Use of High Science Tools in Integrated Watershed Management

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New Tools for Monitoring and Modeling Hydrological Processes in Small Agricultural Watersheds

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Introduction

Integrated watershed management is regarded as the most appropriate strategy to rehabilitate fragile ecosystems and improve the livelihoods of people living in rain-fed areas. The rural people living in such areas are under constant threat of low yields, unemployment and consequently poor living conditions. Effective watershed management can substantially reduce risks, make water for drinking and cultivation available in an equitable manner, increase farm productivity and raise income through a host of auxiliary activities. The comprehensive assessments of watershed programs in India by ICRISAT-led Consortium has shown that considerable improvement in the performance of watershed program can be achieved through scientific planning, management and evaluation of watershed projects. The new common guidelines for watershed development projects (GoI, 2008) also emphasizes using scientific data and new science tools to bring about paradigm shift in the different aspects of watershed programs.

The information on runoff volume, peak runoff rate, soil loss and other related parameters are essential for the proper planning and development of both in-situ and ex-situ soil and water management interventions. However, the adequate availability of the watershed scale hydrological data is scanty in most regions of India. This resulted in higher watershed development costs and often failure of the runoff harvesting and soil conservation structures. There are several reasons for unavailability of adequate hydrological data from the small agricultural watersheds. One such reason is unavailability of good standard equipments for monitoring soil loss from such small watersheds (50-5000 ha).

ICRISAT along with its partners have developed a range of new equipment for monitoring runoff and soil loss and hydrological models, which can be used on small agricultural watersheds. Some of these equipment and hydrological models are discussed in this paper. The salient features of these runoff and soil loss monitoring equipment in terms of accuracy, reliability, and cost effectiveness are also covered. The use of hydrological models in generating required information for proper planning and impact assessment of watershed programs and their key features in term of input data requirements, accuracy and output are also described.

Soil Loss Measurement from Agricultural Watersheds

The monitoring of soil loss and sediment flow from the small agricultural watersheds is a complex and difficult task. There are very few standard types of equipment available in the market, which can be used for measuring the soil loss from the small agricultural watersheds. Some of the serious problem with commonly used method and some new developments (Pathak and Sudi 2004), which has been made at ICRISAT Center for monitoring soil loss and sediment flow from the small agricultural watersheds are discussed below.

Manual Sampling

In India, manual sampling is still the most commonly used method for monitoring sediment flow from the small agricultural watersheds. However, there are some serious problems with this method. The extreme variation in sediment concentration during the runoff events makes this method totally inappropriate for monitoring sediment from small agricultural watersheds (Fig. 1).

Due to this extreme variations in sediment concentration the expected error in estimating the soil loss could be extremely high and are often found in the range of $\pm$ 30 to 420% that of actual soil loss. Also operationally it is very difficult to collect the runoff samples at the right time particularly during high rainfall events. This makes the data collected by manual method highly unreliable and often useless. Therefore the manual method of runoff sampling is not recommended for monitoring soil loss from the small agricultural watersheds.

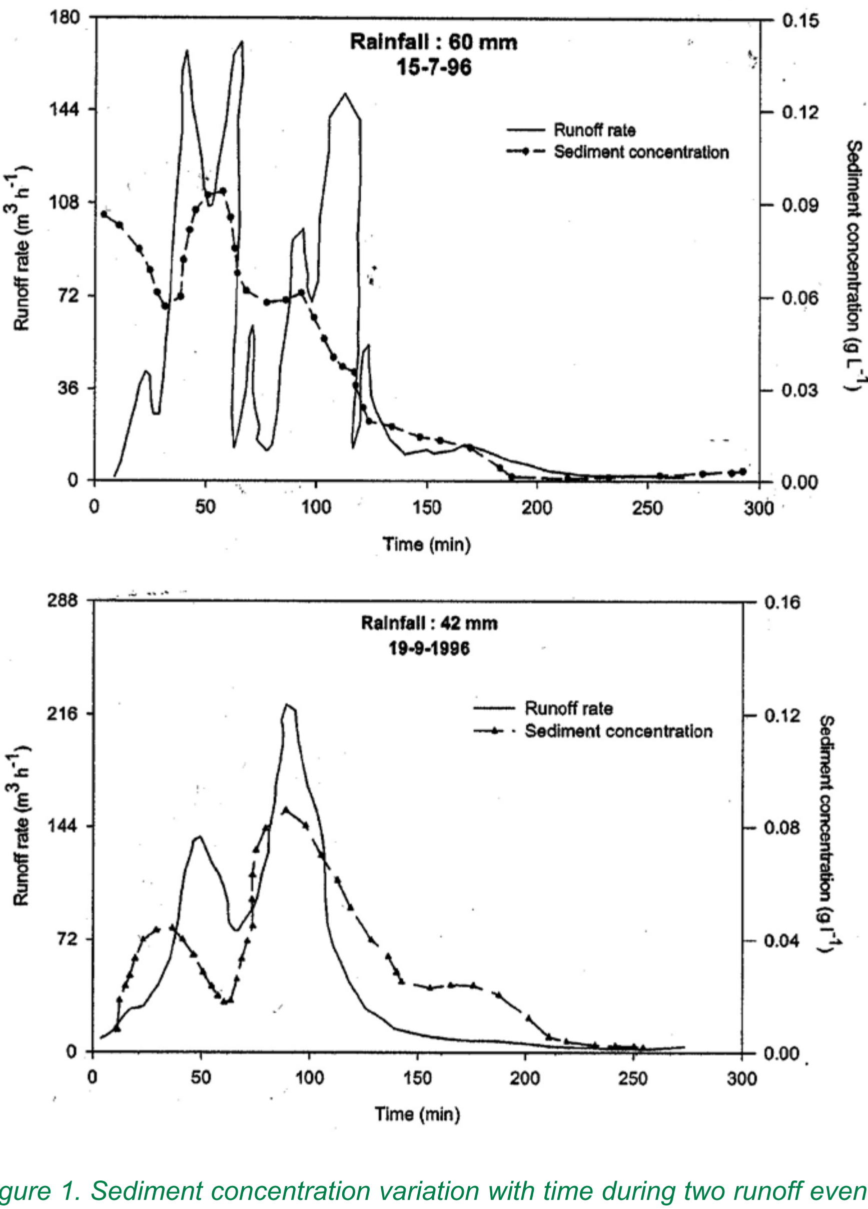


Figure 1. Sediment concentration variation with time during two runoff events at BW7 watershed, ICRISAT Center, Pantancheru, Andhra Pradesh, India (Pathak et al. 2004)

Sediment Samplers

Clock-based automatic sediment sampler

A clock-based automatic sediment sampler was developed at ICRISAT to monitor soil loss from small agricultural watersheds (Fig. 2). The sampler consists of a clock located at the center of a circular channel of 40 cm diameter. The channel is about 2.5 cm wide and 2.5 cm high with 50 small vertical independent partitions. An arm is fixed to the clock and this arm turns in a circle directly over the channel. Using a flexible plastic pipe, the runoff sample is led to the partitions in the circular channel. Each partition has a small pipe connected to the base of the chamber that carries the runoff sample to labeled bottle attached at a somewhat lower level. Once the samples are collected, they are related to the runoff hydrograph.

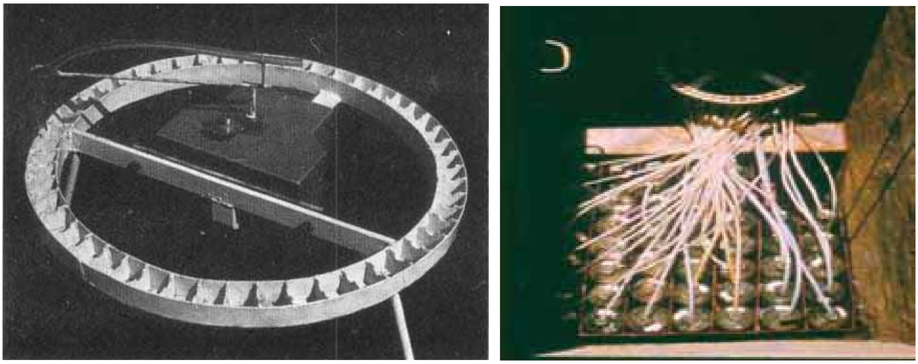


Figure 2. Clock-based automatic sediment sampler for small agricultural watersheds

Depth integrating sediment sampler

A simple depth integrating sediment sampler had been developed (Pathak et al. 1991) for monitoring sediment flow from the small agricultural watersheds (Fig. 3). This sampler has no moving parts and easy to fabricate and install. The working principle and details are given below.

Working principle and details: To simplify the design of the runoff sampler, momentary or instantaneous fluctuations in sediment

Figure 3. Depth integrating sediment sampler for small agricultural watersheds

concentration across a flow section are avoided. This is done by selecting the sampling site near the high-turbulence downstream point where the sediment variation across the flow section is minimized. The rapidly fluctuating nature of runoff flow from small watersheds, and its relation with time, is used in the sampler to account for the time variation in sediment loads (Pathak 1991). This is achieved by taking representative samples for different hydrograph segments and by collecting samples at different flow depths. The samples are taken through small-diameter pipes which are set at specified heights from the bed of the channel (Fig. 4), and are connected to separate containers by plastic pipes.

The working principle of the sampler is explained in Figure 5 in the form of a single-peak runoff hydrograph. The lowest pipe samples the sediment throughout the total runoff period, while the upper pipes, depending upon their relative positions, sample for shorter periods. The sample volume and sediment concentration for each container are determined individually and hydrograph data are recorded at each sampling point. The actual sediment concentrations for the different

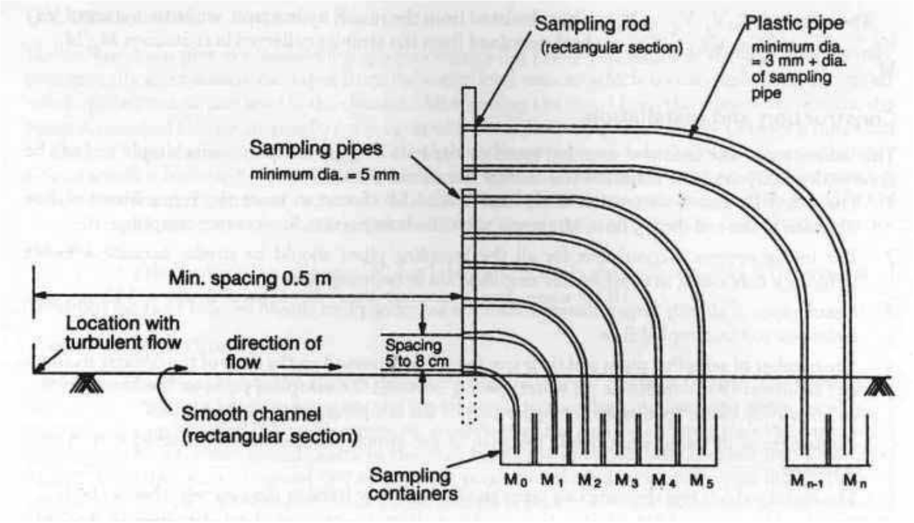


Figure 4. Schematic diagram of the depth integrating sediment sampler

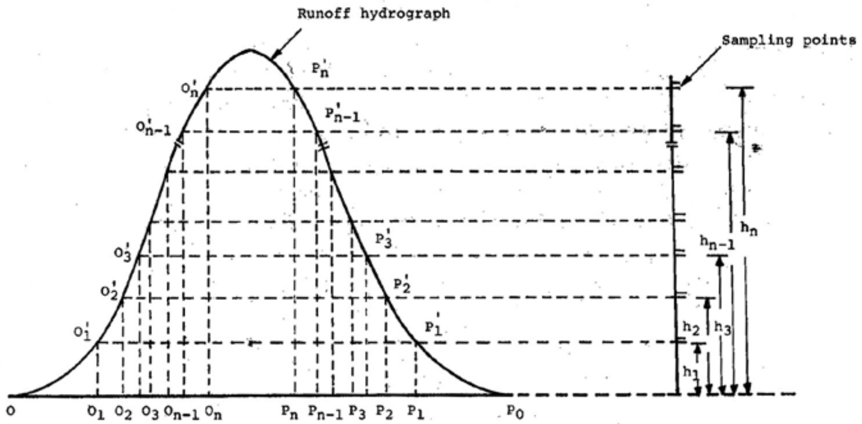


Figure 5. Working principle of the sediment sampler

hydrograph segments and total soil loss are calculated by using the following equation:

$$St = V_0 (Vs_0 Cs_0 - Vs_1 Cs_1) / (Vs_0 - Vs_1) + V_1 (Vs_1 Cs_1 - Vs_2 Cs_2) / (Vs_1 - Vs_2) + V_{n-1}(Vs_{n-1} Cs_{n-1} - Vs_n Cs_n) / (Vs_{n-1} - Vs_n) + V_n Cs_n$$

where $Vs_0, Vs_1, Vs_2, ..., Vs_n$ and $Cs_0, Cs_1, Cs_2, ..., Cs_n$ are the volumes and sediment concentrations of the runoff samples collected in the containers $M_0, M_1, M_2, ..., M_n$, respectively

The $V_0, V_1, V_2, ..., V_{n-1}, V_n$ are the runoff flow volumes for the hydrograph segments, $OO'_1O_1 + P_1P'_1P_0$, $O_1O'_1O'_2O_2 + P_2P'_2P'_1P_1$, $O_2O'_2O'_3O_3 + P_3P'_3P'_2P_2$, ..., $O_{n-1} O'_{n-1}O'_nO_n + P_nP'_nP'_{n-1}P_{n-1}$, $O_nO'_nP'_nP_n$.

The values of $V_0, V_1, V_2, ..., V_n$ can be calculated from the runoff hydrograph, while the values of $Vs_0, Vs_1, ..., Vs_n$ and $Cs_0, Cs_1, ..., Cs_n$ can be determined from the samples collected in containers $M_0, M_1, ..., M_n$.

However, the sediment sampler has few limitations and these include:

- it is not efficient where the eroded sediments contain a high proportion of coarse sands;
- for storms having multiple peaks (more than two) its accuracy to estimate soil loss is low;
- this sampler is useful only for small watersheds (upto 1000 ha).

Microprocessor-based Automatic Sediment Sampler

The Microprocessor-based Automatic Sediment Sampler can be used to measure soil loss as well as temporal changes in sediment movements during the runoff hydrographs from the agricultural watersheds/plots. At ICRISAT a micro-processor based automatic sediment sampler (Fig. 6) has been developed for small agricultural watersheds (Pathak and Sudi 2004).

This sediment sampler consists of circular sample collection unit fitted with DC shunt motor and bottles, microprocessor-based control unit, 12v 55 Amph battery, bilge submergible pump, water level sensors, and solar panel (optional for recharging 12v battery)

Figure 6. Microprocessor based automatic sediment sampler.

Theory of operation and other details of sediment sampler: Under idle conditions the entire system draws a minimum current of about 60 mA. The uninterrupt program enabled it to keep scanning for the runoff water in the channel. The microprocessor-based control unit, which when initialized by the water level sensors, operates the system, first by purging the pipe to clean off the old water sample, positions the nozzle on sample hole and then pumps the sample water into a bottle and positions the nozzle on to the next purge hole. The pump is kept in the channel, completely immersed in the flowing water. About 750 ml of runoff water is pumped into each bottle.

The microprocessor-based control unit: The microprocessor-based control unit controls the pump and motor of the sediment sampler automatically after sensing the input from the water level sensors that are energized when the runoff water reaches to a certain level in the channel/drain.

There are two types of control units viz. (1) single level sensor control unit, and (2) multiple level sensor control unit (Fig. 7). The multiple level

Single level sensor *Multiple level sensor*

Figure 7. Single and multiple level sensors of control unit

sensor control unit having four or more level sensors also performs the operation in the similar fashion. In order to attain higher accuracy, during sampling the sampling periods are shortened in accordance with the new sensors. When the L1 and positive sensors come in contact with water the logic level is “0”. With the addition of a new sensor the sampler switches over to a new sampling period that is half of the previous sampling period. For example, if the initially selected interval (L1) is 40-min then the three different levels L2, L3, and L4 gives new sampling periods of 20-min, 10-min and 5-min, respectively.

Salient features of the sediment sampler

- Fully automatic runoff samples collection
- Samples can be collected at required time interval (15, 30, 60 and 120 minutes or any desired time intervals) as well as at required flow depths
- Can be used for soil loss estimation as well as temporal distribution of sediments during runoff hydrographs
- The 8748 microprocessor-based controller is used which can be reprogrammed easily
- Suitable even for the remotely located gauging station as well as small to medium size watersheds (1-5000 ha)
- Accurate and reliable data acquisition
- Simple and easy to operate
- Efficient and cost-effective

Runoff Measurement from Small Agricultural Watersheds

Accurate determination of runoff volume, peak runoff rate, and other related information from small and medium areas invariably requires the continuous recording of the water level. Stage-level recorders are commonly used for this purpose. Many types of stage-level recorders are commercially available. They can be broadly classified into two types: mechanical type and digital type stage-level recorders.

Mechanical Stage-level Recorder

In India, mechanical type runoff recorders are most commonly used for monitoring runoff. 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 (Fig. 8). The gauge element consists of a float and counterweight-graduated float pulley. The movement of the float is transmitted to a cam and, with the help of a set of gears, it moves the pen on the chart in a vertical direction. Some recorders have a reversing mechanism and can therefore record an unlimited range of flow depth (Pathak 1999).

Figure 8. A drum-type mechanical runoff recorder.

There are several operational problems with the mechanical type runoff recorders. The most common problems are related to clock functioning, gear set functioning, pen and its marking on charts. The processing of data from chart is very time consuming and the recorder needs continuous monitoring.

Digital Automatic Stage-level Recorder (Thalimedes)

Thalimedes is a float operated shaft encoder with digital data logger which can be used to continuously monitor the runoff from the watershed/field (Fig. 9). 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 (Pathak 1999).

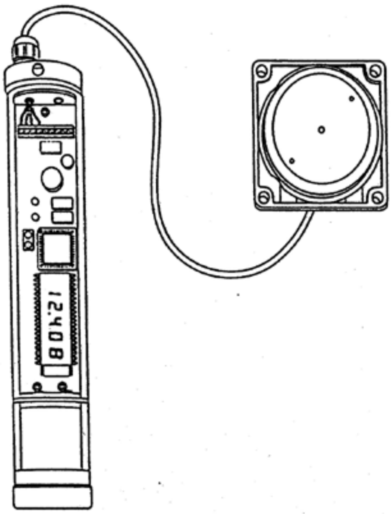


Figure 9. Digital runoff recorder

The in-situ data logging of the measured value results in the reduction of the expenditure of both cost and time as well as in elimination of errors that are brought in when data is readout or transferred manually. It eliminates all the problems associated with the mechanical chart type recorders 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.

Salient features of digital automatic stage-level recorder (Thalimedes) compared to mechanical stage-level recorder are the following

- Thalimedes is a microprocessor-based electronic data logger. Being float operated, the shaft encoder is an ideal stage-level recorder.
- Digital LCD of measured water level (mm, m, or ft), date, time, and battery status (not possible with mechanical models).

- Thalimedes operates on a single 1.5 V DC C type battery, whichlasts up to 15 months at hourly measurement and not possible withmechanical models.
- Ring memory: EEProm stores up to thirty thousand (30000)measured values.
- Sampling and logging intervals can be set from 1 minute to 24 hours (flexibility not possible with mechanical models).
- Data transfer through non-contact IrDA interface (infrared technology) avoiding connectors and cable; 11000 measured values in 4 seconds for further processing.
- No moving parts; problem due to gear/clock and chart mechanism is avoided.
- No switches/connectors; so there are no contact problems.
- Compact, rugged, and light (only 0.32 kg); shaft encoder 0.14 kg.

Integrated Digital Runoff Recorder and Sediment Sampler Device

An Integrated digital runoff recorder and sediment sampler device has been developed by ICRISAT Scientists in collaboration with Farm and Engineering Services at ICRISAT (Fig. 10).

Figure 10. Integrated digital runoff recorder and sediment sampler device (new microprocessor is shown in inset).

The main feature of this new equipment is that all the operations (viz. runoff recording, sediment sampler operation and solar panel controller etc.) are controlled by one single micro-processor unit. The unit can store the data up to 130,000 records in 1 MB flash memory, which has a ring memory system. The complete unit works on a 12 v battery with solar panel to recharge it. Even during the emergency power operation or main battery failure, runoff recording is done with its backup battery. This integrated unit makes the calculation of runoff and soil loss very easy and accurate. It is also very cost effective.

Hydrological Models for Agricultural Watersheds

The hydrological data at the watershed scale are generally not available in most regions of India. The hydrological models can be effectively used to generate such data, which can be used for the planning and design of various watershed interventions. These models can also be used to assess the long-term impact of watershed program on soil and water resources. Some of the hydrological models developed at ICRISAT are discussed below.

Simple Runoff and Water Balance Models

Information on surface runoff is needed in the planning and design of watershed interventions particularly on soil and water management. For example, it is needed in the design of soil conservation structures, runoff harvesting and groundwater recharging structures, drains and other interventions. Runoff models can be used to generate this vital information. Some of the simple hydrological models, which have been developed at ICRISAT for small agricultural watersheds, are described below.

RUNMOD Runoff Model

A parametric simulation model was developed to predict runoff from small agricultural watersheds (Krishna 1979). The input data for it are the daily rainfall amount, storm duration or rainfall intensity, pan evaporation, and soil moisture. By means of a univariate optimization procedure, measured runoff data are used to determine the proportion of rainfall that infiltrates and the part that runs off. Once these parameters are determined for a particular soil and land management treatment, they can be applied directly to other watersheds of similar cover, topography, and moisture storage and transmission properties for predicting runoff and other water balance components. The model embodies upper zone and lower zone soil moisture reservoirs that are depleted by evapotranspiration and recharged by infiltration sequentially from the top. When both reach their capacities, further infiltration causes deep percolation. Daily evapotranspiration is computed from open-pan evaporation, vegetative cover, and the amount of water in the root zone. Hydrologic data from three ICRISAT Vertisol watersheds of similar size, shape, and topography but having different land management treatments were used for deriving and testing the model. Two years of data were used for calibration and the model was tested with data from the third year. In all cases, there was excellent agreement between computed and observed runoff events.

This model can be used on Vertisols for which it has been tested and cablibrated parameters are available. Its performance on other soils is not known. This model's biggest limitation is its parameters, which need to be determined for different soils, different land and water management system and rainfall conditions.

SCS Curve Runoff Model

A runoff model based on a modified SCS curve number technique and on soil moisture accounting procedure was developed for small watersheds in the semi-arid tropics (Pathak et al. 1989). In this model, certain soil characteristics that have strong influence on runoff such as cracking and land smoothing are included. The model uses one day time intervals and needs simple inputs, which are normally available such as: daily rainfall, pan evaporation, canopy cover coefficient, soil depth, initial soil moisture, moisture at wilting point and field capacity. The main outputs are daily runoff volume and soil moisture. The model has four input parameters which are estimated through calibration using measured runoff and soil moisture content data. Once the parameters are determined for a particular soil and land management system, they can be used to predict runoff and soil moisture from other ungauged

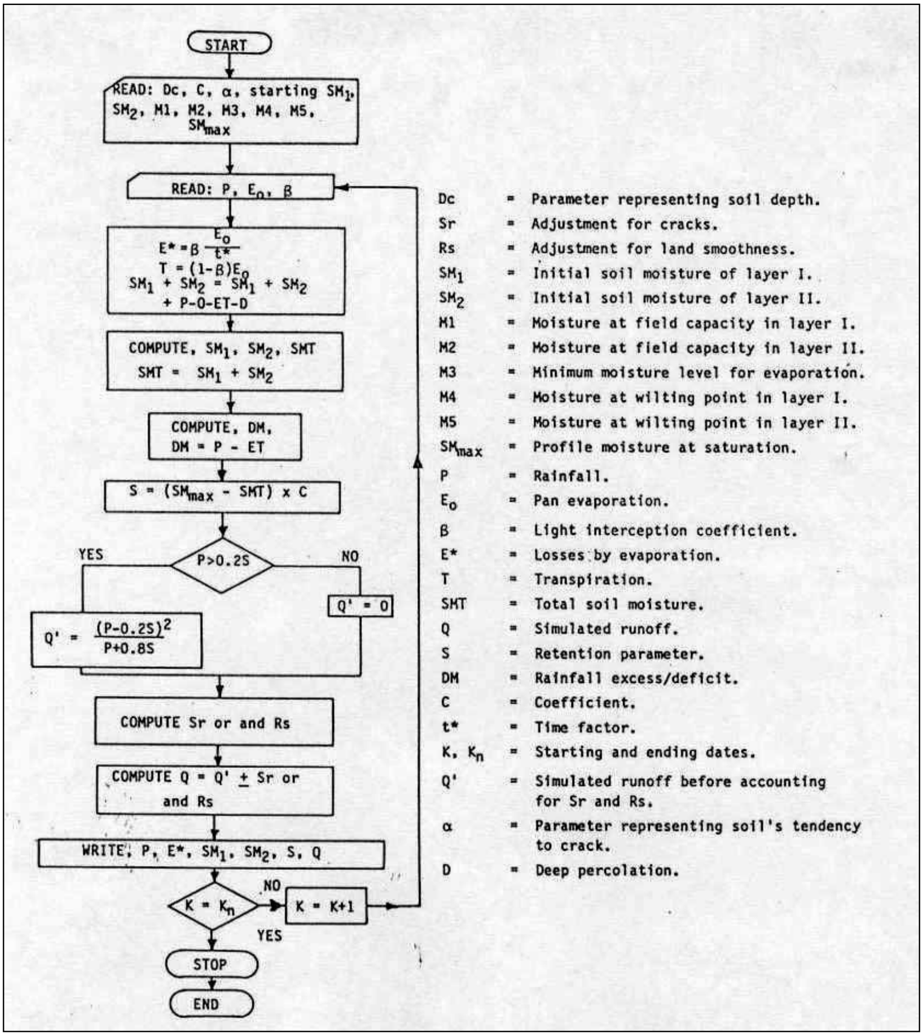
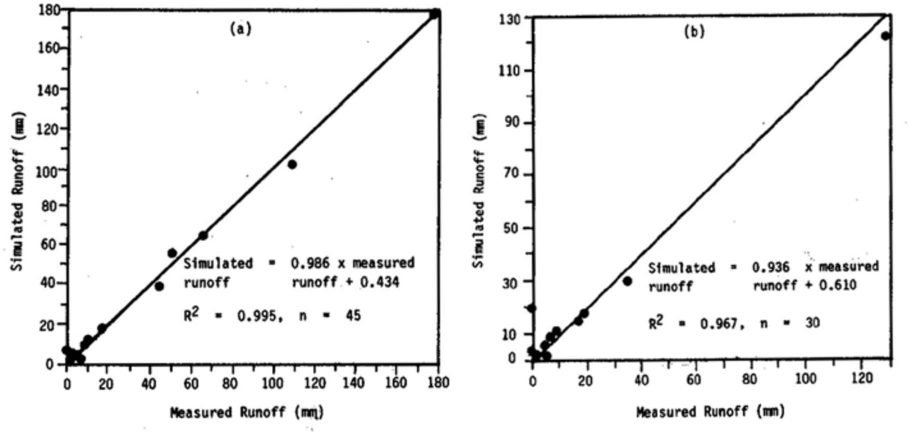


Figure 11. Flow chart of SCS curve runoff model (Pathak et al. 1989).

watersheds with similar soils and management systems. About 10-15 runoff events and daily soil moisture data are sufficient to estimate the parameters of the model. The flow chart of runoff model is shown in Fig. 11.

Tests with data from three small watersheds at ICRISAT Center in India show that the model is capable of simulating daily, monthly, and annual runoff quite accurately (Fig. 12). It is also able to simulate satisfactorily



BW2 watershed BW3A watershed

Figure 12. Runoff model comparison of measured and simulated daily runoff in two Vertisol watersheds at ICRISAT Center, Patancheru, Andhra Pradesh.

the daily moisture. The biggest advantage of this model appears to be its simplicity and accuracy. Also since this model is linked to SCS curve numbers, its use and applicability is quite wide.

Runoff Water Harvesting Models

A runoff cum water harvesting model was developed (Pathak et al. 1989, Ajay Kumar 1991) to simulate the daily runoff, soil moisture and water availability in the tank. The flow chart of the model is shown in Figure 13. This model has main components, the first component predicts the daily runoff and soil moisture and second component calculates the daily water balance in the tank. The basic principles of the water accounting in the tank is shown in Figure 14. This model has been extensively used in different regions of India for calculating various parameters for water harvesting. For example, this model was used to assess the runoff potential from three watersheds in Andhra Pradesh viz. Nandavaram, Sripuram and Kacharam. Hydrological data including daily rainfall and evaporation were used from three watersheds. Probability analysis applied to the results obtained from runoff model. Probabilities of getting 20, 40, 60 and 100 mm of simulated runoff were done based on the 26 years of climatic data (Fig. 15). Input data such as rainfall, evaporation,

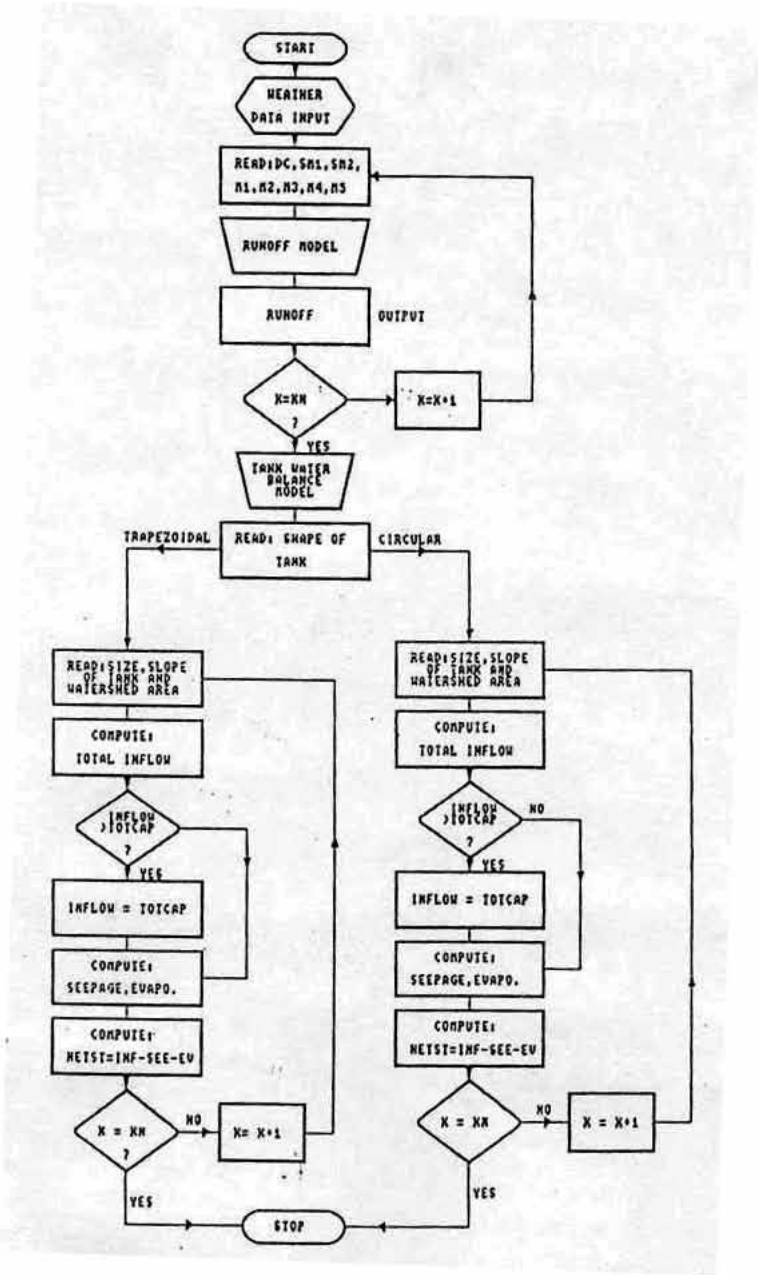


Figure: 13. Flow chart of water harvesting model.

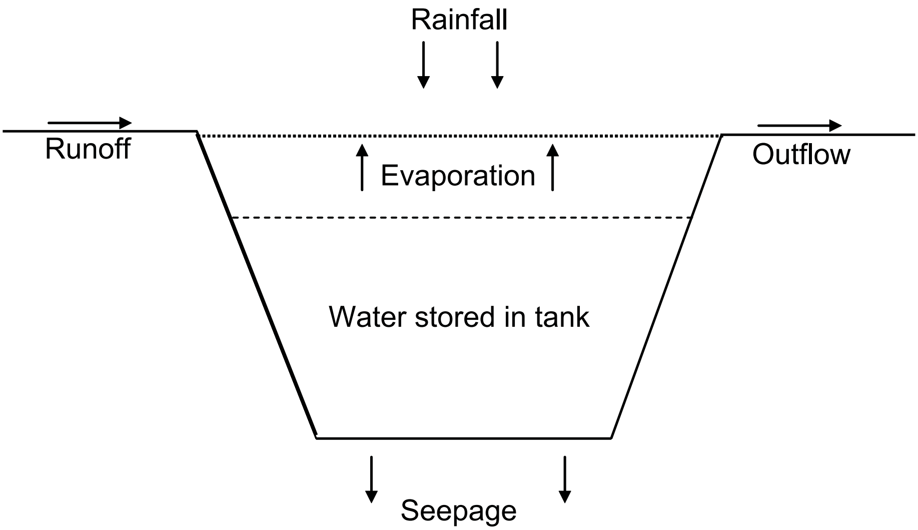


Figure 14. Basic water flow in water harvesting model.

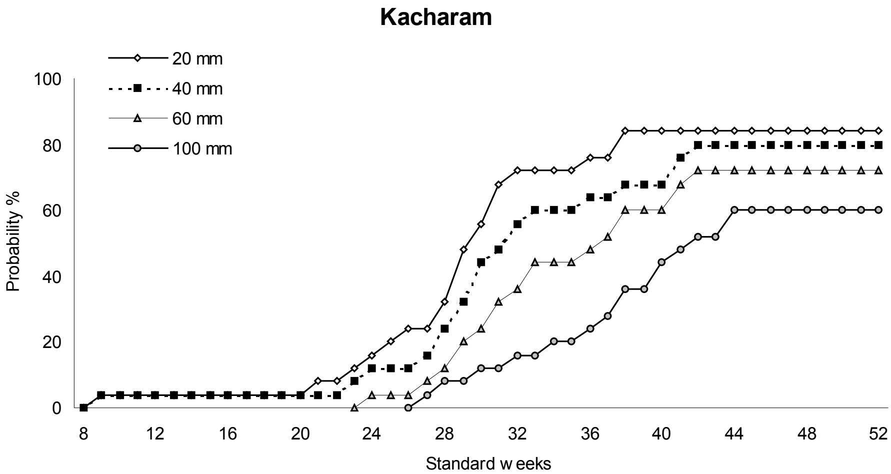


Figure 15. Probabilities of obtaining 20, 40, 60 and 100 mm cumulative runoff in Kacharam watershed (based on 26 years of simulated data).

soil parameters, seepage rate and catchment area were used to runoff water harvesting model (Sireesha 2003).

Considerable information on various aspects of runoff water harvesting could be obtained by using the runoff and water harvesting models.

These models can assess the prospects of runoff water harvesting. It can also be used to estimate the optimum tank size, which is very important for the success of the water harvesting system.

The runoff and water harvesting model can be used for following objectives:

- to assess the prospects of runoff water harvesting and groundwater recharging and its utilization for agriculture,
- to assess the probabilities of getting different amounts of irrigation water in the tank,
- to assess the conditional probabilities of getting different amounts of irrigation water in the tank,
- to find out optimum tank size and other design parameters,
- to develop strategies for scheduling supplemental irrigation.

Digital Terrain Model (DTM)

The automation of terrain analysis and use of digital elevation models (DEM) has made possible to easily quantify the topographic attributes of the landscape and to use topography as one of the major driving variables for many hydrological models. These topographic models, are commonly called as digital terrain models (DTMs). The DTM include the topographic effect on the soil water balance and coupled with a functional soil water balance to spatially simulate the soil water balance. ICRISAT in collaboration with Michigan State University, USA, developed a SALUS-TERRAE, a digital terrain model (Bruno Basso et al., 2000), which can be used at the landscape level. This digital terrain model gives how the terrain affects the vertical and lateral movement of water routing across the landscape. The output of the model is helpful in determining the appropriate management of water resources as well as for identifying the areas across the landscape that are more susceptible for erosion. Few of the outputs from the model are shown in Fig. 16 and 17. These digital terrain models are extremely useful for the watershed programs. However, their major bottleneck is on the accurate availability of topographic data.

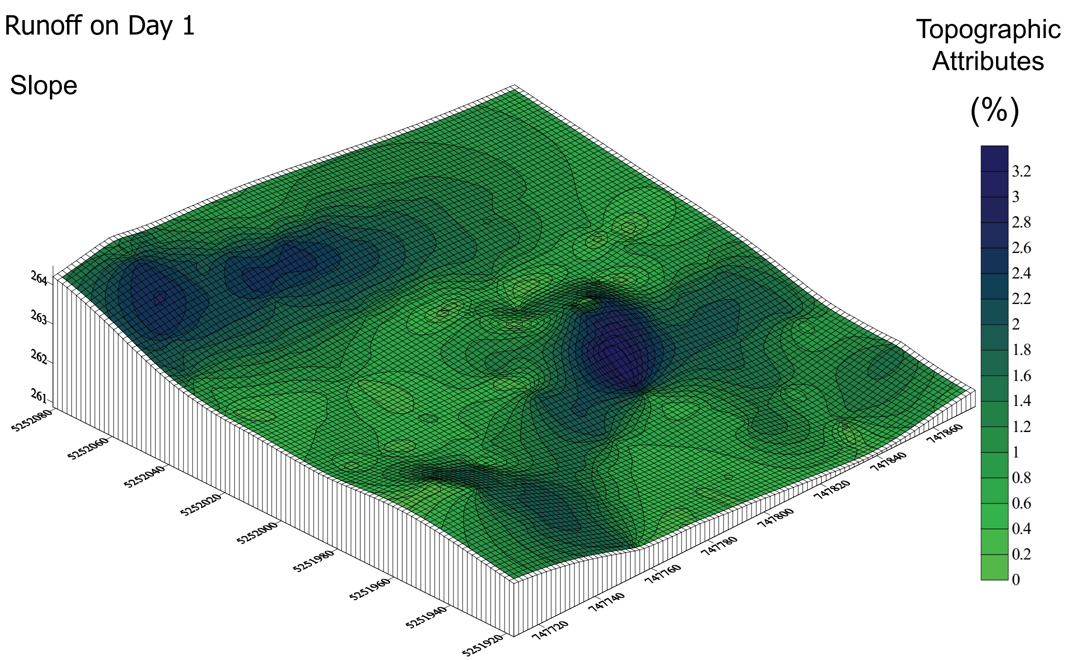


Figure 16. Slope levels in a landscape.

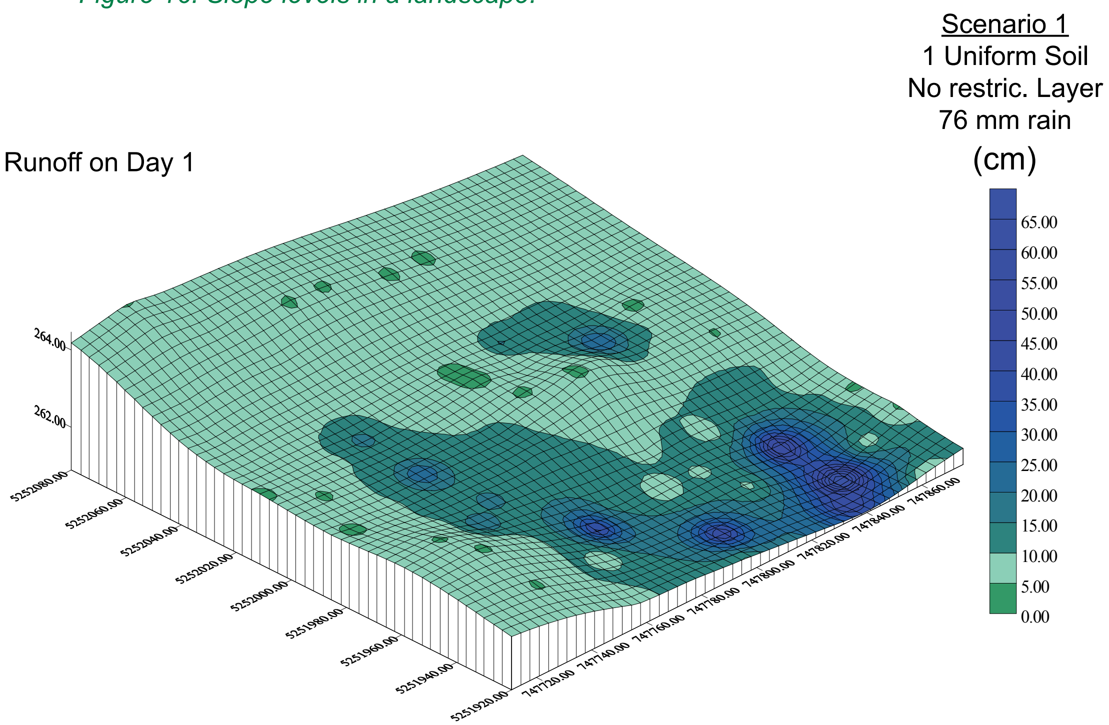


Figure 17. Runoff at day 1 and its ponding at landscape level.

Summary

Watershed development has emerged as a new paradigm for the management of land, water and biomass resources and for improving rural livelihoods. To achieve higher cost effectiveness and greater impact from the watershed programs, its proper planning, development and management based on sound understanding of hydrological processes and data is crucial. In most agro-ecoregions of India, availability of adequate hydrological data at the watersheds scale is lacking. This results in higher development costs, less impact and often failure of the structures and other soil and water management interventions. In this paper, some of the new equipment/tools, which can be used for monitoring runoff and soil loss viz. digital runoff recorder, depth integrating sediment sampler, clock-based automatic sediment sampler and microprocessor-based pumping type sediment sampler are discussed. Some of the key salient features of these equipment in terms of accuracy, reliability and cost effectiveness are also covered. It was found that the most commonly used method of manual sampling is not suitable for estimating soil loss from the small watersheds. This method is found to be highly unreliable and inaccurate. Among the various sediment samplers the microprocessor-based automatic sediment sampler is found to be highly reliable and accurate for monitoring soil loss from small agricultural watersheds. Recently ICRISAT has developed an integrated unit for monitoring runoff and soil loss from the small agricultural watersheds. This integrated unit combines the automatic digital runoff recorder, shaft encoder with microprocessor-based sediment sampler (which includes microprocessor-based control unit, bilge submergible pump, circular sample collection unit fitted with DC shunt motor, battery and solar panel).

Hydrological models are useful for assessing the long-term impact of watershed programs, understanding of complex hydrological processes within the watershed and generating long-term hydrological data for the new areas. In this paper some of the hydrological models developed at ICRISAT, which can be used for small agricultural watersheds are discussed. These include a parametric runoff model "RUNMOD", modified SCS curve number runoff and water balance model, and a runoff water harvesting model. The overall performance

of these models and their key features particularly in terms of input data requirements accuracy and outputs are described. Results have shown that considerable information on the various aspects of runoff water harvesting, groundwater recharging and field-based soil and water management interventions can be obtained by using these models. They can assess the prospects of runoff water harvesting and possible benefits from the irrigation. These models can also be useful to estimate the optimum size of structures and the probability of different amounts of irrigation water in the tank. The information generated from these models can greatly assist in the proper planning, development and management of land and water resources.

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