, are the basic building blocks of the Sacramento model. The important problem has been to represent them in such a way that they permitted effective computation of the percolation and drainage characteristics which serve as important controls of the runoff process.

Upper and Lower Zone Storages

In order to accomplish this objective, it is necessary to divide the soil mantle and, consequently, the tension and free water into upper and lower zones. Although an infinite number of zones could be established, the goal in any parameterization is to use no more than is necessary to effectively describe the physical system.

If we assume that our soil box represents a simple river basin, then the upper zone tension water is restricted to that volume of water which can be applied to the dry soil before any component of leakage takes place from our soil box or basin boundaries. (This volume is represented by the UZTWM parameter in the model.) The leakage is that which is in addition to the fraction of runoff which is due to rainfall over permanent impervious areas of the basin which drain directly to the stream channel. (Permanent impervious areas are represented by the PCTIM parameter.)

Another component of moisture in the upper soil mantle of which we must be aware, is that volume of water which readily moves laterally through the soil to provide interflow or vertically into deeper levels of the soil as the supply for the wetting front. The volume of water utilized for this purpose is a portion of the free water and is identified by its physical position as Upper Zone Free Water (represented by the UZFWM parameter).

Deeper within the soil mantle, tension and free water must also be considered. The Lower Zone Tension Water is that remaining volume of tension water, in excess of the Upper Zone Tension Water component, which is necessary to fully satisfy moisture requirements based on the molecular attraction between dry soils and moisture, but not including any free water in the interstices between the soil molecules (represented by LZTWM parameter).

The Lower Zone Free Water, which fills the soil's interstices below the Upper Zone Free Water, is considered to provide those reservoirs which generate baseflow. It is assumed that drainage from Lower Zone Free Water follows Darcy's Law; that is, drainage is equal to a conductivity constant times the water moving force. In the Sacramento model, the conductivity constant is multiplied by the residual free water volume as a representation of this concept. Such an assumption, unfortunately, does not allow the variety of recessions of baseflow which are observed in nature. However, if we consider that there are two types of Lower Zone Free Water (one a primary type which is very slow draining, providing baseflow over long periods of time and a second type which supplements the baseflow after a period of relatively recent rainfall) then it is possible to combine the two free waters (primary and supplemental), each draining independently in accordance with Darcy's Law, in a manner that allows an approximation of the variety of baseflow conditions found in nature.

Moisture Distribution and Interflow

The problem now becomes one of utilizing these storages to define the moisture distribution and runoff process which accompanies storms of varying magnitudes occurring over a particular river basin. The transfer of these concepts to a river basin and the development of the peripheral logic needed for simulating the percolation and runoff processes, follow from these concepts and are illustrated in Figure 1.

When we visualize rainfall occurring over a basin, we must necessarily consider two basic basin areas:

- o a permeable portion of the soil mantel
- o the impermeable portion of the soil mantle covered by streams, lake surfaces, marshes and other impervious material directly linked to the streamflow network

The permeable area produces runoff when rainfall rates are sufficiently heavy, while the impermeable area produces impervious and direct runoff from any rain.

In the permeable portion of the basin, the model represents the initial soil moisture storage identified as Upper Zone Tension as a volume which must be totally filled before moisture becomes available to enter other storages. Upper Zone Tension represents that volume of precipitation which would be required under dry soil conditions to meet all interception requirements and to provide sufficient moisture to the upper soil mantel so that percolation to deeper zones and sometimes horizontal drainage, can begin. This is consistent with the conclusions of Bodman and Coleman (1944) that, before water can move through the soil to wet dry soil below, the moisture content of the shallow soil must be raised to the minimum value at the wetting front of that soil. When the Upper Zone Tension volume has been filled, excess moisture above the Upper Zone Tension Water capacity is temporarily accumulated in the Upper Zone Free Water. Free water is that water which is not bound to soil particles and is free to move in response to gravity. Although free water is present during filling of Upper Zone Tension Water, it is not necessary to account for it, as it is rapidly transformed into Upper Zone Tension Water until tension water requirements are satisfied. Once the Upper Zone Tension Water is satisfied, Upper Zone Free Water is available to descend to deeper portions of the soil mantle or to move laterally through the soil in response to gravitational and pressure forces. Thus, the Upper Zone Free Water storage supplies a source of water for percolation to lower zones and for interflow. The lateral motion of Upper Zone Free Water in the upper level soil provides that component of observed streamflow which is identified as interflow.

Upper Zone Free Water has two functions, the horizontal potential to generate interflow and, more significantly, a vertical potential which varies with the amount of water available in the upper zone. Interflow is proportional to the available free water volume remaining after percolation:

$$\text{Interflow} = \text{UZK}*\text{UZFWC} \tag{1}$$

where UZK is the Upper Zone Free Water storage depletion coefficient

UZFWC is that volume of free water presently stored in the upper zone

Percolation

The rate of vertical drainage, the percolation to deeper soils, is computed prior to the interflow computation. It is controlled by the contents of the Upper Zone Free Water and the deficiency of lower zone moisture volumes. The preferred path for moisture in Upper Zone Free Water is considered to be downward as percolation. Horizontal flow in the form of interflow occurs only when the rate of precipitation exceed the rate at which downward motion can occur from the Upper Zone Free Water. When the precipitation rate exceeds the percolation rate and the maximum interflow drainage capacity, then the Upper Zone Free

Water capacity is filled completely and the excess precipitation will result in surface runoff. Under this system, surface runoff is a highly rate-dependent volume, with the rate of runoff being determined by the rate of precipitation application and the degree of dryness of the lower zones. In order to describe the complete percolation concept, it is necessary to first complete the visualization of the lower zones.

Lower Zone Tension Water capacity is that depth of water held by the lower zone soils after wetting and drainage which is generally available for evapotranspiration. The two Lower Zone Free Water storages, Primary and Supplemental, represent those volumes which are available for drainage as baseflow or subsurface outflow not appearing in the channel. These free water storages fill simultaneously from percolated water and drain independently at different rates, generating a variable ground water recession.

The percolation mechanics of this system have been designed to correspond with observed characteristics of the motion of moisture through the soil mantle, including the formation and transmission characteristics of the wetting front, as report by Green et al. (1970) and Hanks et al. (1969). The mechanics of transfer from Upper Zone Free Water to lower zone volumes is based upon the computation of a lower zone percolation demand. When the lower zone is totally saturated, then the percolation into the lower zone must be limited to that water which is draining out of the lower zone. This limiting drainage rate is computed as the sum of the products to the two Lower Zone Free Water storages and their respective drainage rates. This limiting rate of drainage from the combined saturated lower zone storages is defined as PBASE:

$$PBASE = LZFSM*LZSK + LZFPM*LZPK \tag{2}$$

where LZFSM is the Lower Zone Free Water maximum supplementary storage, which is the maximum storage capacity for faster draining baseflow

LZSK is the Lower zone supplementary storage depletion coefficient

LZDPM is the Lower Zone Free Water maximum primary storage, which is the maximum storage capacity for slower draining baseflow

LZPK is the Lower zone primary storage depletion coefficient

Following dry periods, however, it is evident that much higher rates of percolation may occur. If we assume that some upper limit of percolation exists, then it can be defined as being equal to:

$$MaxPercolationCapacity = PBASE*(1+ZPERC) \tag{3}$$

where ZPERC provides the necessary multiple to increase percolation potential from the minimum, PBASE, to the maximum, PBASE*(1+ZPERC). If we follow the pattern established by numerous percolation experiments, maximum percolation occurs when the upper zone is saturated and the lower zone is dry, then the maximum percolation demanded by the lower zone can be stated as:

$$\begin{matrix}\text{Lower Zone Maximum}\\ \text{Percolation Demand}\end{matrix} = \text{PBASE}*\left(1+\text{ZPERC}*\left(\frac{\text{Lower zone deficiency}}{\text{Lower zone capacity}}\right)\right) \qquad (4)$$

for under this condition, the deficiency and the capacity are identical. Again, following the results of infiltration experiments, we can say that the change in lower zone percolation demand is exponentially related to the ratio (lower zone deficiency/lower zone capacity). We have now arrived at the equation for percolation demand with varying soil moisture:

$$\begin{matrix}\text{Percolation}\\ \text{Demand}\end{matrix} = \text{PBASE}*\left(1+\text{ZPERC}*\left(\frac{\sum\text{Lower zone deficiencies)}}{\sum\text{(Lower zone capacities)}}\right)^{\text{REXP}}\right) \qquad (5)$$

The actual percolation must, however, also be controlled by the supply of water available for percolation in the Upper Zone Free Water. Consequently, the effective demand must be modified by a function of the available supply in order to define the actual percolation, such that:

$$\text{Percolation} = \text{Percolation Demand}*\left(\frac{\text{UZFWC}}{\text{UZFWM}}\right) \qquad (6)$$

The relationship of percolation demand versus lower zone soil moisture deficiencies is illustrated in Figure 2 for several values of REXP assuming a continuously full Upper Zone Free Water. Such curves allow a very close parallel to the infiltration curves observed in field tests. Under these conditions infiltration is equal to the sum of the losses from the upper zone in the forms of transpiration, horizontal drainage and vertical percolation.

The sums of lower zone capacities and contents include both tension water and free water. Thus, percolation is defined by an interrelationship between soil drainage characteristics and soil moisture conditions. In the event that the wetting process should be discontinuous, a loss of moisture from Upper Zone Tension Water through evapotranspiration and of water drained from Upper Zone Free Water, would require an initial volume to be resupplied before we returned to the percolation characteristics illustrated in Figure 2. This rapid refilling corresponds to the temporary increase in infiltration observed during discontinuous infiltration experiments.

The volume which is percolated to the lower zone is divided among three significant soil moisture storages. The first of these, lower zone tension, represents that volume of moisture in the lower soils which will be claimed by dry soil particles when moisture from a wetting front reaches that depth. Tension water deficiencies are associated with a suction force, so they tend to absorb all percolating water until these deficiencies are satisfied. However, variations in soil conditions and rainfall amounts over a drainage basin cause variations from the average condition. The effect of these variations is approximated in the model by diverting a fraction of the percolated water into Lower Zone Free Water storages before lower zone tension water deficiencies are fully satisfied. A constant PFREE is used to express the fractional split. An examination of Figure 1 indicates that water percolating from the Upper Zone Free Water to the lower zone may go totally to tension water or some fraction of the percolated water may be made available to the primary and supplementary storages. At any time that the Lower Zone Tension Water storage becomes totally filled, continued percolation is divided between the two Lower Zone Free Water storages. At all times, water made available to primary and supplementary storages is distributed between them in response to their relative deficiencies and their relative capacities. The Lower Zone Free Waters represent those volumes which produce horizontal flow generally considered to be baseflow.

Baseflow and Subsurface Drainage

The use of three free water components, one upper zone and two lower zone, allows the generation of a wide variety of recessions and is generally consistent with observed streamflow characteristics. Baseflow is the result of combining the drainages of the two Lower Zone Free Water linear reservoir storages such that baseflow is equal to:

$$(\text{Volume1}*\text{DrainageFactor1})+(\text{Volume2}*\text{DrainageFactor2}) \tag{7}$$

where Volume1 is the primary storage
Volume2 is the supplementary storage

The approximation of baseflow from two Lower Zone Free Water storages with fixed withdrawal functions allows the integration of observed recessions and the computation of the free water volumes with which they are associated. Primary baseflow characteristics are estimated as follows:

$$K_p = (QP_t/QP_o)^{1/t} \tag{8}$$

$$LZPK = 1-K_p \tag{9}$$

$$LZFPM = QP_{max}/LZPK \tag{10}$$

where K_p is the recession coefficient of primary baseflow for the time unit used, usually daily
t is the number of time units
Qp_o is a discharge when recession is occurring at the primary rate
QP_t is the discharge t time units later
Qp_{max} is the maximum primary baseflow that can be inferred from hydrograph analysis

Analysis of the other free water volumes is similar. It is necessarily somewhat more complex, because observed recessions at the higher discharges may include components of flow from two or three of the free water storages.

If the natural boundary conditions of the basin should allow all applied moisture to leave the basin, either at the gaging point or through evapotranspiration, then these soil moisture divisions would be adequate to describe the disposition of liquid water applied at the soil surface. However, subsurface drainage bypasses the gaging site in many basins. In order to approximate this effect within a particular basin, it is assumed that those soils drained by aquifers that do not discharge to the stream channel within the basin have the same basic drainage characteristics as those soils which drain to the stream channel. Thus, the volumes of Lower Zone Free Water storages providing such subsurface flows can be expressed as a fraction of the apparent Lower Zone Free Water storage volumes integrated from the stream channel outflow hydrographs. (The SIDE parameter represents this fraction in the model.) These volumes must exist within the basin in addition to the volumes which will be observed through the surface outflow hydrograph.

Runoff

Runoff is thus the result of processing precipitation through an algorithm representing the uppermost soil mantle and lower soils. This algorithm produces runoff in five basic forms. These are:

- impervious runoff from permanent impervious areas and direct runoff from temporary impervious areas
- surface runoff which occurs when Upper Zone Free Water storage is full and the precipitation intensity exceeds the rate of percolation and interflow
- interflow resulting from the lateral drainage of the Upper Zone Free Water storage
- primary baseflow

Runoff forms 1 and 2 drain with similar characteristics, while the drainage of each of the remaining components have uniquely different characteristics which can be evaluated from hydrograph analysis.

It should be noted that the area of the basin which is impervious does not have to be a constant area in this model. It has been observed in many basins that coincidental with filling the tension water storages, an increasing fraction of the basin may assume impervious characteristics. This fraction, the additional impervious area (represented by the ADIMP parameter in the model), provides a useful representation of the filling of small reservoirs, marshes and temporary seepage outflow areas which achieve impervious characteristics as the soil mantle becomes wetter.

Evapotranspiration

Evaporation from the area covered by surface water or phreatophyte vegetation is computed at the potential rate. Over other portions of the soil mantle, evapotranspiration use varies with both evapotranspiration demand and the volume and distribution of tension water storage. As the soil mantel dries from evapotranspiration, moisture is withdrawn from the Upper Zone Tension Water storage at a rate determined by the potential evapotranspiration unmet by the upper zone times the ratio of the Lower Zone Tension Water contents to total tension water capacity. If evapotranspiration should occur at such a rate that the ratio of contents to capacity for available free water exceeds the ratio of contents to capacity of tension water, then free water is considered to proportionally resupply the tension water and the relative loadings are balanced in order to maintain a moisture profile that is logically consistent. Depending upon basin conditions, some fraction of the Lower Zone Free Water is considered to be below the root zone and, therefore, unavailable for such transfers. This fraction is represented by the parameter RSERV. Starting with a saturated soil and exposing it to a constant evapotranspiration demand would produce an effective evapotranspiration use curve of the type illustrated in Figure 3.

Various algorithms have been utilized to compute evapotranspiration demand. Hounam (1971) has reported on many approaches suitable for such a computation. The methods used are either daily mean values of evapotranspiration demand which vary with day of the year and are defined by model optimization techniques; or redimensioned computations of daily potential evaporation based upon the work of Kohler et al. (1955). If computed values are used, they are adjusted by a PE adjustment coefficient that varies with day of the year.

Conclusion

Although the system mechanics of the generalized hydrologic model are simplified approximations of natural processes, the total effect is consistent with observations of the soil moisture profile made by experimental studies such as those by Green et al. (1970) and Hanks et al. (1969). A formulation such as this which parallels the physical mechanics observed in field experiments suggests significant capabilities for many different kinds of hydrologic analyses (Burnash and Ferral, 1972 and Barnes, 1973).

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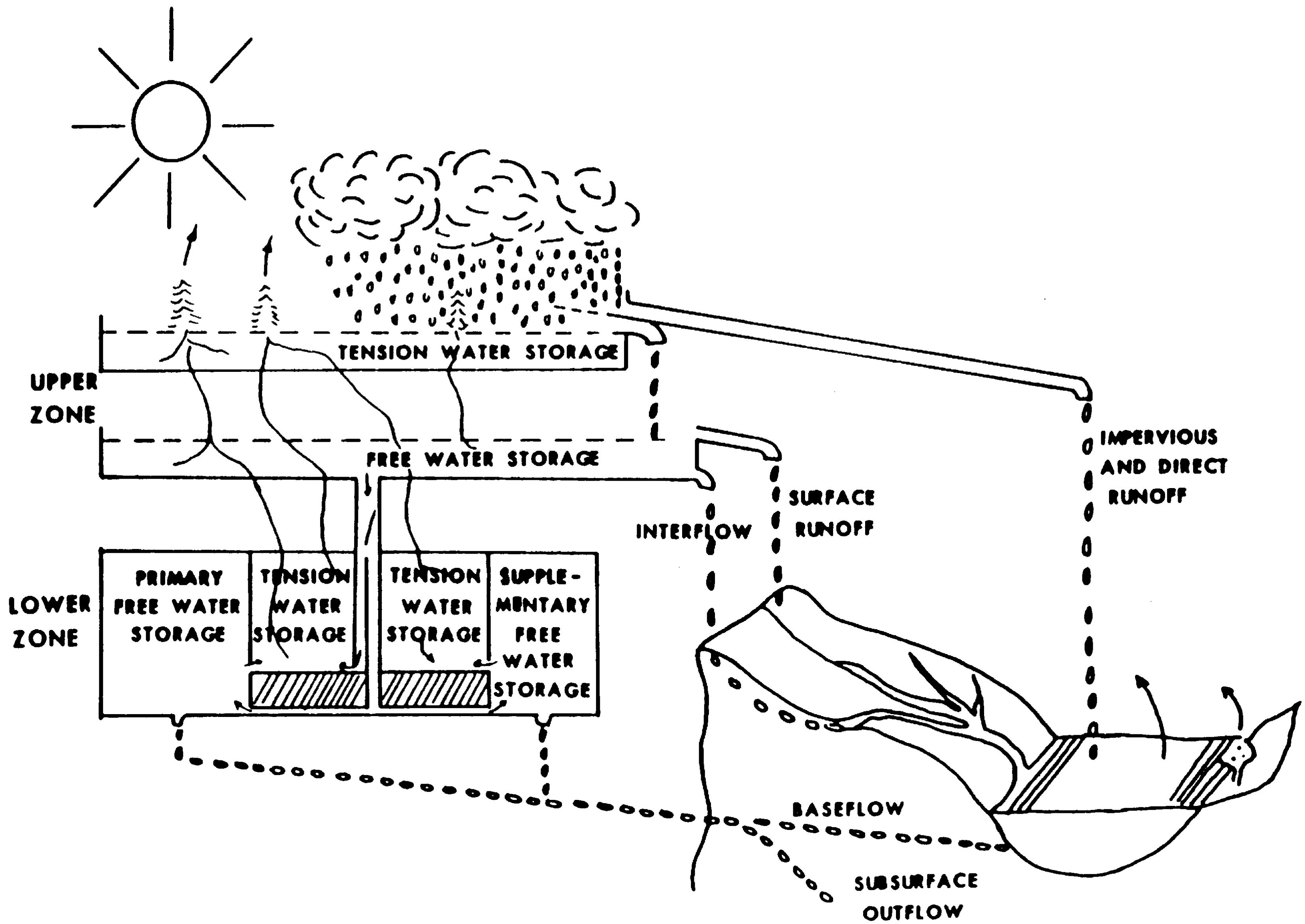

Figure 1. Illustration of a generalized hydrologic model.

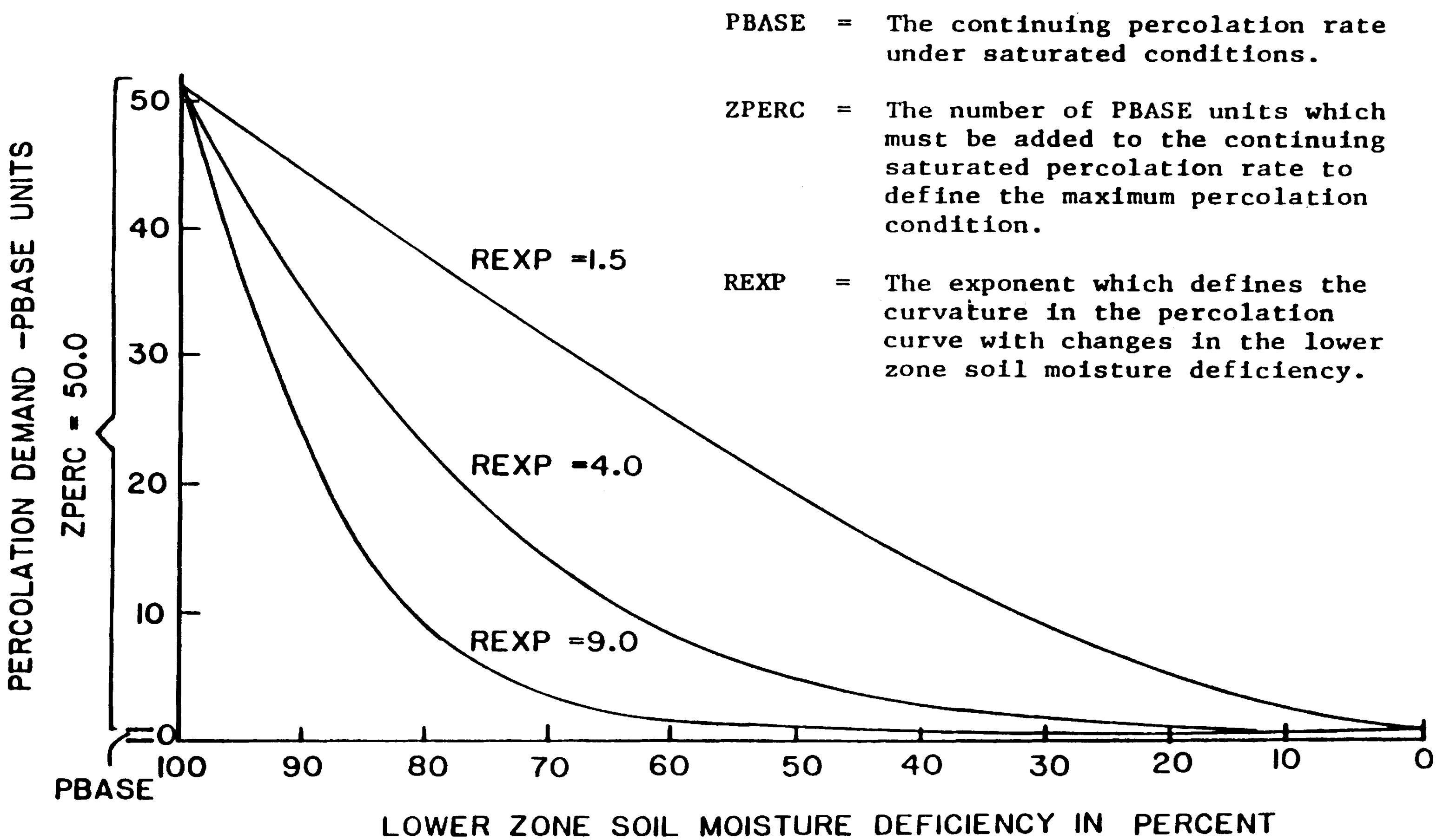

Figure 2. Representation of Percolation Demand

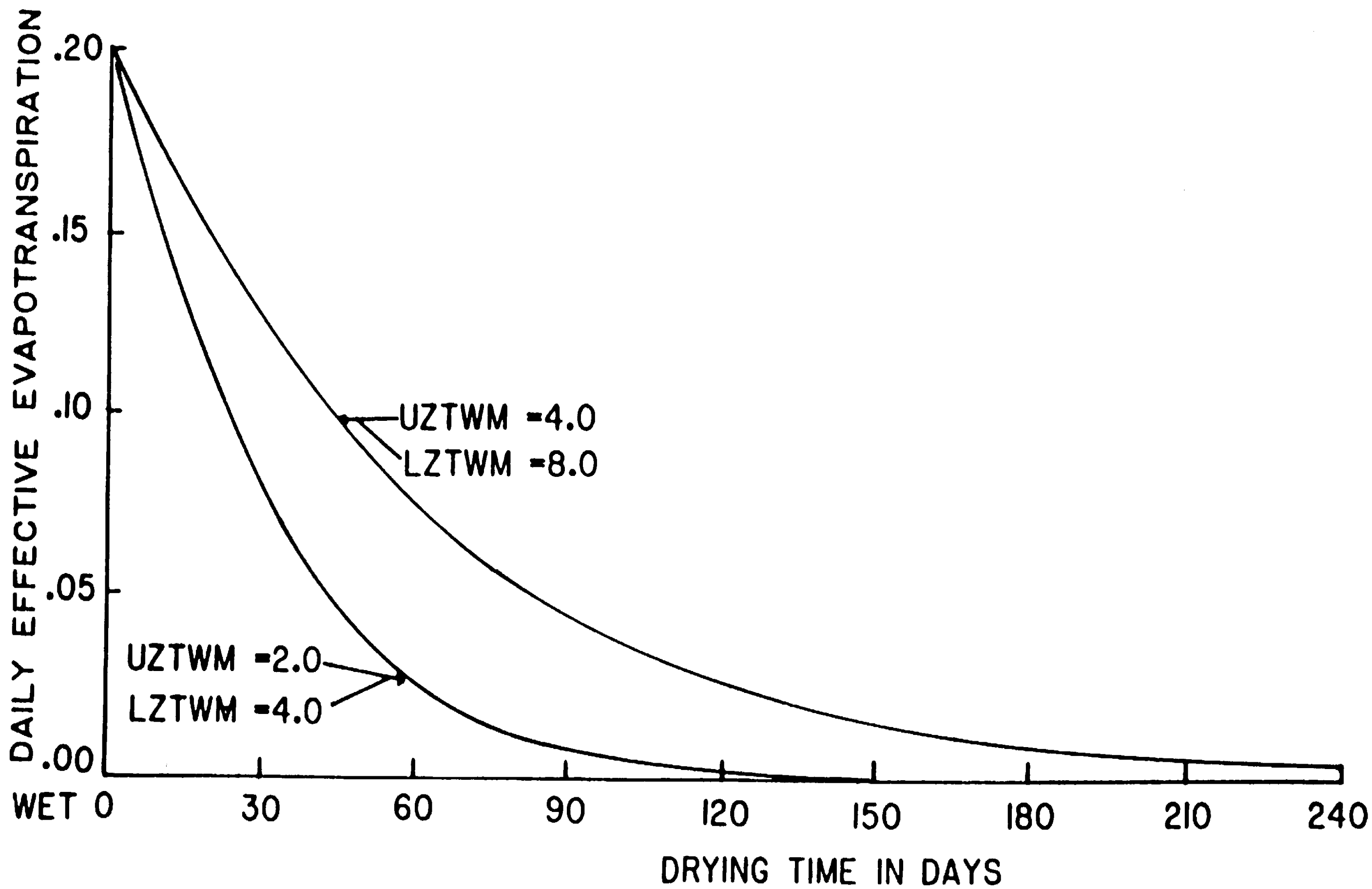

Figure 3. Daily effective evapotranspiration from initially wet soils exposed to a constant evapotranspiration demand.