Hydrological Monitoring and Modeling for Conservation of Natural Resources on Watershed Basis

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Hydrology deals with the occurrence, circulation and distribution of water of the earth and earth's atmosphere. Applied hydrology includes predicting various hydrological processes, engineering storm water conveyance systems, soil loss estimations, and many other water management tasks. Water circulates in the hydrosphere through the maze of paths constituting the hydrologic cycle. The hydrologic cycle is a continuous process by which water is transported from ocean to the atmosphere to the land and back to sea. The cycle emphasizes the four phases of interest to the hydrologist precipitation, evaporation and transpiration, surface stream flow, and ground water. Watershed/ drainage area is the hydrological unit which drains the water through single outlet. Catchment area affords a logical and convenient unit to study various aspects related to the hydrology and water resources of a region. Management of a watershed thus entails the rational utilization of land and water resources for optimum production but with minimum hazard to natural and human resources. Planning and development of hilly watersheds calls for rigorous understanding about the occurrence and movement of water in the surface and sub-surface systems along with soil and nutrient losses. Most applications of hydrology are dependent upon monitoring and modeling of various hydrological processes for conservation and management of natural resources on watershed basis.

Hydrological Monitoring

Rainfall, infiltration, evaporation, runoff, initial abstractions etc. are the various hydrological processes. Hydrological monitoring implies the measurement of these processes. The importance of hydrological monitoring are i) To prioritize the watersheds ii)To quantify the water resources of a watershed iiI)To identify the sites for conservation structures, water harvesting ponds/tanks etc. iv) To study the impact of watershed treatment v)To develop hydrological models. The monitoring of various hydrological parameters are descried below:

Rainfall

The primary source of any form of the water resource is rainfall, which is stochastic in nature. Any rainfall based activity requires quantification for effective utilization and conservation. The rainfall is collected and measured by recording and non recording raingauges. The non recording gauge extensively used in India is Symon's Gauge and it gives 24-hr rainfall. The essential parts of an ordinary raingauge are a funnel through which the rain water is collected in a receiver and a measuring glass (rain measure) with which the rain water collected is measured. Recording raingauges are used to obtain a continuous record of daily or weekly rainfall. It consists of a funnel-shaped collector at the top of the gauge and a float syphon chamber and recording mechanism just below it. the rain water collected by the collector is led into the float chamber. The float is having a central stem on which a pen assembly is fixed. The pen is moving over a daily (or weekly) chart wound over a clock drum. After every one centimetre of rainfall syphoning occurs and recording of rain starts afresh. The recording gauges are siphon gauge, tipping bucket, weighing bucket, telemeter gauges etc. Rainfall analysis are frequency, depth-area-duration, intensity-duration-frequency, probable maximum precipitation analysis.

Runoff and soil loss

The portion of rainfall that makes its way towards streams, lakes, oceans as surface or subsurface flow is known as runoff. Runoff measurement is required for design of soil and water conservation structures, water harvesting structures and effective utilization of water resources of a watershed. Various instruments and structures are available for measuring runoff and soil loss depending upon the specific needs of the location. Each one has its own characteristics that favor its adoption under certain conditions of measurements and limit its use under other sets of conditions. Precalibrated devices for measuring runoff are most commonly used at research stations because of their high accuracy. The two most commonly used devices are H-type flumes, parshal flumes and weirs

H-Flumes: These are the most commonly used for the runoff measurement. Presently, three types of flumes—HS, H, and HL—are available for small-, medium-, and high-discharge rates, respectively. They have different specifications to suit various ranges of water flow. HS-flumes are designed to measure small flow rates ranging from 0.0014 to 0.0227 $m^3\ s^{-1}$ (0.05 to 0.8 $ft^3\ s^{-1}$) with a high accuracy. HL flumes are used where the maximum runoff ranges from 0.009 to 0.85 $m^3\ s^{-1}$ (0.3 to 30 $ft^3\ s^{-1}$). The shape of flume provides the following distinct advantages that favor its use under a variety of flow conditions (USDA 1979):

- The increase of throat opening with the rise of stage facilitates accurate measurement of both low and high flow of water.
- The converging section of flume makes it self-cleaning because of increased velocity. Consequently, the flume is suitable for measuring flows having sediment in suspension and low bed-loads.
- It is simple to construct, rigid and stable in operation, and requires minimal maintenance for retaining its rating.
- Its installation is simple and is generally not affected by the steepness of the channel gradient.

Flumes are basically designed for free-flow conditions and are therefore not recommended for submerged-flow conditions. Flumes are also not recommended for flows carrying excessive amounts of coarse bed-loads. Flumes should be installed with free outfall or no submergence wherever possible.

Parshall flumes: are devices for the measurement of flow of water in open channels, streams when flows carrying excessive amounts of silt and debris. The flume consists of a converging section with a level floor, a throat section with a downward sloping floor, and a diverging section with an upward sloping floor. In deviation from the general rule long throated flumes, where the upstream head is measured in the approach channel, Parshall flumes are calibrated against a piezometric head, ha, measured at a prescribed location in the converging section. The "downstream" piezometric head hb is measured in the throat. In practice this is also used in the cut-throat and H flumes. Parshall flumes were developed in various sizes.

Weirs: are the simplest and reliable structures that can be used in many situations to measure runoff from hilly watersheds. They can be used most effectively where there is a fall of about 18 cm (or 0.6 ft) or more in the waterway, and also where submergence on the upstream section is not undesirable. There are three standard types of weirs namely rectangular, trapezoidal (cipoletti) and triangular (V notch) used for measurement of large, medium and small flows respectively. The cipoletti weir have a slope of 1 horizontal to 4 vertical.

Stage-level recorders: Accurate determination of runoff volume, peak runoff rate, and other related information from hilly watersheds invariably requires the continuous recording of the water level. Stage-level recorders are commonly used for this purpose. A stage-level recorder produces a graphic record of the stage of flow over a control with respect to time, and it is accepted as very reliable. Many types of stage-level recorders are commercially available. They can be broadly classified into two types: mechanical type stage-level recorder and digital automatic stage-level recorder. The mechanical stage-level recorder mechanically converts the vertical movement of a counter-weighted float resting on the surface of a liquid into a curvilinear, inked record of the height of the surface of the liquid relative to a datum plane with respect to time. The time element consists of a weekly winding spring-driven clock supported on a vertical shaft to which the chart drum is firmly secured vertically. The gauge element consists of a float and counterweight-graduated float. Digital automatic stage-level recorder (Thalimedes) is a float operated shaft encoder with digital data logger which can be used to continuously monitor the runoff from the watershed/field. It is easy to handle and its cost-effective ratio makes it an appropriate device for modernization of existing mechanical chart-operated stage-level recorder monitoring stations. It eliminates all the problems associated with the mechanical chart type such as the problems associated with the movement of chart, and drying/clogging/blotting of pen in the chart paper. The continuous recording of water levels ensures an uninterrupted measurement in changes of water level over a long period which in turn yields a reliable database for competent decisions. The well over which the stage-level recorder is installed is essentially a stilling well. Inside it the float and counterweight of the recorder rise and fall in response to fluctuations in the water level without being affected by surges or waves that might result in inaccurate measurements. The connection between the stilling well and the precalibrated structure is accomplished by means of intake pipes. These intakes can be one or more galvanized pipes or several 2.5-cm diameter holes.

Multi-slot divisors: are generally used as standard devices for measuring runoff volume and soil loss from hilly watersheds (Ullah et al. 1972). The divisor consists of a number of slots of equal dimensions fitted at the end of a divisor box. The device is based on the principle that a uniform horizontal velocity of approach will be maintained in the divisor box throughout the entire head variations, to obtain equal division of flow and sediments. Any variation in the velocity distribution is likely to result in unequal division of flow, which in turn will introduce varying degrees of error in measurement. Water passing out from one of the slots is led into a collecting drum and measured. Water from the remaining slots is allowed to drain away. The device is generally useful for low discharge rates and has some advantages: it is simple in design and operation; there is no risk of mechanical failure; data processing is relatively simple; and it can measure both runoff and soil loss. But its use is limited to the determination of total runoff volume and soil loss only, so it is little used in research where detailed information is required on variations with time in runoff and soil loss.

Coshocton wheel samplers: This sampler obtains a proportional sample of runoff water, has one moving part, is simple to maintain, and requires no electric power. The Coshocton Wheel eliminates the need to alternatively obtain and analyze in the laboratory several samples obtained throughout the hydrograph, and eliminates subsequent problems with interpretation of such data.

Current meters: Quick stream flow measuring is best done with a water current meter to measure water current velocity. Stream flow measuring is easily accomplished using a water current meter and a tape measure. The current velocity meter allows to measure stream flow velocity in feet or meters per second and measure water depth in hundredths of a foot up to three feet. The average stream flow velocity times the cross-sectional area of the stream determines the stream flow measurement in cubic feet or meters per second. The water current meter offers two unique methods for determining average water velocity: 1) For small stream flows and pipes, the current velocity meter may be moved smoothly and uniformly throughout the stream flow profile until a steady average reading is displayed. This steady reading is the true average velocity for the stream flow. 2) For larger streams, the current velocity meter may be used to measure a vertical profile of water velocity at several points across a stream channel. The stream flow measurement for the profile is the sum of the average velocity of each subsection of stream flow times its cross-sectional area.

Throughfall & Stem flow

Throughfall is the process which describes how wet leaves shed excess water onto the ground surfac.Rates of throughfall are higher in areas of forest where the leaves are broad-leaved, this is because the flat leaves allow water to collect. Rates of throughfall are lower in coniferous forests as conifers can only hold individual droplets of water on their needles throughfall can be measured by small raingauges/cans are kept on the shade of the vegetation as shown in Fig 2. Stemflow is the flow of water down the trunk or stem of a plant. In tropical rainforests, where this kind of flow can be substantial, erosion gulleys can form at the base of the trunk. However in more temperate climates stemflow levels are low and have little erosional power.Stem flow is measured by cutting the small portion of the stem and drain the water to tank by pipe a pipe as shown in Fig 1.

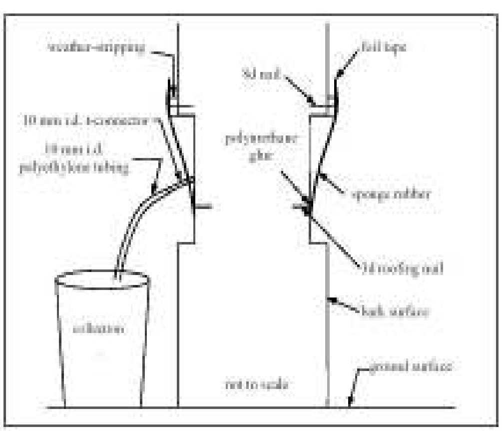

Fig. 1 Stem flow measurement


Fig.2 Throughfall measurement

Evapotranspiration(ET)

It is the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET). Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface (vapour removal). Transpiration is the process by which water in the soil is transferred to the atmosphere by plants as water vapour. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. ET measurement is needed for rational utilization of water resources of a watershed. It is not easy to measure. Various Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. Various methods for ET measurement are lysimeter, field experiment plots, soil moisture studies, pan evaporation method. In lysimeter experiments, the crop under study is grown in large tanks. ET is determined by weighing tha tanks at desired time intervals and observing the difference in weight. Evaporation from an open water surface provides an index of the integrated effect of radiation, air temperature, air humidity and wind. Evaporation measurements are commonly made by using pan evaporimeters. The pan has proved its practical value and has been used successfully to estimate reference evapotranspiration by observing the evaporation loss from a water surface and applying empirical coefficients to relate pan evaporation to ET_o(FAO, 56).

Infiltration

Infiltration is the entry of water in to the soil surface. The measure of infiltration of water into the soil is an important indication concerning: the efficiency of irrigation and drainage, optimizing the availability of water for plants, improving the yield of crops and minimizing erosion. The double ring infiltrometer is a simple instrument that is used to determine the rate of infiltration of water into the soil. The rate of infiltration is determined as the amount of water per surface area and time unit that penetrates the soil. This rate can be calculated on the basis of the measuring results and the Law of Darcy. The standard set of the double ring infiltrometer consists of a number of sets of stainless steel rings with different diameters. Several measurements can be executed simultaneously, yielding a very reliable and accurate mean result. As vertically infiltrated water runs away to the sides, the outer ring of the infiltrometer serves as a separation. The measurements exclusively take place in the inner ring through which the water runs virtually vertical. To achieve good measuring results it is important to take into account several factors that may influence the measurement: the surface vegetation, the extent to which the soil has been compacted, the soil moisture content and the soil layers (strata). The best measuring results are obtained at 'field capacity' of the soil.

In India, watershed management projects have been handled by different Central & state Govt. Depts., organizations and NGOs. In all these projects various hydrological processes has been monitoring on particular purposes. Realizing the importance of hydrological monitoring and gaps in understanding small watershed hydrology in Indian catchments due to paucity of data, the coordinated program on "Hydrology of small watershed" has been launched by Department of Science and Technology, Government of India. The objectives of this programme are

1. To generate data on hydro-meteorological, soil, nutrients and process related parameters at small watershed level in different agro-ecological zones of the country through instrumentation.
2. To carry out modeling studies on watershed hydrology.
3. To develop SDSS for land and water management at small watershed scale.
4. To assess the impact of on-site and off-site management structures for soil and water conservation

Hydrological Modeling

Modeling and simulation approaches have been used in a wide variety of hydrological problems. The Fig. 3 shows various components of watershed based hydrological model. Model is the simplification of reality and it is representation of real world phenomena. The purposes of modeling are: 1) to reduce a complex system to its essential processes, so that system behavior may be simulated under different conditions 2) to reduce time and resources (money, labour, energy). Different types of models such as mathematical models statistical models, simulation models, physical models, computer models, empirical model, GIS based information systems, decision support systems, expert systems has been developed in hydrology for predicting various hydrological processes for management of natural resources on watershed basis. The various hydrological models are explained below.

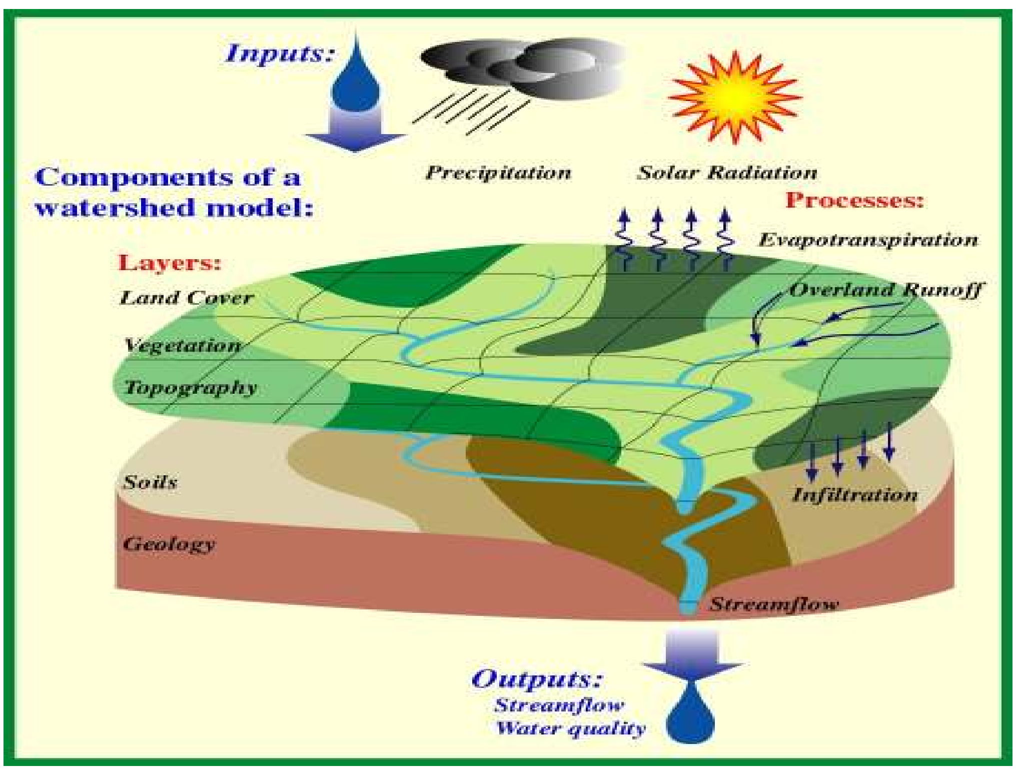

Fig.3 Watershed based hydrological model

Runoff Models

The design of any soil and water conservation structures is to be based on a scientific understanding of the process of runoff generation and a quantitative estimate of the runoff. There is also necessity to estimate runoff from hill slope areas for implementing several soil and water conservation programmes, water resource assessment, development and management. Several complex models are available for predicting runoff, but they require exhaustive input parameters.

(USDA-SCS) Curve Number method: It is most widely used for estimating runoff from agricultural watersheds, not only because of its simplicity but also due to easy availability of input The SCS now renamed as National Resource Conservation Service (NRCS) developed an index, which is called the Runoff Curve Number to represent the combined hydrologic effect of soil, land use and agricultural land treatments. The relationship between rainfall and runoff for these conditions is expressed through Curve Number. Basically, this method was developed for estimating runoff resulting from individual storms.

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

Where,

Q = Direct runoff

S = Potential maximum retention

P = Rainfall

I_a = Initial abstraction

The initial abstraction consists mainly of interception, infiltration and surface storage, which occur over the watershed before runoff begins. The relation between I_a and S was developed by means of rainfall and runoff data from experimental small watersheds (SCS, USDA, 1972) as $I_a = 0.2S$. Substituting this, final equation becomes

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for } P > 0.2S; \quad = 0 \text{ for } P \leq 0.2S$$

The retention parameter (S) is related to parameter (CN) is given by

$$CN = \frac{25400}{254 + S}$$

UDSA-SCS Curve Number method was modified for runoff estimation from daily and weekly rainfall data against individual storm data. This modification reveal that, to achieve a fairly close agreement between the observed and CN estimated runoff for 24-hr and 48-hr total rainfall selected standard CN are to be reduced by 5 and 9 respectively.(Rao *et al*., 2002). CN method was also investigated for runoff estimation from hilly watersheds. This investigation concluded that curve number method for runoff estimation when applied to hilly micro watersheds would lead to underestimation of runoff. The under estimation of runoff by Curve Number method is due to the several reasons, these reasons could be steep slope of the watersheds, heavy rainfall etc. Therefore, if one wants to use USDA-NRCS Curve Number method for realistic runoff estimation from hilly micro watersheds, there should be some modification in original USDA-NRCS Curve Number method with incorporating slope factor, rainfall intensity component, and AMC level(Rao, 2005).

Conservation factor (CF) method: was developed for runoff estimation from small hilly watersheds (Singh, 1995) The conservation factor (CF) over a watershed is given by following equation.

$$CF = \frac{A_1\,(NL_1+NC_1+NS_1)+\text{-----------}A_n\,(NL_n+NC_n+NS_n)}{A}$$

Where, A_1------------- A_n = watershed areas under various land uses, ha.

NL_1 ----------NL_n = assigned numbers to various land uses.

NC_1 ---------NC_n = assigned numbers to various conservation measures.

NS_1 ----------NS_n = assigned numbers to various soil type.

Nine land uses that are common in the country were considered in modeling process. Based on the hydrological information available, these land uses were listed and assigned numbers, which varies from 5 to 80 (table 1). The conservation measures have varied effect on the water yield dynamics and accordingly, were listed and assigned discrete number from 10 to 80 (table). The six major soil types are also taken in to consideration for hydrological studies of soil and water conservation activities of watershed. Based up on infiltration characteristics of these soil types their impact on water yield was also assessed and used. Accordingly, soil type was listed and assigned number from 10 to 40 (table 1).

Table 1: The assigned numerical values (ANV) to various watershed parameters.

Land Use	ANV	SWCE Measures	ANV	Soil Type	ANV
Degraded land	5	No measures	10	Clay	10
Waste / fallow land	10	Bunding, Contour	50	Clay	15
Development work	20	& Vegetative bunding		Loam	
Agriculture	30	Half moon terracing,	60	Silt	25
Horticulture	40	Terracing & Trenching		Loam	
Agro-forestry	55	Terracing & Gabbian	70	Silty	30
Pasture	60	Structure		Sandy	35
Secondary forest	70	Check dam, Quarry	80	Loam	
Virgin Forest	80	& Mines		Sandy	40

Rational Method: Peak rate runoff of a watershed can be calculated using this method

$$Q_P = CIA/360$$

Where, Q_P = Peak runoff rate, m^3/s , C = runoff coefficient , I =rainfall intensity (mm/h) for a duration equal to time of concentration and for a given recurrence interval, A=watershed area, hectare.

There are several empirical relations are available for computing the time of concentration, Kirpich (1940) developed an equation for computing the T_C on the basis of channel length and its average slope. The equation is given as

$$T_C = 0.0195\, L^{0.77}.S^{-0.385}$$ Where, T_C= time of concentration, minutes

Initial abstractions models: Initial abstractions are stem flow, through fall, depression storage, detention storage etc. several models has been developed for predicting these losses. The relationship between throughfall and rainfall is expressed by the following equation.

Throughfall = 0.8934 × Rainfall – 0.7499 (R^2 = 0.98)
Throughfall = 0.9107 × Rainfall intensity + 1.2075 (R^2 = 0.64)

Computer models (software) for predicting various hydrological processes

Several softwares has been developed for estimating various hydrological process such as runoff, evapotranspiration, infiltration, initial abstractions, ground water flow and soil loss etc

WEEP (water erosion prediction project) model: The USDA Water Erosion Prediction Project erosion model represents a new generation technology for estimating runoff, soil erosion on and sediment delivery from hill slope profiles and small watersheds(Arnold *et. al.,*1998) The WEPP computer program calculates spatial and temporal distributions of soil loss, as well as sediment delivery and sediment particle characteristics. Also included as part of the WEPP erosion prediction system are user interface programs, input file building programs, a climate database, a soil database, a crop parameter database, and a tillage implement database. These additional programs and databases make the WEPP model a very powerful tool for users involved in natural resource conservation and environmental assessment. Water Erosion Prediction Project Model (WEPP) was applied to simulate runoff and soil loss from different land-use systems on hill slope. It was found that the model simulated the said parameter with reasonable accuracy (80-86% model efficiency). Simulation results showed that among the food crops, maize inter-cropped with soybean yielded minimum soil loss (14.48 t/ha/yr) as compared to other crops

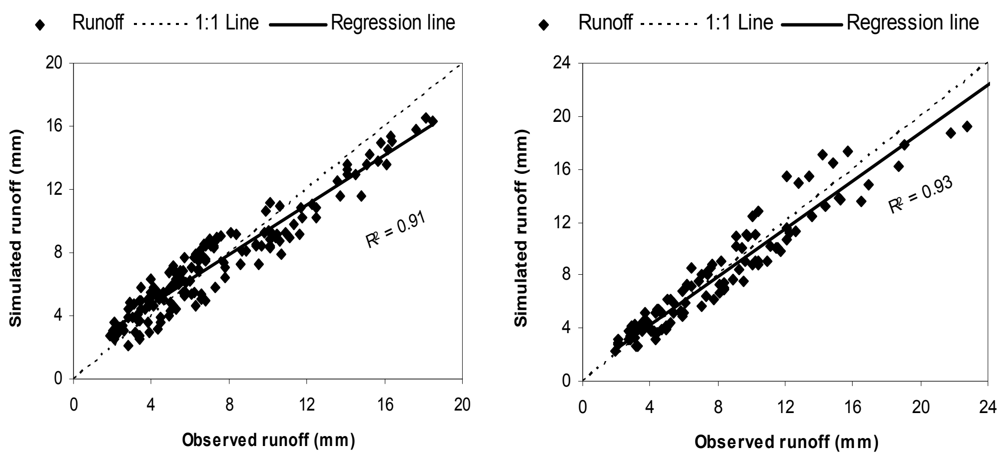

Fig 4. Observed and simulated runoff from cropped plots for (a) model calibration and (b) model validation

EPIC (Erosion productivity impact calculator): EPICis a continuous simulation model that has been used to examine long-term effects of various components of soil erosion on crop production (Williams et al., 1984). The model is used to examine soil erosion, economic factors, hydrologic patterns, weather effects, nutrients, plant growth dynamics, and crop management. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. The model requires input from GIS layers. These include soil series and weather data, although the model can generate the necessary weather parameters. In the calculations for surface runoff, runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number technique. There are two options for estimating the peak runoff rate—the modified rational formula and the SCS TR-55 method.

SWAT ***(Soil & Water Assessment Tool)*****:** The main objectives of this model are 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. The model components are weather, surface runoff, return flow, percolation, ET, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, water transfer.

CRIWAR calculates the crop irrigation water requirements, either per month or per 10-day period, of a cropping pattern in an irrigated area, for various stages of crop development throughout the crops' growing season. Application of the model can assist irrigation engineers to maintain soil water content at a level that will not limit plant growth and crop yield. The crop irrigation water requirement were estimated by Penman-Monteith Method.

CROPWAT is a decision support system developed by the Land and Water Development Division of FAO for planning and management of irrigation. CROPWAT is meant as a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements and crop irrigation requirements, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rainfed conditions or deficit irrigation.Procedures for calculation of the crop water requirements and irrigation requirements are based on methodologies presented in FAO Irrigation and Drainage Papers No. 24, 56.

CWREDSS A decision support system for canal water releases will determine the crop evapotranspiration, total crop water requirement, effective rainfall, and irrigation water requirement of crops(Rao,2005). This system will also determine the seepage losses in the canals, ground water use, canal water demands at head of the canal and finally will develop canal water releases by accounting water demands and canal capacity.

GIS Interface models: Geographic information systems (GIS) offer a unique opportunity to generate otherwise difficult-to-obtain data that can be utilized in various models of natural processes that occur throughout large areas of landscape. It can perform some of the mathematical operations of the existing models using spatial data processing algorithms and can help test the models' effectiveness for describing and predicting the actual situation. Watershed runoff and sediment yield were estimated by using a GIS interface models to Curve Number and MUSLE models. A relatively simple GIS procedure can be used to generate input and output data for the Modified Universal Soil Loss Equation (MUSLE) model to calculate sediment yield. Runoff was estimated by GIS - CN interface model.

GIS based decision support systems for watershed management: These models will help in prioritization of watersheds, planning and implementing various watershed treatment measures. A framework of GIS based decision support systems for watershed management is explained below:

Decision type A: Area selection for schemes

A.1 Which are priority watersheds for intervention by various line departments?

A.1.1 Within a priority watershed, which sub-watersheds should be treated first?
A.2 Where, within a sub-watershed, is the hotspots requiring interventions?
Decision type B: Site selection for infrastructure
B.1 Where should small-scale conservation infrastructure be built?
B.2 Where should water resources infrastructure be built?
Decision type C: Land evaluation for changes in land use
C.1 Land use options which will yield immediate benefit to the land user (*economic options*)
C.2 Land use changes which may yield economic benefits only over the longer term but which increase the sustainability of the land use system (*conservation options*)
C.3 Changes of practice that can be accommodated easily within the existing farming system (*easily implementable options*)
C.4 Land Use options that require a major change in the farming system, or resources

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