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LECTURE NOTE
ON

RAINFALL-RUNOFF MODELLING USING REMOTE SENSING AND GIS

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Introduction

An important question in hydrology is how much stream flow occurs in a river in response to a given amount of rainfall. To answer this question we need to know where water goes when it rains, how long does water reside in a watershed, and what pathway does water take to the stream channel. Answering the question of how much runoff is generated from surface water inputs requires partitioning water inputs at the earth surface into components that infiltrate and components that flow overland and directly enter streams. Some precipitation on vegetation falls through the leaves or runs down stems, branches and trunks to the land surface, where it joins the precipitation that fell directly onto the surface, which is known as interception.

Precipitation falling on the surface may pond, and depending upon the soil type, ground cover, antecedent moisture and other watershed properties, a portion may infiltrate. The pathways followed by infiltrated water need to be understood. Infiltrated water can follow subsurface pathways that take it to the stream relatively quickly, in which case it is called interflow or subsurface stormflow. Infiltrated water can also percolate to deep groundwater, which may sustain the steady flow in streams over much longer time scales that is called *baseflow*. Infiltrated water can also remain in the soil to later evaporate or be transpired back to the atmosphere. The paths taken by water determine many of the characteristics of a landscape, the occurrence and size of floods, the uses to which land may be put and the strategies required for wise land management. Understanding and modeling the rainfall – runoff process is therefore important in many flood and water resources problems. Figure 1 illustrates schematically many of the processes involved in the generation of runoff. The rainfall–runoff question is also at the heart of the interface linking meteorology and hydrology.

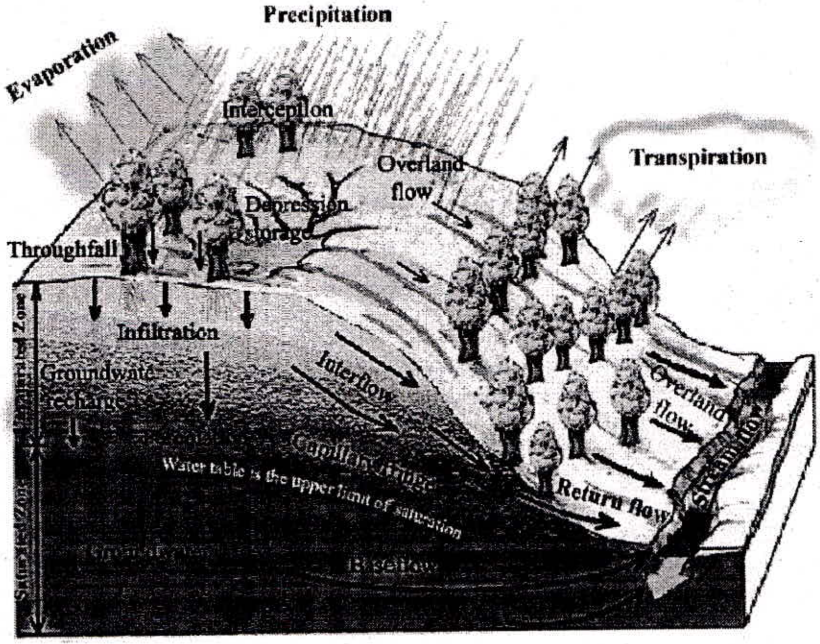


Figure 1. Physical Processes involved in Runoff Generation.

Practical hydrologic models can rarely represent the at a point detail of rainfall – runoff processes, and tend to average or lump hydrologic response over large areas or watersheds. This lumping is at the heart of the scale problem that has received much attention in hydrologic research recently. Averaging is necessary for computational reasons as well as because it is difficult to measure and quantify the full spatial heterogeneity of soil properties involved in runoff generation. In practice rainfall runoff models rely on numerical and conceptual representations of the physical rainfall – runoff processes to achieve continuous runoff generation simulations.

Runoff Processes

The paths water can take in moving to a stream are illustrated in Figure 1. Precipitation may b in the form of rain or snow. Vegetation may *intercept* some fraction of precipitation Precipitation that penetrates the vegetation is referred to as *throughfall* and may consist of bot precipitation that does not contact the vegetation, or that drops or drains off the vegetation afte being intercepted. A large fraction of intercepted water is commonly evaporated back to th atmosphere. There is also flux of water to the atmosphere through transpiration of th vegetation and evaporation from soil and water bodies. The surface water input available fo the generation of runoff consists of throughfall and snowmelt. This surface water input ma accumulate on the surface in *depression storage*, or flow overland towards the streams a *overland flow*, or *infiltrate* into the soil, where it may flow laterally towards the stream contributing to *interflow*. Infiltrated water may also *percolate* through deeper soil and rock layers into the *groundwater*. The *water table* is the surface below which the soil and rock is saturated and at pressure greater than atmospheric. This serves as the boundary between the saturated zone containing groundwater and unsaturated zone. Water added to the groundwater is referred to as *groundwater recharge*. Immediately above the water table is a region of soil that is close to saturation, due to water being held by capillary forces. This is referred to as the *capillary fringe*. Lateral drainage of the groundwater into streams is referred to as *baseflow*, because it sustains streamflow during rainless periods. Subsurface water, either from interflow or from groundwater may flow back across the land surface to add to overland flow. This is referred to as *return flow*. Overland flow and shallower interflow processes that transport water to the stream within the time scale of approximately a day or so are classified as *runoff*. Water that percolates to the groundwater moves at much lower velocities and reaches the stream over longer periods of time such as weeks, months or even years. The terms quick flow and delayed flow are also used to describe and distinguish between runoff and baseflow. Runoff includes *surface runoff* (overland flow) and *subsurface runoff* or *subsurface stormflow* (interflow).

In Figure 2 the *infiltration excess* overland flow mechanism is illustrated. There is a maximum limiting rate at which a soil in a given condition can absorb surface water input. This was referred to by Horton (1933), one of the founding fathers of quantitative hydrology, as the *infiltration capacity* of the soil, and hence this mechanism is also called Horton overland flow. Infiltration capacity is also referred to as *infiltrability*. When surface water input exceeds infiltration capacity the excess water accumulates on the soil surface and fills small depressions. Water in depression storage does not directly contribute to overland flow runoff; it either evaporates or infiltrates later. With continued surface water input, the depression storage capacity is filled, and water spills over to run down slope as an irregular sheet or to converge into rivulets of overland flow. The amount of water stored on the hillside in the process of flowing down slope is called *surface detention*. The transition from depression storage to surface detention and overland flow is not sharp, because some depressions may fill and contribute to overland flow

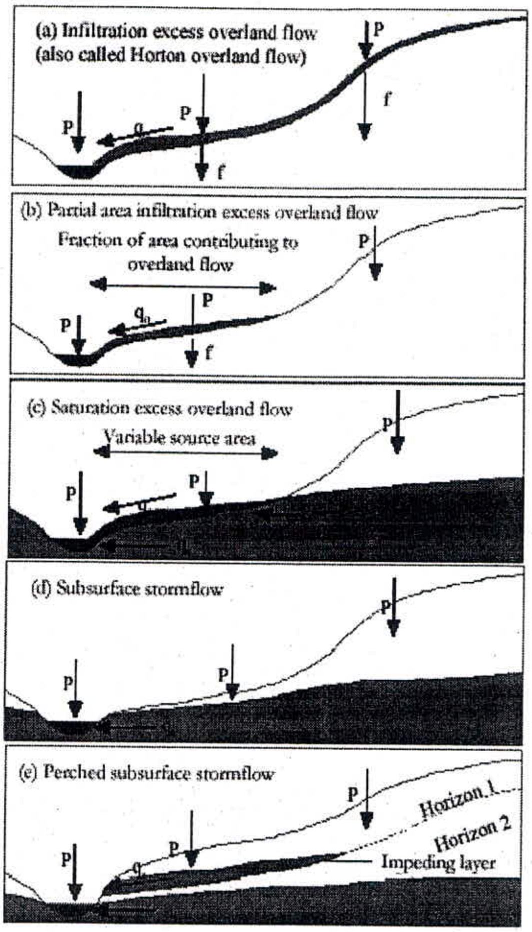


Figure 2. Classification of runoff generation mechanisms (Beven, 2000)

Physical Factors Affecting Runoff

The general climatic regime controls the total volume of runoff in any region through its effect on the water balance. The water balance may be stated as

$$P = Q + E \qquad (1)$$

where P is the precipitation rate, Q the runoff rate, and E the evapotranspiration rate. This equation indicates that the precipitation input is disposed of either into runoff or evapotranspiration. Here groundwater recharge supplying baseflow is included in Q. Because the quantities in equation (1) must be positive, this equation places limits on the values of Q and E given any specific P. Both Q and E are constrained to be less than P. This may be visualized in a space where E is plotted versus P.

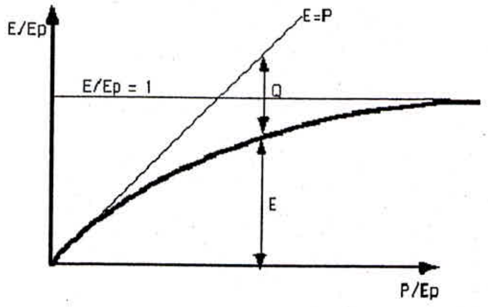


Figure 3. Water balance constraints on runoff and evaporation.

Infiltration Capacity

Infiltration is the movement of water into the soil under the driving forces of gravity and capillarity, and limited by viscous forces involved in the flow into soil pores as quantified in terms of permeability or hydraulic conductivity. The *infiltration rate*, f, is the rate at which this process occurs. The infiltration rate actually experienced in a given soil depends on the amount and distribution of soil moisture and on the availability of water at the surface. There is a maximum rate at which the soil in a given condition can absorb water. This upper limit is called the *infiltration capacity*, $\mathbf{f_c}$. Note that this is a rate, not a depth quantity. It is a limitation on the rate at which water can move into the ground. If surface water input is less than infiltration capacity, the infiltration rate will be equal to the surface water input rate, **w**. If rainfall intensity exceeds the ability of the soil to absorb moisture, infiltration occurs at the infiltration capacity rate. The surface overland flow runoff rate, R, is the excess surface water input that does not infiltrate. This is also often referred to as *precipitation excess*.

$$R = w - f \tag{2}$$

For many purposes the particle size distribution is characterized by the *soil texture,* which is determined by the proportions by weight of clay, silt and sand. Coarse-textured soils such as sands have large pores down which water can easily drain, while the exceedingly fine pores in clays retard drainage. If the soil particles are held together in aggregates by organic matter or a small amount of clay, the soil will have a loose, friable structure that will allow rapid infiltration and drainage. Deep, well-drained, coarse textured soils with large organic matter content will tend to have high infiltration capacities, whereas shallow soil profiles developed in clays will accept only low rates and volumes of infiltration.

Vegetation cover and land use are very important controls of infiltration. The manipulation of vegetation during land use causes large differences in infiltration capacity. The most extreme reduction of infiltration capacity, of course, involves the replacement of vegetation by an asphalt or concrete cover in urban areas.

In many practical applications the parameters in various infiltration models such as the Green – Ampt model (saturated hydraulic conductivity, $\mathbf{K_{sat}}$ and Combined moisture content difference and wetting front suction, **P**) (Green – Ampt, 1911), Horton model (initial infiltration capacity $\mathbf{f_0}$, steady state infiltration capacity, $\mathbf{f_1}$ and **k** is a rate parameter) (Horton, 1939), and Philip model (*sorptivity*, $\mathbf{S_p}$ and $\mathbf{K_p}$ is a hydraulic conductivity) Philip (1957, 1969) are treated simply as empirical parameters whose values are those that best fit infiltration ($\mathbf{f_c}$) data, or as fitting parameters in relating measured rainfall to measured runoff.

The functions derived above provide the basis for the calculation of runoff at a point, given a time series of surface water inputs, and the soil conditions, quantified in terms of infiltration model parameters. The problem considered is: Given a surface water input hyetograph, and the parameters of an infiltration equation, determine the ponding time, the infiltration after ponding occurs, and the runoff generated. The process is illustrated in Figure 4.

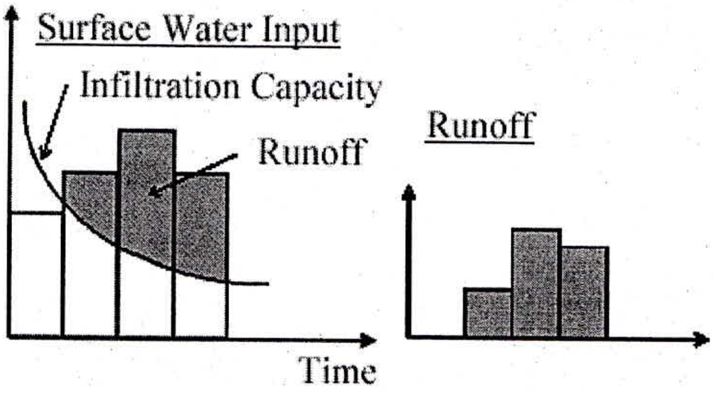


Figure 4: Surface water input hyetograph and infiltration capacity.

Role of Remote Sensing

Remote sensing and specifically, microwave remote sensing can provide information about surface soil water content over large areas. Both active and passive microwave systems exist, with active systems (radar) having higher resolution. Because of the importance of soil moisture in hydrologic response, as well as land surface inputs to the atmosphere, the relationship of soil moisture to remote sensing measurements is an area of active research. The assimilation of remote sensing measurements of soil moisture into hydrologic and atmospheric forecasting models is one exciting aspect of this research that holds the potential for improving hydrologic and atmospheric model forecasts.

During the post monsoon, period using satellite data, base flow contributing areas as well as surface saturated areas can be identified, few examples are shown here.

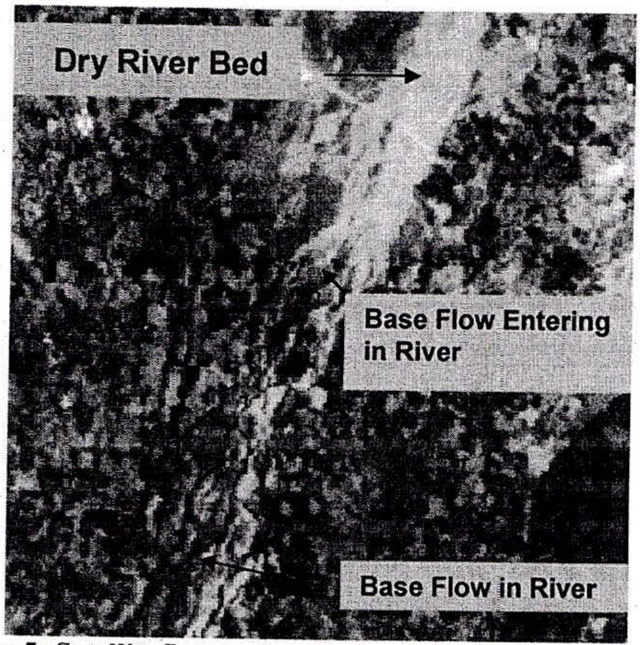


Figure 5: Satellite Image showing base flow reaching river

The surface saturated areas, especially along the drainage channels can be seen as long dark features in the satellite imagery. This may be due to the type of surface soil and also saturated surface conditions, which will contribute runoff very quickly, i.e. quick peak discharge is expected.

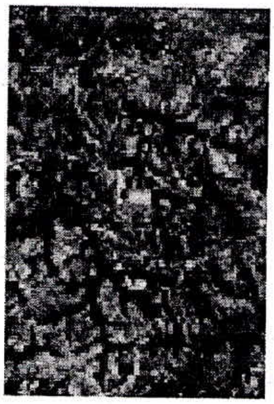


Figure 6: Surface saturated conditions seen as dark patches on satellite imagery.

Runoff can not be quantified directly from remote sensing information. It is done indirectly using spatial information such as land use / land cover area, hydrologic / soil textural information from the contributing area in a hydrologic model such as Soil Conservation Service (SCS), Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS) and Soil

Water Assessment Tool (SWAT) etc. All these models has input from remote sensing data in the form of land use / land cover or hydrologic condition etc.

Simulation of Runoff Generation in Hydrologic Models

The essential feature of a simulation model is that it produces an output or series of outputs in response to an input or series of inputs. In the case of a rainfall-runoff model the inputs are characteristics of the watershed being modeled, such as drainage area and channel network geometry (size and length), topography, oil and land use characteristics and a time series of precipitation as input. The output is a time series of stream flow at an outlet location. Lumped models treat a whole catchment, or a significant portion of it, as a single unit, with inputs, internal state variables and outputs representing the hydrologic processes over the catchment as a whole. Distributed models divide the catchment into a number of sub areas; simulate each of them, and the interactions between them separately, maintaining different state variables for each model element, then combine the outputs to obtain catchment response. However there is also often a difference in representation of the processes between lumped and distributed models, with distributed models being based more on the basic physical equations used to describe the processes involved and taking advantage of physically measurable attributes of the watershed, whereas lumped models use a more conceptual representation of the rainfall runoff process. There is a vast literature on hydrologic modeling (see Freeze and Harlan, 1969; Beven, 1989; Beven and Binley, 1992; Grayson et al.,1992a; Grayson et al., 1992b; Beven, 2000 and the descriptions in a number of hydrology texts), but a review two of the more prominent rainfall runoff models is given here.

The models described here are HEC-HMS and SWAT.

Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS)

Overview

For precipitation-runoff-routing simulation, HEC-HMS provides the following components:

- Precipitation-specification options which can describe an observed (historical) precipitation event, a frequency-based hypothetical precipitation event, or a event that represents the upper limit of precipitation possible at a given location.
- Loss models which can estimate the volume of runoff, given the precipitation and properties of the watershed.

- Direct runoff models that can account for overland flow, storage and energy losses as water runs off a watershed and into the stream channels.
- Hydrologic routing models that account for storage and energy flux as water moves through stream channels.
- Models of naturally occurring confluences and bifurcations.
- Models of water-control measures, including diversions and storage facilities.

These models are similar to those included in HEC-1. In addition to these, HECHMS includes:

- A distributed runoff model for use with distributed precipitation data, such as the data available from weather radar.
- A continuous soil-moisture-accounting model used to simulate the long-term response of a watershed to wetting and drying.

HEC-HMS also includes:

- An automatic calibration package that can estimate certain model parameters and initial conditions, given observations of hydrometeorological conditions.
- Links to a database management system that permits data storage, retrieval and connectivity with other analysis tools available from HEC and other sources.

Remote Sensing-GIS based Hydrology and Hydraulics in support of flood simulation and satellite data interface is shown in figure 8.

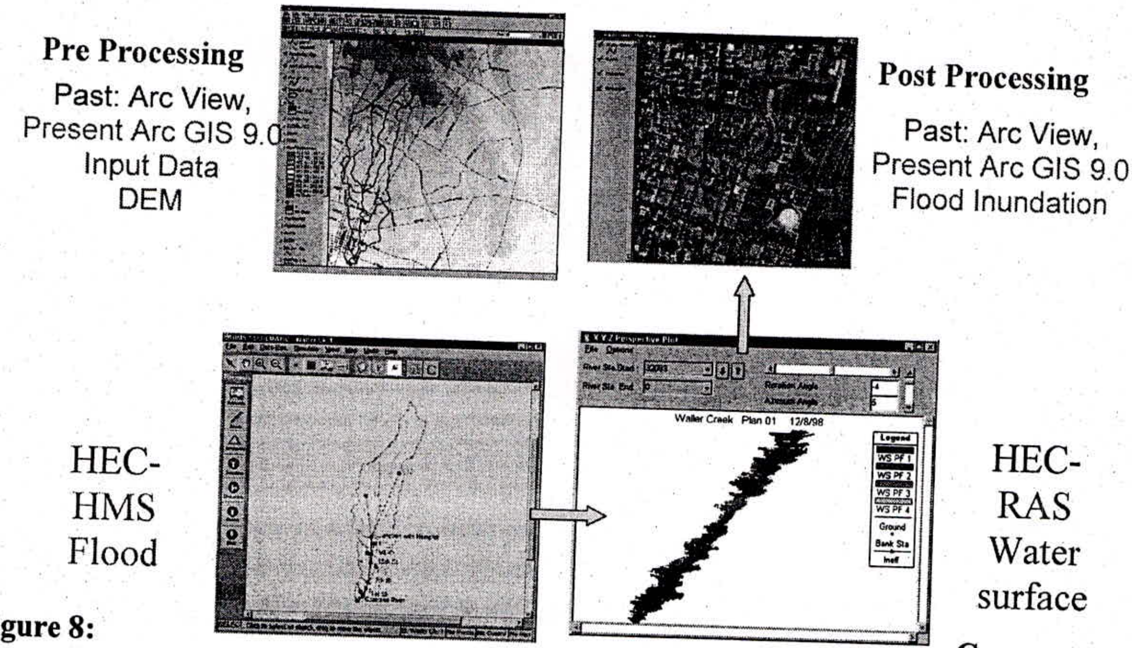


Figure 8: Components involved in Flood estimation and also Flood routing using HEC-HMS and HEC-RAS

Soil and Water Assessment Tool (SWAT) Overview

SWAT is the acronym for **S**oil and **W**ater **A**ssessment **T**ool, a river basin, or watershed, scale model developed at (for the USDA Agricultural Research Service (ARS) (Arnold, 1993). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. SWAT is a continuous time model, i.e. a long-term yield model.

To satisfy this objective,

- is physically based. It requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using this input data.

Among the output, water movement, sediment movement are important with regard to flood studies.

Overview of SWAT

SWAT allows a number of different physical processes to be simulated in a watershed. For modeling purposes, a watershed may be partitioned into a number of sub-watersheds or sub-basins. The use of sub-basins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology.

Input information for each sub-basin is grouped or organized into the following categories: climate; hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the sub-basin.

Simulation of the hydrology of a watershed can be separated into two major components *viz.* **land phase of the hydrologic cycle**, which controls the amount of water, sediment to the main channel in each sub-basin and **water or routing phase of the hydrologic cycle** i.e the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

Land Phase of The Hydrologic Cycle

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

Routing Phase of the Hydrologic Cycle

Once SWAT determines the loadings of water, sediment to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972).

Routing In The Main Channel Or Reach: Routing in the main channel can be divided into two components: water, sediment.

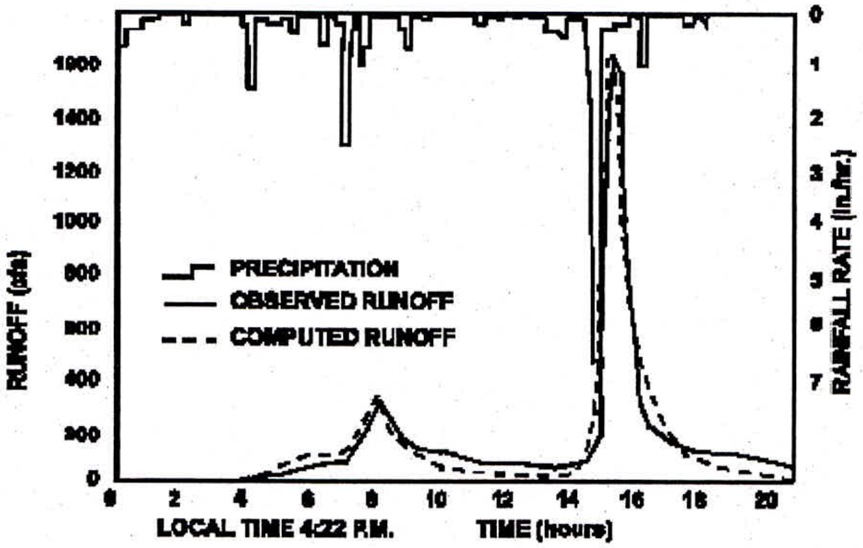
Flood Routing: As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

Sediment Routing: The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT uses stream power to estimate deposition/degradation in the channels (Arnold et al, 1995). Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) used Bagnold's definition of stream power to develop a method for determining degradation as a function of channel slope and velocity.

In this version of SWAT, the equations have been simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. Available stream power is used to reentrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted for stream bed erodibility and cover.

SWAT Output

One of the output generated by SWAT model is a hydrograph at all the selected watershed outlets. An example is shown here.



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