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SPECIAL ISSUE ON THE ROLE OF SMALL WATERSHED HYDROLOGY IN RAINFED AGRICULTURE

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CENTRAL RESEARCH INSTITUTE FOR DRYLAND AGRICULTURE

HYDERABAD - 500 659, A.P., INDIA

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Watershed water balance methodologies techniques and development research priorities

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ABSTRACT

Water balance technology is a standard hydrologic process based on basic physical principel of conservation of mass. In its application to small watershed, where responses of hydrological processes are quite fast, the proper choice of shorter time base is necessary. Response time being short, many a times only conservation of mass principle is not sufficient to describe the hydrologic phenomenon e.g. runoff process. In this paper an attempt has been made to review various water balance methodologies which are presently in use. For overall watershed water balancing requirement, the lumped parameter method has been found to be mostly in use. Also, several research priority areas have been suggested of which the most important one would be the area of taking national policy decision for monitoring the various sizes of watershed over varying agro-climatic zones and with different cultural practices over long period of time.

Watershed is a physical hydrological unit in which water from all over the area flows under gravity to a common drainage channel. This implies that the outer boundary is the ridge line with system valley lines finally meeting to one channel. The development and management of a watershed from the agricultural and animal husbandry point of view would mean the optimal use of all the available resources within the watershed to maximise the return to the farmers and a better standard of living along with social equality.

Among the resources which are indigenous to the watershed are known as system variables e.g. soil, crop etc., whereas others being added to the system may be called as input variables e. g. water resources i. e. rainfall and ground water table, labour, fertilizer etc. But a single input variable water for a given set of system variables, is the most important one from agricultural production point of view. Thus, in the development of the watershed management plans water resources play the most crucial role, rather whole of the development plan

is centered around water resources of the watershed.

So, for the optimal return to the farmers, water resources should have to be optimally used. This would require to have an assessment of the water resources of the watershed. Such an assessment has to be conducted over space and time for both quantity and quality. This should also reflect the water resource potential of the watershed and its present state of utilization where from the clue for further development of the water resources of the watershed will emerge. But both the assessment procedure and optimal utilization, allocation of the available water resources have to be balanced over time and space. In this paper an attempt has been made to provide a brief account of water balancing technologies that are presently used by the researchers and planners.

THE CONCEPT OF WATER BALANCE

The first step towards the study of water balance of a watershed is to identify the various sources from which the water is available and the different ways by which the water gets disposed, absorbed or stored in the watershed. The qualitative description of the above phenomenon is represented by the hydrologic cycle. Figure 1 shows the conceptual representation of the hydrologic cycle.

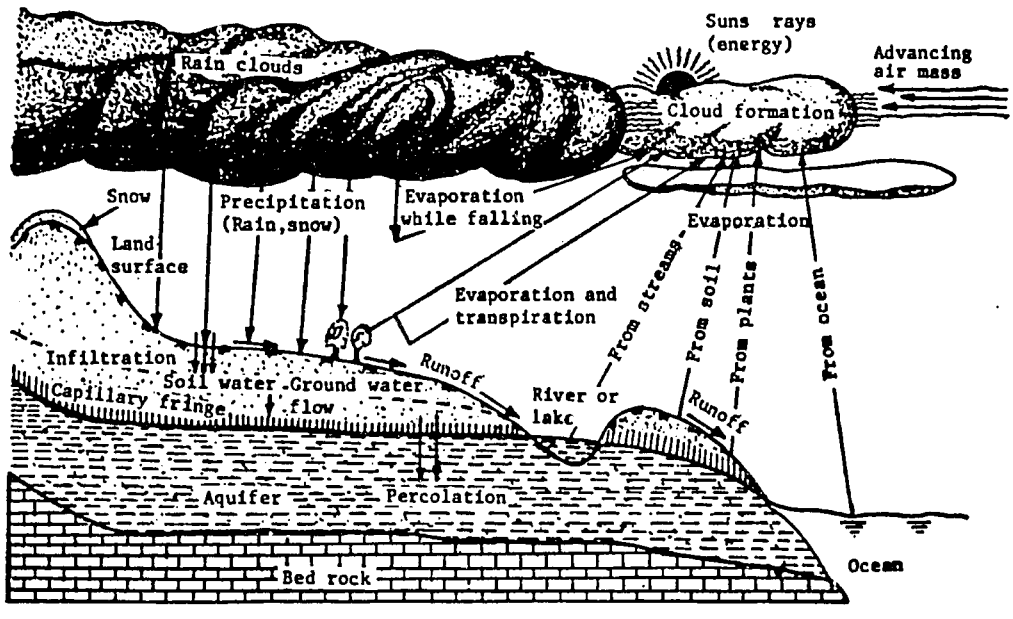

Fig. 1. Schematic diagram illustrating the earth's water cycle—the hydrologic cycle.

The term 'water balance' implies a quantitative accounting of water at different stages of its flow. With respect to a watershed, it would imply a quantitative accounting of water at different stages of its flow over the watershed. This balancing will help us to assess the potential of this resource over space and time and its present state of utilization within a hydrologic boundary.

Quantitative water balance

Water is the single most important renewable natural resource which, through its interaction with the watershed contributes to agricultural production process.

For the watershed water balance to be meaningful and usable for different activities on the watershed such as water storage, distribution, disposal, soil conservation etc., quantification of the different components of water that are relevant to the watershed are necessary. The broad components and their relationship is expressed by the fundamental law of conservation of mass and may be written as :

$$\text{Inflow} = \text{Outflow} + \text{storage} \quad \ldots . \quad (1)$$

It is to be noted that each component of the above mass balance Equation (1) has more than one manifestation such as rainfall, snowmelt, interflow in the case of inflow, surface runoff, subsurface flow, evapotranspiration in the case of outflow and surface storage in the case of storage.

Thus, in a physical watershed system, the quantitative water balancing would involve the solution of the generalised form of Equation(1) which can be expressed as (Figure 2) :

$$P + S_i + G_i + I_i = E + S_o + G_o + I_o \pm \triangle St \pm \triangle G \quad ..(2)$$

where,

P = precipitation including rainfall, snowmelt, vapour condensatio n etc.

S = surface runoff

G = ground water flow

I = irrigation

St = storage

E = evapotranspiration

(Subscript i and o stand for inflow and outflow respectively and the prefix △ stands for change)

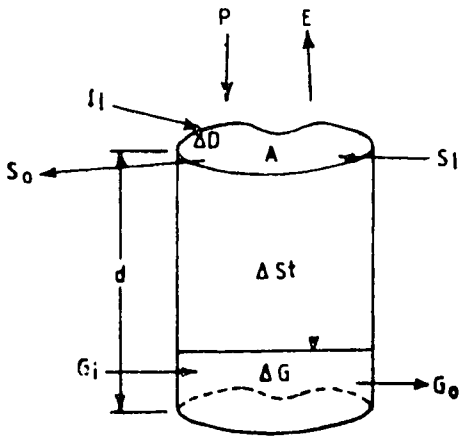

Fig. 2. Conceptul water balance model

All of the above components are expressed in depth units (mm or cm) over a given area and for a given time interval chosen on the basis of existing heterogeneity and the desired level of accuracy in the estimated values of the components of water balance parameters.

It is also to be noted that each of the components of Equation (2) are actually the outcome of certain process which depends on a number of soil, crop and climatic variables. Take for example, the case of surface runoff. The quantity of runoff generated and available at a given place and time from a given quantity of rainfall is dependent upon rainfall variables such as intensity, duration, aerial distribution; soil variables such as land slope, soil texture (infiltration), localised detension; and the crop variables in the form of interception, storage, resistance to flow and also, on the hydraulics of overland flow. To describe some of these processes, the use of simple principles of conservation of momentum or energy are used. An example of this would be the process of overland flow including the routing of flood to quantify the variation of reservoir storage level with respect to time. Normally, when the purpose of water balance is to arrive at the quantified value of one of the components over a large area for a long time interval, the use of simple mass balance approach may be reasonable. However, when the quantification is required over short time intervals, for example, estimation of the runoff characteristics (volume, peak, duration etc.) for given storm event, the dynamics of the process is to be considered by using appropriate energy or momentum balance equations along with the initial and final boundary conditions, to describe the total process.

MODELS IN WATER BALANCE STUDIES

The necessity of models

A model in general represents a certain physical process or a system. In this sense, the runoff as outflow in relation to rainfall as inflow and the storage in the watershed, as given in Equation (1) is a model. Equation (1) can be referred to as a mathematical model. Equation(2) is also a mathematical model but is in an operational or computational form. In Equation (2) any component, for example surface runoff, can be further written as a function of several variables in addition to rainfall such as land slope, soil texture, antecedent moisture condition etc. Apart from these types of functional forms, there can be a physical model of analogous type or same type. A runoff plot is a highly scaled down watershed model of similar type. An electrical network can be constructed to represent a ground water flow system and this will be an analogous model.

The natural processes in the hydrologic cycle are complex. Modelling is a method to arrange these complex

processes within a logical frame work conceptually or physically to better understand the cause-effect relationships between the different variables of the hydrologic cycle. Since it is difficult, if not impossible, to study the contribution of every variable over the large watershed, modelling becomes necessary by which a large system is reduced to a small and manageable system. The degree of correctness of the model or its closeness to the real system will decide the applicability of the model results over the real system with the desired degree of accuracy. Mathematical modelling also helps us in simulating a real system through the incorporation of system variables such that, once the model has been validated for a given location, it can be used in another location by replacing some of the system variables by appropriate values valid for the new location. In summary, in the words of Rosenbleuth and Wiener (1945) "Abstraction consists in replacing the part of the universe under consideration by a model of simpler structure. Models, formal or intellectual on the one hand or material on the other hand, are thus a central necessity of scientific procedure".

Classification of models

The structural frame work of a model depends on the requirements of a particular discipline. Irrespective of the discipline however, models can be categorised as either formal or material. With reference to this hydorologic system, further classification can be denoted by the following format :

- Real hydrologic system
  - Material (physical) model
    - Look alike (uses the same or similar material as in the real system)
    - Analog (uses the similar governing principles)
  - Formal (mathematical) model
    - Empirical
    - Theoretical

In the earlier period of research on watershed water balance, uses were made of look alike models like runoff plots, flumes etc. Analog models had very limited use in some studies related to ground water flow. It is the formal mathematical models which have been used most and are still being used in the watershed water balance work. Really speaking, the two classifications under the mathematical models cannot be carried beyond a certain point as both become intermeshed. All theoretical models simplify the physical system and are, therefore, more or less incorrect. Quite often these models contain empirical components. The empiricism arises due to

our lack of knowledge of the cause-effect relations governing many of the subprocesses of the hydrologic cycle. When this happens, the available data are processed as to yield some kind of relationship between the variables of interest without necessarily looking in the all possible variables and their contribution in defining the relationship. Two examples may suffice to clarify the above points. Infiltration is an important process in the hydrologic cycle and has been included as a component in many watershed runoff models. However, the most frequently used relation is that of the time-infiltration curve and the variation in the infiltration due to soil heterogeneity, entrapped air, presence of root system etc. are overlooked. Secondly, in the runoff model itself, effect of many variables such as soil heterogeneity, effect of cultural practices, antecedent soil moisture effect, effect of slope and many other variables are either ignored or used as a lumped variable and a numerical value assigned to represent the qualitative aspects, to simplify the process of runoff computation with respect to some easily measurable variables such as rainfall.

It has been implied earlier in this section that the classification of models into theoretical and empirical is not rigid as both classes of models are mutually inclusive. Operationally or computationally, a better classification of mathematical models would be fitted parameter and measured parameter models. Take for example infiltration again. No matter how precisely an infiltration relation is obtained, its application to estimate the volume of rainwater absorbed in the soil profile seldom gives consistent values at different times. On the other hand, a model could be made to describe the groundwater recharge as a function of rainfall. From the available data, spread over several years, a comparison between the observed water table rise and the estimated rise on the basis of infiltration characteristics and drainable pore space etc. will permit the establishment of certain average coefficients which when applied to the rainfall, will give an acceptable and reasonably accurate value of its abstraction by the soil. Such a model will be called a fitted parameter model and is in considerable use in water balance works. A measured parameter model on the other hand is the one in which the dependent variable of interest can be predicted through a set of completely measurable or estimable independent variables. In recent times, such models have been developed to estimate the watershed water yield and soil loss as functions of those watershed variables which can be measured from maps such as drainage density, channel length, channel order, relief etc. (Mishra 1986). Measured parameter model approach is more versatile (but more difficult to develop) as its applicability is not restricted to the area where it has been developed.

A hydrologic mathematical model

whether of fitted parameter type or measured parameter type is seldom exhaustive in its representation of the variation of different processes over space. In a watershed of as small as 1000 ha area, the variations in the aerial distribution of rainfall, land features, agricultural practices differ from pocket to pocket. For convenience of working many such factors are represented through an average value in the model. The model is then called a lumped parameter model. The example of these are STANFORD Model, USDAHL-74Model, SCS TR-20Model & SSAR Model etc. as given in Haan *et al* (1982). The other way would be to consider the aerial variation of the relevent features that influence the hydrologic processes. Then the model would be called a distributed parameter model. Examples of such models are the ANSWER Model by Beasley(1977),Model by Ross *et al* (1978) and Model by Moore and Larson (1978). Such models give more accurate results but physical constraints on time, money and computational aids force us to use lumping of parameters to varying extents in all the hydrologic models that are in vogue today.

OBSERVATION AND ESTIMATION OF THE WATER BALANCE COMPONENTS

A reference to Euqation (2) gives an idea about the broad types of data required for operating a mathematical water balance model. These are basically, the data on inflow, storage and outflow. These processes, however, are dependent on a host of other parameters representing the contributions of soil, climate and crop. Therefore, when it comes to the actual computation, numerical values of the relevant data are required. These numerical data may be, historical such as past records of rainfall, temperature and stream flow etc., systemic such as all the information on the fixed characteristics of the watershed like its area, relief, soil texture, drainage, density, characteristics of underground formations etc. which remain unchanged over long time periods, and experimental such as time-infiltration relation, runoff experimental plot results, evapotranspiration of different crops and efficiency of irrigation water application (to estimate quantitatively ground water recharge from irrigation application). These data are to be generated by conducting small or large scale experiments over space and time. The experimental data may be obtained through field experimentation as in the case of infiltration, crop evapotranspiration, determination of soil texture, bulk density, porosity etc. The systemic data are usually available from relevant maps, air photos and survey reports and the historical data on climate are available from the records maintained mainly by the Meteorological offices in the country.

Generally speaking, in the country, all of the above kinds of data are

scanty and there is a lack of their accessibility. A researcher working in a particular area has to exert considerably to collect the data which are normally scattered in different organisations and many times, after collection these are found to be incomplete or inadequate for the purpose of doing watershed water balance. This problem is mostly felt by those researchers who prefer to work with model where the input data requirements are more exhaustive over space and time.

ANALYSIS OF DATA

In the previous section, the kinds of data required for water balance works have been outlined. In most of the cases, the data collected, worked out from maps and air photos, or experimentally found out are not in a form to be directly used in a water balance equatino, for example in Equation (2), prior analysis to varying extents is necessary for the purpose. Such analysis results in mathematical expressions relating one of the components of the water balance equation with a set of independent parameters. An example will be the ground water inflow into the watershed and can be expressed as the function of hydraulic gradient and subsoil characteristics (such as depth to impermeable layer, transmissivity etc.). Another example would be the ground water recharge due to irrigation application and may be quantified through an expression relating the volume of infiltration with the infiltration characteristics, the time schedule of irrigation application and its quantity. Yet another example would be the analysis to work out the total rainfall over a chosen time interval or the calculation of consecutive dry or wet days depending on the purpose for which the model will be used. Averaging of the relevant information is also one important aspect of data analysis which is done in lumped parameter model application and for larger watersheds. Also, getting the model output does not mark an end of the analysis work. A very important analysis pertains to the validation of the model in which the model output is compared with observed data and standard statistical analysis done to investigate about the closeness in agreement between the two. In stochastic modelling, if the model output is decisive factor in undertaking a design and execution work which is to last for a certain period (e.g. drainage system, reservoir etc.), then the model output obtained for a given length of record(e.g. daily water table, seasonal/annual runoff obtained for several years) are subjected to prqbability analysis to estimate the magnitude of the output and associated chance of occurrence. These may be further subjected to economic analysis to find the optimum value of the design variable. This will imply the application of system analysis technique as per the defined objective function. If for example, the objective function is the grain production, then an analysis could be made to work out a cropping pattern among various alternatives which will maximise the objective function with the best utili-

zation of water available in the watershed. These works could be done independent of the main water balance model or as integral parts of it.

The discussions in sections 2 and 3 are given to focus the following :

1. The data requirement for watershed water balance work is vast and are available from different sources.

2. Considerable pre-analysis before working the water balance model and post analysis with the model output are required.

3. The nature of analysis will almost invariably require the facility of working computational fast hardware and also soft-ware packages to save time on the water balance work.

It is a fact that in the country lacuna exists in all three of the above.

RESEARCH NEEDS AND CONCLUSIONS

On the basis of the survey and analysis in Indian context with reference to the planned study of water balance on watershed basis, the following broad conclusions may be drawn :

1. At any level either national or state, there are hardly any policy for systematic study of watersheds on a long term basis which might help in drawing meaningful practical conclusions on the watershed behaviour more so, for their use in ungauged watersheds.

2. Only very few small watersheds under the Central Soil Conservation Research and Training Instiute used to be monitored with respect to runoff and soil loss etc.

3. There is a lack of practical hand book or field personnel engaged in hydrological work. At present there is perhaps only one such publication namely Handbook of Hydrology, prepared by the Soil Conservation Division of Ministry of Agriculture, Govt. of India which also is based upon meagre observed and mostly extrapolated data.

4. Even the space density of the historical data collection e. g. climatic parameters, are so thin that mostly one has to work in extrapolated ranges.

5. The accessibility of the scanty data is poor. Also, some standard formatted analysed data of rainfall intensity, duration and frequency and continuous rainy and dry spell data etc. are almost non-existant.

6. Availability of some standard physical information regarding the watershed e.g. physiographic information, soil types etc. are very limited.

7. Systematically recorded stream gauging data are not only rare but also their accessibility is very difficult. In short, the data base is very weak. Simultaneously, the hardware facilities for processing

such a huge volume of data, even if available are very few, and are extremely localised. Thus, under such conditions the following research priorities be given at different levels :

1. A national policy be developed for monitoring important watersheds for planning and developmental purposes.

2. Simultaneously, various sizes of watersheds be monitored regularly over a long period of time along with varying cultural practices in different agro-climatic regions to develop some standard parameters, which may be used for assessing the ungauged watersheds behaviour.

3. For this reason, availability of air photo at reasonable prices, over time be ensured to all who are engaged in hydrological research. Also there has to be a good number of trained personnel in air photo analysis and interpretation. Government should ensure arranging for proper training facilities in this regard. Steps have already been taken by the Government to make available the SPCT air photos.

4. Climatic data in standard analysed form be made easily available and particularly the continuous dry and wet spells analysed data be made available.

5. In-house hardware e.g. computational facilities be made available. If this is not feasible due to constraint of funds, such facilities be at least made available within reasonable distance from the place of work. In this regard, district level planning along with information centre as planned by the Planning Commission is a good concept as these will be equipped with computer facilities.

6. The country be divided into orographic zones with their characteristic features and routine analysis of rainfall data within the orographic zones of the country, including rainfall intensities, duration and frequency be done and the results made available. Simultaneously, the watershed characteristics, particularly the time of concentration be established for the combined use of the two types of information.

7. Appropriate scaling factors need to be developed for predicting hydrological behaviour (e. g. rainfall and soil loss etc.) of ungauged watersheds from the known behaviour of gauged watersheds of different sizes e.g. if one wants to extrapolate the results of runoff plot studies to larger areas.

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Role of agroforestry in watershed management and development-research priorities

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Agroforestry systems have been defined as the growing of perennial woody tree species deliberately on the same land management system where crops and animals are raised. Agroforestry systems provide higher total boimass per unit area, besides yielding different products, such as fodder, fuel, fibre, fertilizer, fruits, fence material etc. These systems utilize off-season precipitation to the best advantage of the perennials and also utilize the moisture below the root zone of crops. Under rainfed situations, deep percolation losses may vary from 20 to 25% of the total rainfall, depending on the soil and climatic conditions. In India, about 80% of the total rainfall received during the year is obtained during the monsoon season (June to September). The off-season precipitation accounts for about 20 per cent. It is this off-season precipitation that is utilized by the perennial components of the agroforestry systems.

Agroforestry systems help in soil and water conservation. This aspect has not been adequately appreciated by researchers and development workers. Another significant contribution of the agroforestry systems is recycling of nutrients from lower soil horizons. The systems impart stability through production and reduce risk of total faiulre. Additional employment opportunities during the off-season are also best provided by the agroforestry systems. A very significant advantage of agroforestry systems is restoration of the required per cent area under perennial vegetative cover.

Research priorities

Unlike tree farming, where we are concerned mainly with tree species of various kinds raised for different or multiple purposes, in agroforestry systems it is the tree x crop/animal interaction that is of great relevance. We lack basic information on the right type of tree and crop/animal species combination most suited to a particular environment. Under these situations, we look for positive interactions.

We are yet to perfect nursery management and establishment techniques suited to different habitats, canopy management, nutrients and water management, and pest management (including weeds) for different systems covered under the umbrella of agroforestry. Keeping these facts in view, research priorities are proposed here under two major heads, on-station and on-farm.

On-station research

It is extremely important to perfect the nursery and establishment techniques under rainfed situations. Whereas a nursery often has to be raised under limited moisture supply conditions, the establishment of the tree species has to be done under rainfed/limited irrigation situations. We should, therefore, identify the various containers—their size, shape and cost—in which to raise the seedlings. This necessarily implies that we should understand the various techniques of seed treatment for early germination and rapid growth under nursery conditions. If need be, the root growth and training of roots during the period of nursery may have to be studied. In rainfed situations, where rainfall is low and irrigation water supply is limited, it would be important to find out how best to economize water use during nursery phase, which in some cases may run to 6–9 months or more.

Once the seedlings are successfully raised in the nursery, we should study the optimum age of seedlings for transplanting. We may have to evolve specific techniques for successful establishment of seedlings more than one year old, under varying habitats.

The various aspects of establishment that need investigation are :

- optimum size of the pit/hole
- amount of farm yard manure, diammonium phosphate, Benzene hexachloride to be mixed with the soil obtained from the pits
- weed management aspects up to one year of establishment
- subsequent water management and pest control
- pruning of side branches
- stacking, if necessary

After the trees are successfully established, the next question that arises is, which crops are most compatible with the given tree species? The improved agronomic practices to be followed in the crop grown in the alleys will have to be formulated. Canopy management/hedgerow management assumes importance to ensure that light and moisture donot become limiting. Optimum alley widths and cutting heights of the hedgerows will have to be worked out. In short, all aspects of tree x crop interaction, involving rainwater and nutrient management need attention. Economizing water use and nutrients, and taking maximum advantage of the available sunlight, are the twin objectives.

On-farm research

This segment of research activity is most difficult and challenging. Heterogenity of environments under rainfed conditions poses a serious challenge to researchers. Tree stand establishment is the first casualty. Considerable money and efforts are thus wasted, causing frustration to farmers, researchers, development workers and administrators. Identifying tree establishment techniques under difficult and harsh environments is the first research priority.

Very little information exists on the interaction of trees and crops. Traditionally some trees are found growing in the arable lands, especially in dryland areas, such as *Prosopis cineraria* in Rajasthan, *Acacia ferruginea* in Andhra Pradesh and Karnataka, and *Faidherbia albida* in the African Sahel. Farmers generally do not fell these trees, as they are fully aware of the contributions of NFTs in arable crop production.

Since various land capability classes are available within the watershed, the best land use and, for that matter, the best agroforestry system for each of those classes will have to be worked out. Besides looking into the sustainability of a land class for a particular agroforestry system, the multiple needs of the dryland farmers may have to be taken into account. The stability and sustainability of income should get a primary consideration in selecting the most useful system for a watershed (Table 1).

Table 1. Farming system options for different agroclimatic conditions

Annual rainfall (m)	Soil type	Farming systems	Suitable tree/grass/legume species
<0.50	Shallow (0–0.30m)	Tree farming	*Prosopis cineraria, P. juliflora, Acacia aneura, A. nilotica, A. tortilis, Pithecellobium dulce.*
	Medium (0–0.45m)	Pasture management	*Lasiurus sindicus* (light textured soils), *Cenchrus setigerus, Sehima nervosum, Stylosanthes scabra, Clitoria ternatea*
0.50–0.75	Shallow (0–0.30m)	Silvipastoral system	*Acacia nilotica, Colophospermum mopane, Dalbergia sissoo, Hardwickia binata, Cassia sturti, Albizia amara, Leucaena diversifolia, Cenchrus ciliaris, C setigerus, Dicanthium annulatum, Panicum antidotale, Stylosanthes hamata, Macroptilium atropurpureum*

Annual rainfall (m)	Soil type	Farming systems	Suitable tree/grass/legume species
	Medium (0–0.45m)	Hortipastoral system	*Annona squamosa, Zizyphus mauritiana, Syzigium cumini, Emblica officialinis, Tamarindus indica, Feronia limonia, Aegle marmelos, Cenchrus ciliaris, Panicum antidotale, Urchloa mosambicensis, Stylosanthes hamata, Macroptilium atropurpureum, Clitoria ternatea*
>0.75	Shallow (0–0.30m)	Ley farming or silvipastoral system	3 years *Stylosanthes hamata* and 4th year arable crop (sorghum on heavier soils, pearl millet on lighter soils)
			Silvipastoral system as above
	Medium (0–0.45m)	Ley farming or hortipastoral system	Ley farming as above
			Mangifera indica, Achras sapota, Psidium guajava, Emblica officialinis, Stylosanthes hamata/Macroptilium atropurpureum

The ways to best conserve rainwater for growth and development of tree species, and the crops/grasses/animals raised in association with them is an important research priority. The role of agroforestry systems in relation to the hydrology of a watershed will have to be seriously considered. Various water harvesting procedures may have to be worked out, taking into consideration the run-off potential of the area and site characteristics.

Beneficial effects of uses of various tree species are known to the farmers; yet no concrete efforts have gone into extension of tree planting activities. VLWs (Village Level Workers) have so far concentrated on crop production and its various aspects, but lack of know-how of establishment techniques, uses, and marketability of various tree species are serious bottlenecks for the spread of treebased farming systems.

Socio-economic considerations

Above all, the socio-economic aspects of acceptance, diffusion, and the multiplier effects will have to be studied. After all, the dryland farmers are the clientele of the agroforestry systems offered by researchers and development workers. The socio-economic constraints thus need serious consideration. Various aspects of trespassing, uncontrolled grazing and social fencing will have to be thoroughly studied. Keeping in view the socio-economic set-up in an area, mechanisms will have to be evolved to make agroforestry systems acceptable. This requires research by sociologists and economists.

All these aspects need a multidisciplinary approach. We do not have a pure species of agroforesters in this country. Those who know about forestry are not well versed with crop production and vice versa. This is the real challenge. It requires training in research methodologies, involving experimental designs in agroforestry, etc. An in-depth knowledge of the environment, the local tree species available in and around the watershed, together with the needs of the farmers is required.

Transfer of technology

Carrying out on-station research is not enough. The transfer of technology relating to agroforestry systems, quickly and effectively is important. Based on the constraint analysis and on feedback received from the watersheds, the experimenters should be able to reorient their research programmes to suit the ecological requirementsof the watershed and the farmers concerned.

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Resource conservation through watershed management for improving productivity

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ABSTRACT

Unscientific land management has resulted in soil erosion which in turn has resulted in reduced basin retention capacity and siltation of reservoirs. Consequently there are droughts and floods which need to be prevented. The proven experience of development of a watershed on an integrated basis to bring about the improvement of productivity on sustained basis, has been tested at the Chinnatekur watershed which has an area of 1120 ha and receives 0.654m annual rainfall. Based on the resource survey, scientific land use plan was developed which included conservation measures for non arable and arable lands and treatment of waterways/gullies with checkdams, ring *bund* and *nala bund* as gully control cum water harvesting structures. Crops/varieties and management practices were also changed to enhance production. The cost of developing the watershed worked out to Rs. 1892 ha^{-1}.

Monitoring the project revealed that the treated forest land recorded only 5% runoff against 13% from the agricultural lands and the recycling of harvested water increased the groundnut yield by 46%. Graded *bunds* improved groundnut yields by 20% over no *bunds* (0.60 Mg ha^{-1}) and border strips brought about 31% increase in yields. Among the water harvesting structures, earthen structures were cost effective (Rs.4.45 m^{-3} storage) compared to Rs 24 to Rs 27 with masonry structures. With improved ground water storage as a result of water harvesting structures, the command area under the existing wells increased by 25%. Closure to grazing resulted in dry forage yield of 4.40 Mg ha^{-1} compared to only 0.50 Mg ha^{-1} under control. The development based on the above programme has resulted in 225% increase in per capita income compared to the pre-project period indicating its economic viability.

Water, soil and vegetation are the most vital natural resources for agriculture. Agricultural productivity depends on how efficiently these resources are

conserved and managed. But increase in demand for food, fodder, fibre and fuel has resulted in an excessive exploitation of land based resources leading to disruption of their natural balancing. It is estimated that over 5000 million tonnes ($>16 Mgha^{-1}$) of soil is eroded annually due to agriculture and associated activities. 10% of this eroded material is deposited in the lakes and other surface reservoirs causing a reduction of 1 to 2% in their storage capacity annually. Another 30% is permanently lost to the sea (Dhruvanarayana and Rambabu 1983). Thus due to continued soil erosion, the retention capacity of the catchment is reduced which results in more runoff in the future.

Our land area gives an annual runoff of 0.57 m, about twice the amount when compared to the global value of 0.28 m (Dhruvanarayana 1986). The soils are thus impoverished, dislocated from one place to the other leading to their deposition in lower regions and causing floods on the downstream. Thus, droughts and floods have become the two inevitable consequences arising out of breakdown of natural equilibrium of resources. We in India, propose to reach a production target of 225 million tonnes of food grains, 968 million tonnes of fodder and 225 million m^3 of fuel from the exisiting lands to meet the requirement of about one billion population by 2000 A.D. The above demands can only be met through integrated land use planning based on sound principles of soil and water conservation. The three case studies initiated in 1978 in different agroclimatic regions of the country have shown that watershed development approach is economically beneficial (overall benefit cost ratios are greater than 1.8:1) especially in places where dependable water resources are developed (Dhruvanarayana 1985).

Watershed management is a holistic approach aimed at optimising the use of land, water and vegetation in an area and therefore could help alleviate drought, moderate floods, prevent soil erosion, improve water availability, increase fuel, fodder and agricultural production on a sustained basis (Dhruvanarayana *et al.* 1987). In an attempt to give thrust in this direction, Government of India has entrusted Central Soil and Water Conservation Research and Training Institute, Dehradun and Central Research Institute for Dryland Agriculture, Hyderabad of the ICAR the responsibility to technically coordinate the development and management of 47 watersheds jointly with the State Governments. Chinnatekur watershed is one such endeavour and the results achieved, are discussed in this paper.

METHODOLOGY

Location

The Chinnatekur watershed is located 12 km from Kurnool in Andhra Pradesh (latitude of 14°54' N and a longitude of 76°58'E) and covers an area of 1120 ha. It is bounded by hillocks

on eastern and southern sides and Handri river on the northern side. Dryland agriclture is the major land use with average rainfall of 0.654 m. In order to bring about sustained natural resource development of the watershed a master plan was prepared by studying climate, land, water, plant livestock and human resources.

Climate

The climate of the watershed is semi-arid with a mean annual rainfall of 0.654 m. The distribution of the rainfall is fairly good from June to October. The probability of receiving 0.01 m and above is high from 23 (June 4-10) to 39 (Sept. 24-30) meteorological weeks (Fig. 1). The rains recede by the end of October. Frequency of dry spell is less than 45% from June 6 to end of September and except during mid August when it is 65%. Climate analysis suggests that the cropping intensity can be increased by 125 to 200% depending on soil type and its depth by adjusting sowing periods depending upon the receipt of rainfall.

Soil and land capability classification

Soil survey was undertaken for planning soil and water conservation programmes on a comprehensive basis and to develop scientific land use plans for improving productivity. The lands belonging to classes II, III and IV constituted 84 % of 1120 ha. An area of 183ha having limitations of depth, slope and erosion was proposed for afforestation while, an area of 56 ha belonging to class III with limitation of sand dune was proposed to be put under permanent vegetation like horticulture and fuel plantation.

Topographic survey

The watershed is having 27 m higher elevation than Handri river and drains into the river through two *nalas*. Hills being devoid of vegetation, the rain water flows uncontrolled causing severe erosion and gullying on the down-stream. After the contour survey following measures were suggested :

1. Construction of diversion drain/ *bund* for the safe disposal of run-off from the hills
2. Conversion of natural depressions into waterways
3. Layout of graded *bunds* of 0 75m² cross section at 1 m vertical interval draining into natural waterways and farm ponds supported by stone checks
4. Construction of rockfill dams, *nala bund* and arch weir for checking gullies
5. Replacement of stream bank control measures
6. Location of proper field channels and drains in irrigated areas

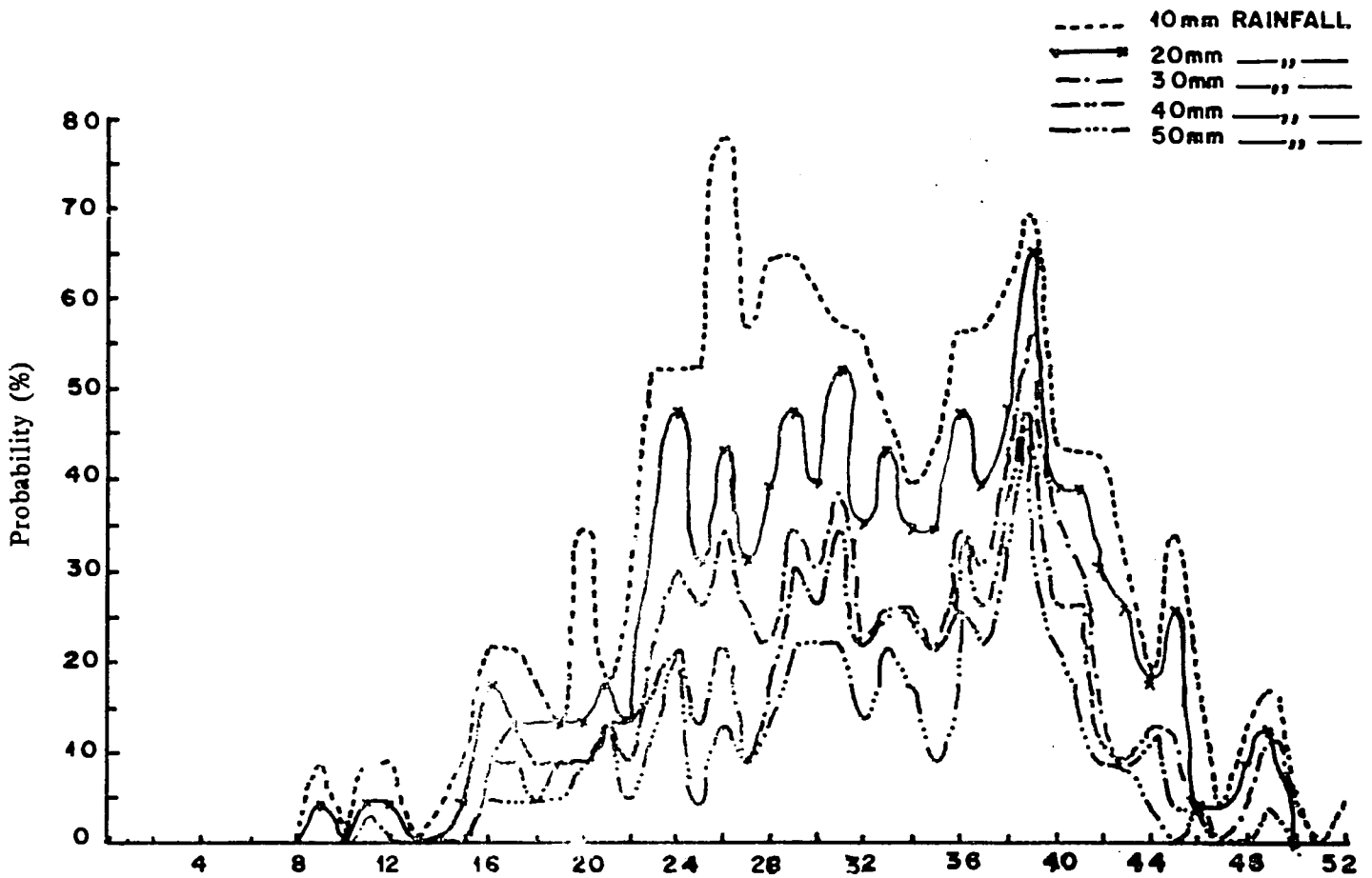

Fig : 1 Weekly Rainfall Probability at Kurnool. (Andhra Pradesh)

Optimisation of water resources

The minor irrigation tank with a storage capacity of 3 million m^3 (with one and half fill : tank once filled is partly used and it gets refilled with rains in the season. Hence the tank capacity is taken as one and half time its capacity). It is presently used to irrigate only 100 ha of wetland and 13 ha of irrigated dry crops. As a result, considerable amount of water is wasted and command area is waterlogged causing problems of salinity and alkalinity.

In order to make an efficient use of water, it was recommended that proper field channels for conserving water through sluice operation be installed. In addition, a fresh channel/on the ridge was proposed to give protective irrigation in *rabi* over an area of 129 ha as against 13 ha. The cropping pattern suggested to the area was sorghum/maize in the *kharif* or early season followed by groundnut in *rabi*

Due to continuous ponding, water-table has risen and the ground water survey revealed that a gross area of 351 ha could be brought under well irrigation as against an area of 89 ha by increasing the number of wells from 47 to 156. To realise full production potentials of such developed resources, cultivation of commercial crops e.g. chillies, cotton and onion has been suggested.

Animal husbandry and pisciculture

The milk yield of cows is poor due to local breed and lack of availability of green fodder. It has been proposed to upgrade the breed with artificial insemination. It is also proposed to increase fodder yields by cultivating superior strains.

It is proposed to use the tank for rearing fresh water fish to increase income to the watershed.

Socio-economic survey

Socio-economic data was collected by interviewing 101 farmers selected at random and their assets and liabilities are presented in Table 1.

Table 1. Socio-economic characteristics of Chinnatekur watershed

Factors studied	Size of holding (ha)			Total
	<1	1–2	<2	
Number of families :				
Farming	34	19	30	83
Other occupation	3	8	7	18
Land holding details (ha) ;				
Dryland	11.5	32.3	165.7	209.5
Irrigated	9.5	8.5	67.7	75.8

(Contd)

Factors studied	Size of holding (ha)			Total
	<1	1–2	>2	
Sources of income generation ('00 Rs) :				
Farming	536	481	3480	4497
Livestock	72	54	53	180
Others	543	47	538	1552
Extent of liabillty (as % of income generated)	50	63	47	50

(Source : Watershed management for higher productivity, Chinnatekur, Kurnool Dist. (AP), Joint Pub. of DRDA (AP) and CS & WCR & TI, Res. Centre, Bellary)

Table 1 shows that the economy of the watershed is agriculture dependant; 72% of the income comes from agriculture. Only 27% of the total watershed area is having some irrigation facilities. Sixtythree percent of the farm families living in the watershed area can be categorized as small and marginal. They represent the population living below the poverty line with their annual income (generated from various sources) ranging from Rs. 3112 to 3726 per family consisting an average of 6 members. As a result of low and fluctuating production levels, the extent of liability expressed as percentage of income generated in such families range between 50and63%while 59% of farm families belong to Scheduled Castes/ Tribes. The literacy rate varied from 22 to 40% amongst the farm families surveyed.

RESULTS AND DISCUSSION

The programmes as envisaged have been implemented by opening diversion drain/*bund* at the foot hills to divert excess water into natural *nalas*.

The rainfed areas (after leaving the areas coming under proposed well irrigation and protective irrigation) are bounded with graded *bunds* draining into natural depressions connected to farm ponds at suitable places. These waterways were provided with stone checks to prevent deep gullying. The main *nala* draining from rainfed areas was protected with 14 rockfill dams, 1 arch weir, 1 *nala bund* and 1 gabion structure in order to encourage surface ponding and thereby the ground water recharge.

A high level channel on the ridge was constructed by lining the sides

with masonry in cement mortar from the tank which facilitated bringing in 129 ha area under protective irrigation.

40 ha of sand dune area was planted to fuel, fruit and flower plantations. In the non-arable lands staggered contour trenches of 4×1.0×0.5 m were made at 10 m horizontal interval and planted with different species. In the arable lands improved technology package was applied. Improved crops/varieties, cultural practices were used to increase overall production. The efficacy of improved treatments was gauged by comparing yield from arable and non arable lands inside the watershed in macro-catchments with untreated areas for their performance. The average expenditure of development was found to be Rs. 1892 per ha.

Consequent to the implementation of the programmes, the land use pattern has undergone a considerable change. The results are shown in Table 2.

Table 2. Changes in the land use pattern after implementation of improved land and water programme

Practice/system	Area (ha) during		Change
	Pre project	Post project	%
Wet land crop production	100	100	0
Dry-cum-wet	13	129	+892
Well irrigation	49	100	+104
Supplemental irrigation (from pond, nalabund and rockfill dams)	0	18	+1800
Garden lands	35	47	+34
Dryland crop production	653	456	—43
Non arable land : hilly area and river bed	227	227	0
Area under village site	42	42	0
Total	1120	1120	

It is seen from Table 2 that the area dependent on rain was reduced from 653 to 456 ha thus stabilising agriculture over 197 ha apart from improving the productivity.

Runoff and soil loss

Agricultural and forest catchments comprising of 97 ha and 31 ha were gauged during 1987 for runorf measurements. There were 12 runoff events from 20-6-87 to 4-11-87. The effect of forest and agricultural cover on runoff is presented in Table 3.

Table 3. Effect of forest and agricultural cover on runoff during 1987

	Forest cover	Agricultural cover
Total rainfall (m)	0.67	0.67
Runoff causing rain (m)	0.30	0.26
Runoff as % of total rainfall	2	5
as % of runoff causing rain	5	15

A typical hydrograph obtained for forest area (31 ha), agriculture treated (97 ha) and untreated agricultural cover (14 ha) for the 0.0353m rainfall on 2-9-88 is presented in Fig. 2. Details of runoff and sediment loss are presented in Table 4.

Table 4. Runoff from different catchments

	Forest cover	Agri. cover (treated)	Agri. cover (untreated)
Peak rate of discharge (m^3sec^{-1})	0.0097	0.0459	0.2613
Total runoff (m^3)	12.16	134.85	499.25
Runoff as % of rainfall	0.11	0.39	9.93
Runoff during 1988 (upto Sept. 88) (m^3 ha^{-1})	19.14	20.59	43.82
Sediment density for the event on 2-9-88 (gl^{-1})	0.708	0.869	2.938

It is evident from Table 4 that there is favourable impact of the conservation practices in reducing the peak discharge and total runoff from treated forest as well as agricultural catchments and there exists considerable scope for *in-situ* moisture conservation and resource conservation for improving productivity in the watershed.

The impact of the individual conservation and production programmes are discussed below :

Conservation programmes

(a) Graded *bunds*

Groundnut crop cultivated under two situations representing presence and absence of graded bunding yielded 16% higher over no bunding (Table 5).

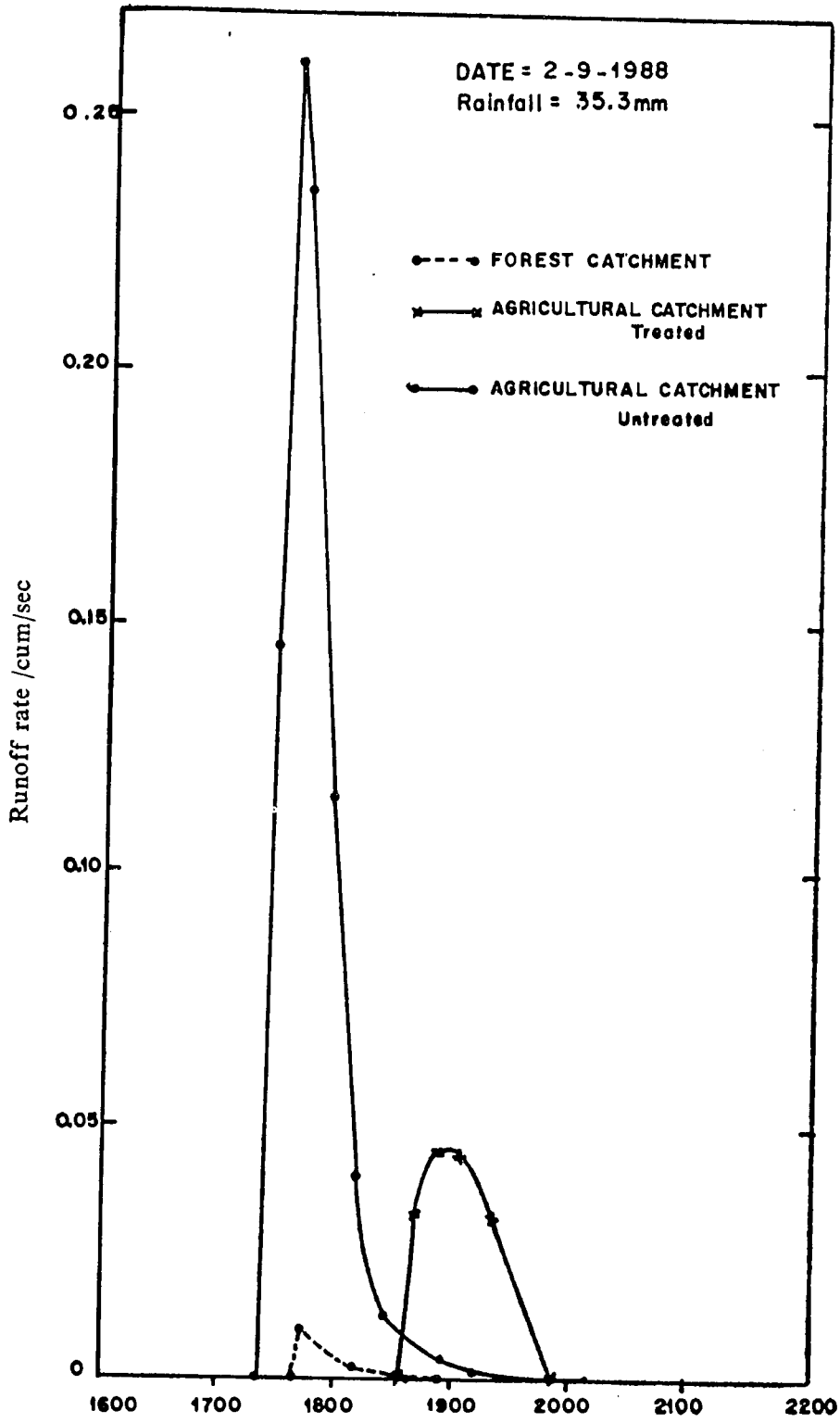

Fig : 2 Runoff Hydrographs for forest Agriculture treated and Agriculture untreated Catchments for rainfall on 2-9-88 at ORP Chinnatekur, Kurnool (dist)

Table 5. Effect of graded *bunding* on groundnut yield (Mg ha^{-1})

Crop	Year	Graded *bunding*	No graded *bunding*
Groundnut (TMV 2)	1986	0.78	0.65
	1987	0.60	0.54
Mean		0.69	0.60

(b) Inter terrace treatments

Land smoothening in the inter-*bunded* area and forming border strip of 10 m width and 40 m length with 0.2% grade with the object of improving *in situ* moisture conservation resulted in increased yields of groundnut by 13 and 30% respectively (Table 6).

Table 6. Comparison of groundnut yields (Mg ha^{-1}) under inter terrace land treatments

	Inter terrace treatment		% increasse
	+	—	
Land smoothening	0.72	0.64	13
Border strip formation	0.79	0.61	30

(c) Providing supplemental irrigation through gully control and water harvesting structures

A total storage of 0.9 ha-m has been created in the watershed through construction of 14 rockfill dams (0.16 ha m) one archweir (0.02 ha m) and one nala-bund (0.38 ha m) and four farm ponds (0.33 ha m) with corresponding costs of storage working out to Rs. 24, Rs 27, Rs 4 and Rs. 25 respectively per m^3 of storage. This showed earthen structures (like *nala-bund*) are more cost effective compared to masonry structures in the short run. Impact of providing supplemental irrigation on groundnut yield is presented in Table 7.

Table 7. Impact of supplemental irrigation on groundnut yield (Mg ha^{-1}) from dug-out farm ponds

Crop	Year	Irrigation		Increase
		+	—	%
Groundnut	1986–87	0.75	0.59	26
	1987–88	0.99	0.59	67
Mean		0.87	0.59	46

Efficient utilization of water resources

Creation of channel on the ridge to provide protective irrigation to 129 ha has changed the economy of the farmers. During the first year itself the entire area was brought under groundnut which yielded an average of 19 Mg ha^{-1}, after *kharif* sorghum, as against 0.70 Mg ha^{-1} obtained under rainfed conditions during *kharif*. Thus protective irrigation in *rabi* has generated an additional yield of 22 Mg of groundnut out of total production of 30 Mg in the irrigated dry area.

Efficient utilization of water with emphasis on on-farm water management has resulted in a total additional groundnut production of 22 Mg and 19Mg after *kharif* crops during 85-86 and 87-88 respectively.

Ground water utilization

With an increase in the basin retention capacity (Fig. 2) and through the surface storage structures, it is to be expected that the groundwater potential would increase considerably. The impact of the same is presented in Table 8.

Table 8. Groundwater development programme for efficient utilization

Year/season	No. of wells	Area irrigated (ha)	% increase in area due to		
			New wells	Old wells	Total
Pre project	47		—	—	—
Kharif		50	—	—	—
Rabi		39	—	—	—
Total		89	—	—	—
1985–86					
Kharif	58	75	23	28	51
Rabi		70	43	37	80
Total		146	32	32	64
1986–87					
Kharif	70	90	54	27	81
Rabi		85	83	36	119
Total		176	66	31	97
1987–88					
Kharif	92	100	102	0	102
Rabi		102	136	26	162
Total		202	117	11	128

From Table 8 it is evident that irrigated area increased from 89 ha (from 47 wells in pre-project period) to 202 ha from 92 wells at present. This stabilised crop yields in an area of 113 ha. An increase in the command area to the tune of 38% was noted under old wells as a result of conservation programmes. The 3 years average showed an increase of 25% in command area under old wells.

Production improvement programmes

In case of non-arable lands, simple protection with contour trenches has yielded about 4.4 Mg dry grass per hectare against a yield of 0.5 Mg ha^{-1} under control conditions.

Similarly the crop yields have been increased by two-to three-folds as a result of the application of improved technology (Table 9).

Table 9 Change in crop yields as a result of improved technology

Crop	Yields (Mg ha^{-1})	
	Pre-project	Post-project
Rainfed crops		
Groundnut	0.40	0.60
Sorghum	0.40	0.80
Setaria Millet	0.30	0.60
Irrigated		
Paddy	2.00	4.70
Groundnut	1.10	2.10
Sorghum	2.50	3.00

Consequent to increase in yields, the overall production in the watershed has increased (Table 10) and raised income to Rs. 7.7 millon from

Table 10. Crop yields in the watershed (Mg ha^{-1})

Crops	1983-84	1984-85	1985-86	1986-87	1987-88
Cereals Rainfed					
Setaria millet	0.79	0.56	0.80	0.64	0.56
Sorghum	0.43	0.40	0.42	0.57	0.69
Pearl millet	—	—	0.40	0.75	0.80
Irrigated					
Setaria millet	1.00	0.80	—	0.75	1.01
Sorghum	2.20	1.80	2.00	3.00	1.52
Paddy	3.75	4.46	4.31	4.60	4.60

(Contd)

Crops	1983–84	1984–85	1985–86	1986–87	1987–88
Oil seeds					
Rainfed					
Groundnut	0.45	0.47	0.47	0.59	0.60
Sunflower	—	—	0.20	0.37	0.20
Irrigated					
Groundnut	1.65	1.65	1.85	1.70	2.06
Sunflower	—	0.20	0.30	0.70	0.90
Pulses					
Pigeonpea	0.50*	0.56*	0.06**	0.07**	0.14**
Others					
Rainfed					
Vegetables	—	2.30	2.50	2.08	—
Cotton	—	—	0.59	0.61	0.20
Jasmine	—	—	3.60	4.00	4.00
Irrigated					
Vegetables	—	—	6.78	5.20	5.00

* Pure crop ** Inter crop

3.2 million in the preproject peried. These increased returns resulted in better future investments by the farmer in applying fertilizers, plant protection measures and creating additional wells. Thus the consumption of N and P which was only 3 Mg and 6 Mg increased to 10 and 18 Mg under rainfed conditions respectvely Similarly in case of irrigated agriculture it has increased from 15 Mg to 32 Mg for N and from 12 Mg to 24 Mg with respect to phosphorus.

The overall impact of improved land and water management programme as assessed by per capita income is given in Table 11.

Table 11. Changes in per capita income with time

Period		Per capita income (Rs)
Before	1984	1443
	1985–86	2396
	1986–87	2357
	1987–88	3246

The increase in per capita income by 225% in a period of 5 years watershed development programmes is highly beneficial and is economically viable. The measures adopted in the watershed also help conserve the natural resources.

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Study on hydrology of a small eroded Shiwalik watershed managed for rainwater harvesting and its utilization

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ABSTRACT

Low productivity of rainfed agriculture in Siwaliks has been responsible for dependence of poor farmers on adjoining forests. This has lead to denudation and soil erosion problems. In Operational Research Project Sukhomajri located in foothills of Haryana, rainwater from a severely eroded small hilly forest watershed of 1.52 ha was harvested by constructing a 6.5m high earthen dam to store 9300 m^3 of water. An underground pipeline (15 cm dia x 220 m length) conveyed water by gravity from reservoir to 2.0 ha of rainfed farm land which was developed by land levelling and shaping. The hydrology of this watershed was studied for 6 years during 1982-87.

This system was designed with 50 percent runoff from mean annual rainfall of 1.20m. The annual rainfall varied from 1.59 to 0.62 m. The observed runoff was 0.83 and 0.13m and constituted 52 and 21 percent of annual rainfall during these two extreme rainfall years. There was reduction in water yield with the improvement in vegetation cover. The small storms which did not produce any runoff increased from 10 to 27 percent with time. The seepage losses from stored water varied from 2 to 7 mm/day depending upon the depth of stored water. After allowing 9, 16, 10 percent for dead storage, seepage and evaporation from October to end of December, the harvested water was sufficient for 3 irrigations of 0.07m each for 1.6 ha in low and 2.4ha in the high rainfall years. On the basis of this information, some norms for field use have been suggested. The mani-fold increase in crop production by supplemental irrigation reduced the farmers dependence on forests and they started protecting the catchment to prolong the life of much needed reservoir.

The increase in food production achieved in 2 previous decades in India have mostly come from irrigated plains and the progress has reached a plateau. Rainfed uplands and dry lands need to contribute to the future food production (Ferrar and Craswell 1988). Soil and water conservation and management shall play a crucial role in increasing crop production from such areas (Randhawa 1981). Shiwalik region constituting parts of Punjab, Haryana and Himachal Pradesh is one out of several agro-climatic zones identified for efficient land and water management on regional basis (Dhruva Narayana *et. al.* 1986). The erratic distribution of rainfall, lack of irrigation facilities and soil fertility depletion on water eroded undulating lands cause frequent crop failures in Shiwaliks (Grewal *et. al,* 1982). The low productivity of rainfed agriculture has been responsibie for dependence of poor farmers on adjoining forests and thus aggravating the problems of denudation and soil erosion (Bhumbla 1976).

In an Operational Research Project located near Kalka in the foot-hills of Haryana State, efforts were made to develop appropriate watershed management technology for solving twin problems of poor agriculture and depleting forests (Mishra *et. al.* 1980). Rainwater otherwise go ng waste to cause floods from small forest watersheds was harvested by constructing earthen dams and used for crop life saving supplemental irrigation in command areas (Mittal *et. al.* 1982). The hydrological behaviour of these reservoirs in and around ORP Sukhomajri is being studied for the last 8 years to develop norms for field use. This paper presents the results of one small watershed near Sukhomajri.

MATERIALS AND METHODS

The Operational Research Project Sukhomajri is located in Kalka Tehsil of Haryana and is about 35 km North-East of Chandigarh The height above mean sea level in the area varies from 500 to 620 metres. The village typically represents soil. climate and socio-economic condition of the Shiwalik region. The mean (1962-86) annual rainfall of the area is 1 08m out of which 0.84m (78%) is received during monsoon months of June to September (Table 1). The rainfall intensities of 0.13 and 0.10 m hr^{-1} for 15 and 30 minutes duration are common. The mean maximum temperature is over 43°C in May-June and minimum around 3°C in January. The average annual pan evaporation is 2 11m. The monthly PE exceeds rainfall except in the months of July and August.

Table 1. Climatic parameters of the project area (Average of 1962-86)

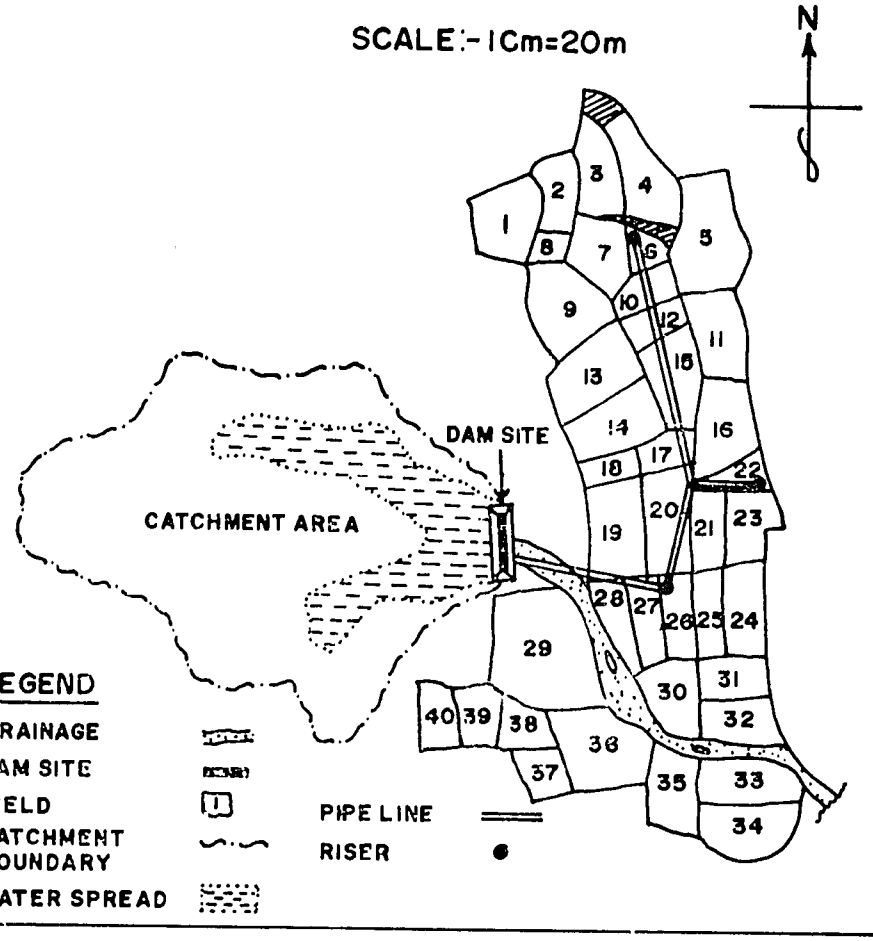
Month	Rainfall (m)	Temperature(°C) Max.	Min.	Pan evapo-ration (m)	Sunshine (hrs)	Wind velocity (km hr^{-1})
Jan.	0.044	24.2	3.1	00.72	6.8	3.9
Feb.	0.040	27.5	3.6	0.093	7.3	4.6
Mar.	0.038	33.8	7.2	0.176	8.1	5.6
Apr.	0.015	39.5	14.7	0,274	9.2	3.9
May	0.037	42.7	17.5	0.363	9.5	6.3
Jun.	0.119	43.3	19.8	0.324	7.9	6.3
Jul.	0.306	38.3	21.5	0.173	6.2	4.5
Aug.	0.302	36.1	21.9	0.131	5.9	3.5
Sep.	0.125	35.7	18.9	0.153	8.2	3.4
Oct.	0.020	34.3	13.2	0.158	9.2	4.4
Nov.	0.012	30.6	7.5	0.117	8.2	4.3
Dec.	0.025	26.7	4.3	0.075	7.1	3.7
Total	1.084			2.108		

The project area forms a part of lower Shiwaliks which are geologically composed of sandstone, grits, conglomerates and clays (Shales) having character of fluviate deposits of torrential streams in shallow basins. The rocks are young and highly susceptible to erosion. There is agricultural land in the valleys and degraded forest on adjoining hill slopes and tops. The forest catchments are composed of highly eroded sandy loams, silty clays and mixed colluvial deposits. The farm lands are terraces on 3 to 15% slope with sandy loam soils.

The project represents a large number of denuded small watersheds typical of Shiwalik region. The salient features of the smallest model taken for this study are: forest watershed area 1.52 ha, total height of earthen dam 6.5 m, maximum storage capacity 9300 m^3 of water, submergence area 0.35 ha at full reservoir level. An underground pipeline of 15 cm dia and 220 m length conveyed water with gravity from reservoir to 2.0 ha of rainfed farm land which was levelled and shaped (Fig. 1). The total cost of catchment treatment (Rs. 1216), dam construction (Rs. 12,334 and pipe line (Rs. 8850) was

Rs. 22,300 in 1979-80. The catchment area was treated with conservation measures such as construction of 222 staggerred contour trenches, 15 stone check dams and planting of Bhabbar grass *(Eulaliopsis binata)* to reduce sediment load. The storage capacity was designed with 50 percent expected runoff from mean annual rainfall of 1.20 m. The rainwater of 1980 monsoon was stored for the first time in the reservoir.

FIG. I CATCHMENT AND COMMAND AREA UNDER A SMALL WATERSHED



Daily rainfall was recorded with a raingauge. Daily depth of stored water was recorded from a gauge installed at the deepest point. The

evaporation losses (lake evaporation) were worked out by multiplying pan evaporation with 0.7 a standard ratio between lake and pan evaporation. The seepage losses were calculated by deducting lake evaporation from the total drop in reservoir level on rain-free days. The runoff was determined from increase in reservoir levels with each storm and the volume of rain-water received over the non-submergence area of the reservoir. Rain falling directly over the reservoir was accounted for separately. Correlation between rainfall and runoff was also worked out.

RESULTS AND DISCUSSION

Rainfall and runoff

Six years 1982-87 mean annual rainfall since construction of dam was 1.17 m (SD ± 0 35). The observed mean annual runoff was 0.44 m or 37.6% of mean annual rainfall. The runoff in general tended to decrease over the years (Table 2). Twenty-seven storms varying in rainfall from 0 to 25 mm produced an average runoff of 44.4 percent in 1982 but 26 storms of this category produced an average runoff of only 2.6 percent in 1987. Similarly, the rainfall storms above 75 mm produced 80 percent runoff in 1982 and 49 4 percent in 1987 (Table 3). While 6 storms varying in rainfall from 7 to 11 mm produced runoff varying from 23 to 83 percent in 1981 but 7 storms varying from 18 to 24 mm rainfall could not produce any runoff in 1987. The trend of diminishing runoff has also been shown by rainfall (x) runoff (y) regression curves ($Y=34.14+0.578x$ ($r=0.73$), $Y=3.24+0.633x$ ($r=0.55$) and $Y=0.5+0.456x$ ($r=0.66$) drawn for 1982, 1986 and 1987, respectively.

Table 2. Annual rainfall and runoff from the catchment area

Year	Annual rainfall (m)	Runoff (m)	Runoff (%)	Rainfall not producing runoff as % of total
1982	1.375	0.704	51.2	11.6
1983	1.587	0.828	52.2	10.1
1984	0.942	0.436	46.3	15.0
1985	0.625	0.129	20.6	40.0
1986	1.397	0.563	40.3	27.1
1987	1.090	0.243	22.3	23.0
Mean	1.169	0.439	37.6	21.5
SD ±	0.353	—	—	—

Table 3. Runoff from the annual rainfall of 3 years

Year	Runoff (%) from different classes of rainfall storms (mm)				Mean
	0–25	25–50	50–75	75 & above	
1982	44.4 (27)	53.2 (12)	0 (0)	80.0 (3)	51.2 (42)
1986	16.1 (12)	26.4 (8)	49.1 (5)	60.0 (5)	40.3 (30)
1987	2.6 (26)	18.8 (11)	27.7 (6)	49.4 (1)	22.3 (44)

Figures in parentheses shows number of storms

The reduction in runoff was apparently due to improvement in vegetation cover consequent upon soil and water conservation treatments and protection from grazing and illicit cutting. The total *Bhabbar* grass (*Eulaliopsis binata)* production from the catchment increased by 2.5 and number of trees (above 5 cm dbh) by 9 times in the study period. Similar results were reported in an earlier study conducted in another watershed of Sukhomajri (Agnihotri *et al.* 1985).

Seepage and evaportion losses

The reservoir attained the highest storage levels on varying dates between August and October depending upon rainfall distribution. The levels then gradually decreased in the post monsoon months. The stored water was subjected to seepage and evaporation losses. In the months of August-October, the seepage losses varied from 1.26 to 14.8 mm day^{-1} in 1980 when operating hydraulic head varied from 4.0 to 4.5 metres (Table 4). In these months at similar head 7 years later during 1987, the losses were reduced to the range of 3.9 to 5 2mm day^{-1}. The seepage losses were relatively low (4.3 to 5.2 mm day^{-1}) at heads lower than 3.8 metres even in 1980 but were further reduced by about 25 percent by 1987. There was a conducting porous layer above 3 8 m height which permitted heavy seepage in earlier years but appears to have been impregnated with suspended clay and silt. After the intial 5-6 years, the seepage losses stabilised in the range of 2 to 7 mm day^{-1} depending upon operating hydraulic head.

Table 4. Seepage and evaporation losses (mm day^{-1}) from stored water during August-December in 1980 and 1987

Months	1980			1987		
	Seepage	Evaporation	Total	Seepage	Evaporation	Total
August	14.8	3.7	18.5	3.9	4.0	7.9
September	12.6	3.3	15.9	4.2	3.9	8.1
October	13.1	3.7	16.8	5.2	3.7	8.9
November	4.3	2.1	6.4	3.4	2.4	5.8
December	5.2	1.3	6.5	3.6	1.4	5.0
Hydraulic head (m)	3.6 - 4.2			3.9 – 4.5		

On the basis of 1987 data, the loss of water in the post-monsoon months of October, November and December was 8.5 hacm through seepage and 5.33 hacm through evaporation (Table 5). Out of the total of 52 ha cm of water stored in the reservoir on 1.10.1987, about 16 percent was lost through seepage and 10 percent through evaporation in these three months. Considering 8 to 10 percent of water reserved for dead storage, 25 percent for seepage and evaporation loss, the remaining 65 percent of the monsoon stored water was available for supplemental irrigation.

Table 5. Seepage and evaporation losses from the stored water in post-monsoon months (based on 1987 data)

Months	Water losses (hacm)			Mean operating hydraulic head (m)
	Seepage	Evaporation	Total	
October	3.93	2.80	6.73	4.46
November	2.35	1.66	4.01	4.23
December	2.22	0.87	3.09	3.94
Total	8.50	5.33	13.83	
Losses as % of monsoon storage	16.3	10.2	26.5	

Reservoir storage and supplemental irrigation

The reservoir was designed to store 93 ha cm of runoff. In 4 good rainfall years, the average storage after the monsoon rains was 75 ha cm out of which 4 89 ha cm was available for use and the same could cover 2.4 hectare area with three supplemental irrigations (Table 6). In the remaining 3 bad rainfall years, the average storage was 51.0 hacm out of which 33.4 hacm was available for use and could cover 1.6 hectare area with 3 irrigations. This does not include 1980, being the first year without any spill over. The spill over from good rainfall years (when need for irrigation was less) and off season rains supplemented the reservoir storage. After allowing 16% for seepage, 10% for evaporation and 9% for dead storage, the forest catchment of 1.52 ha was capable of proivding 3 crop life saving irrigations of 0.07 m each (one to maize near maturity, two to wheat at pre-sowing and at CRI stage) to about 2 hectare farm land in command.

Table 6. Monsoon rainfall, water stored and available for irrigation and area which could be covered in good and bad rainfall years

Type of years	Year	Monsoon rainfall (m)	Total reservoir storage after monsoon (hacm)	Water available for irrigation (hacm)	Area which could be irrigated (ha)
Good rainfall	1982	0.822	68	44.2	2 1
Years	1983	0.904	89	57,9	2.8
	1984	0.809	70	45,5	2.2
	1986	1.095	74	48.1	2 3
Mean		0.913	75	48.9	2.4
Bad rainfall	1981	0.664	46	29.9	1.4
Years	1985	0.502	56	36 4	1.7
	1987	0.584	52	33.8	1.6
Mean		0.584	51	33.4	1.6

with 3 irrigations of 7 cm each

Incidently, part of the catchment and whole of the reservoir area was composed of heavy textured silt loam to silty clay loam soils in which silt varied from 23-29 percent and clay from 25-39 percent. The pH (1.2) of the soil ranged from 8.9 to 9.4. Earlier studies conducted by Grewal *et al* (1982) on these soils at Sukhomajri have revealed that high silt and clay content, clay being of swelling type, dispersion of clay under alkaline conditions, presence of insoluble $CaCo_3$ and longer tortuous path for water flow in platy structure of sub-surface layers are some of the factors responsible for clogging the soil pores. Hence the soil is conducive for high runoff and slow seepage.

Conclusions

On the basis of above information and 8 years experience of the project, some norms for field use are suggested. If the soil and site conditions are suitable, even small watersheds around 1.5 ha may be considered for rainwater harvesting programme. The expected runoff of 50 percent used in the earlier designs may be revised to about 25-35 percent. After making allowances for seepage, evaporation and dead storage, about 60-65 percent of the monsoon stored water may be available for supplemental irrigation. These broad norms may be true in areas of Shiwaliks where soil, site, vegetation and rainfall conditions are more or less identical to Sukhomajri watersheds. The watershed management technology developed at ORP Sukhomajri was economically viable and socially acceptable because of direct visible benefits to the people. The local community, threfore, started protecting the forest to increase the life span of much needed reservoirs.

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A mathematical model of upland erosion

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ABSTRACT

A mathematical model to simulate the overland flow and sediment delivery from the fallow and upland small watersheds is presented. Overland flow is simulated using Saint-Venant equations with kinematic wave approximation. Manning's equation has been used to determine flow discharge rate. Mein and Larson's approach based on original Green and Ampt method has been used to estimate rainfall excess rate. Dynamic conservation of mass equation is used to simulate sediment routing. Empirical rill and interrill erosion relationships have been used for estimating soil detachment rate. Modified Yalin's equation has been used to compute transport capacity of flow for non-uniform sediment mixtures. The solution to the governing partial differential equations of flow and sediment have been obtained using finite element technique. The model has been validated using the published soil erosion data.

It is estimated that about 45 percent of the land suffer from serious soil erosion by water and wind (Das 1985). An estimated 6000 million tonnes of top soil are getting lost annually from the Indian subcontinent. This leads to the loss of nutrient rich soil, thereby, limiting the choice of crops which can be grown on the depleted soil. Available data indicate that the observed sedimentation rates into some of the major reservoirs/rivers of India range from 1.45 to 7.5 times of the generally assumed sedimentation rates (GOI 1985, Dhruvanarayana *et al.* 1983).In dryland agriculture most of the rain water gets lost as surface runoff creating drought

conditions and serious erosion hazards due to poor land management practices.

Complete understanding of the soil erosion processes is important for better control of soil erosion and for maintaining maximum levels of agricultural production A mathematical model logically representing erosional processes from small watersheds may prove to be a useful tool.

Mathematical models to estimate the soil loss may be grouped into two categories, one that uses rainfall erosivity as the main criterion and the other that relates the erosion processes to both the rainfall and overland flow processes. The example of the first category is the well-known Universal Soil Loss Equation (USLE) developed by Wischemeier and Smith (1960) which is the widely used empirical relationship for predicting erosion losses. But it cannot be used to predict the soil loss on event basis. Also, it is basically an erosion equation and does not estimate the deposition within the catchment. The second category of the soil erosion models uses rainfall and runoff rate as the driving force for the soil loss estimation from the catchments. The soil erosion components of these models derive its inputs from some hydrologic models. The Stanford Watershed Model (Negev 1967, Fleming and Fahmy 1973 and David and Beer 1975) and USDA HL-73 (Onstad and Foster 1975) have been reportedly used for this purpose. These models do not correctly predict the peak values (Subramanya 1984) which is of great importance in sediment yeild estimates. Moreover, these models have tremendous data requirement which limits the applicability of these models in the developing countries.

A mathematical model that employs the hydraulic routing to the flow, is considered better representative of the dynamics of the flow (Viessman *et al.* 1972). Also, a mathematical model that integrates the spatial variability of the controlling parameters on an ungauged watershed can provide reliable prediction of spatial and temporal distribution of watershed response.

DEVELOPMENT OF THE MODEL

Water routing

Overland flow can be simulated using hydrodynamic equations of continuity and momentum.

Continuity equation : The continuity equation can be expressed as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

Where Q = discharge per unit width of the overland flow plane, $m^2\ sec^{-1}$

A = cross-sectional area of the flow per unit width of the overland flow plane, m

x = distance in the direc-

tion of flow, m
t = time, sec, and
q = lateral inflow per unit length per unit width of the flow plane(rainfall excess rate), m sec^{-1}.

Rainfall excess is estimated by Green and Ampt infiltration equation (Green and Ampt 1971) modified for rainfall infiltration (Mein and Larson 1973) and for dealing with unsteady rainfall cases (Chu 1978).

The equation that predicts the infiltration amount prior to ponding is given by

$$F_p = \frac{S.M}{(I/K - 1)} \quad \text{for } I \geq K \quad (2)$$

Where F_p = cumulative infiltration prior to ponding, mm
I = rainfall intensity, mm sec^{-1}
K = hydraulic conductivity of the wetted zone, mm sec^{-1}
S = average suction at the wetting front, mm, and
M = saturation moisture deficit.

Time to surface ponding can be estimated by

$$t_p = F_p / I \quad (3)$$

Equations (2) and (3) are used only when rainfall intensity exceeds hydraulic conductivity of the wetted zone (K). When the rainfall intensity is less than K all the rain infiltrates, that is,

$$F = I . t \quad \text{for } I < K \quad (4)$$

Where F = cumulative infiltration at any time, mm.

Infiltration at any time during post ponding period is given by

$$K (t - t_p + t'_p) = F - S. M. \ln (1 + F / S.M.) \quad (5)$$

Where t'_p = a pseudo time, equivalent to the time it would have taken to infiltrate the amount Fp under ponded surface conditions, sec.

Momentum equation : The momentum equation can be expressed as

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A)}{\partial x} + g A \frac{\partial h}{\partial x} = g A (S - S_f) \quad (6)$$

Where S=bed slope of flow plane, mm^{-1}
S_f = frictional slope, mm^{-1}
h = depth of flow, m, and
g = acceleration due to gravity, m sec^{-2}.

Kinematic wave approximation : The assumption of the kinematic wave approximation(Lighthill and Whitham 1955) is that the friction slope is equal to the bed slope. In other words, the gradients due to the local and convective accelerations are assumed to be negligible and the water surface slope is assumed to be equal to the bed slope implying uniform flow for which Manning's equation can be used.

$$Q = V A = R^{2/3} S^{1/2} A/n \quad (7)$$

Where V = velocity of flow, m sec^{-1}
R = hydraulic radius, m, and
n = Manning's roughness coefficient

Sediment routing

The movement of the sediment from an area is governed by the equation of continuity for the sediment and sediment transport equation.

Continuity equation for sediment : Sediment routing has been simulated using a sediment mass conservation equation of the form (Foster 1982) :

$$\frac{\partial q_s}{\partial x} + \frac{\partial A_s}{\partial t} = D \qquad (8)$$

Where q_s = sediment load per unit width of the overland flow plane, kg m^{-2} h^{-1}

A_s = mass of sediment in water per unit area, kg m^{-2}, which is equal to q_s/v

D = soil detachment rate, kg m^{-2} h^{-1}, which is equal to (DI + DR)

DI = interrill erosion rate due to rainfall, kg m^{-2} h^{-1}, and

DR = rill erosion rate due to flow, kg m^{-2} h^{-1}.

Interrill erosion rate, DI, due to rainfall splash has been computed by the relationship of the form(Foster 1982) :

$$DI = COFI.\ C.\ K\ .\ i^2.\ (2.96\ S^{0.70} + 0.56) \qquad (9)$$

Where COFI = a coefficient whose value has to be obtained by calibration with the observed erosion data

C = cropping and management factor of the USLE

K = soil erodibilty factor of the USLE, and

i = rainfall intensity, mm h^{-1}.

Rill detachment rate due to overland flow has been computed by the relationship of the form (Foster 1982) :

$$DR = COFR.\ C.K.\ \tau^{1.5} \qquad (10)$$

Where τ = average shear stress, N m^{-2} and

COFR = a coefficient whose value has to be obtained by calibration with the observed erosion data.

The sediment continuity equation has been further developed to consider the routing of sediment by sizes. Hence, the percentage of sediment for various particle types is accounted for in the continuity equation as follows :

$$\frac{\partial q_{si}}{\partial x} - \frac{\partial A_{si}}{\partial t} = D_i \qquad (11)$$

$$i = 1,2, \ldots, N$$

Where i = the size fraction index and

N = the number of size fractions.

Sediment transport equation : In this study, Yalin's(1963) bed load formula has been used which is given by following series of equations :

$$T_{ci} = P_{ci}, SG_i, P_w d_i U \quad (12)$$

$$P_{ci} = P_i(\delta_i/TS) \quad (13)$$

$$P_i = 0.635 (1 - (1/\sigma_i) \ln (1+\sigma_i) \quad (14)$$

$$\delta_i = (Y_i / Y_{cri}) - 1 ; \delta_i = 0 \text{ when } Y_i \leq Y_{cri} \quad (15)$$

$$TS = \sum_{i=1}^{N} \delta i \quad (16)$$

$$\sigma_i = 2.45 (SG_i)^{-0.4} (Y_{cri})^{0.5} d_i \quad (17)$$

$$Y_i = U^2/ ((SG_i-1) gd_i) \quad (18)$$

Where T_{ci} = sediment transport capacity, Kg $m^{-1}h^{-1}$

Y_{cri} = critical shear stress for ith particle size from Shield's diagram

SG_i = specific gravity of ith particle size

d_i = ith sediment particle size, m

P_w = density of water, Kg m^{-3}

U = shear velocity, mm h^{-1}.

Other variables like σ_i, Y_i, δ_i, P_i, P_{ci} and TS are defined by equations (13) through (18). The Shield's diagram as extended by Mantz (1977) for small particles is used to estimate Y_{cri} . A scheme proposed by Foster (1982) has been used to accomodate the non-uniform sediment.

Initial and boundary conditions

To solve the equations of flow and sediment movement on a sloping plane subjected to rainfall and infiltration the following initial and boundary conditions can be assumed.

$$A(x,0) = 0 ; \quad Q(x,0) = 0 \quad \text{for } 0 \leq x \leq L \quad (19)$$

$$A(0,t) = 0 ; \quad Q(0,t) = 0 \quad \text{for } t \geq 0 \quad (20)$$

$$A_s(x,0) = 0 ; \quad q_s(x,0) = 0 \quad \text{for } 0 \leq x \leq L \quad (21)$$

$$A_s(0,t) = 0 ; \quad q_s(0,t) = 0 \quad \text{for } t \geq 0 \quad (22)$$

Where L = length of the flow plane, m.

FINITE ELEMENT FORMULATION

Overland flow : Using Galerkin residual method to develop the algebraic equations from the partial differential equation of flow following finite element equation is obtained for a linear element.

$$l\ [KM]\ \{A\} + [LM]\ \{Q\} - l\,q\ \{M\} = 0$$

Where

$$[KM] = \begin{Bmatrix} \frac{1}{3} & \frac{1}{6} \\ \frac{1}{6} & \frac{1}{3} \end{Bmatrix} ; \quad [LM] = \begin{Bmatrix} -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{Bmatrix}$$

$$\{M\} = \begin{Bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{Bmatrix} ; \quad \{A\} = \begin{Bmatrix} A_1 \\ A_2 \end{Bmatrix} \quad \{Q\} = \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix}$$

l = length of the element, m, and

A = time differential of the area

If the time differential of the area is represented by a simple explicit time integration procedure

$$A(t) = \frac{A(t+dt) - A(t)}{dt} \qquad (23)$$

Where dt = time increment, the equation for one linear element becomes

$$\frac{1}{dt}\ [KM]\ \{A\}_{t+dt} - \frac{l}{dt}\ [KM]\ \{A\}_t + [LM]\ \{Q\}_t - l\,q\ \{M\} = 0 \qquad (24)$$

For the element equation to be adapted to a finite element grid consisting of more than one element, it must be arranged to cover the total number of elements. The direct stiffness method (Desai and Abel 1972) has been used in this formulation to obtain the assembled matrices

Similarily, one can derive finite element equation of continuity equation using cubic interpolation function as follows :

$$[KM] = \frac{1}{1680}\begin{Bmatrix} 128 & 99 & -36 & 19 \\ 99 & 648 & -81 & -36 \\ -36 & -81 & 648 & 99 \\ 19 & -36 & 99 & 128 \end{Bmatrix}$$

$$[LM] = \frac{1}{240}\begin{Bmatrix} -120 & 171 & -72 & 21 \\ -171 & 0 & 243 & -72 \\ 72 & -243 & 0 & 171 \\ -21 & 72 & -171 & 120 \end{Bmatrix}$$

$$\{M\} = \frac{1}{8}\begin{Bmatrix} 1 \\ 3 \\ 3 \\ 1 \end{Bmatrix} \quad ; \quad \{\dot{A}\} = \begin{Bmatrix} \dot{A}_1 \\ \dot{A}_2 \\ \dot{A}_3 \\ \dot{A}_4 \end{Bmatrix}$$

and $\{Q\} = \begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{Bmatrix}$

Time increment for solution convergence : Courant condition (Viessman 1972) has been used as the criterion to select the time increment, dt, which states

$$dt \leq l/c \qquad (25)$$

Where c = kinematic wave speed, m sec^{-1}, which is equal to (5/3 v)

UPLAND EROSION

Because of the similarity between equations (1) and (8) sediment continuity equation can be expressed in its finite element form as

$$l\,[KM]\{A_s\}+[LM]\{q_s\}-l\,D\{M\}=0 \quad (26)$$

At each time step q may be determined by $q_s = A_s V$ (27)

For the solution of Eq. (26) it has been assumed that untill flow initiates sediment detached due to rainfall is reattached to the soil surface and no movement of the sediment occur in the rills. Also, the

interrill erosion results primarily from detachment by rainfall and transport capacities of the rainfall and interrill sheet flow are only high enough to carry the detached soil material from interrill areas into rills.

The steps followed to solve Eq. (26) are :

1. Compute total available sediment load at last node of the overland strip from Eq (26),
2. Compute transport capacity, T_c, at last node of the strip,
3. If $T_c \geq q_s$, the sediment load is limited by availability of the eroded material and $q_s = q_s$,
4. If $T_c \leq q_s$, soil erosion is transport capacity limited and therefore $q_s = T_c$,

VERIFICATION OF FINITE ELEMENT METHOD WITH ANALYTICAL SOLUTION

Since the analytical solutions to the kinematic wave approximation are not available the verification of the finite element solution (FES) has been made with analytical solution (Eagleson 1970) based on the following assumptions.

1. Rainfall excess is invarient in time and space,
2. Catchment is a uniform plane whose surface roughness, slope and flow regime are invarient in time and space, and
3. Duration of rainfall excess is finite.

Analytical solution (Eagleson 1970) is presented here. The notations used are as follows :

x = distance along the plane, m

h = depth of flow, m

L = length of the plane, m

i = rainfall excess, m sec^{-1}

$\alpha = S^{1/2}/n$

$m = 2$ in the flow equation

$$Q = \alpha h_m$$

t_r = duration of rainfall excess, sec

t_c = time of concentration, sec, which is equal to $(L.i^{1-m}/\alpha)^{1/m}$

Case (1) $t \leq t_c \leq t_r$ (28)

$$h = i.t$$

Case (2) $t_c \leq t \leq t_r$

$$h = (L.i/\alpha)^{1/m} \quad (29)$$

for the computation of the flow profile

$$h = (x.i / \alpha)^{1/m}, \quad 0 \leq x \leq L \qquad (30)$$

Case (3) $t \geq t_r \geq t_c$

h is given by the implicit relation.

$$L = h^{m-1} (h.i^{-1} m (t-t_r)$$

A computer program has been written to compute the depth and discharge as a function of space and time for a given rainfall excess rate.

Comparison of FES (using linear interpolation function) with analytical solution

Finite element solution has been obtained using linear interpolation for a hypothetical case of flow over a flow plane of 100 m depth. The parameters assumed were :

Slope = 0.01

Manning's n = 0. 025

Time step = 30 sec.

A rainfall excess rate of 6 mm h^{-1} is assumed for a period of 2h and the flow plane has been divided into three elements of equal length. Solution has been obtained using explicit time integration scheme. The comparison is shown in Fig. 1

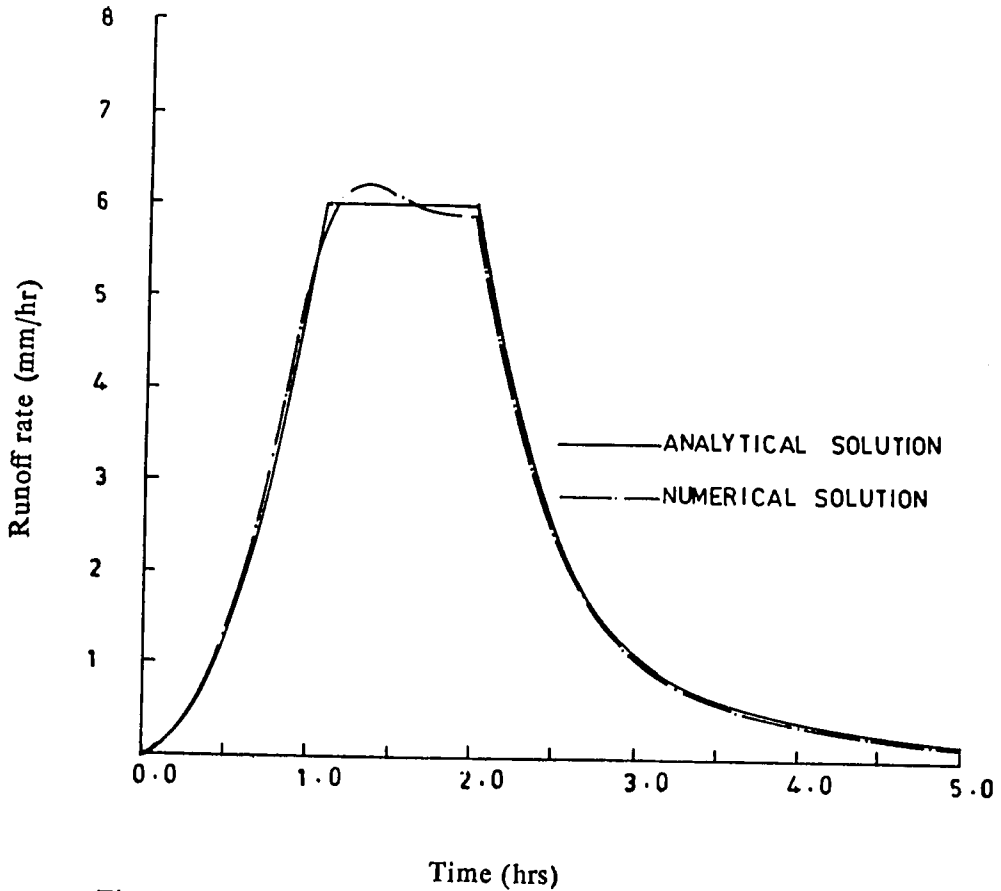

Fig. 1 Comparison of the hydrograph of numerical solution using linear interpolation function with that of the analytical solution

Comparison of FES (using cubic interpolation function) with analytical solution

A similar comparison is made using cubic interpolation function in the finite element solution. In this case the flow plane has been considered to be consist of one cubic element and rest of the conditions and value of parameters are assumed to be same as that in the solution obtained using linear interpolation function. The result is shown in Fig 2. It illustrates that both the interpolation functions give good agreement with the analytic solution. A comparison of flow profiles using three cubic elements give good agreement between analytical and numerical solution (Fig. 3) .

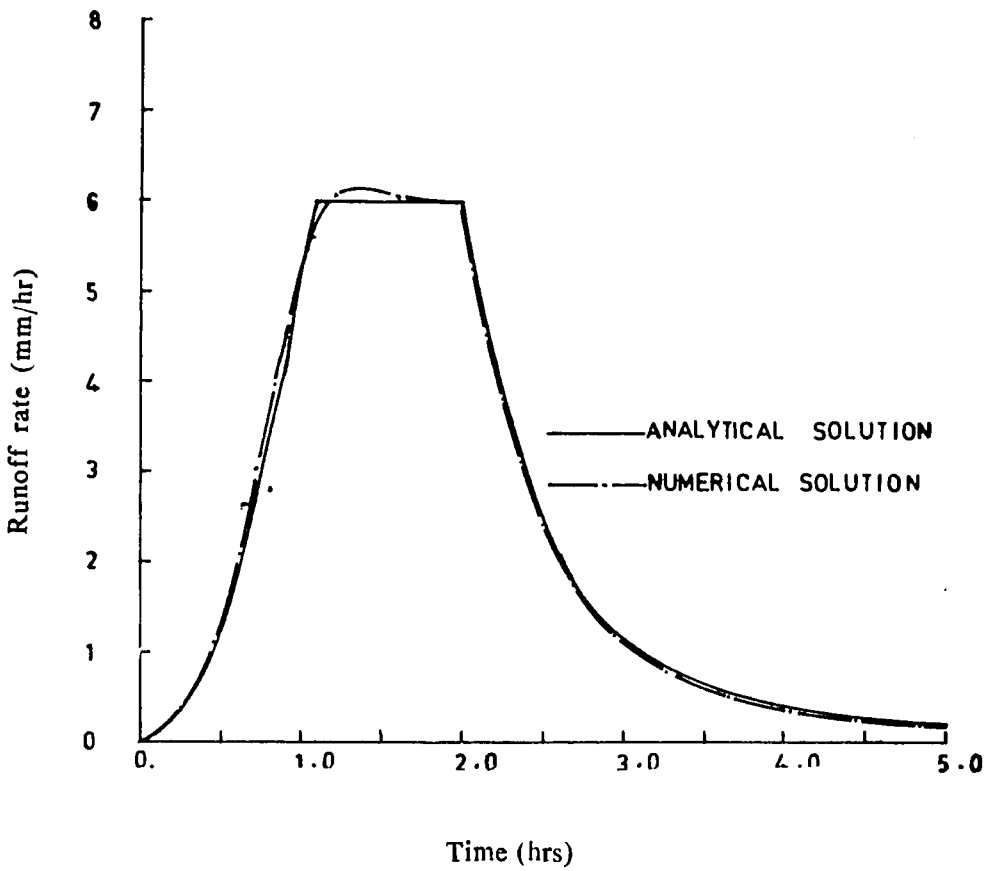

Fig. 2 Comparison of the hydrograph of numerical solution using cubic interpolation function with the analytical solution

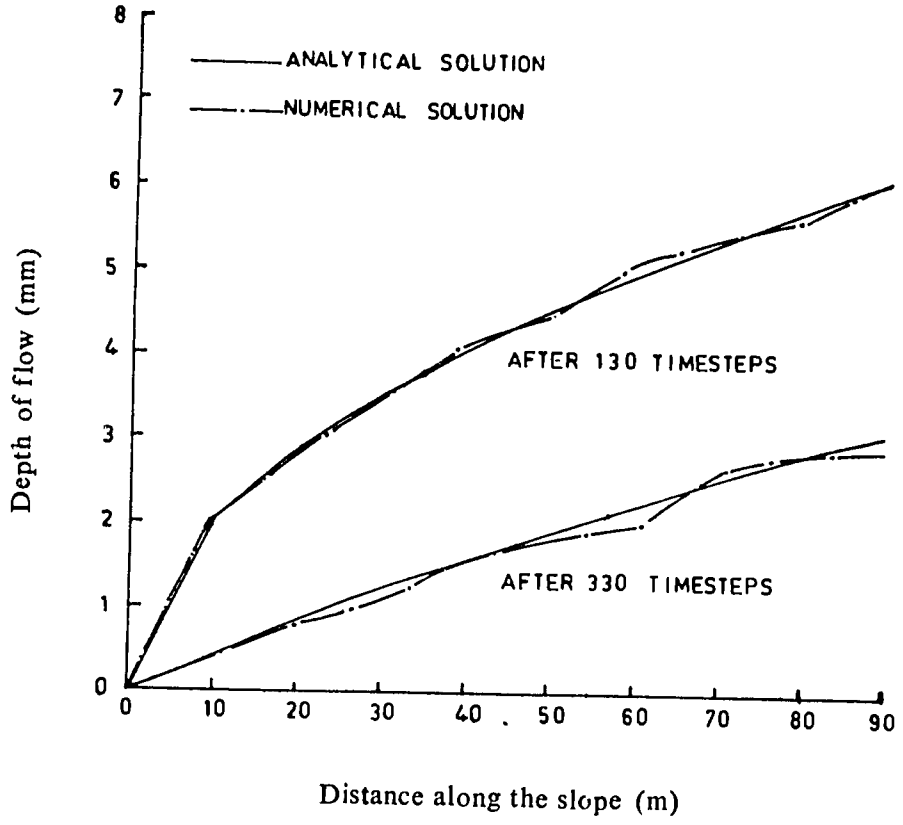

Fig.3. Comparision of flow profiles using cubic interpolation function

VALIDATION OF THE MODEL

The mathematical model has been verified by a set of observed data reported by Akan and Ezen (1982). The composition of the given soil is 22% clay, 24% silt and 54% sand. It has a hydraulic conductivity of 0.324 mm h^{-1}, suction at the wetting front of 400 mm. The particle sizes of different fractions of soil are taken as 0.002 mm for clay, 0.01 mm for silt and 0.2mm for sand. The kinematic viscosity of water is taken as 1.146×10^{-6} $m^{-2}sec^{-1}$ at 15°C. The other parameters adopted for this soil in the numerical solution are,

COFI=0.001, COFI=0.1, K = 0.011
SG = 2.65 for all particle types.

Eight different flow conditions examined together with the assumed saturated moisture deficit (M) and Manning's n values are summarized in Table 1. In the first four cases the overland flow length is 23m with a bottom slope of 0.10. In the remaining cases the overland flow plane is 21.9m long and a bottom slope of 0.17.

The FES has been obtained by using cubic interpolation function. Also shown in the Table 1 are the observed and the computed results.

Table 1. Comparison of computed and observed results

Case no.	M	n	Rainfall intensity (mm h^{-1})	Rainfall duration (min)	Soil loss (Kg m^{-1}) observed	Soil loss (Kg m^{-1}) computed	Runoff(m^3) observed	Runoff(m^3) computed
1	0.310	0.180	18.0	10	0.014	0.013	0.001	0.002
2	0.255	0.012	23.8	15	0.070	0.080	0.040	0.051
3	0.155	0.006	37.8	12	0.115	0.123	0.100	0.111
4	0.220	0.020	10.8	35	0.055	0.055	0 026	0.026
5	0.310	0.180	18.0	10	0.022	0.023	0.002	0 002
6	0.255	0.012	23.8	15	0.120	0.119	0.048	0.051
7	0.155	0.006	37.8	12	0.170	0.169	0.110	0.111
8	0.220	0.020	10.8	35	0.090	0.087	0 027	0.026

A perusal of the tabulated values show that good agreement exists between the simulated values and the observed results for all the four cases examined.

CONCLUSIONS

The event based soil erosion simulation model, presented in the paper, utilizing the distributed parameter approach, gives good agreement with the total soil loss from the overland flow plane. It need to be further tested with the observed sediment graph to test its potential for temporal distribution of the sediment load. The model requires only limited data input which is not difficult to collect. The model has the potential to assess the effect of the land use changes on the sediment yield because it utilizes the cropping and management factor of the USLE in the soil erosion component of the model.

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Planning and managing manmade forests in the hydel catchments of the Nilgiris

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ABSTRACT

The wealth of the plains depends on the health of the hill. The Nilgiri plateau located in Southern India forms a strategic part of the catchments of the rivers Moyar and Bhavani and their tributaries. It has been estimated that these reservoirs located across the tributaries of these rivers account for about 40 per cent of the hydro-electric power generation in Tamil Nadu State. The major portion of these catchments was originally under natural grasslands with pockets of natural *Shola* forests. The present land use in the district comprises of seasonal crops like potato and vegetables, tea and coffee plantations and manmade forests of *Acacia mearnsil* (black wattle) and *Eucalyptus globulus* (bluegum) which were planted up in many of these hydel catchments. The catchment studies in an area of 64 ha conducted at Glenmorgan of the Central Soil & Water Conservation Research & Training Institute, Research Centre Udhagamandalam revealed a reduction of 16 percent on an average in the expected water yield from the open grasslands, if the bluegum plantations are raised in these watersheds for the first rotation of 10 years (1972-1982), but these plantations do not add any sediment load into the reservoirs. During the first half of the second rotation (1983-1987), the reduction in total flow has further increased to about 25 per cent. Manmade forests were observed to have some moderating effects on instantaneous flow as compared to grasslands and hence planning and managing of the catchment areas for assured and steady inflow into the hydel reservoirs through appropriate silvicultural management is stressed.

The Nilgiris is located in South India (11°1' and 11°40'N.L. 70°10' and 76°10'E.L.) and the climate is warm temperate. It receives a mean annual rainfall of 0.759 to 2.537 m. The soils in the plateau are lateritic and derived from charnockites.

Out of the total geographical area of 2546 7 sq.km, the forests occupy 56.6 percent. This plateau forms a strategic part of the catchment of the rivers Moyar and Bhavani. The tributaries of these rivers have been harnessed for generating hydroelectric power and irrigation. About 40 percent of the total hydroelectric power production in Tamil Nadu is contributed by the Nilgiris district. Large scale afforestation of fast growing species such as *Acacia mearnsil* (black wattle) and *Eucalyptus globulus* (bluegum) were taken up on the grasslands in the hydel catchments by the Forest Department to meet the demands of fuel and industrial raw materials. The State Electricity Department objected to this large scale conversion of grassland into manmade plantations contending that this will deplete the runoff and affect the inflow into the hydel reservoirs. Hence the present investigation on stream flow were taken up at Glenmorgan Valley catchment by the Central Soil & Water Conservation Research & Training Institute, Research Centre, Udhagamandalam to quantify the effect of such conversions on stream flows at these two different locations.

MATERIALS AND METHODS

Two watersheds A and B having an extent of 33.18 and 31.89 ha respectively separated by a common ridge and having identical slope, soil, geology and land use were selected at Glenmorgan for the hydrological studies. The initial topographical, soil and vegetation surveys were conducted and gauging stations were established across the streams originating from the individual watersheds. A meteorological observatory to record daily rainfall and its intensity, maximum and minimum temperature and also open pan evaporation was set up on the ridge demarcating the two watersheds. At the time of initiation of the hydrological studies, the research watersheds A and B were having 15.67 percent and 8.34 percent area under *Shola* forests, 76.80 percent and 84.14 percent area under grassland while the remaining area of 7.53 percent and 7.52 percent was under swamps, respectively. The important characteristics of both the watersheds are given in Table 1.

Table 1. Topographical characteristics of the watersheds

Characteristics	Watershed	
	A	B
Area (ha)	33.18	31.89
Shape index	2.22	1.03
Max. length of stream (m)	450	380
Stream density (km/km²)	1.36	1.19
Average slope (%)	21	17
Mean elevation (m)	2266	2216
Watershed relief (m)	55	61
Time of concentration (minutes)	10.30	9.10
Perimeter (m)	2315	2214
Form factor	0.41	0.49
Compactness coefficient	1.13	1.11

Data on total monthly discharge were collected for four years, viz., 1968-69 to 1971-72 (calibration period) from both watersheds A and B in its original conditions, under natural grassland and *Shola*. In one of the watersheds B, bluegum was raised in part of the area above the frost line during July, 1972. The rest of the area in watershed B and the entire watershed A was maintained in its original conditions under natural grassland and *Shola*. The stream gauging was done with the help of 2:1 broad-crested masonary weir with automatic stage level recorders during calibration period and post calibration period. At the end of 10 years(1982) rotation, the bluegum was felled under coppice system and the data were analysed. In both the watersheds, one with coppiced *E. globulus* and other with natural vegetation, studies have been carried out from 1983 to find out the effect of coppiced *E. globulus* on water yield. In order to quantify the effect of conversion of natural grasslands with bluegum plantations on water yield in the Nilgiris, the paired watershed technique was adopted.

RESULTS AND DISCUSSION

Negligible difference was observed in the total monthly discharge from the watershed during the calibration period confirming the hydrological homogenity of the watershed. The regression equations were developed based on data collected during this period (1968-72) for estimating the total runoff for watershed B from the observed values for watershed A such that any future change in hydrological behaviour brought about due to change in land use could be quantified in relation to the equations developed during the calibration period (1968-72). Linear regression equation was developed for total runoff in watershed A Vs. total runoff in watershed B. The runoff calibration equation is given below:

$$Y_1 = (-)\ 4.4377 + 1.1736\ X_1 \quad \ldots \qquad (1)$$

$$r = 0.987, \text{ significant at 1 percent level}$$

Where Y_1 = Total runoff in catchment B, mm

X_1 = Total runoff in catchment A, mm

The high value of correlation coefficient indicates that the two watersheds are identical in their hydrological behaviour.

POST CALIBRATION PERIOD

before coppicing

Double mass curve for total runoff was drawn to study the behaviour of water yield in both the watersheds. It was observed that during the period 1972 to 1974 after the plantation of bluegum in watershed B, the difference in total flow between the two watersheds continued to be negligible. However, from 1975 onwards watershed B has produced relatively lesser discharge as compared to watershed A. To assess the impact of bluegum plantation on water yield, the equation developed during the calibration period was used to compute the total runoff in watershed B as compared to watershed A, had the same earlier land use continued. These computed values when compared with the observed values of total flow in watershed B during the treatment period depict the net reduction due to the effect of bluegum plantation (Table 2).

Table 2. Observed and computed values of total runoff for catchment B

Year	Total runoff (m)	
	Computed	Observed
	Treatment period (1972-1981)	
1972	0.609	0.600
1973	0.541	0.523
1974	0.431	0.432
1975	0.787	0.585
1976	0.259	0.203
1977	0.556	0.479
1978	0.713	0.619
1979	0.697	0.516
1980	0.436	0.301
1981	0.463	0.368
	Coppicing period (1982-1987)	
1982	0.216	0.209
1983	0.221	0.189
1984	0.432	0.291
1985	0.266	0.219
1986	0.339	0.278
1987	0.277	0.183

To assess as to whether the differences in total runoff in the two watersheds is statistically significant or not, the student's 't' test was applied for the treatment period. The 't' test has revealed that the total flow in water shed B was significantly reduced after the treatment of bluegum plantation was imposed during 1972 to 1981. The average annual reduction in total flow was found to be 87 mm (16 percent) which is significant at 1 percent level. The study has further indicated that there was no soil loss after conversion of grasslands into bluegum plantations.

After coppicing

Both the watersheds A and B one with natural vegetation (grassland, *Shola* and swamps)and the other with coppiced *E globulus* were studied from 1982 to find out the effect of coppiced *E.globulus* on water yield. The monthly observed runoff (total flow) for the calender years 1982-87 for watersheds B and A and the computed runoff from watershed B during the coppicing period clearly indicated that the coppiced Eucalyptus caused further reduction in the total annual flow, the percent reduction varying from 16 to 34. The observed runoff data from the watersheds A and B and the computed runoff data for watershed B were subjected to student 't' test for finding out the statistical significance of the reduction in runoff. It was observed that the reduction in runoff was statistically significant at 1 percent level.

The reduction in total water yield from the moderately grazed grassland on account of conversion into *E. globulus* is given in Table 3.

The entire period of the experimentation from (1968-1987) has been divided into four periods, viz., calibration period (1968-72), middle of first rotation (1973-77), end of first rotation (1978 - 82) and first half of second rotation (1983 - 87). The runoff ratios for the treated watershed A for four quarters of the year (January-March, April-June, July-September and October-December) have been worked out. It was seen that the B/A ratios had progressively reduced in all quarters over years indicating the reduction on account of bluegum plantation. The reduction is more pronounced in the first quarter (January-March). Similar trends have been observed for half yearly periods also (January-June and July - December). On an annual basis also reduction has been observed in B/A ratios and it is to the tune of 23 percent.

CONCLUSIONS

If the resevoir capacities are not affected adversely due to plantations of black wattle and bluegum in hydel catchments and the reduction of 16 to 20 percent in the expected water yield can be afforded, the plantation of these fast growing species can be economically practised as the loss in water yield will certainly outweigh by the good returns from them after a period

Table 3. Runoff depth (mm) and runoff ratios

Quarter-year periods	1968-1972 (Calibration period)			1973-1977 (Middle of rotation)			1978-1982 (End of 1st rotation)			1983-1987 (2nd rotation first half)		
	A	B	B/A	A	B	B/A	A	B	B/A	A	B	B/A
January-March	36.84	30.88	0.838	38.41	30.52	0.795	44.30	26.67	0.602	28 00	15.91	0.568
April-June	76.73	62.35	0.813	67.83	55.92	0.824	66.45	42.59	0.641	43.05	27.85	0.647
July-September	169.57	185.11	1.092	241.97	240.97	0.996	222.62	189.11	0.849	121.43	100.29	0.826
October-Dec.	128.50	143.59	1.117	139.85	133.13	0.952	168.98	154.61	0.915	94.63	88.08	0.931
	411.64	421.93	1.025	488.06	460.54	0.944	502.35	412.98	0.822	287.11	232.13	0.808
Half year periods												
January-June	113.57	93.23	0.821	106.24	84.44	0.814	110.75	69.26	0.625	71.05	43.76	0.616
July-Dec.	298.07	328.70	1.103	381.82	374.10	0.980	391.60	343.72	0.878	216.06	188.37	0.872

of ten years. The reduction in total water yield can be further minimised by adoption of suitable silvicultural management practices such as wider plant spacing and by reducing rotation period from ten years to a lesser period of eight years. If these plantations are to be raised over the entire catchment area, the area should be covered with different maturity periods of plantation to minimise their undesirable effect such as drastic reduction in water yields due to simultaneous peak water consumption, lack of enough canopy in the initial stages etc. As these two fast growing species are managed on similar rotation periods and since these do not hinder the management practices, it is desirable to have these two species mixed in alternate rows under a two storeyed high forest system.

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A water yield model for small semi-arid watersheds of India

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ABSTRACT

A physically based hydrological model for predicting storm runoff, soil moisture storage, evapotranspiration and deep percolation for small watersheds is presented. The model integrates the processes such as infiltration, soil moisture redistribution and evapotranspiration with a reasonable data demand. The model was tested on two small watersheds in India under two extremes of land use. Close agreement between measured and predicted runoff and soil moisture was observed. By virtue of its physical basis, the model found a possible wide range of applications beside the prediction of surface water yield. It can be used for scheduling irrigation, estimating natural recharge to groundwater, determining effective rainfall and evaluating hydrological effects of land use changes in watersheds.

Most hydrological models in practical use today are of the conceptual type, i.e, based on a simplified conceptualization of the hydrological cycle and to a large degree ignoring the physical basis of the individual hydrological processes. Such models have proved very useful for some applications, e.g. extension of runoff time series, provided that historical data exist to calibrate the model parameters. Although the parameters of such models bear some relation to the subsystems which they represent, they do not have a direct physical interpretation and cannot be measured in the field. Hence, in some important investigations involving hydrology of ungauged catchments or effects of land use changes the modelling approach must necessarily be changed to include physical and measurable parameters.

However, hydrological processes are so complex in nature that it is almost impossible to develop a purely physically based model. Such a model would be so complex and data demanding that its practical value will be questionable. Hence, the present model allowing for some degree of conceptualization of its physically based parameters can be viewed as a compromise between the complexity of the hydrological processes, limitations on data availability and the advantages of model simplicity. This model type obviate rigorous calibration. Even a single storm event is sufficient to calibrate the model.

The present model is confined to the prediction of runoff, soil moisture storage in the root zone, evapotranspiration and deep percolation largely from small, flat agricultural water-

sheds. A small watershed is considered as a point source of runoff generation and the model does not account for possible spatial variability of the individual hydrological processes within a watershed. Routing of the generated runoff to the outlet of the watershed is beyond the scope of the model as from an agricultural point of view, it is the amount of runoff which is considered important.

THE MODEL

The model integrates the following hydrological processes : infiltration, surface depression storage, soil water flow in the root zone, soil evaporation, plant transpiration, deep percolation and direct runoff. Fig. 1 gives physical delineation of the above processes. Interception and interflow are not taken into account, as these processes can be assumed to be negligible in most small flat watersheds with agricultural crops.

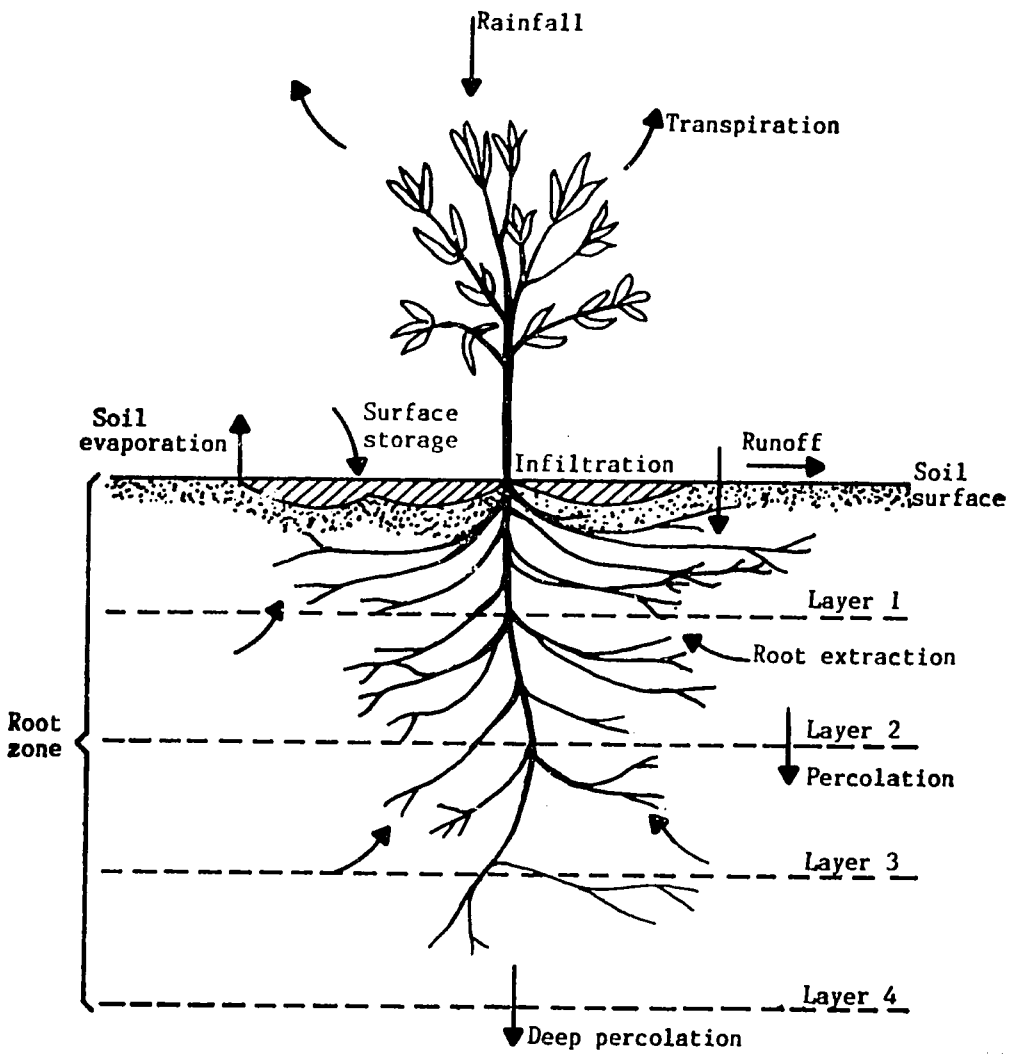

Fig.1. Hydrologic processes included in the model

Infiltration

The infiltration process is modelled by the Green-Ampt model with its later modifications introduced by Mein and Larson (1971) to describe the pre-ponding and post-ponding stages of the infiltration process as follows :

$$f = I; \qquad F = I.t \leq F_p \qquad \text{(pre-ponding)}$$

$$f = I; \qquad F = F_p = \frac{M.S}{(I/k_s) - 1} \qquad \text{(at ponding)}$$

$$f = k_s \left(1 + \frac{M.S}{F} \right); \quad F = \int f dt \geq F_p \qquad \text{(post ponding)}$$

where f = infiltration rate (mm hr^{-1})

I = rainfall intensity (mm hr^{-1})

F = infiltrated volume (mm)

F_p = infiltrated volume at time of surface ponding (mm)

M = soil moisture deficit (vol vol^{-1})

S = suction at the wetting front (mm)

k_s = hydraulic conductivity at field saturation (mm hr^{-1})

This model has been chosen due to the physical significance of the parameters and because of simplicity and flexibility of the model. The model has been verified experimentally and performs satisfactory under field conditions (Idike *et al.* 1982). Furthermore the model can be adopted to account for variable rainfall intensity by introducing the concept of surface indicators of ponding (Chu 1978).

Runoff

The infiltration component decides the amount of runoff. In case the current infiltration capacity is exceeded the excess stays as the surface depression storage. If this storage gets filled up the excess goes out as runoff.

Soil moisture flow

For an accurate simulation of the current soil moisture deficit (M) used in the Green-Ampt-Mein-Larson infiltration model, a model for soil moisture flow was developed based on the governing equations, i.e. Darcy's Law and the continuity equation.

Darcy's Law can be written in its diffusive form as

$$q = K(\theta) - D(\theta)\frac{d\theta}{dz} \quad (1)$$

where q = soil water flux

$K(\theta)$ = hydraulic conductivity

$D(\theta)$ = soil moisture diffusivity

θ = actual soil moisture content

The continuity equation will read

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S \quad (2)$$

where S represents a sink term accounting for evapotranspiration loss.

Combining (1) and (2) results in Richard's equation which is the governing equation for soil moisture flow in the unsaturated zone.

To solve the governing flow equations a simple difference scheme is adopted in the present model. First the root zone is divided into four layers of equal thickness, and the soil moisture content in each layer at each time step is estimated using Eq. (2) in its finite difference form.

$$\theta_{nt+1} = \theta_{nt} - \Delta t\,(q_o - q_i + S)/L_n \quad (3)$$

where n = layer number

q_i = inflow to layer n

q_o = outflow from layer n

L_n = thickness of layer n

q_o and q_i are estimated from Eq. (1) using average values of $K(\theta)$ and $D(\theta)$ between two layers. The inflow to the upper layer is the infiltration simulated by the Mein–Larson model. Simulated outflow from the fourth layer to the saturated layer below is regarded as deep percolation.

Evapotranspiration

Actual evapotranspiration from the soil moisture storage is determined as a fraction of the potential evapotranspiration using a slightly modified version of the model used by Refsgaard (1981), which has been verified

experimentally under field conditions. According to this model the transpiration component from each layer is derived as follows :

$$ET_n = EP.f_1(\theta_r).f_2(LAI).RDF_n \quad (4)$$

where ET_n = actual transpiration from layer n

EP = potential evapotranspiration

LAI = leaf area index

RDF_n = root distribution factor for layer n

θ_r = relative moisture content = $(\theta_n - \theta_{wp})/(\theta_{FC} - \theta_{wp})$

θ_n = actual moisture content in layer n

θ_{wp} = moisture content at wilting point

θ_{FC} = moisture content at field capacity

and f_1, f_2 = two functions as illustrated in Fig. 2.

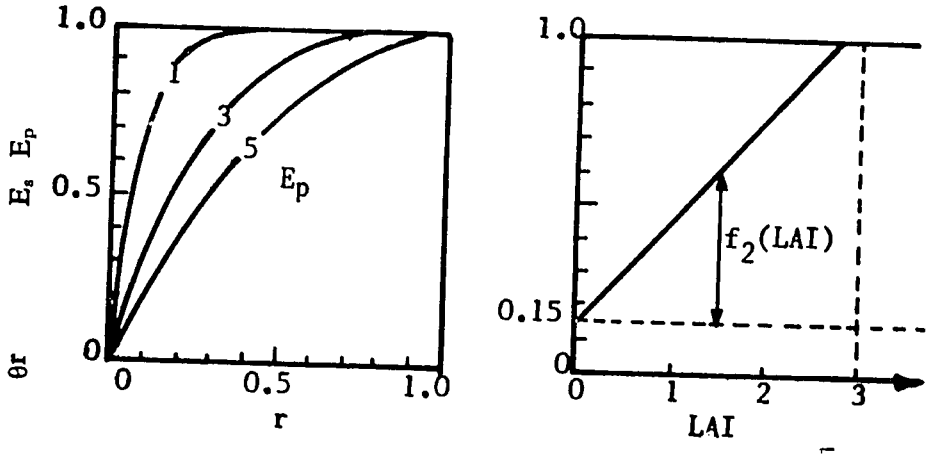

Fig.2. Functions used for determining the transpiration component

To estimate the actual evapotranspiration, soil evaporation E_s must be added. In the model, soil evaporation is assumed to depend on the moisture content of the uppermost layer and the vegetation cover. An emperical relationship is used for the prediction of soil evaporation, which in the case of bare soil is illustrated in Fig. 3. If the soil is covered by vegetation the soil evaporation function is adjusted to account for the corresponding reduction of evaporation.

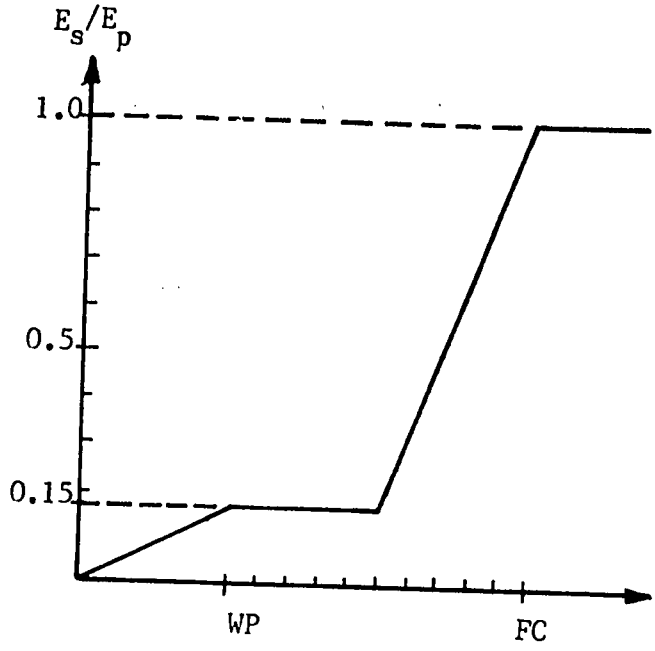

Fig.3. Soil evaporation in case of a bare soil

DATA REQUIREMENTS

The data required for running the computer model is listed and explained below.

Meteorological data

— Rainfall data, hourly data are better.

— Potential evapotranspiration, daily data. As an alternative daily evaporation data from a Class A pan. The model will adjust the evaporation data by a pan coefficient depending on location of the pan, the relative humidity and wind speed according to Doorenbos and Pruitt (1977).

— Daily runoff data, for calibration and test period only.

Soil data

— Saturated hydraulic conductivity K_s is the most important parameter in the infiltration equation. Bouwer (1969) recognized that the hydraulic conductivity in the Green–Ampt equation should not be taken as the K_s from laboratory experiments but rather as 0.5 K_s due to air entrapment in field situations.

— Retention curve for the actual soil, i e, the relationship between suction ψ and soil moisture content θ, is required for the soil moisture flow submodel and may be obtained from experiments.

— Given the retention curve the K–θ and D–θ relationships can be derived theoretically by the method given by Jackson (1972). Furthermore the K-ψ relationship can be derived and the average suction rate S at the wetting front can then be estimated to be used in the infiltration submodel.

— Moisture content at saturation, field capacity and wilting point can be assessed from experiments.

Vegetation data

— Leaf area index during the growing season.

— Root distribution in the various layers of the root zone during the growing season.

Calibration parameters

Due to the physical basis of the present model only 3 empirical parameters are left for calibration. Two of them are related to the evapotranspiration submodel, one for the transpiration process (Fig. 2) and one for the soil evaporation (Fig. 3). Previous studies, Refsgaard (1981) and Panda (1986) have shown that these two parameters are very little sensitive to evapotranspiration simulation, and they are approximated by calibration.

The more important calibration parameter is the detention storage capacity in the field. This is not easy to measure in the field and is determined by calibration.

CALIBRATION AND TEST OF THE MODEL

The model was calibrated and tested on two small research watersheds BW1 and BW4C at ICRISAT, India. BW1 has an area of 3.4 ha, slope 1.2–1.5%, the land treatment practice is broad bed furrows which intercept runoff and increases the opportunity time for infiltration. The watershed is cropped with sorghum with sowing date 15th June. BW4C has an area of 3.5 ha, slope 1.3% and remains fallow.

Data assessment

All data required for the model simulation of the two watersheds were obtained from ICRISAT. The soils of both watersheds are deep clay Vertisols with soil moisture at saturation 48%, field capacity 44% and average wilting point for the total root zone 30%. The saturated hydraulic conductivity is 0.41 mm hr^{-1}, whereas the equilibrium infiltration rate was estimated to 0.26 mm hr^{-1} for BW1 and 0.16 mm hr^{-1} for BW4C based on field measurements. The lower value for BW4C is due to lower infiltration rate exhibited by an uncropped watershed. A retention curve for the two watersheds was available and for the cropped watershed BW1 also a seasonal leaf area function and root distribution function.

Model calibration

The model was calibrated against observed runoff data of 1975 for watershed BW1 and runoff data of 1976 for watershed BW4C. Remaining runoff and soil moisture data from 1974–76 were kept to be utilized for verificaotion of the model for both watersheds.

The calibration was performed mainly by varying the detention storage capacity (DS) and comparing the simulated and the observed storm runoff volume by eye judgement. As expected, an increase of DS caused a decrease in runoff and *vice versa*. The final calibration values of DS giving the best fit were 2.0 mm for watershed BW1 and 0.5 mm for watershed BW4C, reflecting the difference between the land treatment and land use of the two watersheds.

The calibration results are given in Fig.4 and Fig.5 for the two watersheds, comparing the simulated and observed runoff volumes for storms with generated or observed runoff. All storms except the first few events at the beginning of the wet season are simulated very close to the observed values. The overprediction of the first few events may be attributed to high infiltration due to the presence of surface cracks resulting from the inherent low soil moisture content in the beginning of the wet season.

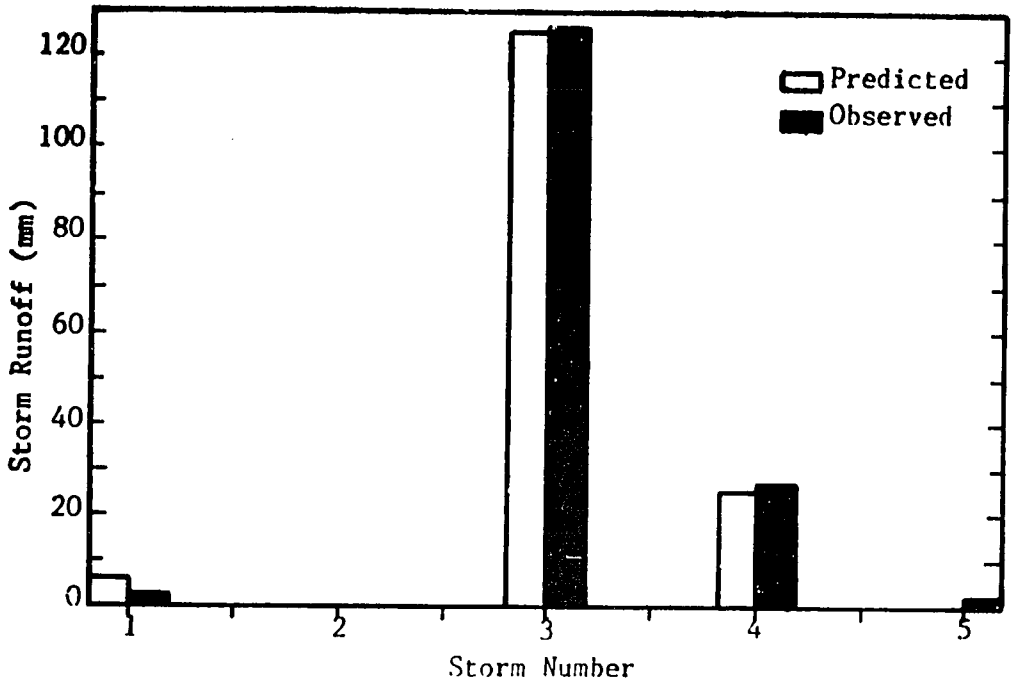

Fig.4. Predicted runoff vs. observed runoff, BW1, 1975 (Calibration)

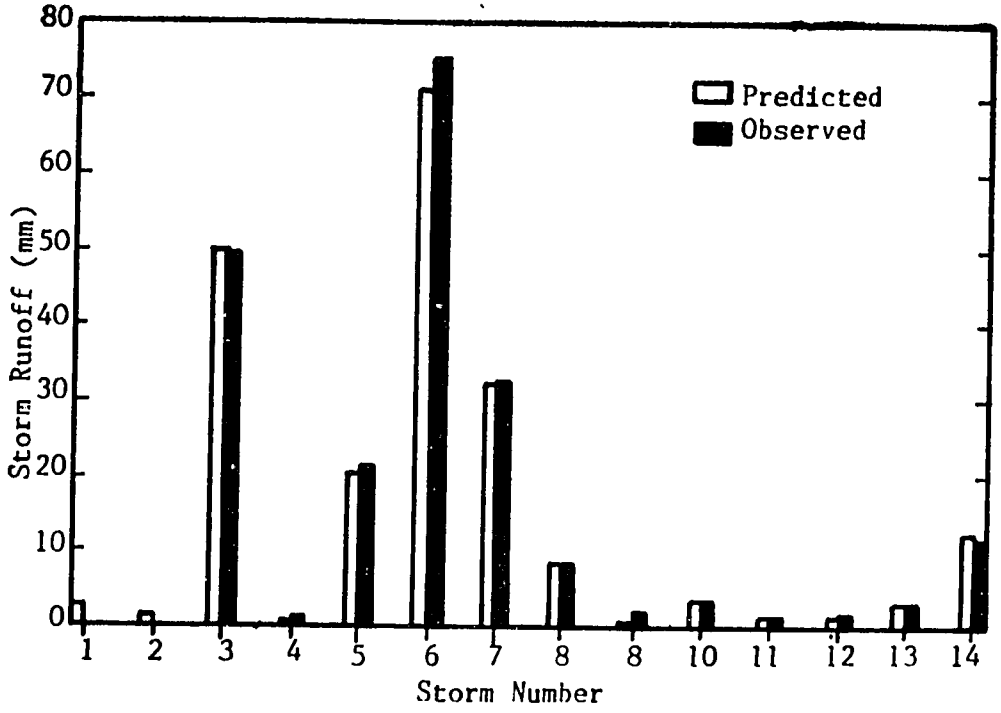

Fig.5. Predicted runoff vs. observed runoff, BW4C, 1976 (Calibration)

Model testing and discussion

The model was tested for the two watersheds using observed runoff and soil moisture data for years different from those used for calibration. In Tables 1 and 2 the predicted and observed runoff volumes from the two watersheds are given for all runoff generating events. Figs 6 and 7 show the comparison betwen predicted and observed soil moisture content in 1974 for both watersheds.

Table 1. Comparison of predicted and observed runoff events for BW1 (verification)

Day	Rainfall (m)	Runoff Predicted (m)	Runoff Observed (m)
27/06/74	0.075	0.026	0.026
09/08/74	0.051	0.001	0.003
10/08/74	0.036	0.005	0.005
13/09/74	0.037	0.005	0.005
24/09/74	0.036	0.002	0.001
16/10/74	0.089	0.065	0.061
23/10/74	0.052	0.011	0.012
24/10/74	0.010	0.000	0.002
02/07/76	0.014	0.003	0.002
21/07/76	0.098	0.016	0.017
04/08/76	0.027	0.004	0.002
19/08/76	0.110	0.025	0.027
20/08/76	0.042	0.019	0.020
21/08/76	0.010	0.003	0.004
Total		0.185	0.186

Table 2. Comparison of predicted and observed runoff for watershed BW4C (verification)

Day	Rainfall, m	Runoff Predicted, m	Runoff Observed, m
27/06/74	0.064	0.018	0.017
05/07/74	0.027	0.004	0.002
09/08/74	0.051	0.011	0.011
10/08/74	0.035	0.015	0.016
11/09/74	0.042	0.011	0.010
13/09/74	0.037	0.014	0.014
24/09/74	0.028	0.001	0.001
25/09/74	0.014	0.006	0.005
13/10/74	0.032	0.009	0.011
05/10/74	0.014	0.009	0.008
16/10/74	0.089	0.068	0.068
23/10/74	0.056	0.039	0.036
24/10/74	0.012	0.010	0.011
06/07/75	0.012	0.002	0.000
08/07/75	0.052	0.002	0.000
30/07/75	0.050	0.004	0.005
16/08/75	0.022	0.002	0.002
04/09/75	0.024	0.007	0.005
07/09/75	0.014	0.002	0.002
08/09/75	0.024	0.010	0.009
09/09/75	0.162	0.140	0.139
16/09/75	0.028	0.006	0.006
17/09/75	0.014	0.001	0.002
24/09/75	0.073	0.044	0.045
07/10/75	0.017	0.002	0.001
10/10/75	0.012	0.003	0.001
17/10/75	0.023	0.002	0.003
18/10/75	0.024	0.009	0.012
19/10/75	0.014	0.008	0.007
23/10/75	0.018	0.003	0.003
27/10/75	0.016	0.003	0.003
28/10/75	0.006	0.001	0.001
29/10/75	0.009	0.002	0.004
Total		0.468	0.460

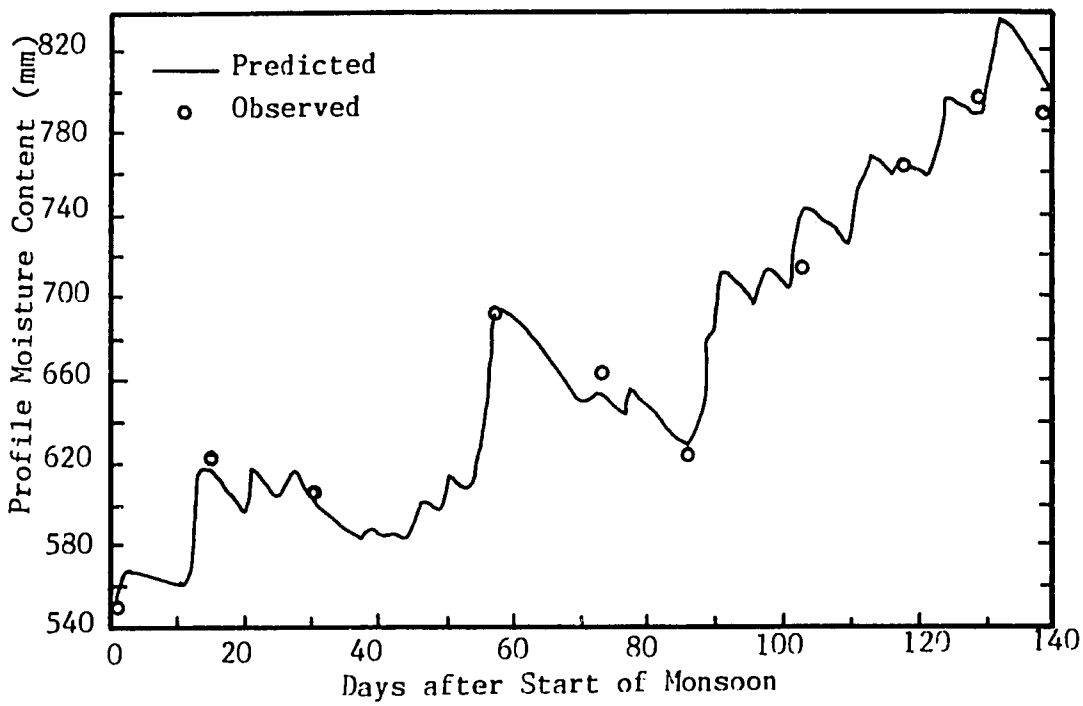

Fig. 6. Predicted vs. observed profile soil moisture, BW1, 1974

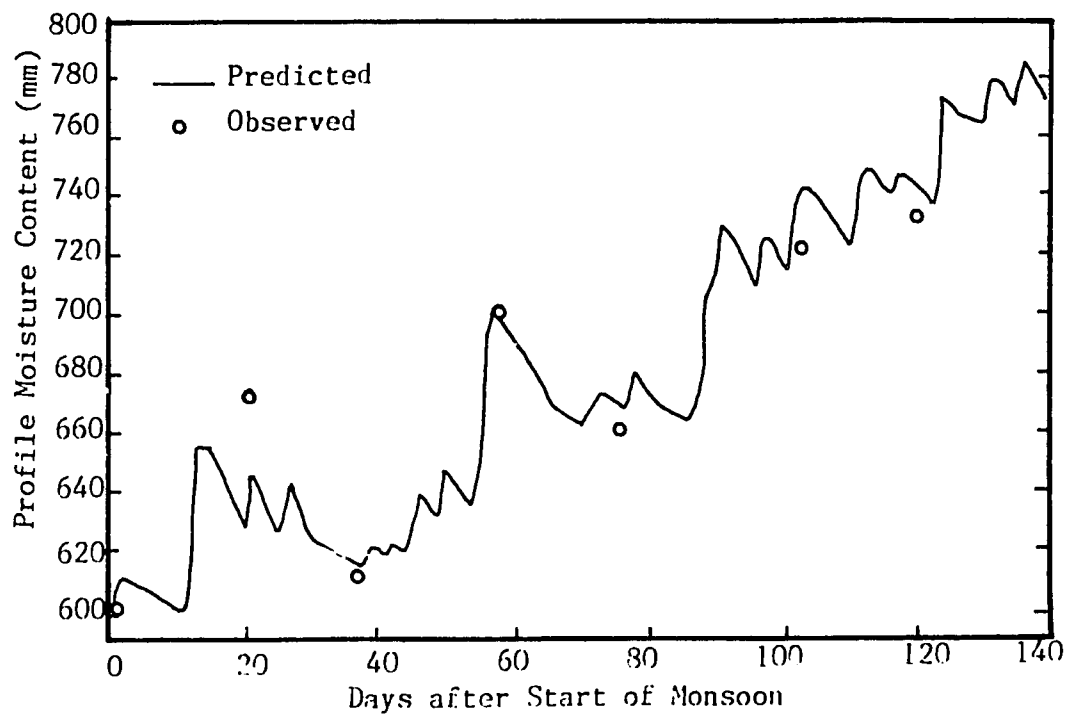

Fig.7. Predicted vs. observed profile soil moisture, BW4C, 1974

The results show that extremely good prediction of runoff and soil moisture content for both watersheds. The runoff values agree excellent as well on an event basis as on an annual basis. As for the calibration year there is a tendency to over predict the runoff in the first event in each year, probably caused by soil cracking due to low soil moisture content in the beginning of the wet season as shown in Fig. 6 and Fig 7.

It is interesting to note the difference in runoff from the two watersheds. Tables 1 and 2 show that the runoff is much higher from the bare soil watershed BW4C than from the cropped watershed BW1. On an annual basis the runoff volume varies between 26 and 32% of the annual rainfall for BW4C and between 11 and 17% for BW1. This difference is due to higher infiltration and higher evapotranspiration in a cropped watershed compared to a bare soil watershed.

In summary, the performance of the model is very satisfactory and encouraging with respect to future tests and application for ungauged small watersheds or areas subject to landuse changes.

Potential fields of application

Being of physically based model the present model overcomes the shortcomings of conceptual models which are not well-suited for several important applications, e.g. prediction of runoff from ungauged watersheds, i.e. watesheds where calibration is not possible. To overcome this problem there may be no alternative but to use a physically based model. Some examples of typical fields of application for the present model are :

- Prediction of the effects of changes in small watersheds, such as changes in landuse, urbanization and irrigation. The parameters of the model are directly physical parameters and therefore the change in parameter values corresponding to the watershed changes can be obtained directly.

- Prediction of runoff from ungauged watersheds and from watersheds with very short records. As opposed to the conceptual models, which require long historical time series of rainfall, runoff and evaporation data for the parameter assessment, the parameters of this model can be assessed directly from intensive, short-term field investigations.

- In addition to the prediction of runoff, the model predicts natural recharge to groundwater (deep percolation), variation of soil moisture content in the root zone which can be used for scheduling irrigation, and effective rainfall as the part of rainfall which is not lost for plant consumption as runoff and deep percolation.

Since the development of a general hydrologic model was not the scope of this study, some restrictions to the use of the model are obvious :

- the model may not apply to watersheds with significant spatial variability in soil properties.

- for hill slope watersheds where interflow may be a major contributor to stream flow, the model in the present form may not be valid.

- for areas with groundwater table close to the ground surface influencing the soil moisture status in the root zone, the soil moisture component of the model is to be modified.

- since the model does not account for interception loss the model predictions will not be reliable for watersheds covered by forest.

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A hydrological model for small agricultural watersheds

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ABSTRACT

A one-parameter model is developed to predict the surface runoff and deep percolation from rainfall on agricultural watersheds. The meteorological data needed as input for the model are: daily rainfall, wind speed, relative humidity, temperature, and sunshine hours. The root zone of the soil is divided into two layers, the top layer being smaller. The rainfall first fills the top layer to saturation, and any excess will appear as surface runoff. The moisture in the top layer is then redistributed over a depth just enough to bring it to the field capacity. Any excess moisture over that required to bring the entire root one to field capacity is considered to recharge the groundwater. The moisture in the top layer is subject to direct evaporation before sowing. After a crop is sown, evapotranspiration occurs depleting the moisture in the root zone. An actual evapotranspiration model is used to predict moisture depletion at higher tension values. A daily soil moisture account is maintained to provide initial conditions for the simulation on each succeeding day. Three categories of land use are considered, viz., bare soil, purely rainfed cropland and irrigated cropland. The depth of the top layer of soil, which represents the parameter to be calibrated, is determined from mean runoff.

The runoff from an agricultural catchment, which has a crop stand, is influenced by the presence of the crop through evapotranspiration and resistance to flow offered by the plants besides, slope of the land and tillage practice. There have been many hydrological models proposed from time to time, some of them very elaborate (Linsley et al. 1982). However, the kind of data that many models need as input is often not available in India. In this model, therefore, the effect of several factors have been lumped into a single parameter, and

a water balance approach has been used to estimate runoff on daily basis.

DESCRIPTION OF THE MODEL

The model is based on the calculation of the daily water balance for any desired length of time. A starting date is first chosen, which may be the first day for which data is available or the first day of the first calender year of the period, for which simulation is desired. On this date the root zone soil moisture is assigned a suitable value. If 1st January is chosen for starting, the soil moisture can be assumed to be at permanent wilting point (PWP). Any error in the assumed moisture content is likely to die down after a few days, and not propagate thereafter. The root zone soil is divided into a top layer (thickness t_1) and a bottom layer (thickness t_2), the top layer being relatively thin.

The thickness of the top layer of the soil, t_1, which is the only parameter required to be calibrated, is first assigned a trial value. The final moisture content θ_f on any day in the top layer is provisionally calculated as

$$\theta_f = \theta_i + \frac{P - E_a}{t_1} \quad (1)$$

Where θ_i = initial moisture content on the day, P = rainfall during the day and E_a = actual evaportion from the top layer during the day.

Evaporation occurs from bare soil till sowing takes place. The sowing date in any calender year is defined as the first day after 1st June when the total rainfall in the preceding 48 hours is not less than 20 mm. After sowing, evapotranspiration takes place according to evapotranspirative demand (determined by the weather and crop growth stage) and soil moisture status.

Potential evaporation : First, the potential evaporation E_a was calculated using the modified Penman method (Doorenbos and Pruitt 1979). The weather data required for the purpose was obtained from the University of Agricultural Sciences Meteorological Station at Bangalore. Data were available for 20 years from 1964 to 1983, and included daily rainfall amounts, windspeed, relative humidity, temperature and sunshine duration.

Bare soil evaporation : From the beginning of the year till the sowing date, only evaporation occurs from bare soil. This was considered to take place only from the top layer of thickness t_1 and soil moisture below this layer is not depleted. The actual rate of evaporation is taken as equal to the potential rate when moisture tension is less than 98 K Pa (Feddes 1986). If soil moisture is depleted further, actual evaporation will be less than potantial. The ratio of actual to potential evaporation becomes smaller with increasing tension, till a tension of 1472 K Pa (PWP) is reached, at which evaporation ceases to take place. The actual evaporation model used in the simulation is shown in Fig. 1. The soil moisture characteristic is needed to use this model. The moisture characteristics

for two soils chosen for simulation were generated from the mechanical properties of soils encountered in the Bangalore region, using regression coefficients developed by Gupta and Larson (1979) and are shown in Table 1.

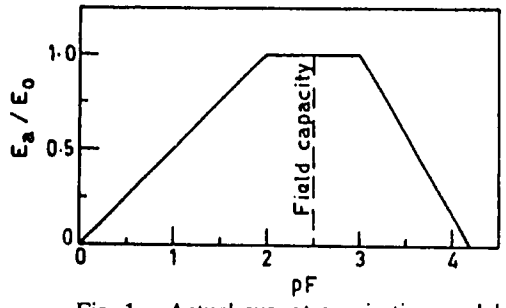

Fig. 1 Actual evapotranspiration model

Table 1. Moisture characteristics of soils for simulation

Soil No.	Tension, K Pa 3.9	6.9	9.8	19.6	29.4	58.9	98.1	196.2	686.7	1471.5
	Moisture content %									
1	52.5	47.7	44.5	39.2	36.1	33.3	31.2	28.9	25.3	23.4
2	62.0	57.4	54.2	48.1	44.3	40.4	37.7	34.5	30.0	27.9

Runoff : Runoff is assumed to occur when the top layer of the soil attains saturation. although in practice, infiltration in saturated soil continues to occur at a rate equal to the saturated hydraulic conductivity, the model accounts as surface runoff the entire surplus of daily rainfall over what is required to saturate the top layer. This assumption is made for the sake of simplicity, since the time distribution of daily rainfall is not known. Further, the full thickness of the top layer is considered to be saturated before runoff occurs, while in the actual process there would be a moisture gradient starting from saturation at the surface. The additional water quantity required to saturate the entire top layer will therefore tend to compensate the neglect of infiltration after saturation is reached. In order to determine the surface runoff R, θ_f is first calculated from eq. (1) and if θ_f is greater than the saturation moisture content θ_s, the excess is equal to R.

$$R = \theta_1\theta_f - \theta_s \qquad (2)$$

The value of θ_f is then reduced to θ_s in this case. If θ_f from eq. (1) does not exceed θ_s, its value is retained and surface runoff for the day is zero.

If the moisture content in the top layer is greater than the field capacity (θ_{fc}), it is redistributed over such a depth that the moisture content therein becomes equal to the field capacity. This depth, called the infiltration depth D_i, is given by the equation

$$D_i = t_1\left[\frac{\theta_s-\theta_{fc}}{\theta_{fc}-\theta_i}\right] \qquad (3)$$

If D_i is greater than the root depth, the amount of water that has infiltrated below the maximum root depth is assmed to join the groundwater. The model effectively assumes that soil below the maximum root depth is always at field capacity, since there is no depletion of moisture from it.

No further redistribution is assumed to take place, since the hydraulic conductivity of the soil at field capacity is very small and further movement of soil moisture is very slow. If θ_f as calculated by eq. (1) is less than θ_{fc}, no redistribution is assumed to take place. Until the sowing date, there is no depletion of moisture by evapotranspiration.

SIMULATION

Simulation of the hydrology of agricultural catchments was carried out for several scenarios. Three of them, discussed in this paper, are as follows :

(i) Purely rainfed crop.
(ii) Just enough irrigation is given to bring the soil to field capacity when the moisture tension exceeds 196 k Pa.
(iii) Bare soil.

The second simulation above was carried out mainly with a view to determine runoff from cropland irrigated with water from farm ponds.

Purely rainfed crop : After the sowing date, there will be depletion of soil moisture from the entire root zone, the depth of which keeps increasing over thirty days, and remains constant thereafter. The runoff after the land has been sown was calculated using the same criterion as that of bare soil, viz., saturation of the top layer, since the presence of the crop does not significantly affect the infiltration rate. As such, the rainfall is first added to the moisture in the top layer alone, as per eq. (1). The residual moisture in the top layer after adjusting for runoff is then uniformly distributed over the root depth for calculating the crop evapotranspiration based on the corresponding value of moisture content. The criterion for recharge occurrence was retained as for bare soil.

After harvest, the simulation is continued as for bare soil. The end-of-the-year moisture content becomes the initial moisture content for the succeeding year. Simulation was carried out in this way for twenty years, from 1964 to 1983, for which data were available. The crop chosen for simulation was sorghum. Crop coefficients for different growth stages were taken from Doorenbos and Pruitt (1979). The maximum rooting depth was taken as 1.83 m, and a linear growth rate of rooting depth of 0.061 m d^{-1} was assumed.

Irrigated crop : In the case of the crop with just enough irrigation being given to bring the soil upto field capacity, the timing of irrigation was decided on the basis of a moisture tension threshold. This threshold (or critical) moisture tension was taken here as 196 k Pa. As soon as the final moisture content θ_f in the

root zone falls below the value θ_{cr} corresponding to tension of 196 k Pa for the soil being simulated, irrigation of depth I was calculated from the equation

$$I = (t_1 + t_2)(\theta_{fc} - \theta_f) \quad (4)$$

After the irrigation, soil moisture content becomes equal to θ_{fc}, and subsequent simulation was carried out as before.

Bare soil : This case has been studied to determine the recharge and runoff from land left fallow, which happens in a small fraction of cultivable land due to special reasons such as land used as nurseries for seedlings being left fallow for the rest of the season, inability of farmers to raise resources, inadequate rainfall in the earlier part of the crop season etc. Since there is no depletion of soil moisture by roots, only the top layer figures in this simulation.

Parameter calibration : The parameter t_1 was determined by repeated trial and error, using the average runoff for the period of simulation for calibration. From streamflow records, it was found that the average runoff from catchments of predominantly rainfed cropland varied from 25% to 30% of the rainfall at different gauging stations. A value of 0.075 m for t_1 gave this magnitude of runoff, and is adopted here. The effect of various factors which affect runoff, namely, land slope, crop type, soil type etc. are all lumped into this one parameter, whose value is therefore specific to a region.

RESULTS AND DISCUSSION

Rainfed conditions : Figs. 2 and 3 show the runoff and groundwater recharge for Soils 1 and 2 respectively, plotted against rainfall under purely rainfed conditions for the twenty years of simulation, all quantities being taken for the crop season (from sowing to harvest.) A linear trend in the runoff-rainfall relationship can be noticed for both soils, but the presence of scatter indicates that antecedent moisture conditions cause deviations from the mean as is to be expected. The mean line is roughly the same for both soils and is given by the equation

$$R = 0.543P - 145 \quad (5)$$

In contrast, groundwater recharge is higher in the case of soil 1, which has an available moisture of 12.7%, than in soil 2, whose available moisture is higher at 16.4%. Because of the ability of soil 2 to store a larger amount of moisture, deep percolation into groundwater is reduced and a correspondingly larger evapotranspiration occured. The average recharge during the crop season over twenty years amounts to 0.025 m for soil 1 against 0.005 m for soil 2, the average seasonal rainfall being 0.528 m.

Irrigated conditions : Figs. 4 and 5 show the results of the simulation in irrigated conditions for soil 1 and soil 2, respectively. The mean runoff is higher than in rainfed conditions, especially when the seasonal rainfall was high. Recharge is also higher than in the rainfed case. Again, soil 1 allows higher recharge than

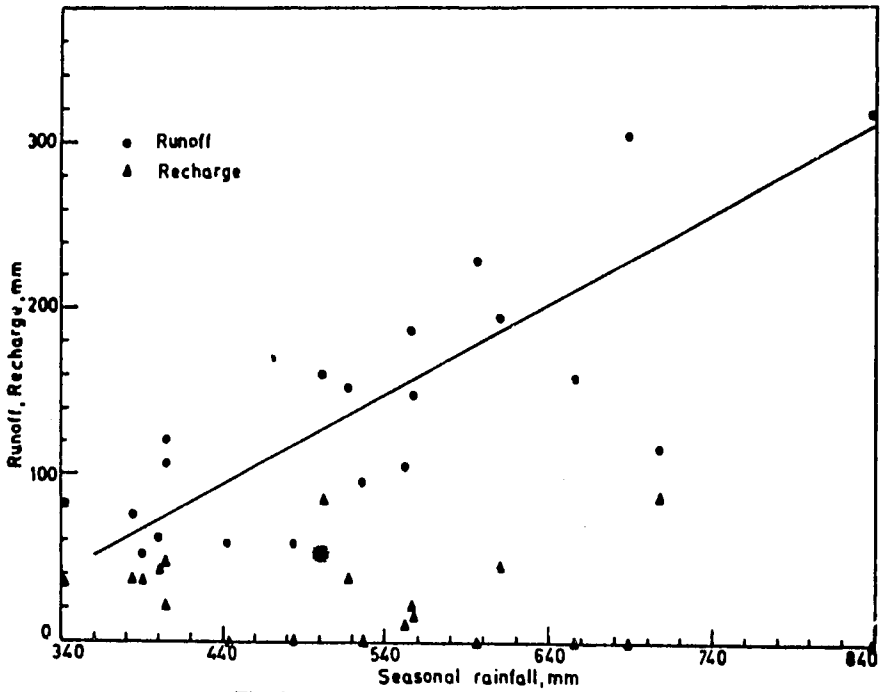

Fig. 2 Simulation results for soil 1 - Rainfed crop

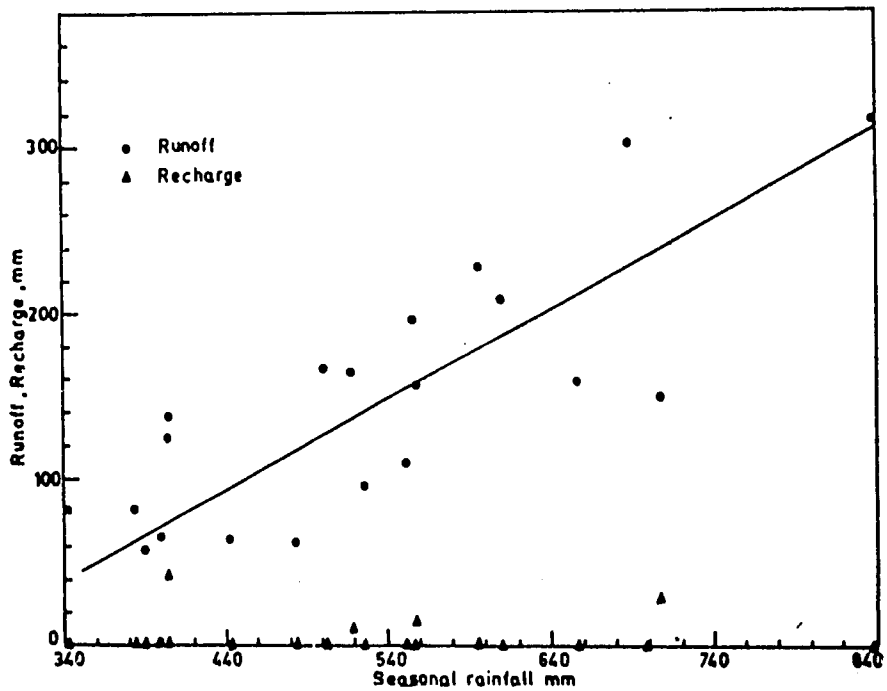

Fig. 3 Simulation results for soil 2 - Rainfed crop

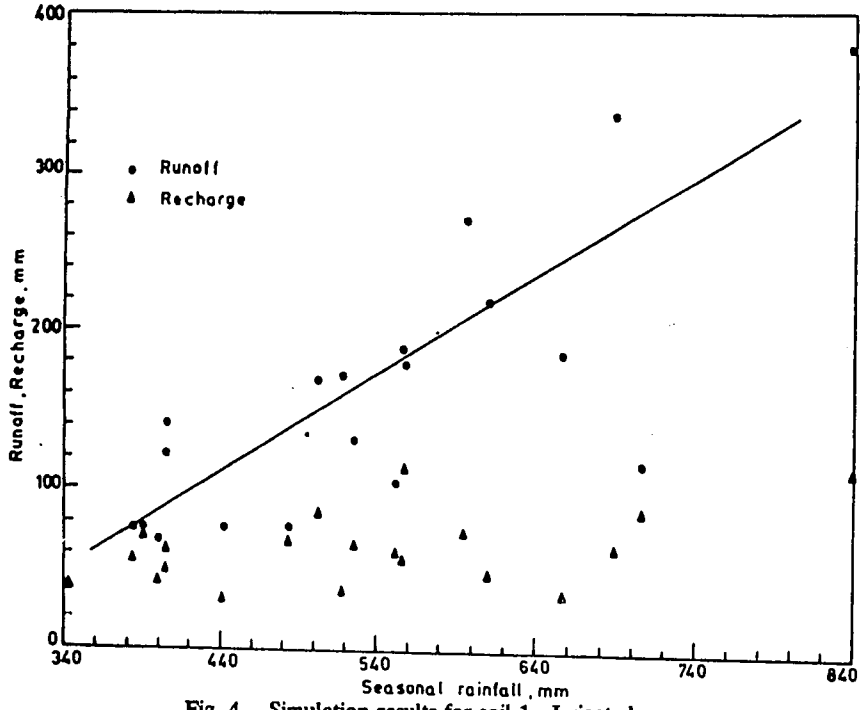

Fig. 4 Simulation results for soil 1 - Irrigated crop

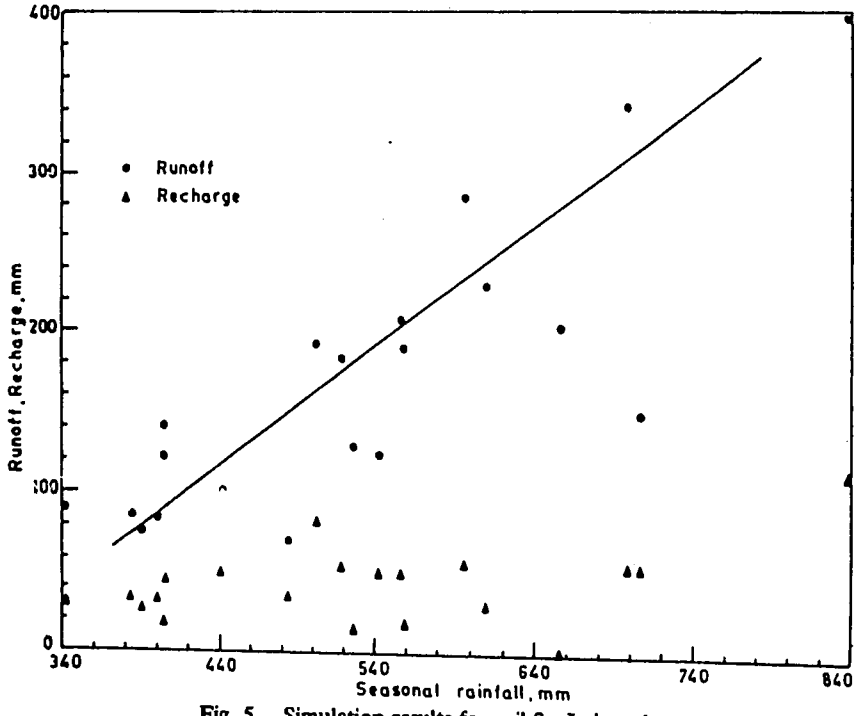

Fig. 5 Simulation results for soil 2 - Irrigated crop

soil 2. The average crop season recharge is 0.062 m for soil 1 and 0.041 m for soil 2. It must be noted that an irrigation application efficiency of 100% is implied in the simulation by the assumption that the irrigation applied is just enough to bring the soil to field capacity. Hence, no direct recharge from irrigation water occurs, in contrast to the check irrigation practised with canal systems where application efficiency is around 65%. The recharge is therefore a result of generally wetter soil conditions, with a lower proportion of rainfall being stored in the soil and contributing to the seasonal evapotranspiration.

Bare soil conditions : Figs. 6 and 7 show the runoff and recharge under bare soil conditions. From a comparison with Figs. 4 and 5, it is apparent that the runoff from bare soil was about the same as that from irrigated soil, but groundwater recharge was much higher. Since only 0.075 m thick top layer contributes to evaporation, the total evaporation from bare soil is much less than the evapotranspiration when the land was cropped. The result of simulation shows that the saving in evapotranspiration almost entirely goes to recharge the groundwater.

Validation : Although model validation has not been done due to non availability of reliable recharge and runoff data, an indirect validation was attempted using average estimates of recharge. Keeping in view the fact that the parameter t_1 was calibrated using average estimates of runoff. The average recharge (as per cent of rainfall) for twenty years as given by the simulation is given in Table 2 for each land use for the two soils.

Table 2. Recharge estimates from simulation, as per cent of rainfall

Soil	Irrigated area	Rainfed area	Bare soil
Soil 1	11.7	4.8	33.2
Soil 2	7.8	0.9	27.6

According to the data obtained from the Bureau of Economic and Statistics (1984), the average extents of irrigated area, rainfed area and fallow area as per cent of the total are 13, 78 and 9% respectively, for the district. The volume of recharge from bare soil is of the same order as that from rainfed cropland, although the former occupies an area about one-ninth of the latter. If the recharge per cent of Table 2 are weighted in the same proportions as the per cent areas, the average recharge for soil 1 comes to 8.3% and for soil 2 to 4.2%. These compare quite well with the 5 to 10% recharge estimated by Radhakrishna and Jitendra Kumar (1972) for region. The model is therefore considered to be indirectly validated.

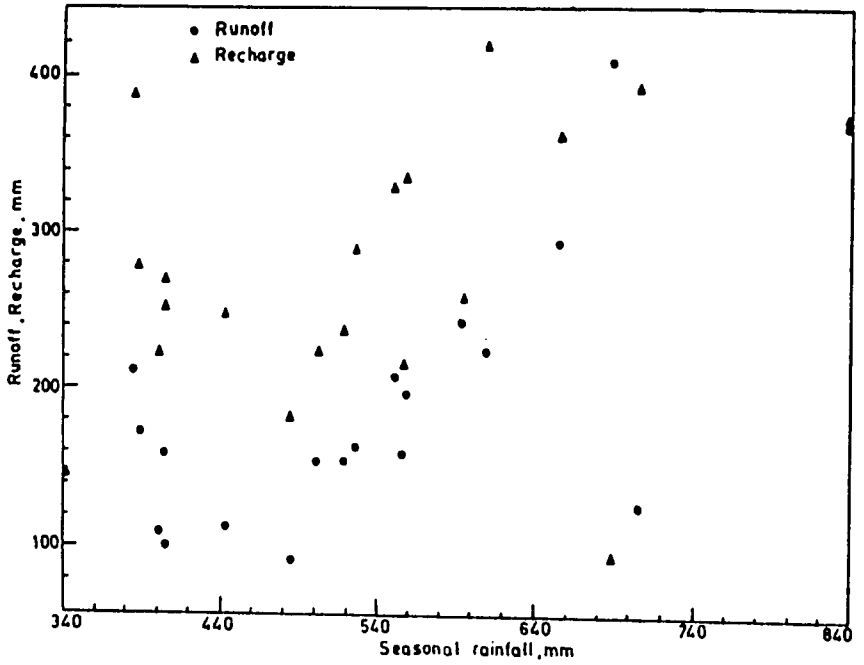

Fig. 6 Simulation results for soil 1 - Bare soil

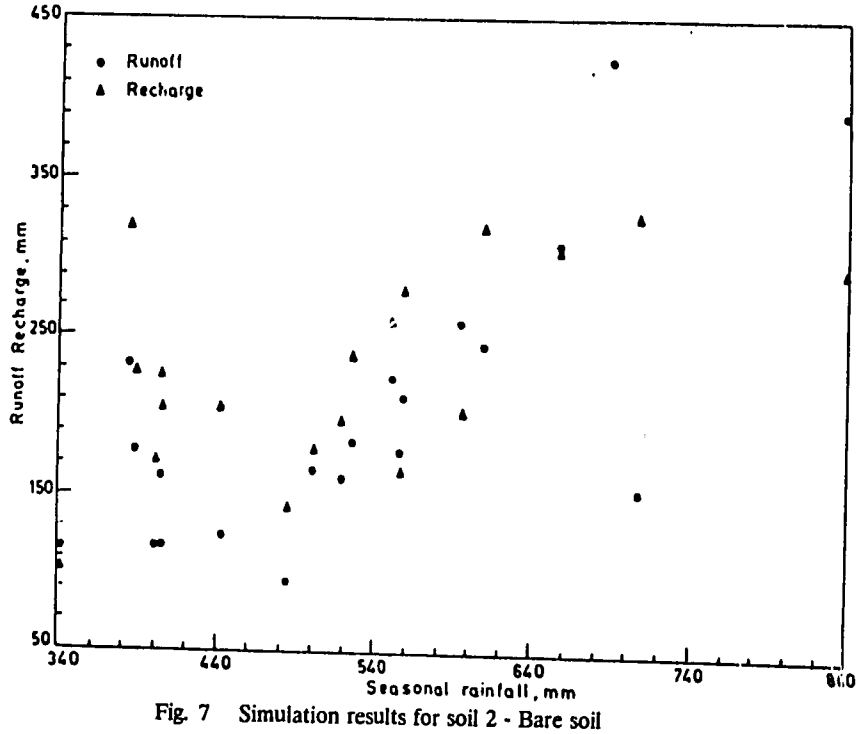

Fig. 7 Simulation results for soil 2 - Bare soil

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Effect of farming systems on hydrological behaviour in hilly microwatersheds

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ABSTRACT

Results of studies conducted in North Eastern Hill Region of India on Hydrological behaviour are reviewed. Available results indicate that (i) runoff and soil erosion increases up to a certain limit of slope and beyond which both decline with the further increase in slope percent, (ii) it is feasible to check soil erosion on steep slopes within permissible limits while practising agriculture, horticulture, livestock, forest or mixed land use systems, (iii) there exists good scope for dug out-cum-embankment type of water harvesting structures in hills and (iv) water yield potential of hilly micro catchment varies between 0.10 to 0.72 ha m ha^{-1}. Concepts of cumulative rainfall, runoff, soil loss, threshold rainfall and conservation factor have shown new approaches on hydrological modeling.

Watershed management is well recognised as an integrated approach for management and use of soil and water resources. Technical solution based on research results are available but they often inapplicate in the existing socioeconomic environment of hills. Land users with limited resources and varying interests in their source of livelihood will have to be provided with a feasible technological solutions which suits to their needs and resources. The word 'small' when used with watershed is itself diversely understood and interpreted by different experts. Usually watersheds, between 1000-25000 hectares are considered small. This author defines "Small" as the operational area of an individual. It is on this point the author would like to emphasize while discussing the role of small watershed hydrology in rainfed agriculture. Rainfall, landuse, land slope and soil type are major factors which influence hydrology of any area. The most

ideal situation with any land use may be to manage the available rainfall within the water retained locally and the excess (if any) is disposed off safely without inflicting any appreciable damage to the land resource of the area.

During the past decade, studies conducted in North Eastern Hills(NEH) Region of India, indicate that through watershed based farming systems 80 to 100 percent of through rainfall can be retained in situ (Singh 1986). This helps not only in practising successful rainfed agriculture but also restores the processes of underground water movement. In this paper, attempt has been made to review the research findings from NEH region on the hydrological behaviour of small watersheds.

The study area : North Eastern Hill region of India, lying between 21.5-29.5^0 N latitudes and 88.0-97.5^0 E longitude represents a distinct agro-climatic area. Vast area of hills interspersed with fertile valleys represents agro-climate of altitude range of few metres to 5000 m above mean sea level (msl). Annual rainfall varies from 2-4 m with distinction of receiving World's highest rainfall over 10 m at Cherrapunji. Traditionally, the hill people (tribals) prefer to stay on high hills and earn their livelihood from crops grown on hill slopes. Farm technology has remained stagnant around cultivation and its variants. Systems such as shifting cultivation, growing of tuber crops on raised beds formed along the slope, pineapple cultivation in rows along the slope and homestead areas are reported to result in soil loss between 5.10-83.30, 40-50, 24.0-62.6 and 16.8 t ha^{-1} yr^{-1}, respectively (Singh and Singh 1981, 1984, Ghosh 1976, Singh 1987). Soil erosion in these areas has resulted in emergence of flat valleys in between hills which are usually being used for intensive paddy production and have become valuable agriculture lands.

Review of results presented in this paper are based on the work done at Byrnihat (26.2^0 N Latitude and 91.5^0 E Longitute) and Barapani (15.35^0 N Latitude and 91.34^0 E Longitude) having 100 m, and 1000 m, msl elevation, respectively.

Rainfall behaviour on steep lands : Behaviour of rainfall on land surface is highly dependent on land use and vegetation. Data on runoff and soil loss from small runoff plots and micro watersheds shows vast variation (Tables 1 and 2).

Singh (1985) reported the trend of runoff and soil loss as affected by land slope. His observations revealed that soil erosion increases upto a certain limit and beyond which runoff and soil loss both decline with the further increase in slope percent. The trend was explained by the following form of equations.

$$E = 17.28 + 4.32 \, \mathrm{Sin}\left(\frac{X_2 - 35.1}{20.66}\right) \qquad (1)$$

$$R = 546.75 - 84.1 \, \mathrm{Sin}\left(\frac{X_2 - 64.9}{20.66}\right) \qquad (2)$$

Where E is soil loss (t ha^{-1} Yr^{-1}), R is runoff (mm) and X_2 is slope % of the land. Similar trend was also confirmed

by Singh (1987) in his studies at a different location. However, the values of the constants in the equation differed. Rai (1981) in his studies found that runoff and loss of organic carbon increases with the land slope upto 21 percent but the former was found to decrease linearly with the further increase in slope.

Water harvesting in micro-watersheds: Dugout-cum-embankment type of water storage structures in the foot hills at appropriate locations were found effective in blocking the path of base flow and accumulation of water in the ponds. Depending on the foundation conditions and nature of streams such water bodies may be of seasonal or perennial type. In micro-watershed, where base flow appeared within the area, water yield potential (runoff + base flow) was found to vary between 0.10 to 0.72 ha m ha^{-1} of catchment area where mean annual rainfall was 2.36 m. Four years observation on a dugout-cum-embankment type of seasonal pond located at the foot hills in 11.1 ha catchment received water yield of 2.51 ha m in the form of runoff (2.16%), direct rainfall(17.5 %) and base flow (80.4 %). Threshold rainfall (cumulative rainfall during the year beyond which water accumulation in the pond begins) was found to be 0.77 m. Life of storage varied between 69 to 181 days (Singh, 1988).

Rainfall-runoff and rainfall-soil loss relations: Singh et al. (1988) have worked out relationships between rainfall-runoff and rainfall-soil loss while introducing the concept of "Threshold" rainfall. Threshold rainfall has been defined as the minimum cumulative rainfall during the year beyond which runoff and soil loss begins from the area/watersheds. Relationships were reported to be of following forms:

$$Y_{1mc} \text{ or } Y_{2mc} = A(X_{mc} - C)^B \qquad (3)$$

For the study areas the values of C varies from 115 to 540.

A = 0.0073 to 0.3154 for Y_{1mc}

= 0.11×10^{-6} to 0.0691 for Y_{2mc}

B = 0.7449 to 0.9637 for Y_{1mc}

= 0.8166 to 2.1091 for Y_{2mc}

Where Y_{1mc} is monthly cumulative runoff (mm), Y_{2mc} is monthly cumulative soil loss (t ha^{-1} yr^{-1}), X_{mc} is monthly cumulative rainfall (mm) and C is threshold rainfall (mm). The equation (3) gave fairly good curve fit with coefficient of determination varying from 0.957 to 0.990 for Y_{1mc} and 0.783 to 0.990 for Y_{2mc}. The inter relationship between Y_{2mc} and Y_{1mc} was found as

$$Y_{2mc} = A\ Y_{1mc}^{B} \qquad (4)$$

Where A = 0.0046 to 0.0764

B = 1.0187 to 2.275

The coefficient of determination of equation (4) varied between 0.865 to 0.942.

Models for estimating runoff, peak

runoff and soil loss : Singh et al. (1987) developed models for estimating runoff, peak runoff and soil loss from hilly micro watersheds. The effect of conservaton measures, land use and human/or animal interference have been accomodated in "Conservation factor". This newly introduced parameter alongwith slope, annual rainfall and threshold rainfall have been used to establish models for estimating runoff, peak runoff and soil loss from micro-watersheds in hilly terrain. The models suggested are as follows :

$$Y_1 = 1.216 \left(\frac{X_1 X_2}{X_3} - 68.64\right) \quad (5)$$

$$Y_2 = 0.096 \left(\frac{X_1}{X_2 X_3} - 36.10\right) \quad (6)$$

$$Y_3 = 0.0707 \left(\frac{X_1 - C}{X_3} - 4.38\right) \quad (7)$$

Where X_1 is annual rainfall (mm); X_2 is mean slope of the micro-watersheds (mm^{-1}) ; X_3 is conservation factor; C is threshold rainfall (mm); Y_1 is annual runoff (mm); Y_2 is annual soil loss (t ha^{-1}) and Y_3 is peak rate of runoff ($mmhr^{-1}$) during the year. Conservation factor (X_3) and threshold rainfall (C) can be worked out from the following equations.

$$X_3 = \frac{A_1(NL_1 + NC_1 + NH/a_1) + \ldots An(NL_n + NC_n + NH/a_n)}{(A_1 + \ldots + A_n)} \quad (8)$$

Where NL, NC, NH/a are assigned numbers for land use, conservation measures and human/animal activities corresponding to the areas $A_1, A_2, A_3 \ldots A_n$ respectively (Singh, 1987).

$$C = 59.46 + 21.81\, X_3 + 1.999\, X_3^2 \quad (9)$$

The values of coefficient of determination for equations (5), (6), (7) and (9) were found as 0.984, 0.830, 0.676 and 0.863. The main point in developing the models as reported, is the introduction of a "Conservation factor" as a parameter to describe the effects of several conservation measures in predicting runoff, peak runoff and soil loss from watershed based farming systems.

DISCUSSION AND CONCLUSIONS

Studies reveal that 80 to 100% of annual rainfall can be retained in soil in situ in well managed watershed based farming systems. This goes against the common experience of hydrological data analysis of much flatter lands where runoff from individual storms ranges between 20-50% i.e., retention of 50 to 80%. A close visual observation to the soils in hilly area reveal that soils area highly a porous media. A lot of root holes, micro-channels (visible in a soil profile) are present. Activities of soil fauna, high organic matter (1.00 to 2.03%), soil aggregation due to the presence of iron oxide, low pH (4.7 to 5.4) yielding higher water stable aggregate etc. were responsible to make the soils of the study area as a highly porous medium. From the observations on annual runoff and soil loss (Table 2) it can be concluded that use of conservation measures developed from local resources (soil, vegetation and man power) as reinforcement to the desired land use is capable to perform functions as that of forest (or natural vegetation) in the

Table 1. Runoff and soil loss behaviour on steep slopes under different landuse systems at 3 different locations, altitude and soil type in NEH region

Landuse	Land slope, %	Area of the plot, m^2	Runoff as % of annual rainfall	Soil loss, t ha^{-1} yr^{-1}	Source
	100 m, msl - sandy loam soil, rainfall 1600 mm				
Agriculture (C)	55	48.0	6.0 - 6.6	19.7 - 25.4	Rai 1981
Agriculture (C)	0-100	5.0	5.1 - 16.9	10.8 - 45.0	Rai 1981
Bare fallow	65	40.0	6.6 - 18.0	17.8 - 205.6	Awasthi 1984
Grass cover	65	40.0	1.5 - 4.0	2.7 - 20.7	Awasthi 1984
Agriculture (C)	65	40.0	3.5 - 17.9	9.1 - 212.3	Awasthi 1984
Bare fallow	58-70	40.0	13.1 - 20.4	258.7 - 543.7	Singh 1987
Bare fallow	0	5.0	29.3	125.0	Singh 1987
	1000 m, msl - clay loam soil, rainfall 2361 mm				
Bare fallow	0-100	0.5	18.5 - 26.8	13.2 - 21.5	Singh 1985
	1900 m, msl - clay loam soil, rainfall 1900 mm				
Agriculture	48	4.3	NM	25.1	Singh 1979
Agriculture (T)	0	5.0	11.0 - 15.0	7.94 - 8.26	Rai 1981

C Cereal crops T tuber and root crop Data are from landuses without having any mechanical soil and water conservation measures. NM not measured.

Table 2. Runoff and soil loss behaviour on steep slopes under different landuse systems in microwatersheds at two different locations, altitude and soil type in NEH region

Landuse	Mean slope, %	Area of the water-shed, ha	Soil and water conservation measures	Runoff as per cent of annual rainfall	Soil loss, t ha^{-1} yr^{-1}
	*100 m, msl, snady loam soil 1600 mm annual rainfall**				
Bamboo forest	45	0.47	–	0.08 - 0.45	00.04 - 00.52
Agriculture (S)	40	0.15	–	1.06 - 9.73	5.10 - 83.30
Agriculture (C)	42	0.11	Bench terrace	0.00 - 4.79	0.00 - 7.70
Agriculture (C)	43	0.09	Contour bunds	0.21 - 19.26	0.60 - 68.20
Agriculture (F)	44	0.41	Contour bunds Bench terrace	0.34 - 2.92	0.88 -14.23
Agri(C) + Horti	44	0.19	-do-	0.02 - 6.63	0.04 - 10.30
	*1000 m, msl, clay loam soil, 236 mm annual rainfall * ***				
Natural fallow	46	1.00	–	0.00 - 0.03	T - 0.05
Agriculture (F)	32	1.40	Contour trench	0.00 - 0.03	T - 0.004
Agriculture (C)	32	0.60	Contour bunds + Bench terrace	0.23 - 0.53	T - 0.15
Agri(C) - horti 7 Silvipasture	42	1.60	Contour bunds + Bench terrace	0.01 - 0.27	T - 0.12
Horticulture	53	3.10	Bench terrace + half moon terrace	0.24 - 0.50	T - 0.53

* 8 years data * * 4 years data C Cereal crops S Shifting cultivation T Trace F fodder crops All the watersheds at 1000 m, msl have pine forest on the top of the hill slope (Singh 1988)

matter of receiving rainfall, retaining it and contributing towards ground water recharge. From the studies the following conclusions can be drawn.

1. Eighty to hundred per cent of the annual rainfall can be retained or conserved even if the slope is quite steep and rainfall is high.

2. Annual runoff and soil loss increases up to certain limit and beyond that, both decrease with the increase in slope.

3. The concepts of cumulative monthly runoff, cumulative monthly soil loss and threshold rainfall are meaningful.

4. The concept of conservation factor (Eq. 8) is effective in predicting annual runoff, soil loss and peak flow from micro-watersheds.

5. The total rainfall (in absence of rainfall intensity, erosivity and other rainfall characteristics) may suitably be used to estimate runoff, soil loss and peak flow (Eqs. 5,6 and 7).

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Studies on runoff, soil loss and productivity of small agricultural watershed

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ABSTRACT

A study was conducted for 6 years (1981-86) to assess the runoff, soil loss, and productivity of a small agricultural watershed (1.48 ha) by adopoting soil and water conservation measures, proper land use pattern, and improved agronomic practices. The watershed was developed into five terraces by land levelling (1% slope), field bunding, and making arrangement for proper disposal of runoff water. Agricultural crops were raised in three lower terraces and Leucaena leucocephala for fodder and fuel and Eucalyptus hybrid for fuel in upper two terraces. The monsoon rainfall varied between 0.48 and 0.78m. The mean runoff recorded was 24.9% (0.14 ha m) and soil loss 2.488 t ha^{-1}. There was consistent decrease in peak discharge. There is possibility of collecting 0.14 ha m runoff water in dugout farm pond for supplemental irrigation in the donor watershed. Mean yields obtained were; maize 1.19 Mg ha^{-1}, pulses 0.37 Mg ha^{-1} and sorghum fodder (airdry) 7.45 Mg ha^{-1} under rainfed condition. Leucaena produced on an average 7.4 Mg na^{-1} airdry fodder and 9.4 Mg ha^{-1} and fuel wood 18.06 Mg ha^{-1} when harvested annually. Eucalyptus harvested after a three year rotation produced 47.76 Mg ha^{-1} of airdry fuel wood. The net returns from the sytem were Rs. 2769 ha^{-1} with a B : C ratio of 1.9.

Undulating topography coupled with faulty agricultural practices result in more runoff and loss of top fertile soil. The agriculture being rainfed, farmers are sceptical about the use of soil and water conservation measures and improved agronomic practices. The degree of runoff under such conditions depend on rainfall, especially during the early periods of low crop cover (Celestino 1984). Various methods of controlling soil erosion by water have been suggested (El-

Swaify and Dangler 1982). According to Celestinom (1984) agronomic measures are more effective in controlling soil erosion than mechanical measures. Hudson (1971) has reported that improved farm practices minimise soil erosion. Sastry et al. (1980) and Verma et al. (1984) have reported the possibility of collecting runoff water in farm ponds. The stored water when used for supplemental irrigation increased wheat yield. The economic feasibility of farm ponds for runoff harvesting has been substantiated by Selvarajan et al. (1984).

A study was undertaken at the farm of the Research Centre, Chandigarh to find out the impact of soil and water conservation measures, proper land use and improved agronomic practices on runoff, soil loss and productivity of a small agricultural watershed and to explore the possibility of harvesting runoff water for supplemental irrigation.

MATERIALS AND METHODS

Area in general is undulating with 3 to 5% slope. The soil is gravelly throughout the profile in all the plots, with maximum gravel concentration in sub-surface layer, loamy sand (80% sand, 11% silt, and 9% clay) with a pH of 8.2. The average annual rainfall is 1.12 m with a CV of 25 %. Out of this 0.89 m (CV 28% is received during kharif and 0.16 m (CV 57%) during rabi.

Studies were conducted between 1981-86 on an undulating 1.48 ha area converting it into 5 terraces, varying in area between 0.1 and 0.44 ha having 1% slope, by land levelling. Individual fields were bunded from all sides and surplus rain water was allowed to flow through box-type outlets into a grassed water way and then measured with an automatic F-4 Stevens stage level recorder. Soil loss was estimated by collecting samples from the flowing water.

Agricultural crops were raised in 3 lower terraces (1.24 ha). Leucaena leucocephala for fodder and fuel ws raised at 1m x 1m spacing in the 4th terrace (0.14 ha). The top most terrace (0.1 ha) was put under Eucalyptus hybrid for fuel at 1m x 1m spacing.

RESULTS AND DISCUSSION

Runoff : Monsoon rainfall varied from year to year. It was minimum (0.48 m) in 1981 and 1984 and maximum (0.78 m) in 1983 with a mean of 0.58 m (Table 1). The mean runoff recorded from the agricultural watershed was 0.14 m (24.9%). The runoff varied from 17.7% in 1983 to 31.1% in 1982. Inspite of maximum rainfall of 0.78 m in 1983, the runoff was the lowest due to uniform distribution of rains throughout the season and less runoff occurred in August (Fig. 1). The total runoff in 1985 was also less. This might be due to less amount of rainfall and consequently less runoff in July. Maximum runoff (31.1%) occurred in 1982. It was the higher rainfall of August which was responsible for the higher runoff. A similar trend was observed in 1986.

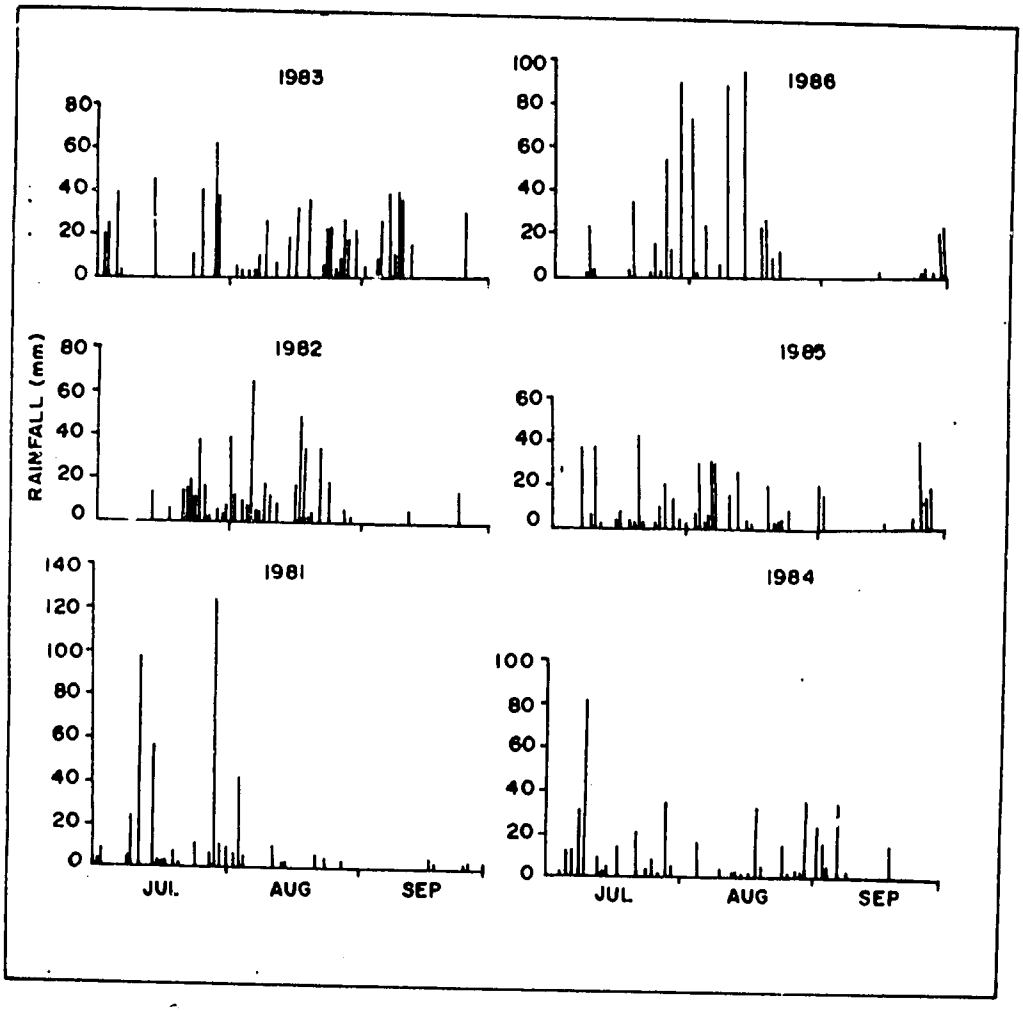

Fig. 1 Daily rainfall for monsoon period

Table 1. Month wise rainfall, runoff, peak discharge and soil loss from agricultural watershed for the period 1981-86

Month	Rainfall, m	Runoff, m	Runoff, %	Peak, $m^3 h^{-1}$	Soil loss, $Mg ha^{-1}$
1981					
July	0.384	0.129	33.5	0.103	1.963
Aug	0.083	0.017	20.5	0.047	0.219
Sept	0.015	0	0.0	0.000	0.000
Total	0.482	0.146	30.3	-	2.182
1982					
July	0.204	0.045	22.2	0.102	2.060
Aug	0.325	0.126	38.7	0.088	0.942
Sept	0.020	0	0.0	0.000	0.000
Total	0.549	0.171	31.1	-	3.002
1983					
July	0.279	0.082	29.4	0.099	2.209
Aug	0.280	0.023	8.2	0.046	1.938
Sept	0.216	0.032	14.8	0.035	0.123
Total	0.775	0.137	17.7	-	4.270
1984					
July	0.251	0.070	27.8	0.088	1.365
Aug	0.126	0.017	13.5	0.041	0.162
Sept	0.105	0.024	23.0	0.038	0.066
Total	0.482	0.111	23.0	-	1.593
1985					
July	0.199	0.035	17.6	0.065	0.732
Aug	0.208	0.052	25.0	0.033	0.109
Sept	0.099	0.011	11.1	0.031	0.014
Total	0.506	0.098	19.7	-	0.855

1986					
July	0.252	0.064	25.4	0.081	0.825
Aug	0.369	0.138	37.4	0.099	2.199
Sept	0.56	0	0.0	0.000	0.000
Total	0.677	0.202	29.8	-	3.024
Mean (1981-86)	0.578	0.144	24.9	-	2.488

Peak discharge : There was consistent reduction in peak discharge from 1981 to 1985 (Table 1). This might be due to the combined effect of soil and water conservation measures,improved agronomic practices and gradual reduction in slope in fields which resulted in stabilization of the watershed. The peak discharge increased marginally in 1986 due to higher rainfall and unusually heavy showers in August. The seasonal peak invariably occurred in July in all the years except in 1986, when the crop canopy was just developing and did not provide adequate ground cover. During 1986 a heavy storm of 0.097 m marginally increased the peak in August.

Soil loss : The impact of soil and water conservation measures, proper land use and improved agronomic practices was clearly visible in soil loss. The soil loss was within permissible limits in all the years (Table 1). Maximum soil loss (4.27 Mg ha^{-1}) was recorded in 1983 and the minimum (0.855 Mg ha^{-1}) in 1985. Soil loss was maximum in July in all the years, except in 1986 when it was maximum in August.The reason for more soil loss in July was lack of crop canopy to protect the soil from the impact of falling raindrops. Secondly the soil was also loose due to weedings and hoeings in early stages of crop growth.

Water yield : The runoff data indicated that even after best land, water and crop management practices 0.14 ha m of rain water went out as runoff from the agricultural watershed. This could possibly be stored in a dug out farm pond with a surface area of on an average of 500 sq m and depth 3 m, which will occupy only 6% of the total agricultural land.

Productivity : The productivity of the agricultural watershed was assessed in terms of food, fodder and fuel. Since maize is the staple food, maximum area was put under maize followed by sorghum fodder and pulses. The mean yield of crops obtained was maize 1.19 Mg ha^{-1}, pulses 0.37 Mg ha^{-1}, and sorghum fodder 745 Mg ha^{-1} under rainfed condition (Table 2). The yield of these crops before the land development were 0.65, 0.10 and 2.50 Mg ha^{-1} for maize, pulses and sorghum fodder, respectively.

Table 2. Yield of different crops and total net returns from agricultural watershed

Year	Crop yield, Mg ha^{-1}					Total net returns, Rs. ha^{-1}
	Maize grain	Straw	Pulses grain	haulm	Sorghum dry fodder	
1981	0.82	2.20	0.24	2.10	8.25	1773
1982	1.29	3.10	0.60	1.20	6.80	1392
1983	1.30	3.20	0.22	1.95	7.50	2494
1984	2.08	4.85	0.22	1.80	11.15	5290
1985	0.92	2.20	1.01	2.60	5.00	4188
1986	0.73	1.90	0.47	0.98	6.00	1475
Average	1.19	2.91	0.37	1.77	7.45	2769

To supplement the requirement of fodder, about 10% of the area was put under Leucaena, which produced an average 7.4 Mg ha^{-1} dry matter and 9.4 Mg ha^{-1} air dry fuelwood when harvested periodically. It produced 4.02 Mg ha^{-1} dry matter and 18.06 Mg ha^{-1} of airdry fuel wood when harvested annually.

Eucalyptus was harvested after a three year rotation and 47.76 Mg ha^{-1} of fuel wood was obtained which works out to 15.92 Mg ha^{-1} per year.

The system gives an average Rs. 2769 per ha net returns based on 6 years productivity. The B:C ratio worked out to be 1.9.

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Pay offs from hydrologic improvements in watersheds 1987 drought experience

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ABSTRACT

Development of dryland agriculture on watershed basis was launched as a national program by the Government of India in 1983. The Indian Council of Agricultural Research in collaboration with State Governments, established 47 model watersheds all over the country. Of these, 30 model watersheds were surveyed, master plans prepared, priorities and budgets set out and training programmes counducted by the Central Research Institute for Dryland Agriculture, Hyderabad, besides carrying out evaluation and monitoring. Operational research programmes of Resource Management were initiated in 16 of these watersheds. The watershed program involves five types of activities : i) engineering measures for improvement of water resources, ii) mechanical and agronomic measures of in situ soil and water conservation, iii) improved crop husbandry practices for meeting the food and fodder requirements of human beings and livestock, iv) alternate land use systems for efficient use of lands as per land capability, and v) providing improved infrastructure for credit and marketing of the produce. The principal objective was to demonstrate optimal utilization of natural resources like soil, water and vegetation, through the Improved Dryland Technology.

The success of the watershed development program lies in creating a dependable water resource in the watershed, to reduce runoff and soil loss, and increase the productivity, cropping intensity and fertiliser use in the area. The program has, by and large, resulted in modifying the hydrology of watersheds in terms of runoff reduction and improvement in ground water table. During the century's worst drought of 1987, impact of watershed program was clear

and visible due to successful crop production and better soil conservation in the watersheds. More systematic watershed research on hydrology, agrometeorology, forestry, horticulture, agriculture and economics is suggested. The socio-economi implications of such programmes have to be clearly understood and documented.

Sustained production and productivity in drylands is a big task in developing countries. On one side, there is an urgent task of meeting the growing food requirements of human beings and fodder needs of livestock; on the other hand, there is a necessity for maintaining the land productivity for producing adequate food, fodder, fuel, timber and fruits required for the increasing population with time. By and large, it has been recognised that the best way to develop dryland agriculture is by following the watershed approach (Mishra et al. 1980). In order to reduce the severity of adverse effects of droughts, different soil conservation and water harvesting programmes are useful, as evidenced by Sukhomajri project, which has received the nation-wide acclaim by one and all. As a result, 47 model watersheds were established in different agro-climatic zones of the country in 1983. The main objective was to demonstrate the optimal use of land and water resources by following dryland technology. Thirty of these, as shown in Fig. 1 & Table 1, had the backup of Central Research Institute for Dryland Agriculture, Hyderabad in terms of conducting survey, preparation of master plans, fixing priorities, budgeting, evaluation and monitoring besides training the personnel engaged in watershed development program. The Indian Council of Agricultural Research has further augmented the research input in this program by providing 16 Water Resource Development ORPs, headed by a scientist at different locations. The salient features of the watershed development program along with major achievements are highlighted in this paper.

Management of cultivated Lands : Most of these model watersheds are predominantly agricultural watersheds. Two types of land treatments have been adopted in the cultivated lands depending upon the capability (Sharma 1988).

Basic land treatment program : The hard-core basic land treatments including engineering measures have been carried out to increase the time of concentration of runoff flow. Many of these measures, such as bunding and terracing etc., not only help in conserving soil and water in the land; in addition they also divide a long slope into a number of short ones and thereby reducing the velocity of runoff before it reaches the critical limit of causing erosion. Contour bunds have been constructed in the low rainfall areas like Nigana-Bhiwani and Yerracheruvu-Anantapur. In the higher rainfall areas, measures like graded bunds, submergence bundhis and zingg and bench type terracing have been adopted on the basis of soil and slope consideration. Graded bunds have been particularly adopted on slopes upto 6% in relatively high rainfall areas and poorly permeable

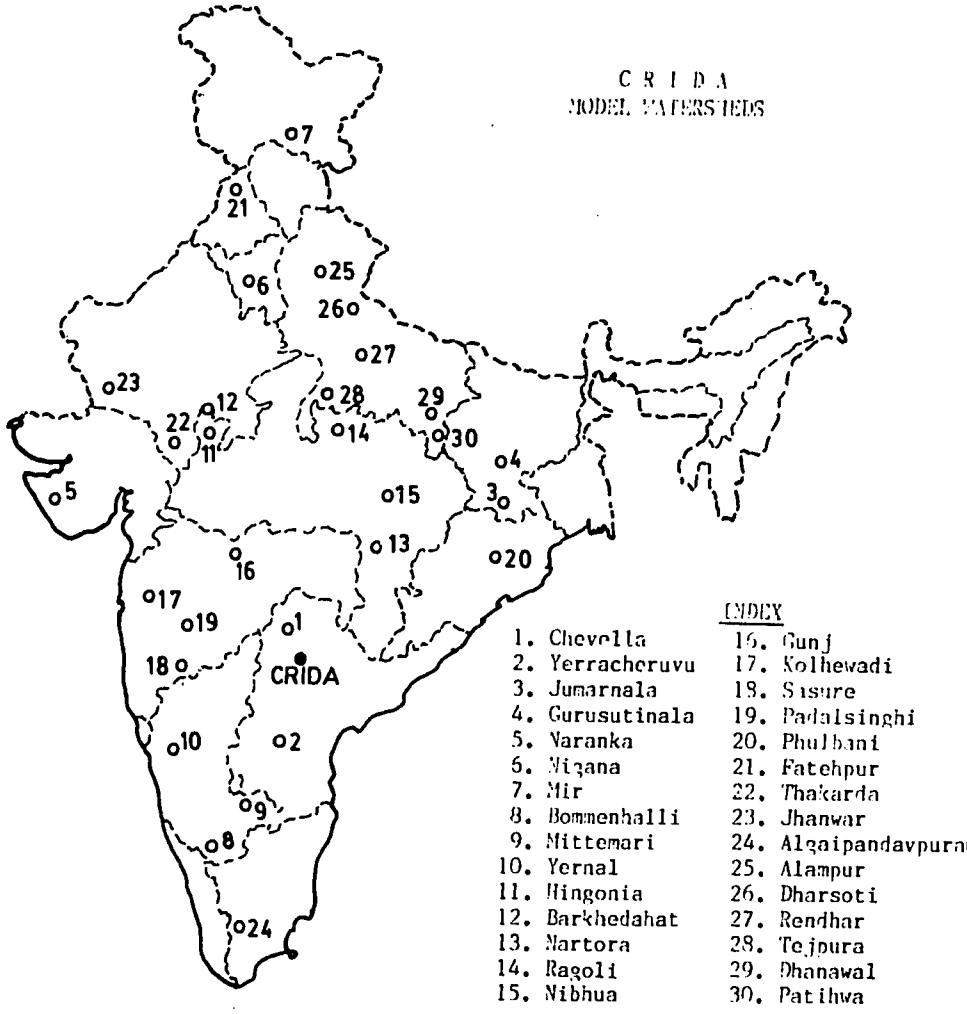

Fig. 1 Map of India showing location of Model Watersheds

Table 1. Cultivated and non-arable lands in model watersheds

Watershed	State	Watershed area, ha	Cultivated area, ha	Non-arable land, ha
Nigana	Haryana	2120	1871	249
Jhanawar	Rajasthan	3490	1326	2164
Kolhewadi	Maharashtra	489	460	29
Naranka	Gujarat	1478	1033	445
Yernal	Karnataka	390	375	15
Padalsinghi	Maharashtra	765	242	523
Thakarda	Rajasthan	194	97	97
Yerracheruvu	Andhra Pradesh	567	445	122
Patihwa	Uttar Pradesh	700	350	350
Dhanawal	Uttar Pradesh	680	645	35
Rendhar	Uttar Pradesh	787	695	92
Tejpura	Uttar Pradesh	775	526	249
Aril	Uttar Pradesh	2975	2317	658
Chevella	Andhra Pradesh	673	635	38
Gunj	Maharashtra	507	420	87
Sasure	Maharashtra	180	117	63
Hingonia	Madhya Pradesh	424	311	113
Mittemari	Karnataka	1245	583	662
Bommenhalli	Karnataka	824	642	182
Algaipandavpuram	Tamil Nadu	992	726	266
Fatehpur	Punjab	303	155	148
Naratora	Madhya Pradesh	1005	659	346
Dharsoti	Uttar Pradesh	220	170	50
Nibhua	Madhya pradesh	500	325	175
Mir	Jammu & Kashmir	1894	52	1842
Munsiguda	Orissa	848	330	518
Ragoli	Madhya Pradesh	866	649	217
Barkhedahat	Madhya Pradesh	504	312	192
Gurusutinala	Bihar	2259	1457	802
Jumarnala	Bihar	1326	950	376

soils. Ragoli (Chattarpur) and Chevella (Medak) figure prominent with considerable area covered under this practice. Submergence bundhis have been prepared in relatively moderate rainfall areas (0.70 m or so) having relatively deeper soils and flatter slopes. These have been created over large areas in watersheds like Rendhar (Jalaun) and Tejpura (Jhansi). Similarly on lands having slopes of more than 10% bench terracing is practised for safe runoff disposal in situations like Mir (Udhampur).

Water resource development : In line with the watershed approach, attempts have been made for creation of relatively less expensive small scale water resources - on - ground surface as well as underground - in most of the model watersheds (Singh 1987). Thus, the stored water in ponds and tanks serves as an insurance against occasional dry spells during the growing season.

For watersheds having broad Nallas or gullies and receiving 0.50 - 1.10 m rainfall, percolation tanks/Nalla bunds have been constructed with the primary aim of recharging ground water. Such structures have received wide acceptance from village people, at places like Kolhewadi (Ahmednagar).

Wherever there are relatively stable foundation conditions, permanent structures in the form of stop dams have been constructed. In Tejpura watershed situated in Bundelkhand region, such structures have been useful in raising water level in the Nalla by 1m to a distance of 500 m.

In watersheds having relatively deep soils and with annual rainfall of 0.70 - 1.10 m - like Rendhar (Jalaun) and Ragoli (Chattarpur) - water harvesting bundhis as well as submergence bundhis have been made to ensure relatively more ponding time for runoff water as well as recharging the water table.

Agronomic program : Providing suitable land treatments had not been an end in itself; more importantly they have been followed by different improved agronomic practices (Singh 1988). In this category are programmes like introduction of short duration high yielding varieties of crops, improved cropping systems and conservation tillage which are being adopted with full co-operation of farmers in most of the model watersheds. Efficient fertiliser management, timely weed control and proper plant protection measures are being popularised through block demonstrations. Improved agricultural implements like ridger-seeder, two bowl seed drill and dryland weeder are finding acceptance in some of the watersheds.

Watershed program in non-arable lands: Sizeable areas in the model watersheds are non-arable. These areas, therefore, have been used under different alternate land uses. Social and agro-forestry programmes have been taken up in most of the watersheds considering the fact that on such lands which are usually highly impoverished in terms of water and nutrients, trees are comparatively less prone to drought as compared to agricultural crops. Similarly, dryland horticulture has been taken up on rather small scale with

the consent and co-operation of cultivators and this has particularly found favour in all the model watersheds situated in Karnataka state. All these plantations have been taken up after providing adequate soil moisure conservation practices like contour trenches for planting fuel and fodder tree species and crescent bunding for raising fruit plants.

Financial support and credit facilities : The financial support for the program was extended by Govt. of India, through Ministry of Agriculture and Rural Development. The subsidy and loan patterns were decided by the State Govts. depending upon their norms. Necessary credit facilities were arranged through different Nationalised and Commercial Banks. Of late, efforts are also being made to provide infrastructure for marketing different farm produce in some places.

Major achievements of the watershed program : At most sites the watershed program is a complete success; while at others it is not. In general, there has been considerable improvement in water resources in model watersheds, where water storage structures have been constructed as per hydrologic conditions and in this respect, particular mention can be made of Yernal-Bijapur and Tejpura-Jhansi watersheds, which have been awarded the First and Second prizes respectively by the National Productivity Council.

It has been observed that after the inception of the watershed program there has been considerable increase in the number of dug wells (Table 2). Not only the wells have increased in number, there is also improvement in ground water status of most watersheds (Table 3).

Table 2. Ground water resources in model watersheds

Watershed	State	Open Wells (No.) 1984-85	1985-86	1986-87	1987-88
Mittemari	Karnataka	28	29	30	30
Naranka	Gujarat	72	82	97	97
Kolhewad	Maharashtra	38	–	45	45
Rendhar	Uttar Pradesh	12	–	20	25
Tejpura	Uttar Pradesh	6	–	12	20
Aril	Uttar Pradesh	33	–	66	80
Naratora	Madhya Pradesh*	4	–	9	10
Chevella	Andhra Pradesh	–	–	–	2
Rendhar	Uttar Pradesh	–	–	–	2

* Tube wells

Table 3. Increase in water table (m) in the dug wells in model watersheds

Watershed	Base Year 1984-85	Present 1987-88	Rise in water table, m
Naranka	16.00	15.00	1.00
Rendhar	14.50	11.00	3.50
Tejpura	11.00	6.50	4.50
Dharsoti	7.00	6.50	0.50

The increased water availability in wells and bundhis has enabled farmers to provide life-saving irrigation in tne additional areas. Thus, there is significant increase in the irrigated area in each watershed as compared to the base year. Quite significantly, an additional 314 ha area has been provided with life-saving irrigation in Tejpura watershed.

Treatment of lands with soil conservation measures has created wide interest among farmers to go in for improved intercrop systems in cultivable lands. The cropping intensity has thus improved (Table 4).

Interestingly, the crop productivity showed increasing trend inspite of the past couple of years being un-favourable rainfall years (Table 5).

Among oilseed crops, groundnut recorded appreciable yield increases. Sunflower crop - a new introduction in most of the watersheds - is catching up. However, pulses have shown only marginal improvements.

Watershed program and 1987 drought: There have been fairly severe drought situations in earlier years in the country. And, historical records of rainfall also indicate high variability in the rainfall which actually cause more severe problem of droughts. The analysis of rainfall data has revealed that the coefficient of variation in the monsoon rainfall in watersheds located in the rainfall zones <0.50 m , 0.50-0.70 m, 0.70-1.10 m and >1.10m is in the range of 50-55, 40-50, 30-40 and 20-30%, respectively (Dhruvan arayana et al. 1987). Thus, probability of drought occurrence in most watersheds is very high. But, the 1987 drought was unprecedented in the sense that nearly three fourths of country was in the grip of severe drought - at one point of time or the other - during South West monsoon period. And apart from this, in 1987, the south-west monsoon introduced one more climatic aberration i.e. the total failure of monsoon in some parts of the country, which never happened before during the last 110 years.

Table 4. Increase in cropping intensity in model watersheds (average of 14 watersheds)

Year	Cropping Intensity, %
1983-84	79.93
1984-85	91.07
1985-86	110.28
1986-87	117.36
1987-88	122.92

Table 5. Productivity gains in dryland crops in some model watersheds

	Yield, Mg ha^{-1}				
Crop	1983-84	1984-85	1985-86	1986-87	1987-88
Sorghum (10)	0.66	0.68	0.91	1.01	1.71
Greengram (11)	0.58	0.26	0.57	0.51	0.52
Groundnut (10)	0.41	0.51	0.91	0.98	1.19

Figures in parantheses indicate number of watersheds considered for averaging the yield

It was observed that most of the watersheds located in Haryana, West Uttar Pradesh, Rajasthan, Gujarat and Madhya Pradesh, had rainfall deficit (June-August) of the order of 50 to 80%. The watersheds located in Eastern Uttar Pradesh and Maharashtra and Nartora model watershed in Madhya Pradesh experienced 25 to 50% rainfall deficit.

The performance of watersheds were reviewed by ICAR Review Team and impact of watershed measures in alleviating drought was quantified in terms of kharif areas sown or reduction in normally cropped area (Sharma 1988). For this, crop data were collected from areas inside watershed as well as from adjoining areas. It was revealed that in the severely drought affected areas like Alampur-Bareilley, the percentage reduction in sown area was 85 and 50 for outside area and inside the watershed respectively. Similarly, in moderately affected areas, the area loss inside and outside the watershed was 0-20% and 40-90% respectively.

The analysis of yield data of crops grown during drought period, also indicates that in some of watersheds the improvement in crop yield could be maintained as a result of water conservation measures (Table 5).

Particular mention can be made of Tejpura watershed with reference to grain yield harvested during 1987 for maintaining fairly higher production levels as compared to bench mark year in almost all crops (Table 6).

Thus, these experiences lead to conclude that watershed measures have certainly helped in maintaining stability in production during the 1987 kharif drought and more particularly in locations having mild to moderate drought intensity.

Table 6. Increased productivity of different crops in Tejpura watershed in 1987

Crop	Yield, Mg ha^{-1} Before the commencement (1982-83)	After the watershed program (1987-88)
Sorghum	0.55	2.00
Sorghum + pigeonpea	0.45	1.80
Sorghum + greengram	– – (1.70+0.20)	1.90
Sorghum + blackgram	– –	1.90 (1.70+0.20)
Blackgram	0.30	0.62
Greengram	0.25	0.55
Cowpea	– –	0.70
Groundnut	– –	1.30
Soybean	– –	1.35
Sesamum	0.10	0.35

Line indicate non-existence of practice in the bench mark year

Research gaps and future thrusts : By and large, the watershed program has been successful. However, at few locations, there are difficulties like non-release of funds, lack of co-ordination among line departments ; weak linkages between scientists and extension workers etc. and these are being ironed out. The experiences indicate a few major research gaps as given below:

1. Systematic watershed research is required to be undertaken on the aspects like hydrology, agrometeorology, forestry, horticulture and agriculture.

2. Research work for reducing bund section is to be taken up. Similarly, efficacy of vegetative barriers vis-a-vis earthen bunds needs to be studied.

3. Cheap and efficient seeding devices and other agricultural implements are either lacking or have not reached the farmers.

4. There is a need to conduct intensive research on transfer of technology in watersheds so as to encourage peoples' participation.

5. Procedures for detailed socio-economic survey and economic analysis for watershed program are to be standardised.

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Field evaluation of microwatersheds

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ABSTRACT

Microwatershed shape is one of the factors that can be manoeuvred for redistribution of precipitation. Four microwatershed shapes and surface cover combinations, viz., contour watershed, V shape watershed and diagonal watershed, with and withot partial cover (Polythene sheet spread from upstream side to cover 50% of microwatershed) were studied under field condition for determining their runoff inducement efficacy and soil loss behaviour in deep alluvial soil. The runoff inducement efficacy ranging from 40 to 70% was different for different shapes and surface cover with daily rainfall. The V shape microwatershed produced (30-85% of rainfall) nearly 8-10% more runoff than that of contour watershed (20-80%). Partial cover produced 5% more runoff than without cover. Diagonal watershed produced 43% runoff. The treatment induced various spatially differential moisture regimes. The crop performance under these moisture regimes will determine suitability of microwatersheds in a given agroclimatic zone.

Nearly 60% of precipitation in arid and semi-arid areas is lost by evaporation. Need for efficient distribution of precipitation and recognition of its potential was pointed out after extensive review of 170 articles (Bores and Ben Asher 1979, Bores and Ben Asher 1982) on rain water harvesting published in 1970-80. In India, research on rainwater management got impetus after the advent of All India Co-ordinated Research Project on Dryland Agriculture in early 70s. Many studies have been conducted on proportion of watershed area to receiving area. These were classified under different nomenclature, viz., inter-row water harvesing and interplot water harvesting for in situ storage and watershed water harvesting for storage in pond and subsequent use as supplementary irrigation (Yadav 1979,

Mann and Ramana Rao 1981, Bores and Ben Asher 1982).

The precipitation redistribution and utilisation depends on efficient inducement of surface runoff and efficient recycling for use by the crops. The runoff inducement from the watershed is dependent on watershed characteristics (soil type, land slope, infiltration capacity and surface storage) and rainfall characteristics (rainfall intensity, amount, duration). It is a well established fact that runoff can be altered by management of vegetation in watershed areas with annual precipitation in excess of 280 mm (Cooley 1975). The main effect of removal of vegetation is that it reduces the infiltration capacity. The surface treatments such as weeding, smoothing and compacting in combinations (Evenari 1971), (Frith 1975) and (Ehrier 1982) in Jodhpur soil established that 5 to 7 m long length of run at 5% slope produces maximum runoff. Fairbourn (1975) showed that mulched microwatersheds were very useful where most rainfall comes as high intensity thunder storms and on soils that have slow water permeability.

In the sloping terrains such as gullies and ravines, sand dunes and many other similar situations some land development work is involved. Under such situations it is possible to develop land by contour bench levelling at minimum cost. There can also be several ways in which land can be developed but at varying costs. The hydrological regimes can be manoeuvred by modifying the physical shapes of land surface. The objective of this study was to assess the efficacy of runoff inducement and soil loss of different microwatershed shapes and surface cover in deep alluvial soil of ravine region of Uttar Pradesh.

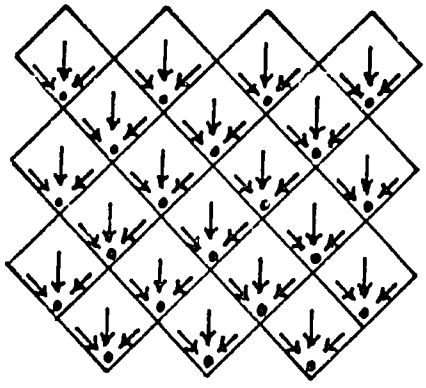
MATERIALS AND METHODS

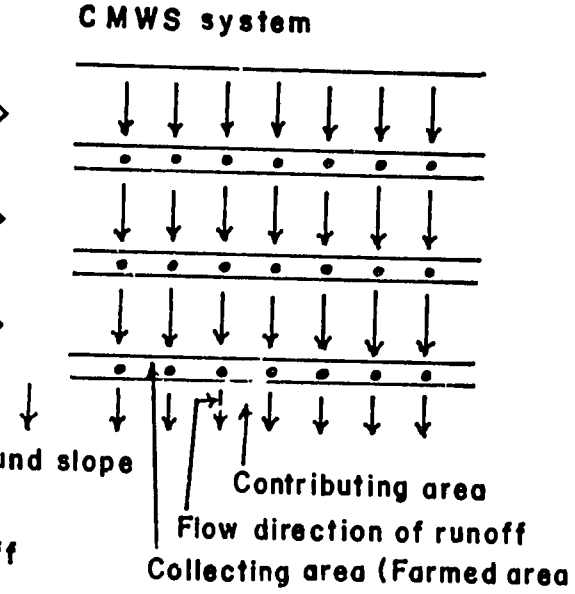
Long term field studies are being conducted at the Central Soil and Water Conservation Research Farm, Chhalesar, Agra since 1986 in the sandy loam deep alluvial soil (sand 78%, silt 8% and clay 14%) with a view to redistribute the precipitation and increase water use efficiency by zizyphus and citrus plants. The experiment has been laid out in randomised block design with treatments listed below (Table 1, Fig.1). The treatments were replicated four times. The plot size was 20m × 4m. To assess the runoff inducement and sediment flow, runoff plots of 2m width were specially created by the side of experiment.

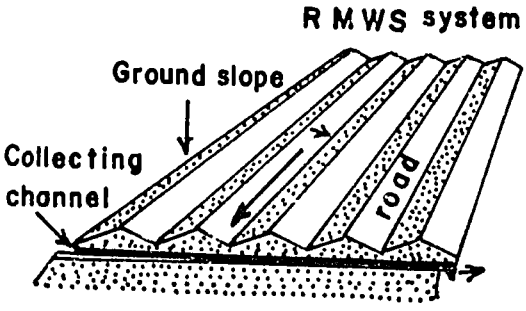
The microwatersheds were shaped to 5% slope. Rainfall was measured 300 m away from the experimental site. Runoff water collected in the tank down stream of plot was measured after each rain storm. Sediment samples were drawn after thorough mixing and soil loss was determined. Soil moisture samples were taken periodically from plantation zone and moisture content determined gravimetrically.

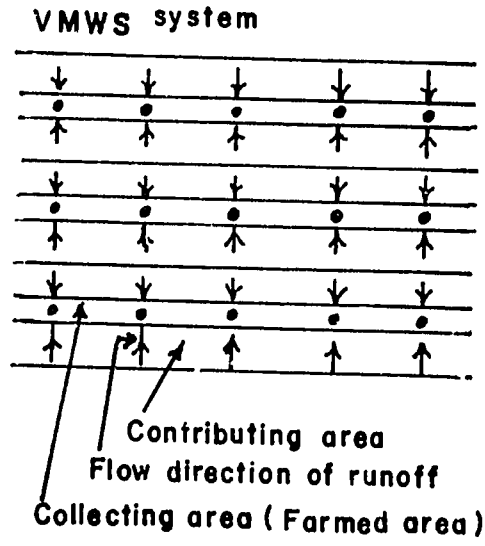
Table 1. Description of microwatershed shapes and surface covers in the experiment

Nomenclature	Nota-tions	Length of run, m	Area of plot, m^2	Applicability-Site conditions and mode of surface cover	Watershed shape researched upon by previous researchers
Contour watershed	L	4	8	Strips on contour, suitable for regular sloping lands.	Jones and Hauser 1975
Contour watershed with polyethylene cover	L+P	4	8	-do- +(2 m from top covered with polyethylene sheet)	-
V-shape watershed	V	2	8	Land developed V shape leaving one - metre plantation zone in the centre, suitable for irregular sloping land.	Fairborn 1975, Yadav et al. 1978
V shape watershed with polythylene sheet cover	V+P	2	8	-do- +(1 m from top covered with polythylene sheet)	
Diagonal watershed	D	7.14	25	Shaped diagonally	Evenari et al. 1971
Control	C	4	25	Irregularities removed	- no grading to any specific direction.


D MWS system
Tree in infiltration basin
Flow direction of runoff


C MWS system
Ground slope
Contributing area
Flow direction of runoff
Collecting area (Farmed area)


R MWS system
Ground slope
Collecting channel
road


VMWS system
Contributing area
Flow direction of runoff
Collecting area (Farmed area)

RESULTS AND DISCUSSION

Runoff: The runoff inducement efficacy of different microwatersheds varied with daily rainfall (Table 2). Daily rainfall of less than 0.020 m produced runoff less than 45% whereas rainspells more than 0.020 m produced runoff in the range of 60 to 80%. The runoff inducement with respect to microwatershed shapes was highest with V shape under all rainfall classes followed by contour watershed and diagonal watershed, respectively. With daily rainfall less than 0.010 m, surface cover induced more runoff (10-12%) than without cover on controur watershed. With daily rainfall more than 0.010 m surface cover induced nearly 5% more runoff than without cover on all watershed slopes. The V shaped microwatershed covered with polyethylene sheet produced maximum runoff (40-90%).

Table 2. Runoff inducement efficacy of different microwatershed shapes and surface covers in relation to daily rainfall classes

Treatment	Daily rainfall classes, m 0.010	0.011-0.020	0.04-0.030	0.031-0.040	0.051-0.060
	Runoff, % of rainfall				
L	22	29	54	77	66
L+P	39	34	59	81	73
V	42	31	59	89	79
V+P	47	37	79	89	84
D	34	30	35	66	41
C	-	-	2	1	1

The trend of runoff inducement efficacy became clear with weighted mean data with respect to rainfall (Fig. 2). The V shaped watershed induced maximum runoff (66%), nearly 8% more runoff than contour watershed (53%). Partial cover of polyethylene sheet produced nerly 5% more runoff than without cover. This indicates that land shaping is quite efficient for runoff inducement. The weighted mean runoff inducement with diagonal watershed was nearly 43% whereas the corresponding value for control was only 2%.

The variation in runoff inducement efficacy of microwwatersheds and surface covers was affected by the season in which rainfall occurred. In winter season runoff occurred in the range of 14 to 22% of rainfall. In rainy season the runoff was in the range of 35 to 65% (Fig. 2). This is because of higher soil moisture prior to rain and higher rainfall intensities during rainy season than that of winter. Murty et al. (1980) also reported 40-90% runoff with different water proofing treatments during high rainfall years and 10 to 60% during low rainfall years.

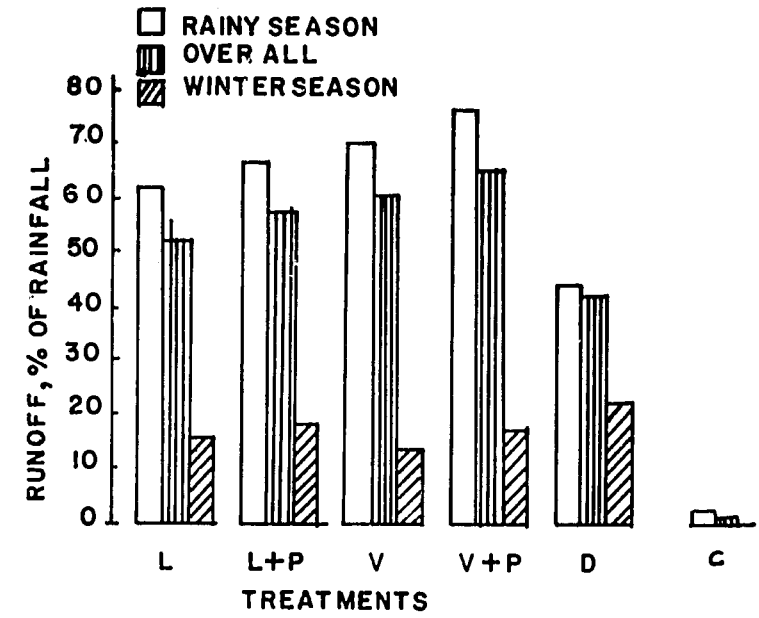
Threshold rainfall : The rainfall runoff relationship of these microwatersheds (Table 3) can be expressed by straight line (r = 0.97). It is evident that runoff from microwatersheds was highly dependent on rainfall (coefficient of determination r^2 = 0.94) for V shape and contour watersheds. In diagonal watershed the runoff inducement was however, 79% dependent on rainfall and rest 21% on other factors. Threshold rainfall to initiate runoff from diagonal watersheds was 0.006 m only whereas for others it was 0.009 m.

Total runoff potential : With the treatment combinations it was possible to induce a wide range of runoff volumes for the plantation crops. The maximum runoff water (2764 l) brought to individual plant was with diagonal watersheds followed by V shape microwatershed partially covered with polyethylene sheet (1941 l). The V shape microwatershed without surface cover produced as much water as contour watershed with polythylene sheet cover (Fig. 3).

Table 3. Regression coefficient and threshold rainfall in relation to microwatershed and surface cover

Treatment	m**	c	Correlation coefficient, r	Threshold rainfall, m
L	0.857	7.75	0.970*	0.009
L+P	0.938	8.37	0.973*	0.009
V	1.031	3.51	0.969*	0.009
V+P	1.070	9.65	0.972*	0.009
D	0.570	3.28	0.888*	0.006
C	-	-	-	-

** Y = mx+c ; Y = runoff mm ; x = rainfall; mm ; m = slope ; c = constant; * significant at 5% ; - = very few events produced runoff hence no relationship could be derived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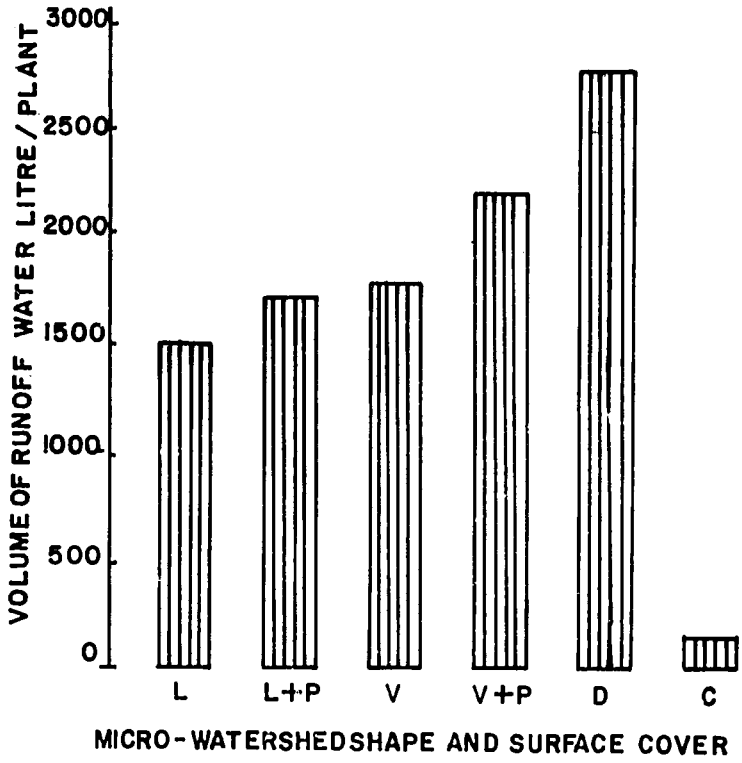
VOLUME OF RUNOFF WATER LITRE / PLANT
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L+P
V
V+P
D
C
MICRO-WATERSHED SHAPE AND SURFACE COVER

Soil moisture : Soil moisture in the centre of plant rows monitored 9 days after last rainy day revealed a different pattern. Maximum soil moisture of 0.059 m and 0.060 m in a soil profile of 7 m was in contour watershed and in diagonal watershed and 0.046 m in V shape watershed (Fig. 4). Runoff from entire microwatershed is concentrated at the basin in the diagonal watershed and on one side of plant rows in contour watershed. Because of this there was more moisture in the deeper soil layers. V shape microwatershed diverted runoff both sides of plant rows. As a result wider area was covered with relatively more moisture content from where the moisture samples were drawn. With surface covers differences in the moisture regimes will be wider. The crop performance under such diverse moisture regimes will help in identifying the suitable microwatershd for a given agro-climatic zone.

Soil loss : Soil loss from the contour microwatershed covered with polyethylene sheet was more than that from similar watershed without cover (Table 4).

Table 4. Soil loss in relation to microwatershed shape and surface covers

Treatment	Soil loss, Mg ha^{-1}
L	5.07
L+P	8.93
V	5.80
V+P	7.61
D	25.29
C	0.13

The soil loss from microwatersheds (L shape and V shape) was proportional to runoff induced. Polyethylene cover produced more runoff resulting in higher (2-3 Mg ha^{-1}) soil loss than without cover. Soil loss from the diagonal microwatershed was high (25-29 Mg ha^{-1}). The soil loss figures were higher as a result of occurrence of an exceptionally high intensity rainfall of 0.054 m (rainfall intensity over 0.13 mh^{-1}) with high wind velocity.

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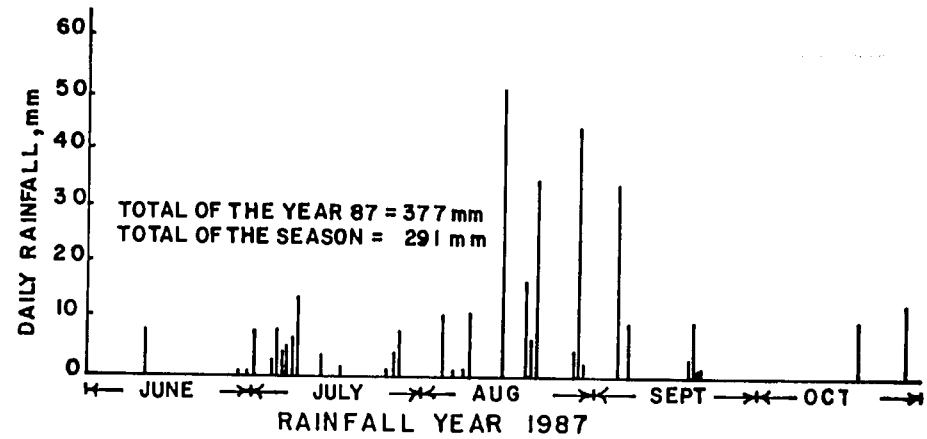
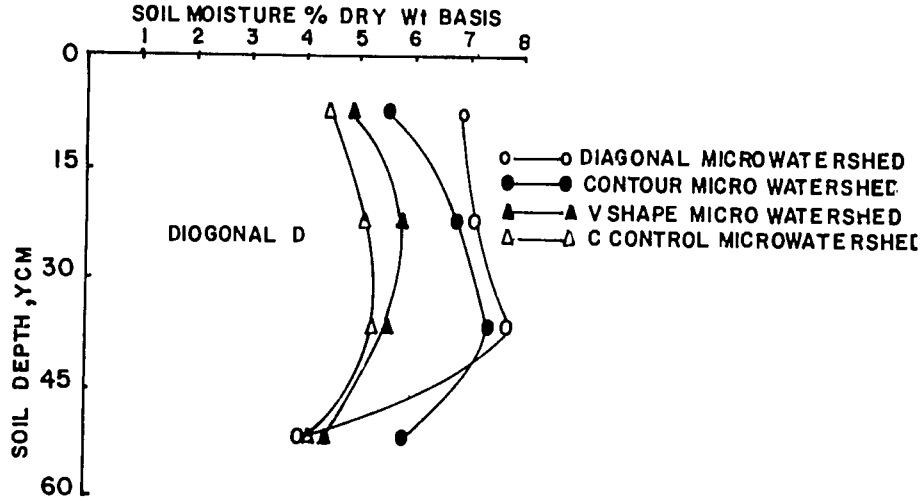
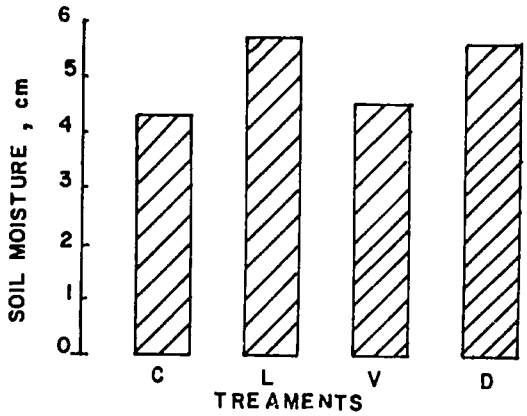




MOISTURE IN SOIL PROFILE (28-8-87)
9 DAYS AFTER LAST RAINY DAY (19-10-87)



and providing necessary facilities for the study.

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Hydrologic modeling of small agricultural watersheds – The ICRISAT experience

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ABSTRACT

The hydrologic response of a watershed integrates the effect of several complex processes and their interaction, involving land and soil features, climate, vegetation characteristics and management changes. Modeling has been used as a tool for designing soil and water management practices and structures.

Two important soils of semi-arid tropics, Alfisols and Vertisols, are represented at ICRISAT center. The paper reviews the development of three models based on data from watershed studies on these soils. The models are (a) a runoff simulation model (RUNMOD), (b) a modified curve number model (MCNM), and (c) a numerical technique runoff model (NTRM). The first two models require calibration at a given site, whereas the third model can be used without calibration. The first model requires daily rainfall amount and duration; the second model requires only daily rainfall amount; and the third model requires data on storm intensity and duration. RUNMOD and MCNM could be used for extending the length of runnoff records for the small watersheds with atleast one to two years of measured runoff data, or to predict water yield for nearby ungauged watersheds. NTRM provides event-based outputs and insights into physical processes, but it necessitates further improvements.

Hydrologic models are needed for design of land treatments, water conservation and disposal structures, supplemental irrigation strategies, and many other management changes. A mathematical model of a given system is designed to simulate the response of the system to specified inputs. But the range and complexity of hydrologic processes in a watershed are such that, at the present

stage of hydrologic science, it is difficult to simulate all of them with adequae precision. Renard et al. (1982), in reviewing a large number of small watershed models, noted that many of them contain simplifications and assumptions that preclude their universal use. There is a dearth of measured hydrologic data in the semi-arid tropics (SAT) for testing and adapting existing models or for developing new models.

Vertisols and Alfisols, two important soil orders of the SAT, are represented at ICRISAT center, Patancheru, Andhra Pradesh, India. The major characteristics of the two specific soil series (Kasireddypalli series for the Vertisol and Patancheru series for the Alfisol) at the center have been described by El-Swaify et al. (1985).

Several small agricultural watersheds at ICRISAT center have been monitored during the last 10-15 years. This paper reviews three surface runoff models, which are based on these watershed studies. The paper also suggests a future line of work.

Description of models : Three models have been discussed in this paper. The first model 'RUNMOD', is a lumped, parametric model and is based on data from the Vertisol watersheds. It estimates surface runoff volume, profile moisture, evapotranspiration and deep percolation on a daily basis (Harikrishna 1980, 1982). The second model, MCNM, is also a lumped parametric model, based on curve number technique and a soil moisture accounting procedure (ICRISAT 1984, Pathak et al. 1988). The type of output from RUNMOD and MCNM are similar (Table 1). The third model, NTRM, is deterministic and it is based on the principle of conservation of mass and momentum; it provides rates of runoff and infiltration for individual rainfall events. Summaries of input parameters and resulting output of these models are given in Table 1.

(a) RUNMOD : RUNMOD (Harikrishna 1982) utilizes the concept of two soil moisture zones, an upper zone of 0.2 m and lower zone that is the remaining part of the root profile. The daily evaporation loss is assumed to occur exclusively from the upper zone initially; only after the available moisture in the upper zone if exhausted, will evaporation loss occur from the lower zone. The soil-water budget is maintained on a daily basis and when rainfall is received, the upper zone is fully recharged before any moisture is added to the lower zone. The daily input data required are rainfall amount, duration, and pan evaporation.

The evapotranspiration is computed as follows :

$$AE = PE * (AW/AWX) \quad P=0 ; MU = MUI \qquad (1)$$

$$AE = PE \quad P=0 ; MUI < MU < MUX \qquad (2)$$

$$AE = 0.5\ 8\ PE\ (AW/AWX) \quad P>0 ; MU = MUI \qquad (3)$$

Table 1. Input parameters and outputs obtained for three models

	Input parameters				
			Soil		
Model	Climate	Measured	Opti-mized	Crop	Output
RUNMOD	daily rainfall amount and water initial soil moisture	min. & max. profile RIL	RIH and duration	crop coeffi-cient, crop duration,pan evaporation	daily runoff, ET, soil mois-ture, deep percolation
MCNM	daily rainfall amount, pan evaporation	min. & max. profile water initial soil water, air dry soil moisture, soil, mois-ture at saturation	DC and α	radiation transmission coeff., crop duration	daily runoff, ET, soil mois-ture, deep percolation
NTRM	pan evaporation storm, rain intensity and duration	land slope, min. & max. soil mois-ture, max. soil moisture in top 10 cm soil, field soil sat. conductivity, average wet-ting front suction		crop coefficient and duration	runoff hydro-graph, infil-tration rate, ET, soil moisture, deep per-colation

$$AE = 0.5 * PE$$

$$P>0 \; ; \; MUI < MU < MUX \qquad (4)$$

Where,

AE = actual crop evapotranspiration (mm)

PE = potential crop evapotranspiration, a product of crop coefficient and pan evaporation (mm)

AW = available moisture in lower zone on any given day (mm)

AWX = maximum available moisture in lower zone at field capacity (mm)

P = daily precipitation (mm)

MU = moisture in upper zone on any given day (mm)

MUI = initial moisture content in upper zone (mm)

MUX = maximum moisture content in upper zone (mm)

An infiltration index F (mm h^{-1}), is computed on the basis of two parameters RIH and RIL, which refer to 'high' and 'low' rates of infiltration. The higher value is assumed when the soil surface is totally dry, which corresponds to 0.060 m for a Vertisol at ICRISAT center. The parameter RIL is used when the upper zone moisture, MUX, equals 0.090 m. AWX is 0.220 m in Vertisols at ICRISAT.

Depending upon the value of MU on any given day, F for a given storm is computed according to one of the following relationships :

$$F = RIH \quad \text{if} \quad MU = MUI \qquad (5)$$

$$F = RIL \quad \text{if} \quad MU = MUX \qquad (6)$$

$$F = RIH - [\,(RIH-RIL) * (MU-MUI)/(MUX-MUI)\,] \qquad (7)$$

$$MUX > MU > MUI$$

The infiltrated depth INF (mm), is obtained as follows :

$$INF = F * SD \qquad (8)$$

where

SD = storm duration, h

The computed strom runoff, CRO, (mm) is then computed as

$$CRO = P\text{-}INF \qquad (9)$$

The computed and measured runoff data are compared through a univariate optimization procedure, to select values of RIH and RIL at new location having limited runoff records.

(b) Modified curve number model (MCNM) : The model (ICRISAT 1985, Pathak et al. 1988) is based on the curve number technique (USDA-SCS 1972) and the Hawkins (1978) approach. It takes into consideration the continuous

relationship between runoff curve number and soil moisture content and effects of surface runoff.

The runoff is simulated from daily rainfall using the relationship

$$Q = (P - 0.2)^2/(P+0.8S) \quad (10)$$

Where Q is daily runoff (mm), P is daily rainfall (mm) and S is a water retention parameter (mm). The parameter S is related to curve number, CN as :

$$S = (25400/CN) - 254 \quad (11)$$

The relationship between S and total water storage, V_n at day n is given as :

$$V_n = V_{n-1} + (AE)_{n-1} - (P_{n-1} - Q_{n-1}) = 1.2S_n \quad (12)$$

The model uses a soil depth parameter, DC which is determined through optimization.

The water retention parameter, S (mm) is computed using the relationship

$$S = C\,(SM_{max} - SMT) \quad (13)$$

SM_{max} is soil moisture at saturation, SMT the soil moisture at any particular day, and C is a coefficient whose value is determined through calibration. SMT is determined by using a soil moisture accounting procedure described below.

Soil moisture accounting procedure : The procedure utilizes the concept of two moisture zones : an upper zone of 0.3 m, and a lower zone below 0.3 m up to the end of the rooting zone. The daily evaporation is assumed to occur exclusively from the upper zone and it is only after the evaporable moisture from this zone is depleted then evaporation loss will occur from the lower zone. However, transpiration demand is met by plants extracting water uniformly from the entire zone. The soil water budget is calculated on a daily basis. Whenever there is rainfall, the upper zone is fully recharged before any moisture is transferred to the lower zone. The evaporation and transpiration is calculated using the following equations :

$$E^* = \beta * (E/t^*) \quad (14)$$

$$T = (1 - \beta)E_o \quad (15)$$

where, E is open pan evaporation, E^* the evaporation from soil, β the radiation transmission coefficient, T the transpiration, and t^* the time factor, days. When soil is wetted either by rainfall or by irrigation then t^* = 1, 2, 3, - - - n days, where 1 represents the rainy day, 2 the first non-rainy day, 3 the second non-rainy day, and so on throughout the subsequent rain free period. For subsequent rains if rainfall < open pan evaporation, then the value of t^* proceeds uninterrupted, otherwise t^* starts again at 1.

Daily soil moisture levels are calculated as follows :

$$SM_2 = SM_1 + (P - Q - AE) \quad (16)$$

where, SM_1 is the previous day's soil moisture content, SM_2 the soil moisture content for day under consideration. For alfisols, instantaneous transfer of excess moisture from the first zone to the second is considered; but for clayey soils like Vertisols a delay factor of 1 day is assumed.

Accounting for changes in soil surface conditions : Due to cracks present in dry Vertisols, infiltration is increased. Land smoothness created by preceding runoff events enhances runoff. These changes in soil surface conditions are accounted for the model as follows :

Reduction of runoff due to cracks, applied only when total evaporative demand exceeds 20 mm, is expressed as :

$$Sr = \alpha \sum_{1}^{n} E^* \quad (17)$$

Where,

Sr = cracking adjustment factor, substracted from simulated runoff for next storm

α = a function of amount and type of clay in the soil and represents soil's inherent tendency to crack; it is determined by calibration

E^* = total evaporative demand on the soil during an extended rainless period

n = no. of days with no rain or rainfall less than soil evaporation.

Runoff correction for land smoothness caused by preceeding runoff is accounted for as follows :

$$L_s = (Q_1)^{0.5} - 0.85 \quad (18)$$

where, L_s is smoothness correction (mm) created by runoff event and Q_1 is previous runoff amount (mm). The contribution of land smoothness is given by the factor R_s, which is related to L_s, runoff volume of preceding storm Q_1, and current simulated runoff Q_2 before applying land smoothness correction as follows :

$$R_s = L_s * Q_2/Q_1 \quad (19)$$

Numerical technique runoff model (NTRM) : The model is based on well known one-dimensional equations of continuity of mass and momentum. The equation for momentum has been simplified assuming kinematic wave approximation, i.e., equating bed slope and energy slope. The topographic features, i.e., width and slope of the flow plane and channel characteristics, are required as input to find the numerical solution of the mass and momentum equations. The rainfall excess rate for the continuity equation is an addtional input for the solution.

Evapotranspiration : A simple water balance equation (Reddy 1983) is used to estimate daily actual evapotranspiration (AE) :

$$(AE/E)_n = [1+(5-E_n)/10(t_n/En)^{0.5}]$$

$$exp[(l - t_n + a)/b_n - K] \quad (20)$$

Where, n is the day number, b the crop growth stage coefficient, t the time (days) after rainfall (depending upon history of wetting of soil profile as suggested by Reddy (1983), 'a' the number of days following a rainy day for which available soil moisture in the top 10 cm soil layer can meet potential evaporation demand, and K the maximum available soil storage capacity of soil in the root zone. The daily evapotranspiration is distributed diurnally following Singh and Kumar (1983) as :

$$AEB = 0.1\ AE \quad (21)$$

$$AED = 0.9\ AE \quad (22)$$

$$AEN = AEB/24 \quad (23)$$

$$\text{and } AER = AEB/24 + \text{Sin}\ (t_6 2\pi/24)\ AED/24 \quad (24)$$

Where, AEB is the base evapotranspiration, AED the evapotranspiration due to solar energy during a 12 h day, AEN the rate of evapotranspiration any time during a 12 h night, AER the rate of evapotranspiration any time during a 12 h day, and t_6 is the time in hours counted from 0600 h. Soil saturation deficit at the beginning of a given storm (D_2) is estimated as follows :

$$D_2 = D_1 - ET \quad (25)$$

Where D_1 is the soil saturation deficit at the end of the preceeding storm, and ET is the cumulative evapotranspiration for the intervening period.

Infiltration and rain excess rate : Rain excess rate is determined following a procedure described by Mein and Larson (1973) and modified by Chu (1978) for nonuniform intensity rains. The input requirement for estimating rain excess rate are : average suction at the wetting-front, soil saturation deficit, field saturated conductivity and rain intensity.

The continuity equation is solved using the finite element method for space domain and the finite difference method for time domain. The details of the model are discussed by Sachan (1985), and Sachan and Murty (1986).

Testing of models : The surface runoff from two Vertisol watersheds (BWl and BW4C, Table 2) were used for calibration during 1975 and 1976 and subsequently for prediction in other years (Table 3). Table 3 shows a fairly good agreement between simulated and observed seasonal runoff. Harikrishna (1982) demonstrated the model's capability to simulate individual storm runoff also. The model also provides reasonable estimates of the component of water balance (Srivastava and Jangwad (1988).

Though the model requires the rainstorm amount and duration or intensity, its outputs are cumulative runoff and infiltration. Its testing has been done only on the Vertisol at ICRISAT center.

Table 2. Land management practices used in different Vertisol (1976-85) and Alfisol (1976-80) watersheds at ICRISAT center

Watersheds	Practices
BW1 (Vertisol)	Broad and furrow (BBF) at 0.6% gradient, double cropping, no field boundaries, improved crop management
BW2 (Vertisol)	BBF at 0.6% gradient laid within small field boundaries, double cropping, improved crop management
BW4C (Vertisol)	Rainy season fallowing, postrainy season cropping, flat cultivation, traditional management
RW1C (Alfisol)	Flat-on-grade (0.4%), improved crop management
RW1D (Alfisol)	BBF (0.4%), improved crop management

Table 3. A comparison of measured and predicted seasonal runoff for the Vertisol watersheds at ICRISAT center by RUNMOD

Watershed/ year	Rainfall, m	Measured runoff, m	Predicted runoff, m
BW1			
1976	0.648	0.072	0.070
1977	0.523	0	0
1978	1.063	0.271	0.291
1979	0.610	0.073	0.079
1980	0.622	0.122	0.116
1981	1.096	0.322	0.323

1982	0.526	0.010	0.011
1983	0.937	0.162	0.154
1984	0.513	0.010	0.011
1985	0.442	0.002	0.004
BW4C			
1976	0.666	0.209	0.191
1977	0.516	0.052	0.051
1978	1.054	0.409	0.405
1979	0.600	0.178	0.166
1980	0.595	0.164	0.176
1981	1.088	0.434	0.434
1982	0.515	0	0.005
1983	0.975	0.290	0.288
1984	0.523	0.083	0.075
1985	0.442	0.019	0.018

The parameters of this model have limited physical significance. They can be obtained by optimization from available runoff records of at least 1 to 2 years.

This model was tested by comparing seasonal runoff data from two Vertisol watersheds (BWI and BW2, Table 2) and two Alfisol watersheds (RWIC and RWID, Table 2). Measured and predicted seasonal runoff for these watersheds are shown in Fig. 1 and 2. The agreements are satisfactory. Pathak et al. (1988) have also demonstrated good agreement between simulated and recorded monthly runoff values and weekly soil moisture values on the Vertisol. However, the model is less accurate for predicting daily runoff events, especially under crusted Alfisol conditions (ICRISAT 1984).

The main merit of the model is that it uses a continuous simulation of soil moisture instead of three discrete antecedent soil-moisture conditions envisaged in the original USDA-SCS curve number technique (1972). Since the model is based on a point simulation of soil moisture, it is not applicable to large watersheds with significant soil and topographic heterogenities. The model needs to be calibrated with measured runoff for 1-2 years and necessitates considerable data on soil physical properties. The correction factors for cracking and surface smoothness are empirical and will change with soil types.

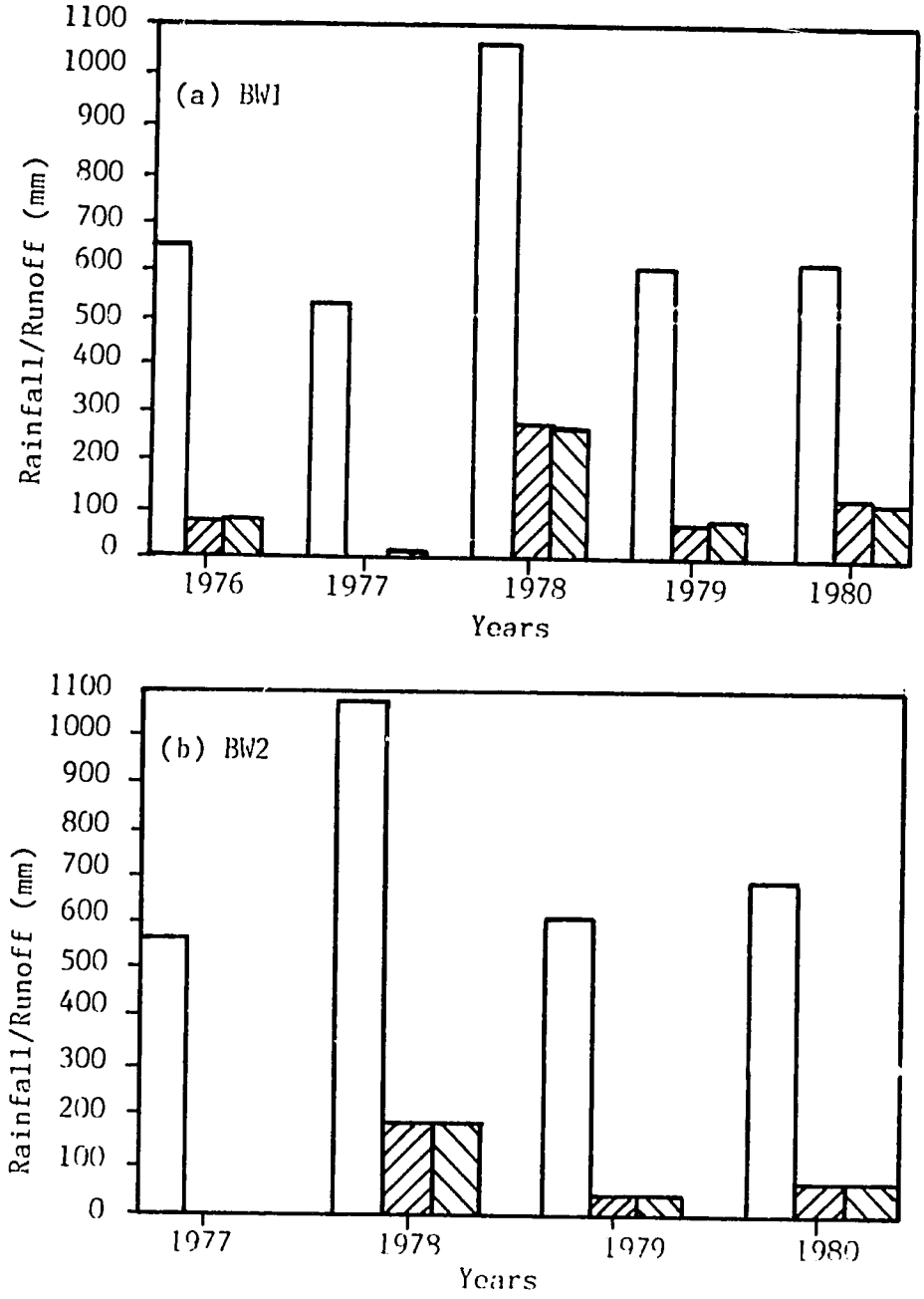

Fig. 1 Seasonal rainfall, measured runoff and predicted runoff by MCNM for two Vertisol watersheds (a) BW1 and (b) BW2 at ICRISAT Center

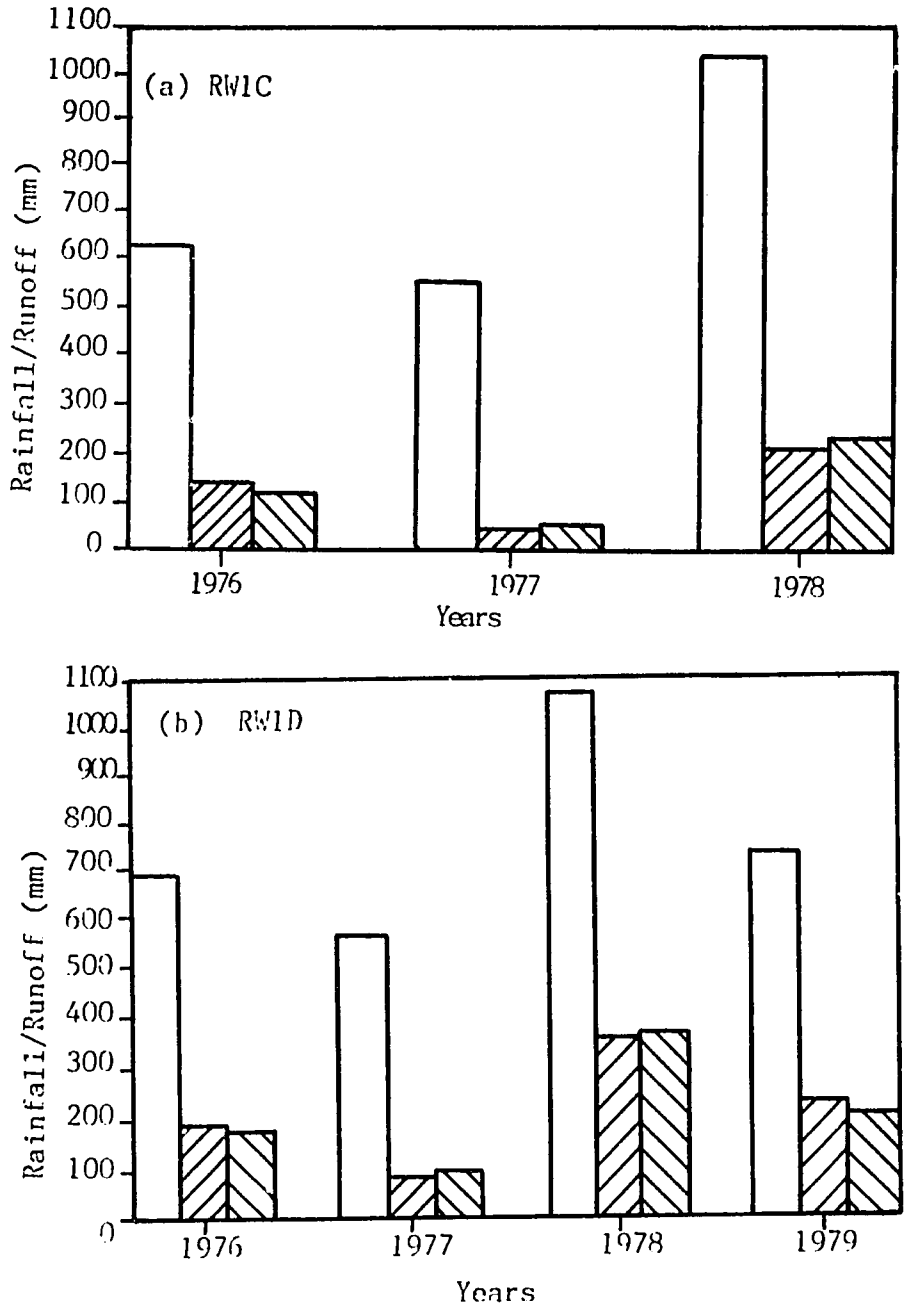

Fig. 2 Seasonal rainfall, measured runoff and predicted runoff by MCNM for two Alfisol watersheds (a) RW1C and (b) RW1D at ICRISAT Center

This model was validated, without parameter optimization, using surface runoff observations from eight plots (0.21 ha) on an Alfisol under a sorghum crop. There were two land surface configurations : (i) flat and (ii) broad bed and furrow ; two crop row grades (i) 0.3% and (ii) 0.5%; and two plot shapes (i) 70 m along and 30 m across the slope (ii) 52.5 m along and 40 m across the slope. Typical results of observed and simulated surface runoff at the last node of channels for a rainfall event of 0.050 m on 14 September 1982 having a uniform intensity of 0.052 m h^{-1} for 3300 sec. are shown in Table 4. Simulated peak runoff rates and total runoff were underestimated, and simulated timings to peak runoff were delayed as compared to observed runoff values. The prediction errors may be attributed to (1) non-precise estimation of Manning's n which changes with flow depth and crop stage, (2) extreme soil heterogenity, (3) crusted condition when soil surface was dry, and (4) convergence problem in numerical solution due to small node lengths and explicit finite difference scheme for time integration in the broadbed-and-furrow system (node length 1.5 m space between center of two furrows). The difference between observed and predicted runoff volume was in the range of 5.5 to 37.1%.

Table 4. A sample of comparison between observed and predicted runoff characteristics for an Alfisol at ICRISAT center by NTRM for a 50 mm rainfall event (Sept 14, 1982)

Configuration/shape	Row grade, %	Observed			Simulated		
		Total peak runoff, m	Time to runoff, sec	Peak runoff, mm sec^{-1}	Total peak, mm	Time to runoff, sec	Peak, mm sec^{-1}
BBF/1	0.5	0.032	1740	0.015	0.027	3114	0.010
BBF/1	0.3	0.042	1680	0.021	0.026	3116	0.010
Flat/2	0.5	0.030	1920	0.015	0.027	3066	0.011
BBF/2	0.3	0.035	1740	0.017	0.030	3109	0.011
Flat/1	0.5	0.038	1920	0.018	0.028	3061	0.011
Flat/1	0.3	0.038	1920	0.015	0.025	3020	0.011
BBF/2	0.5	0.036	1800	0.012	0.033	3112	0.013
Flat/2	0.3	0.038	1440	0.015	0.036	2063	0.011

Shape 1. Plot 70 m along and 30 m across the slope

Shape 2. Plot 52.5 m across and 40 m along slope

The model has the capability of incorporating spatial heterogenity of rainfall, soil variables, land surface variations, and other variation in space domain because the space domain can be discretized into subdomains and the flow is modelled for each subdomain interconnected through nodes. Its output is in terms of rates of runoff, infiltration, and flow velocity. This information can be used for erosion modelling (Ahluwalia et al. 1988), comparison of land management treatments, designing mechanical structures, vegetative barriers, and land-use changes. However, the major limitation of this model is that it needs large computer resources. To improve its performance, several improvements are desirable : (a) improved estimation of resistance offered to flow by crop and tillage practices, (b) infiltration and rainfall excess rate for cracking and crusted soils, and (c) a modified time-integration technique to accommodate large time steps for a solution. The model has undergone limited testing on 0.21 ha plots on an event basis. In order to simulate the runoff and other components of water balance on a large watershed on a seasonal basis, faster solution techniques are needed. Because of these limitations, NTRM in its present form should be viewed as a research tool rather than as an operational model for routine runoff prediction.

Conclusions: Watershed managers and researchers must select a hydrologic model keeping in view their design or investigation objectives; soil, climatic, and management features; and input data availability. MCNM and RUNMOD could be used for extrapolating short periods of runoff (1-2 years) into long-term periods for the calibrated watersheds or to predict water yield for nearby ungauged watersheds. Further work is required to improve the NTRM which includes measurable parameters and provides a runoff hydrograph. This latter model is capable of providing physical insights into hydrologic processes, for which the first two models are inadequate.

Rain infiltration, a key process in runoff modeling and management of rainfed agriculture, requires a better understanding under different soil and management conditions. For a fuller understanding of the infiltration process, experiments on rain infiltration under controlled conditions using rainfall simulators should be taken up. This should result in more powerful hydrologic models and improved management practices.

All the three models discussed in this paper assume a piston flow of infiltrated water in the soil profile. But cracking soils have a significant amount of bypass flow (Hoogmoed and Bouma, 1980). Also, none of these models deal with infiltration in crusted soils. These topics need further studies.

Prospective users of the models discussed in this paper may obtain further information from the authors.

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Water balance and erosion rates of vertisol watersheds under different management

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ABSTRACT

The water balance of two small agricultural watersheds on a Vertisol at ICRISAT Center was studied for 12 years. One of these watersheds has an improved management system that includes double cropping, and a broad bed-and-furrow (BBF) land treatment. The other watershed has a traditional management system, characterised by rainy season fallowing, post-rainy season cropping, and flat cultivation. The runoff from the two watersheds was measured, and was predicted using a parametric runoff simulation model, RUNMOD. The model was used to predict other components of water balance viz., evapotranspiration, bare soil evaporation, profile moisture accretion, and deep drainage. The soil loss from the watersheds was measured. The improved system lost only 13.7% rainfall as runoff and 1.46 Mg ha^{-1} yr^{-1} soil as compared to 24.1% runoff, and 6.38 Mg ha^{-1} yr^{-1} soil lost by the traditional system. The model predicted higher evapotranspiration and deep drainage, and lower bare soil evaporation for the improved system than for the traditional one. The study demonstrates the role of management in controlling soil erosion, and the productive and unproductive uses of rainfall.

Little research work has been reported on the consequences of agricultural management practices on water balance and soil erosion from the Vertisols in the semi-arid tropics (SAT). Freebairn et al. (1986) studied the effect of four surface cover conditions on watershed runoff on a Vertisol in southeast Queensland, Australia. Gardner et al. (1987) underlined the need to use simulation models

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to evaluate the long-term consequences of management treatments at locations where rainfall is highly variable from year to year. Harikrishna (1979 1982) proposed a runoff simulation model (RUNMOD) for predicting runoff and other components of water balance on a daily basis. This model was developed using two years' hydrologic data of three watersheds at ICRISAT Center, and is a lumped, parametric model. The calibrated model has been tested for its accuracy in predicting seasonal runoff for 10 years and found satisfactory (Sachan and Srivastava 1989). This paper focuses on comparisons of : (a) runoff predicted by RUNMOD with measured runoff from two watersheds under different management systems on a mean weekly basis over 12 years; (b) the predicted water balance of the two systems; and (c) annual soil loss from the two systems for a period of 8 years.

MATERIALS AND METHODS

Study watersheds : Both the study watersheds are located on a Vertisol at ICRISAT Center, Patancheru. The soil is classified as a Typic Pellustert (Kasireddipalli series) and is about 1.8 m deep. The land slope is about 1.7%. The physical and chemical properties of the soil have been reported by El-Swaify et al. (1985). One of these watersheds (BW1) covers an area of 3.4 ha, and has an improved management system. The second watershed (BW4C) covers an area of 3.5 ha and has a traditional management system; both the management systems have been described in detail by El-Swaify et al. (1985). However, the main management features affecting water balance and erosion are as follows :

Improved system: Broad bed-and-furrow (BBF) land treatment, with broad beds and furrows laid across the slope at a gradient of about 0.6%, mould board ploughing (to 15 cm depth) in the bed zone once every year during February or March, 2-3 shallow cultivations or harrowings before dry sowing of rainy-season crops, cropping during both rainy and post-rainy seasons.

Traditional system: Flat cultivation, generally one blade harrowing before the start of the rainy season, 3-4 blade harrowings for weed control during brief dry periods in the rainy season, fallowing during the rainy season and cropping only during the post-rainy season.

Analysis : The water balance was estimated using RUNMOD for a 12-year period (1976-77 to 1987-88). The model was calibrated for the study watersheds using data from 1975 and 1976, and uses the following input information : daily rainfall amount and duration, daily pan evaporation, minimum and maximum profile water, initial soil moisture, and crop duration. It predicts daily runoff, crop evapotranspiration, bare soil evaporation, profile moisture, and deep drainage. The details of the model have been described by Harikrishna (1979, 1982) and Sachan and Srivastava (1988). The output of the model was tabulated on weekly basis for the period 1 June to 31 January each year. A crop duration of

108 days (15 June to 30 September) was asumed for the rainy-season crop (maize, *Zea mays* L.) and of 113 days (11 October to 31 January) for the post-rainy season crop (chickpea, *Cicer arietinum* L.).

To monitor runoff, the study watersheds were instrumented with parshall flumes and stage level recorders. Each week the measured runoff was compared with predicted runoff. To estimate soil loss two runoff samples (each 500 ml) from each rain storm were manually collected for a 8-year period (1976-77 to 1983-84).

RESULTS AND DISCUSSION

Runoff prediction : Table 1 shows the mean measured and predicted weekly runoff over 12 years. In general, runoff predictions are fairly accurate for longer time periods (e.g. weekly, fortnightly etc.) particularly if they are averaged over several years. The predictions of daily runoff are relatively less accurate (Srivastava and Jangawad, unpublished data). Obviously, errors in prediction are cancelled out when longer time periods are considered. In general, the model seems to be suitable for computing runoff probabilities using at least 20-30 years' climatic records for locations that have the necessary input data. But before undertaking such computations, the model must be calibrated for a given location and management system using at least 2 years' measured runoff data.

Table 1. Mean measured and predicted weekly runoff from two differently managed watersheds, on a Vertisol, ICRISAT center, 1976/77 to 1987/88

Standard week	Rainfall, m	Runoff, m			
		Improved (BW1)		Traditional (BW4C)	
		Measured	Predicted	Measured	Predicted
23	0.008	0	0	0	0
24	0.053	0.02	0.002	0.001	0.001
25	0.029	0.001	0.001	0.001	0
26	0.030	0.007	0.007	0.005	0.003
27	0.032	0.001	0.001	0	0.001
28	0.027	0.002	0.001	0.004	0.005
29	0.045	0.003	0.002	0.007	0.008
30	0.049	0.002	0.002	0.004	0.005
31	0.062	0.003	0.002	0.012	0.012
32	0.041	0.003	0.003	0.012	0.013

33	0.068	0.023	0.027	0.038	0.038
34	0.038	0.012	0.011	0.018	0.015
35	0.028	0.001	0.001	0.006	0.006
36	0.028	0.001	0.001	0.004	0.004
37	0.040	0.004	0.004	0.008	0.009
38	0.036	0.007	0.007	0.013	0.012
39	0.032	0.009	0.010	0.015	0.015
40	0.043	0.015	0.013	0.017	0.019
41	0.013	0.002	0.002	0.004	0.004
42	0.007	0	0	0	0
43	0.003	0	0	0	0
44	0.013	0.001	0.001	0.004	0.004

Runoff variation : Table 1 shows that during the first 3-4 weeks of the rainy season, runoff was similar in both the management systems. But, during the subseqent period, runoff was markedly lower in the improved system. On an annual basis, the improved system produced 50% less runoff than the traditional system. About 10% of this reduction could be attributed to the BBF land configuration in the improved system (Srivastava et al. 1982), but the most prominent factor responsible for this difference is obviously the rainy-season crop in the improved system (in contrast to the fallow in the traditional system). Drying of the soil profile by crop roots, and crop cannopy effects probably cause much higher infiltration in the improved system than in the traditional.

In the improved system, runoff ranged from 0 in 1977-78 to 0.332 m in 1981-82 (Table 2); in the traditional system, it ranged from 0.018 m in 1985-86 to 0.434 m in 1981-82 (Table 3). In very low rainfall years, runoff was negligible in both the systems; but in years of moderate and high rainfall, runoff was substantially higher in the traditional system.

Table 2. Water balance components (m) of a watershed (BW1) with an improved management system during a period from 1 Jun to 31 Jan, 1976 to 1988

Year	Rainfall P	Measured runoff R(m)	Predicted runoff R(p)	Evapotran-spiration ET	Bare soil evapo-ration BSE	Profile moisture accretion PMA	Deep drainage DD
1976/77	0.710	0.072	0.071	0.505	0.011	0.063	0.060
1977/78	0.545	0	0	0.483	0.008	0.054	0
1978/79	1.110	0.271	0.281	0.513	0.017	0.079	0.220
1979/80	0.681	0.073	0.082	0.508	0.017	0.074	0
1980/81	0.731	0.122	0.137	0.521	0.014	0.059	0
1981/82	1.123	0.332	0.323	0.536	0.011	0.080	0.173
1982/83	0.580	0.010	0.010	0.500	0.015	0.055	0
1983/84	1.000	0.154	0.165	0.556	0.016	0.085	0.173
1984/85	0.564	0.011	0.012	0.500	0.006	0.046	0
1985/86	0.538	0.004	0.003	0.468	0.015	0.052	0
1986/87	0.586	0.037	0.035	0.499	0.009	0.043	0
1987/88	0.837	0.118	0.121	0.521	0.018	0.080	0.097

Table 3. Water balance components (m) of a watershed (BW4C) with a traditional management system during a period from 1 Jun to 31 Jan. 1976 to 1988

Year	P	R(m)	R(p)	ET	BSE	PMA	DD
1976/77	0.710	0.209	0.178	0.191	0.286	0.055	0
1977/78	0.545	0.052	0.051	0.187	0.250	0.057	0
1978/79	1.110	0.409	0.417	0.252	0.300	0.075	0.066
1979/80	0.681	0.178	0.171	0.206	0.242	0.062	0
1980/81	0.731	0.164	0.174	0.184	0.311	0.062	0
1981/82	1.123	0.434	0.441	0.232	0.319	0.073	0.058
1982/83	0.580	0.020	0.024	0.187	0.300	0.069	0
1983/84	1.000	0.288	0.291	0.249	0.307	0.070	0.083
1984/85	0.564	0.075	0.084	0.196	0.240	0.044	0

1985/86	0.538	0.018	0.020	0.156	0.310	0.052	0
1986/87	0.586	0.114	0.107	0.163	0.264	0.052	0
1987/88	0.837	0.206	0.210	0.249	0.276	0.070	0.032

Crop evapotranspiration and bare soil evaporation : Tables 2 and 3 show variations in the predicted values of crop evapotranspiration (ET) and bare soil evaporation (BSE), in the study watersheds from 1 Jun to 31 Jan, 1976 to 1988. Under the traditional management system : ET ranged from 0.156 m in 1985-86 to 0.252 m in 1978-79; and BSE ranged from 0.24 m in 1979-80 to 0.31 m in 1978-79 and 1985-86. For the improved system ET ranged from 0.468 to 0.556 m and BSE was negligible in comparison to ET. Table 4 shows an overall comparison of mean annual values of ET and BSE between the two systems. These differences are attributed largely to the absence of a rainy season crop in the traditional system.

Profile moisture accretion and deep drainage : Profile moisture accretion (PMA) is defined here as the difference between profile moisture on Jun 1 and Jan 31. Tables 2 and 3 show variations in predicted values of PMA, and deep drainage (DD) for the two watersheds from 1 Jun to 31 Jan, 1976 to 1988. In the traditional system, PMA ranged from 0.044 m in 1984-85 to 0.102 m in 1987-88; in the improved system, it ranged from 0.047 m in 1984-85 to 0.132 m in 1987-88. However, the mean PMA was about 0.06 m in each system during the study period (Table 4).

Table 4. Summary (mean of 12 years) of the predicted water balance of two watersheds, under different management systems during a period from 1 Jun to 31 Jan, 1976 to 1988

Item/component (m)	Management Improved (BW1)	Traditional (BW4C)
Rainfall (P)	0.750	0.750
Runoff (R)	0.103 (13.7)	0.181 (24.1)
Crop evapotranspiration (ET)	0.509 (67.8)	0.201 (26.8)
Bare soil evaporation (BSE)	0.014 (1.9)	0.286 (38.1)
Profile moisture accretion (PMA)	0.063 (8.4)	0.062 (8.4)

Deep drainage (DD)	0.061 (8.1)	0.020 (2.7)

Figures in parentheses are values of components expressed as a percentage of rainfall.

Overall, the moisture stored in the soil profile was estimated to be higher on 31 January than on 1 June by same amount (about 0.06 m) in both systems (Table 4).

In years when there was less than 0.80 m rainfall, deep drainage below 180 cm depth was zero in both systems (Tables 2 and 3). But in high rainfall years, deep drainage was substaintally higher in the improved system than in thetraditional one. This may be attributed to the substntially higher infiltration in the improved system.

Soil erosion : Soil loss from the improved system was less than 25% of that from the traditional system (Table 5). Part of this reduction may be explained by the difference in runoff; but even the soil loss per unit runoff was lower in the improved system. This was probably due to the protection against soil detachment given by the crop canopy in the improved system.

Table 5. A comparison (mean of 8 years) of soil loss form two watersheds under different management systems during a period from 1 Jun to 31 Jan, 1976 to 1984

Management system/watershed	Total soil loss, Mg ha^{-1} yr^{-1}	Soil loss/ unit runoff, kg mm^{-1}
Improved, (BW1)	1.46	14.6
Traditional (BW4C)	6.38	35.4

This study showed that the improved management system increased crop evapotranspiration and deep drainage, and reduced bare soil evaporation, runoff, and soil loss in comparison to the traditional system in the two study watersheds. The model, RUNMOD appears satisfactory for such investigations particularly if estimates for weekly or longer time periods are needed. The transferability of RUNMOD is limited by its input data requirement and need for local calibration. The search for better hydrologic models must therefore continue.

Agricultural technologies are often only characterized for their annual productivity and economics. In order to ensure efficient and sustainable utilization of soil and water resources, the hydrologic characterization of alternative technologies should also be emphasized.

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Spatial variability of rainfall and its impact on the productivity of Alfisols and Vertisols

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ABSTRACT

The impact of rainfall variability on soil water, runoff, and crop yield was quantified using rainfall from a network of 28 raingauge stations located in the 14 km^2 area of ICRISAT Center (Patancheru) near Hyderbad, India (latitude 18^0N, longitude 78^0E, altitude 545 m above mean sea level). Results based on the data from 1983 to 1988 show that there is a significant variation of rainfall over the test site on a daily, monthly or seasonal basis. A modified curve number model was used to estimate runoff for two agricultural watersheds (Alfisol: 1.2 ha; Vertisol: 3.4 ha). Sorghum yields were simulated for these two watersheds using a crop simulation model called Resource Capture Model (RESCAP). Simulated values of soil water, runoff and crop yields for two soils and rainfall environments of 6 years (1983-1988) indicated the need to monitor rainfall at site to evaluate results of field trials. However, for general planning, rainfall data from the Meteorological Observatory would be sufficient, particularly for deeper soils.

Eastimates of spatial and temporal variability of rainfall are needed for optimum use of land and water resources and to stabilize crop production. Studies on spatial variability of rainfall are limited in comparison to those concerning temporal variability. Quantitaive description of the spatial variability of rainfall requires operation of an intensive raingauge network which is often not available. Some spatial rainfall variability studies in the tropics have used annual and monthly totals as well as individual daily rainstorms. Nicholson (1980) used monthly means between stations for West Africa to derive rainfall anomaly types. Huff and Shipp (1969) studied storm, monthly and seasonal rainfall amounts and showed the

effect of rain type, synoptic storm type and other factors on spatial correlation.

Sivakumar and Hatfield (1989) described the nature of spatial variability of individual rain storms, monthly and seasonal totals using a dense network of rainguage at a large experimental (5 km^2) station in Niger.

The effectiveness of rainfall is modified by soil types and crop growth stages. The objective of this paper is to quantify the impact of spatial rainfall variability on runoff, water loss (deep drainage and runoff) and crop yields using data from ICRISAT Center (latitude 18^0 N, longitude 78^0 E, and altitude 545 m).

MATERIALS AND METHODS

This study was conducted at ICRISAT Center, for 6 years (1983-88) using a network of 28 rain gauge stations and an 'A' class Meteorological Observatory located in a 14-km^2 area (1400 ha). Daily rainfall was measured in 23 non-recording and 5 recording rainguages.

Rainfall variations were examined on a daily, monthly and seasonal basis. Surface runoff was estimated using modified curve number technique (Pathak et al. 1988) for two soil types (Alfisols and Vertisols) using rainfall measurements taken from the nearest raingauge. The Meteorological Observatory data were used as a reference standard. The runoff model (ICRISAT 1985, Pathak et al. 1988) takes into consideration the continuous relationship between curve number, soil moisture content and effects of surface runoff. The soil inputs include minimum and maximum profile soil water, air dry soil moisture and soil moisture at saturation. The crop inputs include date of planting and harvest, and radiation transmission coefficient. Daily rainfall amount and pan evaporation are the climate data needed for the model.

Water loss (deep drainage and runoff), soil water availability and sorghum grain yields were simulated using a Resource Capture Model, RESCAP (Monteith et al. 1989), for two soil types using rainfall data from the nearest raingauge and other weather data observed at the Meteorological Observatory. Central to this model are two assumptions, well supported by field evidence: (i) that the amount of dry matter produced per unit of radiation intercepted by foliage is effectively constant during vegetative growth when water is not limiting and (ii) that the amount of dry matter produced per unit of water transpired is inversely proportional to mean saturation deficit whether water is limiting or not. Climate input data driving the model are: daily rainfall, minimum and maximum air temperature, solar radiation, open pan evaporation and saturation deficit; soil data requirements are : available water holding capacity, initial soil moisture and response time for water extraction; and crop inputs are : thermal and photoperiod effects on phenology, light use efficiency, specific leaf area, specific root weight and root length density. Data of crop emergence, plant population, and dates and amount of irrigation are the agronomical data.

Rainfall (year, month, day) in the tropics varies considerably temporally and therefore its measurement over a shorter time interval (e.g. day) has always been found useful for water management research and development. However, it is time consuming and costly. Therefore, most experimental stations rely on data only from a Meteorological Observatory located at some distance form the experimental site. In out study we assessed the spatial variability of rainfall, in order to examine the relevance of data observed at the Meteorological Observatory for defining the moisture environments (e.g. runoff, soil water availability) in nearby watersheds. We studied the following aspects of rainfall :

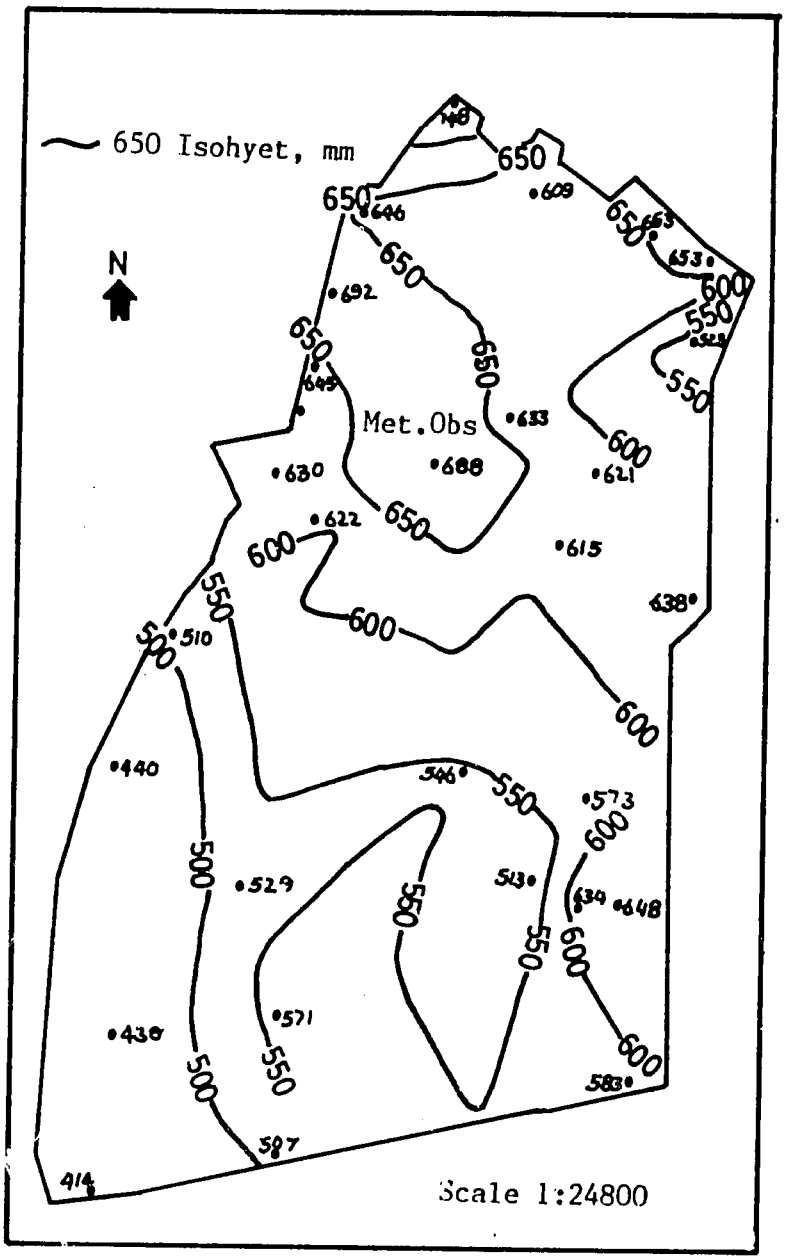
i) Average seasonal rainfall
ii) Monthly variations of rainfall
iii) Variations within a selected month (September 1988)
iv) Daily rainfall variations for three specified raingauges during September 1988.
v) Extreme variations of rainfall on selected rainy days recording at least 0.020 m rainfall in 24 h in the Meteorological Observatory.

RESULTS AND DISCUSSION

Seasonal rainfall: Total seasonal rainfall (June to October) averaged over the datum period (1983-1988) shows that monthly rainfall varied considerably from year to year. The data observed a the ICRISAT Meteorological Observatory are given in Table 1. The coefficient of variability of monthly rainfall is fairly high. Average rainfall in August was 0.184 m, and its coefficient of variation was 55%. The analysis of seasonal rainfall over the 6-year period, shows that the amount of rainfall recorded across ICRISAT Center varies considerably. The south-west corner of the Center (3.4 km from the Meteorological Observatory) recorded 40% less rainfall (0.414) compared to that of the Meteorological Observatory (0.688 m) (Fig. 1). This is a fairly large difference and is because of differences in rainfall observed during the season across the Center. Fig. 2 shows such rainfall variation for a month (September 1988).

Table 1. Statistics on monthly total rainfall recorded (m) at the Meteorological Observatory, averaged over 6 years (1983-1988), ICRISAT Center

Month	Met-Obs	Standard deviation	Highest	Lowest
Jun	0.109	±0.023	0.143	0.087
Jul	0.181	±0.046	0.256	0.131
Aug	0.184	±0.102	0.305	0.046
Sep	0.138	±0.102	0.286	0.057
Oct	0.76	±0.063	0.149	0.000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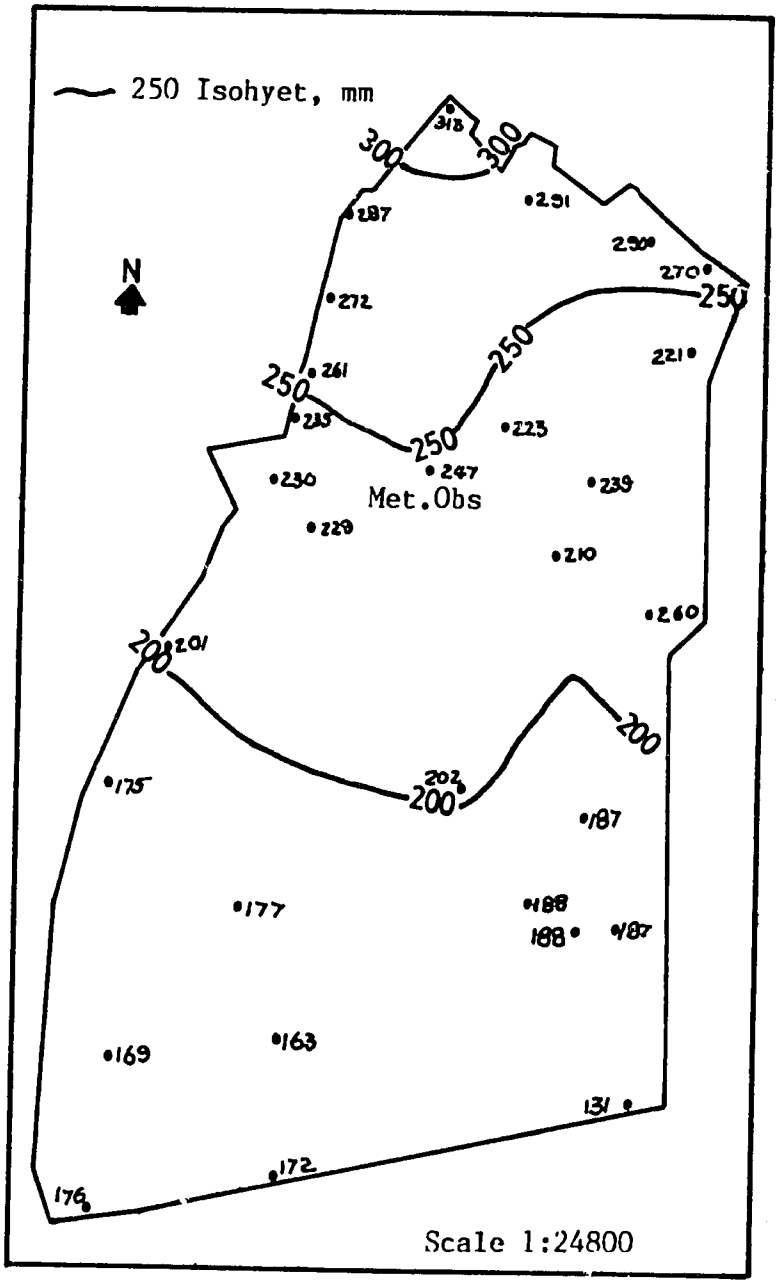
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Further, averaging the rainfall over the season may mask some important attributes for water management. This fact is apparent from an analysis of the 1988 rainfall records. The amount of rainfall recorded at the Meteorological Observatory is within 0.026 m of those averaged over 28 raingauge stations (Table 2) but significant differences in shor-term rainfall exist.

Table 2. Statistics on the total monthly rainfall recorded (m) at the Meteorological Observatory and 28 additional raingauges, ICRISAT Center, 1988

Month	Met-Obs	Standard deviation	Raingauges average	Standard deviation
Jun	0.122	±0.009	0.106	±0.008
Jul	0.256	±0.013	0.240	±0.013
Aug	0.273	±0.018	0.249	±0.017
Sep	0.247	±0.013	0.221	±0.013

In 1988, a total of 0.898 m seasonal rainfall was recorded at the Meteorological Observatory. However, the rainfall measured at other network raingauges ranged between 0.677 m (southern side) and 1.020 m (northern side). The range in rainfall in each month across the Center is quite high. For example, in 1988, it ranged between 0.086 and 0.125 m in June, 0.192 and 0.283 m in July, 0.214 and 0.309 m in August, and 0.169 and 0.313 m in September. We further compared the daily rainfall data of September 1988 recorded at the Meteorological Observatory and at two other raingauges. Variations of rainfall on any particular day, differences in the dry periods, and the number of days receiving at least 0.020 m rainfall in a month (Fig. 3) demonstrate that a detailed rainfall data network is needed for land and water management research. Variations in rainfall on a day receiving at least 0.020 m rainfall were studied. Two days in the months of June, July, August, and September 1988 were selected to depict the range of observed rainfall (the highest and the lowest rainfall) at the Center (Table 3). For example, on 29 August, rainfall observed at the Meteorological Observatory was 0.078 m, it ranged between 0.045 and 0.102 m across the Center. Such variations in rainfall over time and space could cause appreciable changes in estimates of water loss requiring differential conservation practices. The impacts of variations in rainfall on runoff, water loss, soil water availability and crop yields are presented in the following sections.

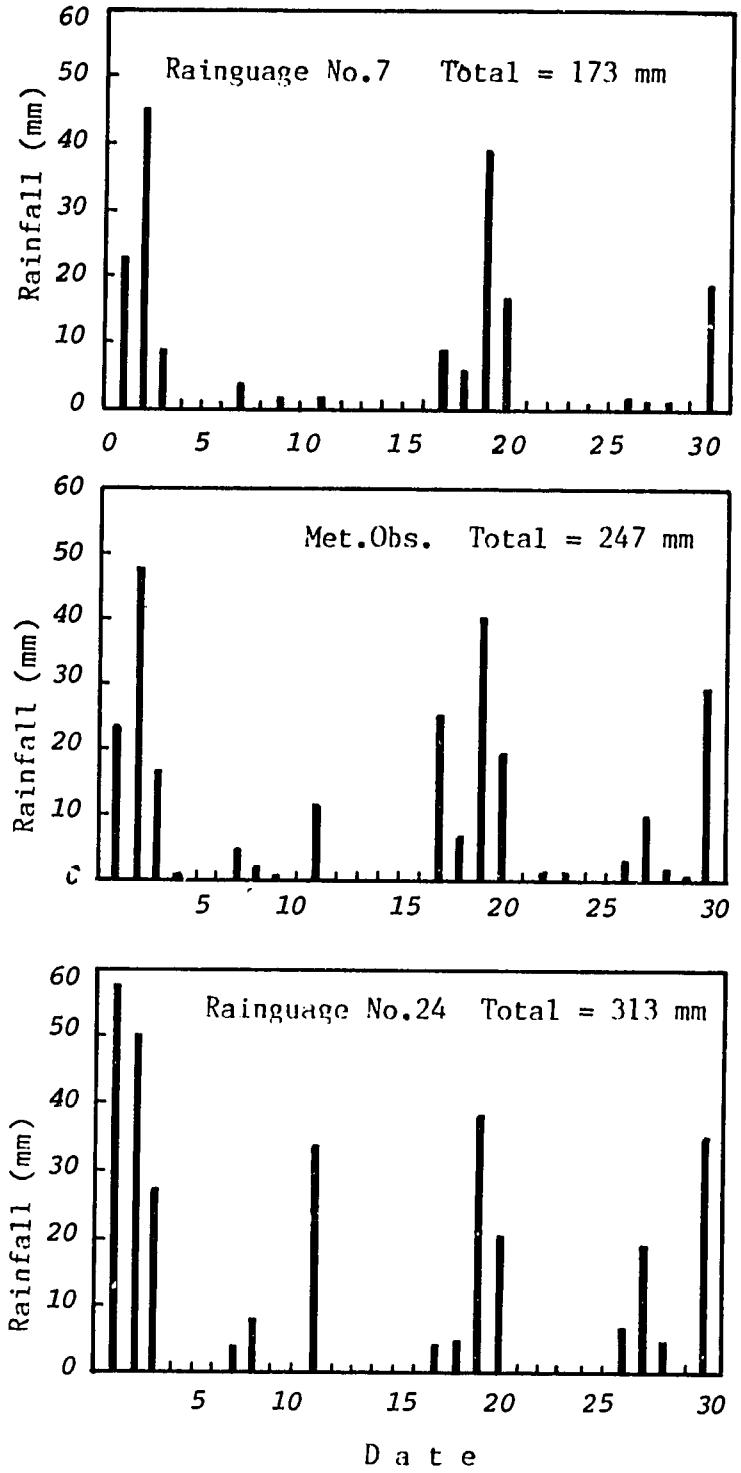
Rainguage No.7 Total = 173 mm
Met.Obs. Total = 247 mm
Rainguage No.24 Total = 313 mm
Rainfall (mm)
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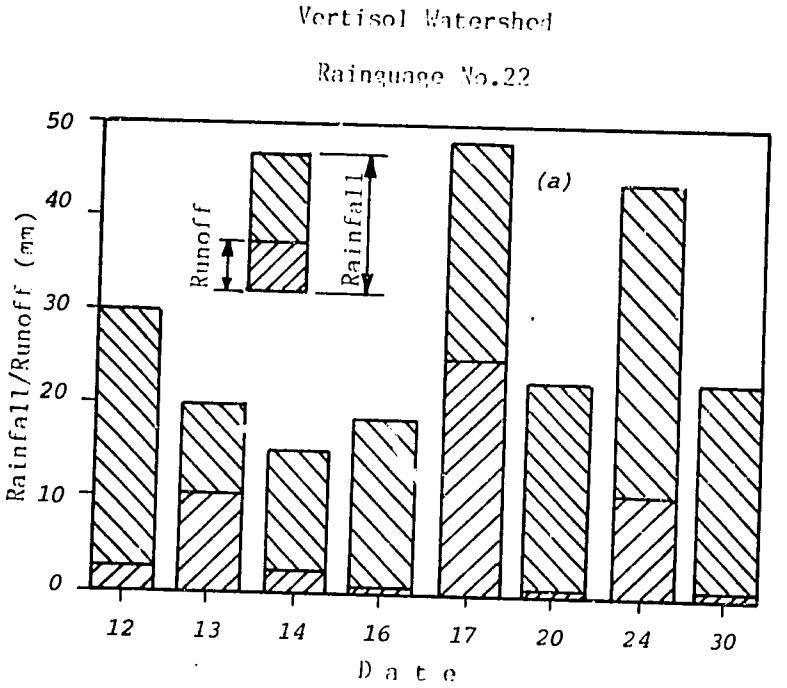
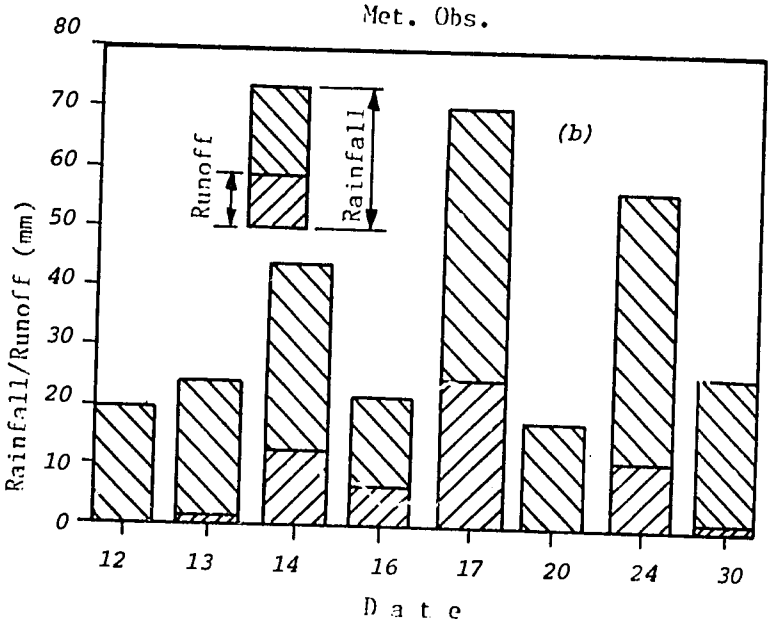
Table 3. Variations in rainfall (m) on any particular day at ICRISAT Center, 1988

Month	Day	Met-Obs	Highest	Lowest
Jun	18	0.041	0.044	0.019
Jun	23	0.028	0.036	0.016
Jul	16	0.052	0.057	0.031
Jul	30	0.050	0.046	0.035
Aug	18	0.060	0.066	0.047
Aug	29	0.078	0.102	0.045
Sep	1	0.024	0.058	0.022
Sep	2	0.048	0.050	0.035

Runoff: A modified curve number technique was used to simulate runoff for two watersheds (Alfisol : 1.2 ha; Vertisol : 3.4 ha). Rainfall data of September 1988 from the Meteorological Observatory and from the raingauge stations nearest to the respective watersheds were used to compare runoff. On 13 September, the estimated runoff on an Alfisol watershed is 0.002 m if rainfall from the nearest raingauge is used and the runoff is 0.01 m if the rainfall from the Meteorological Observatory is used (Fig. 4a or 4b). However, for the Vertisol watershed, the estimated runoff is 0.01 m if rainfall form the nearest raingauge is used, and almost no runoff is indicated if the rainfall data of the Meteorological Observatory are used (Fig. 5a or 5b).

Runoff was simulated for July, August, and September for 1983 to 1987 using rainfall data from Meteorological Observatory and the nearest raingauge station of a Vertisol watershed. Measured runoff data from this watershed were compared with the simulated values arrived at by using rainfall figures form those two sources. Results (Table 4) show that the estimates of runoff are significantly different depending on the source of rainfall data used. Simulated runoff using the rainfall data from the nearest raingauge is usually closer to the measured values. For example, in August 1986, 0.034 m runoff was measured in the Vertisol while the simulated runoff was 0.033 m if rainfall from the nearest raingauge was used, and 0.004 m if rainfall from the Meteorological Observatory is used.


Vertisol Watershed
Rainguage No.22
(a)
Runoff
Rainfall
Rainfall/Runoff (mm)
50
40
30
20
10
0
12
13
14
16
17
20
24
30
Date


Met. Obs.
(b)
Runoff
Rainfall
Rainfall/Runoff (mm)
80
70
60
50
40
30
20
10
0
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13
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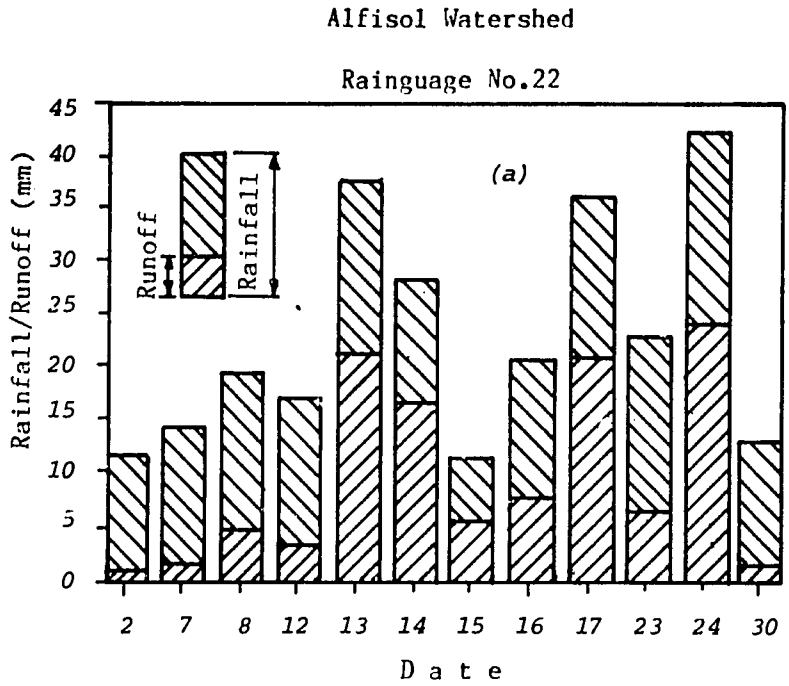
16
17
20
24
30
Date


Alfisol Watershed
Rainguage No.22
(a)
Runoff
Rainfall
Rainfall/Runoff (mm)
45
40
35
30
25
20
15
10
5
0
2 7 8 12 13 14 15 16 17 23 24 30
D a t e

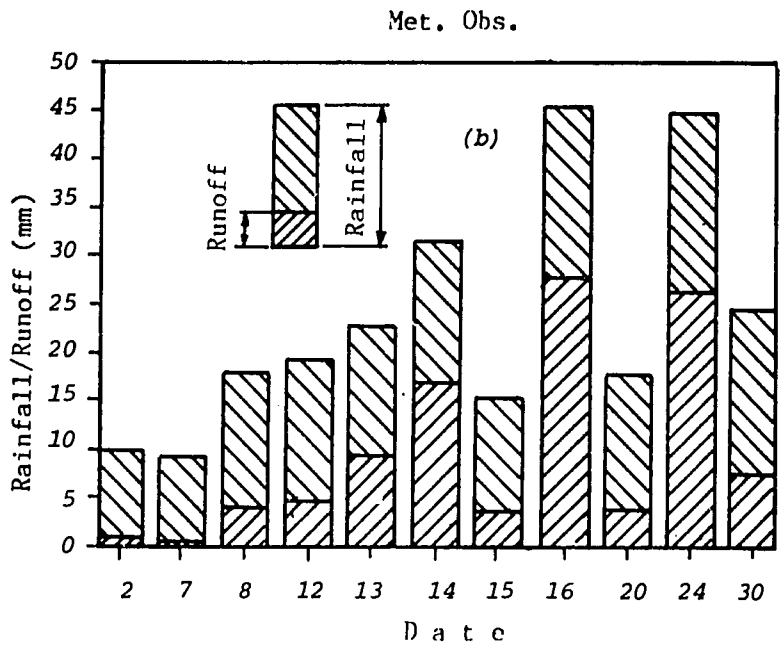

Met. Obs.
(b)
Runoff
Rainfall
Rainfall/Runoff (mm)
50
45
40
35
30
25
20
15
10
5
0
2 7 8 12 13 14 15 16 20 24 30
D a t e

Table 4. Comparison of measured runoff with the simulated runoff (m) using rainfall (m) data from the Meteorological Observatory and from the nearest raingauges of a Vertisol watershed, ICRISAT Center, 1983-1987 (A modified curve number model was used)

Year	August			September		
	Measured	Simulated		Measured	Simulated	
		* 1	** 2		* 1	** 2
1983	0.030	0.048	0.008	0.066	0.051	0.007
1984	0.011	0.015	0.016	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000	0.000	0.000
1986	0.034	0.033	0.005	0.000	0.000	0.000
1987	0.000	0.000	0.000	0.006	0.000	0.000

* 1 Using rainfall from the nearest raingauge.

** 2 Using rainfall data from the Meteorological Observatory.

For the Alfisol watershed studies, the simulated values of runoff using rainfall from two different sources (Table 5). In 1987, the runoff is significantly different when estimated from different rainfall sources (for example, the difference is of 0.030 m in July 1987).

Table 5. Simulated runoff (m) using rainfall (m) from the Meteorological Observatory and from the nearest raingauge of Alfisol watershed, ICRISAT Center, 1983-1987 (A modified curve number model was used)

Year	August			September		
	Measured	Simulated		Measured	Simulated	
		* 1	** 2		* 1	** 2
1983	0.028	0.014	0.125	0.109	0.115	0.105
1984	0.016	0.015	0.072	0.076	0.009	0.012
1985	0.017	0.006	0.000	0.000	0.004	0.004
1986	0.010	0.014	0.044	0.059	0.000	0.007
1987	0.022	0.052	0.021	0.000	0.024	0.011
1988	0.065	0.067	0.130	0.114	0.115	0.087

* 1 Using rainfall from the nearest raingauge.

** 2 Using rainfall from data from the Meteorological Observatory.

Water loss and soil water : Total rainfall at the Meteorological Observatory during the crop season ranged from 0.251 m in 1985 to 0.744 m in 1988. In 1986, rainfall at the Meteorological Observatory was 0.458 m, while it was 0.283 m in the Alfisol watershed, and 0.425 m in the Vertisol watershed (Table 6). This variation in rainfall has resulted in differential water loss (runoff and deep drainage). If rainfall data from the Meteorological Observatory are used to calculate water loss for these watersheds, the figures are different from those obtained when rainfall data from the nearest raingauges are used. For example, in 1988, the calculated water loss from the Alfisol watershed estimated is 0.392 m when rainfall from the nearest raingauge was used; it is 0.483 m when rainfall data from the Meteorological Observatory are used.

Table 6. Total rainfall during the crop season, total water loss (runoff and deep drainage), and percentage of filled soil profile with available water after growing a sorghum crop in the rainy season. (A Resource Capture Model (RESCAP) developed by Monteith et al. (1989) was used to calculate water loss and soil water. The maximum available water in the 2-m rooted Alfisol profile is 150 mm, and in the Vertisol profile is 250 mm)

	Alfisol watershed			Vertisol watershed		
Year	Rain, m	Water Loss, m	Soil profile filled with water, %	Rain, m	Water loss, m	Soil profile filled with water, %
a) Using rainfall from the nearest raingauges						
1983	0.786	0.500	100	0.605	0.257	100
1984	0.402	0.229	87	0.402	0.125	54
1985	0.212	0.000	35	0.262	0.000	48
1986	0.283	0.100	19	0.425	0.036	77
1987	0.330	0.138	28	0.337	0.000	85
1988	0.637	0.392	100	0.797	0.457	100
b) Using rainfall from the Meteorological Observatory						
1983	0.741	0.465	100	0.741	0.388	100
1984	0.397	0.215	87	0.397	0.105	64
1985	0.251	0.000	54	0.251	0.000	42
1986	0.458	0.142	71	0.458	0.000	100
1987	0.369	0.105	74	0.369	0.035	79
1988	0.744	0.483	100	0.744	0.415	100

The effect of rainfall variation across the farm is also evident on the stored soil water left after cropping in the rainy season (Table 6). Variations in the soil water have implications on the opportunities of cropping intensity (e.g., intercropping, double cropping, etc.).

Grain yield: Grain yields of sorghum (CSH 6) crop were simulated for a plant stand of 150,000 plants ha^{-1} under adequate management (Table 7). Rainfall data from the Meteorological Observatory and from the nearest raingauges were used to simulate yields. Differences in simulated sorghum yields, using rainfall from the Meteorological Observatory or from the nearest raingauges, exceeded 10% in 3 or 6 years for Alfisols and in 1 of 6 years for Vertisols. A maximum difference of 1.7 $Mgha^{-1}$ is noted for the Alfisol watershed in 1987.

Table 7. Simulated grain yield (mg ha^{-1}) of sorghum (CSH 6) in Alfisol and Vertisol watersheds using rainfall data from the Meteorological Observatory and from the nearest raingauges, ICRISAT Center, 1983-1988. (A Resource Capture Model (RESCAP) developed by Monteith et al. (1989) was used in calculating grain yield)

	Using rainfall from the			
	Nearest raingauges		Meteorological Observatory	
Year	Alfisol	Vertisol	Alfisol	Vertisol
1983	5.2	4.7	4.7	4.9
1984	3.2	4.5	3.8	4.1
1985	4.8	5.4	5.1	5.3
1986	3.6	4.0	4.3	4.8
1987	5.3	3.6	3.6	4.0
1988	3.8	4.0	4.1	4.3

An intensive instrumentation to collect minimum data on crops, soils, and weather for relating the environmental factors to crop production and runoff would be required for research watersheds in the semi-arid tropics. For shallower soils, the network of raingauge stations has to be more intensive than for deeper soils because the rainfall variability in shallower soils has a comparatively large effect on agricultural production.

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A design for simple tipping buckets to monitor runoff from small plots

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ABSTRACT

Conventional methods of measuring discharge rates and volumes using weirs, flumes, orifices, velocity meters etc. may be inaccurate at low flow rates. The tipping bucket principle widely used in rain gauges provides an alternative for small catchments. A tipping bucket consists of two chambers, symmetrical about a central wall, which pivot on an axle and bearing, located on the line of symmetry. When the bucket assembly is at rest inflowing water fills one chamber until the centre of mass moves and the axle rotates, emptying the full chamber and bringing the empty chamber under the inlet. If the tipping volume and the number of tips are known the flow can be measured. As tipping volume changes with flow rate, buckets must be calibrated against a known flow rate. We have developed a simple design for a tipping bucket that can be made in a basic workshop from readily available materials.

In studies of infiltration, runoff and erosion processes it is often necessary to measure flow from relatively small watersheds, for example, <1000 m^2. In iarger watersheds, flow measurements are usually based on the known relation between the discharge head above a zero datum point in a particular stream cross-section

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and the flow rate. Barfield and Hirschi (1986) have listed sources of errors with this system - incorrect levelling, siltation, float inaccuracies, and inaccurate setting of the zero point. Their table of errors for three measurement devices is used to derive the figures in Table 1. They developed a tipping bucket flow metering device with a relative error of only 2.5%.

Tipping buckets have been used for measuring water flow for many years. One of the earliest reports is that of Johnston (1942) and the tipping bucket principle has long been employed in measuring rain. Edwards et al. (1974) advocated use of tipping buckets for catchments <1000 m^2 and discussed design criteria.

Table 1. Errors in measured flow rate due to head measurement errors when three devices are used to measure a flow rate of 72 mm h^{-1} from a standard erosion plot of 101.1 m^2 (derived from data of Barfield and Hirschi 1986).

Flow measuring device	Size, mm	Head error, mm	Flow rate error, mm min^{-1}	Flow rate error as % actual flow
HS Flume	121	3	4.3	6.1
		6	8.7	12.2
		9.1	13.0	18.3
H Flume	152	3	6.3	8.9
		6	12.6	17.8
		9.1	18.9	26.7
Drop Box Weir	152	3	6.9	9.8
		6	13.9	19.6
		9.1	20.8	29.5

The basic tipping bucket design consists of two symmetrical chambers with a common separating wall ; each chamber has a float, a vertical wall and two end section walls. The whole assembly pivots on an axle on the line of symmetry and rests on stops in either of two stable positions. As water flows into the chamber below the inlet the centre of mass moves towards the vertical axis until the system becomes metastable. Finally it becomes unstable and rotates on the axle. coming to rest on the other spot.

During this action the full chamber empties and the formerly empty chamber begins to fill. If the mean tip volume is known, the total volume of discharge can

be computed by counting the number of tips and if this is done over set periods, the flow rate can be calculated.

A number of factors have to be taken into account when using tipping buckets: The tipping volume changes with the flow rate. The static tipping volume is the volume of water that, added very slowly to the bucket, will cause it to tip. As the flow rate increases, the tipping volume changes due to a number of factors : the variable amount of water what flows in while the bucket is tipping, drainage efficiency, sediment concentration and deposition, surge and water inflow velocity effects on bucket balance, and splash losses. Edwards et al. (1974) list 2 main sources as :

(a) continued inflow of water into the filling chamber, after tipping has started, increases tipping volume as flow rate increases, and

(b) the increased turbulence at higher flow rates increases the variation in tipping volume.

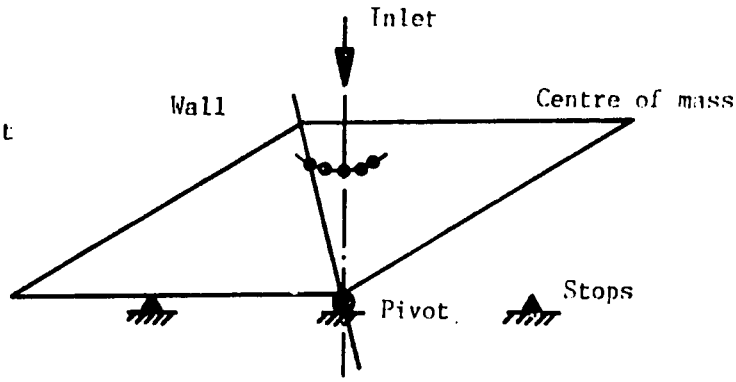
It is possible by designing elaborate inlet manifolds (or constant rate inflow storage devices) to reduce the change in tipping volume with increasing flow rate, but in practice if tips are counted over time on a chart or by an electronic logger, a calibration relation can be used to correct for the changes. Our approach has been to use an electronic logger which counts the number of closures of a reed switch activated by a magnet when the bucket changes position. The magnet and reed switch are arranged so that when the bucket is at rest the switch is either open or closed ; the logger checks for change of position once per second.

Bucket size: This depends on expected runoff rate. Relatively large buckets tip infrequently at, and are therefore unsuitable for, low flow rates. As bucket size (that is, tip volume) increases, the impact effect means that a damping mechanism is needed to avoid metal fatigue and loosening of the bucket mountings. Also as size increases, soil erosion due to wash can undermine the foundations. Bucket dimensions - width and height - are also influenced by the vertical interval available.

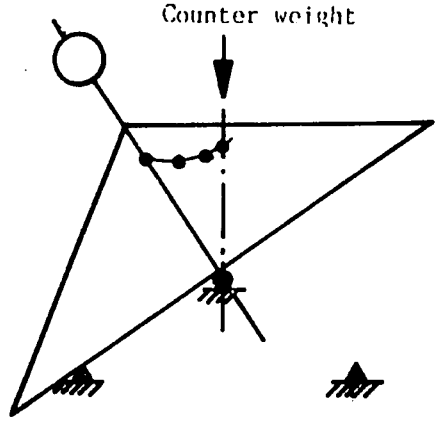
Bucket shape: Floors can be either flat or made from sections of cylinders; the floor and the dividing wall can meet at 90° or some acute angle. Some designs include counter weights. Fig. 1 shows three different designs. Edwards et al. (1974) state that acute-angled chambers offer advantages in that the moment of inertia is reduced and the centre of mass of the empty bucket is more effectively positioned. However, because the floor of the draining bucket is usually nearly horizontal, the acute angle design will not drain as quickly as 90° buckets.

As part of an experiment to study the effects of changes in soil structure on infiltration we needed to measure runoff from plots approximately 140 m^2. This paper reports a simple tipping bucket design, sound fairly suitable for this purpose.

(a) Acute angle bucket



(b) 90° bucket with counter weight



(c) 90° bucket as used at ICRISAT

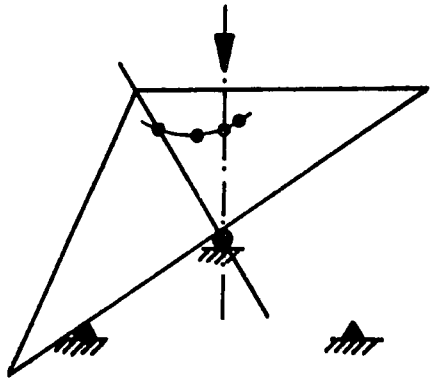


Fig. 1 End sections of three bucket designs

MATERIALS AND METHODS

Major factors influencing the design:

(i) The expected maximum flow rate, based on rainfall and runoff (on a similar soil type) records at the ICRISAT, was of the order of 0.100 m/h for a period of one minute, giving a flow rate of about 230 l/min. from plots 140 m^2.

(ii) Buckets were to be monitored with an electronic logger (via a magnet-activated reed switch) which would check for a bucket tip once per second.

(iii) Buckets must be low-cost and easy to build using readily available materials and basic workshop facilities.

(iv) The total vertical interval available for installation of the bucket was 0.3 m.

(v) The buckets must empty quickly and be self-cleaning.

Design: The buckets were made from 16 gauge mild steel sheet. By using a 90° internal angle between the floor and the wall only three welded seams were needed (to mount the dividing wall). The end section walls and floor sections were formed by putting two 90° bends in a pre-cut piece of steel sheet. A 10 mm mild steel rod was welded beneath the floor to serve as an axle. This axle rotated in simple nylon bearings, the metal frames of which were welded to a steel support which was in turn welded to a base frame made of 32 mm steel box section. An adjustable metal bar, supported at each end of the base frame, served as a bucket stop. The stop position was adjusted (by moving nuts on a threaded rod) to give the desired tipping volume (tested by adding water until the bucket tipped). The nuts were then welded in place. A rubber strip glued to the stop-bar served as a cushion. A static tipping volume of 6 l was used giving a theoretical maximum flow rate of 360 l min^{-1} at a tip rate of once per second. The reed switch and activating magnet were mounted so that when the bucket was at rest the switch was either open or closed. Water entered the buckets via two 20 mm wide vertical chutes running nearly the full length of the bucket central wall. Two chutes were used because splash was reduced and there was less chance of trash causing blockages. Plans of the design are available on request. Bucket assemblies were made by a workshop in Patancheru at a cost of Rs 450.

Bucket calibration: A 22.5 degree V-notch weir was calibrated by relating discharge head to the time taken to fill a known volume. This weir was used to measure flow rates in a pumped circulation system, the structural components of which, closely resembled the field set up. For a range of flow rates, the number of tips in a given time, were used to derive a calibration relation.

RESULTS AND DISCUSSION

Calibration relation: Fig. 2 shows the

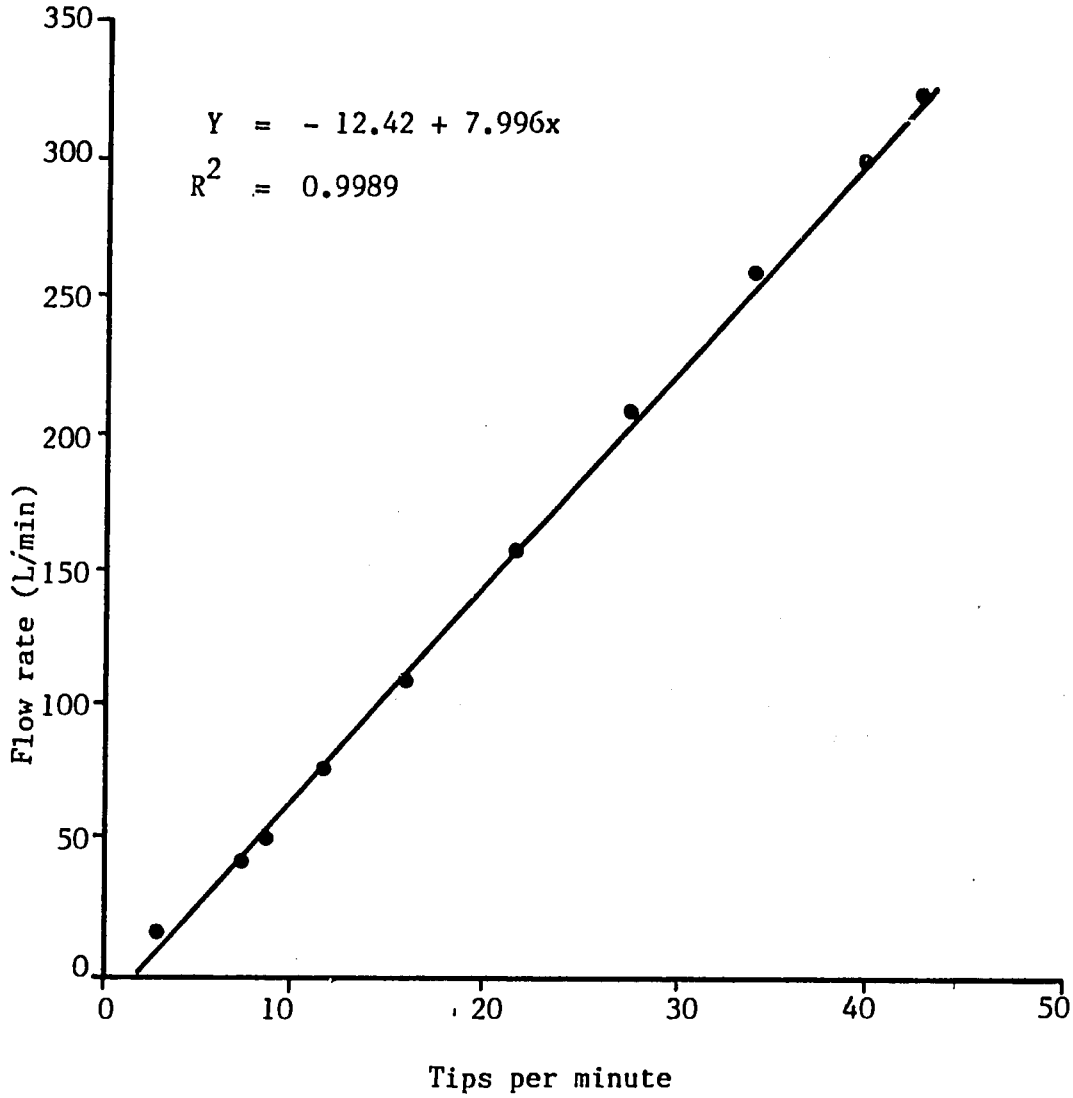


Fig. 2 Relation between flow rate and tips per minute (for bucket no.1).

relation between flow rate and tipping rate for one bucket. There is a highly significant (r^2 = 0.9989) linear relation with no sign of deviation at the highest flow rate is approximately 140 mm h^{-1}; these results suggest the calibration relation would be reliable at runoff rates of at least 150 mm h^{-1} on these plots.

However, the negative intercept means that at tip rates of less than about 5 tips per minute, predictions based on this equation will have appreciable negative error. To overcome this problem we use the actual tip volume for tip rates less than 6 per minute.

Field operations: Full details of the field setup will be reported in a separate paper. In brief, the logger continuously monitors an electronic rain gauge and if rain is recorded it switches on circuits to monitor the buckets. Buckets are checked once per second for change in position of the magnet, and monitoring is stopped after a 15 minute period without tips. After an event, data from the logger is sent by wire via an RS 232 interface to a personal computer 1.25 km away.

Provided an electronic logger is available to record bucket tips over time, simple tipping buckets constructed in a basic workshop can be used to measure runoff from relatively small plots. However a calibration relation between flow rate and tipping rate should be used, for each bucket, to correct for the increase in tipping volume as flow rate increases. Observations during calibration indicate that relative errors are usually less than 5 % and seldom exceed 10 %.

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A simple rotary type runoff sampler

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ABSTRACT

A simple rotary type runoff sampler was developed to measure runoff precisely and permit sediment sampling. Sampler conisted of 12 cm diameter water wheel with six curved vanes. Six cups were mounted on the conveyor chain, which was connected to a shaft. This sampler is not sensitive to float rates of less then 12 l min^{-1}. Suitable counting device to watch number of revolutions and design of the cups to avoid splashing are required to overcome the present problems.

Information on magnitude of runoff and soil loss is essential for planning and evaluation of soil and water conservation practices (SWCP) in agricultural watersheds.

H-flume/weir with standard water stage recorder presents serious problem to maintain a reliable runoff record at very low and high flow rates (Sharma 1983). Divisors with moving parts are usually considered to be unsatisfactory because of the risk of something going wrong or getting stuck (Hudson 1981). Research on instrumentation for soil loss measurement in small watershed (< 10 ha) has not received enough attention and till date the Coshocton wheel type sampler remains as the best known and most widely used automatic runoff sampler for small flows (Pathak and Miranda 1982). The Coshocton wheel type sampler was studied and/or modified by numerous scientists (Parson 1954, Carter and Parsons 1967, Wang et al. 1971). Following limitations were commonly noticed while using the Coshocton wheel sampler.

1. Maintenance of uniform turning rate throughout a revolution of the sampling wheel was difficult.

2. At high rate of discharge from the flume and consequently high turning rates, sampling was erratic.

3. The proportions of sediment material in the sample differed from that

the total flow and changed with varying rate of flow.

The above apprisal reveals that there is great need to develop a simple device which can precisely measure runoff and permit integrated sediment sampling. This paper attempts development of one such simple rotary type runoff sampler.

MATERIALS AND METHODS

Description of sampler: Rotary type runoff sampler was developed at JNKVV, Jabalpur (MP) as shown in Fig.1. The sampler consisted of 61 cm diameter water wheel with six curved vanes made of 20 gauge thick G.I.sheet. The vanes were 9 cm wide and provided with 3 cm side plates. Outer edge of each vane was connected with a circular plate of 2 cm width for strength. The wheel was fixed on horizontal shaft. A bicycle sprocket (18 cm) was also fixed adjacent to the wheel on the same shaft and was connected with endless chain to another shaft. Six equally spaced sampling cups each of 13 ml capacity were mounted on the chain conveyor. Both the shafts were supported on ball bearings fixed on angle iron frame. One man could carry the sampler to the site of measurement.

Testing: The sampler was tested using regulated discharge from tubewell inflow tank fitted with calibrated V-notch and 30.5 cm H-flume. The sampler wheel was positioned below the H-flume as shown in Fig.1. Observations on number of revolutions and sampled volumes of flow were recorded for 10 minutes duration for flow rates of 19.2, 36.6, 49.2, 71.4, 90.6, 109.8, 129.6, 142.2, 168.6 and 174.6 l min^{-1}. The observations were replicated three times for each flow rate. The sediment concentration was kept the same throughout the test run.

RESULTS AND DISCUSSION

For any fixed position of sampler number of revolutions of wheel increased directly in proportion to rate of flow (Table 1). Results of regression analysis reveal that the relationship between flow rates and number of revolutions per minute (RPM) is linear and could be expressed as :

$$RPM = 18.8 + 0.139\ Q_r \qquad (1)$$

Where Q_r is rate of flow in l min^{-1}. The correlation coefficient (r) for Equation (1) was 0.996 which is statistically significant at $P < 0.001$. While testing, it was noticed that the wheel did not rotate with flow rates less than 12 l min^{-1}. But, these very low flow rates are not likely to contribute significantly to total runoff or sediment loss in a runoff event. Further, the relationship between cummulative volume of flow and total number of revolutions of wheel in runoff events during a period could be expressed as:

$$Q_v = 7.2\left[\sum_{i=1}^{n}(N_i - 18.8)\right] \qquad (2)$$

Where Q_v = volume of flow in litres; N_i = total number of revolutions during the ith event of runoff; n = total number of runoff events in the sampling period. The value of r was 0.998 which is statistically significant at $p < 0.001$.

The sampler ratio (S_r), that is, ratio of total volume of flow (Q_r) to total sampled volume (S_v) increased with the flow rate.

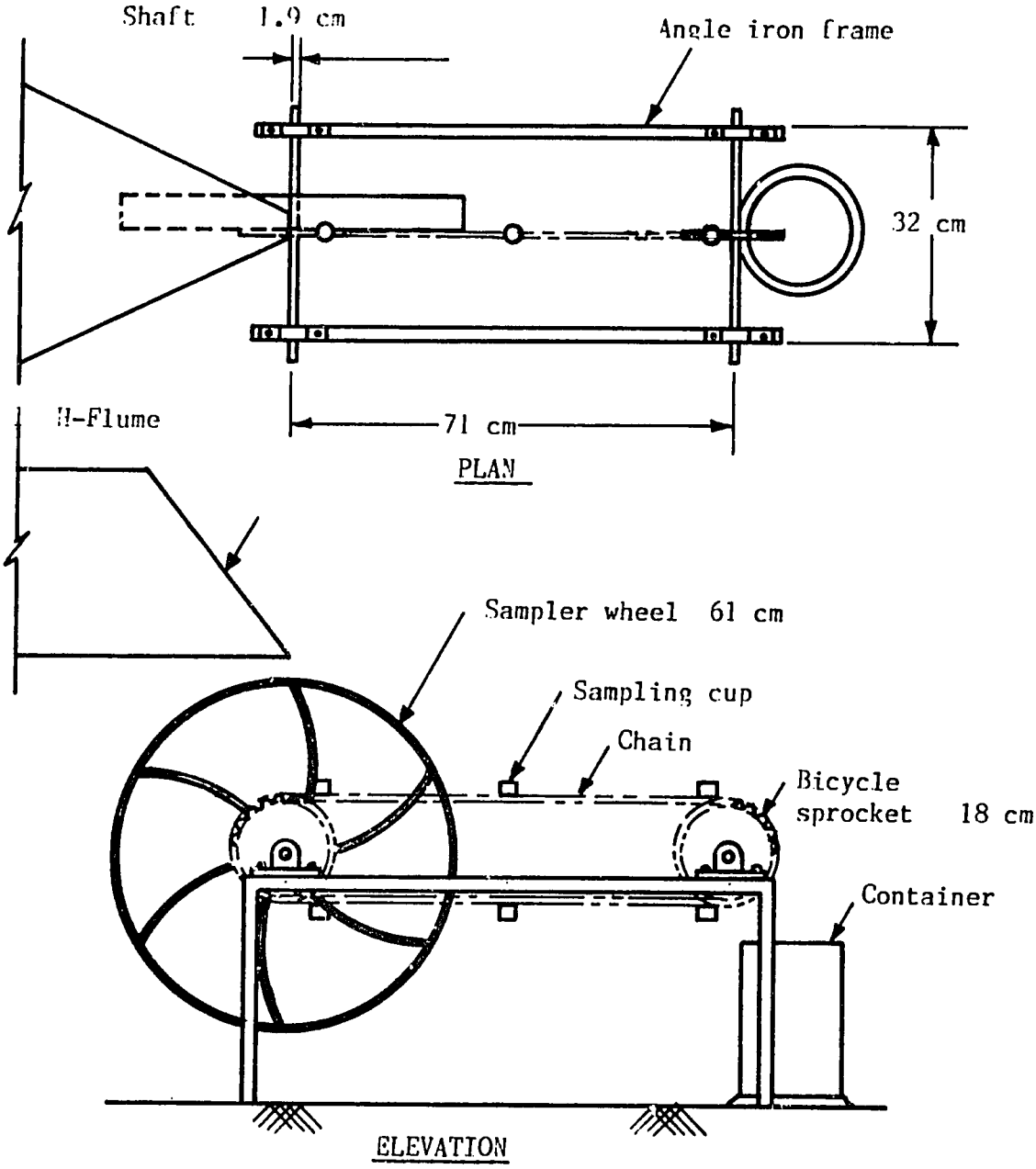

Fig. 1 Details of Rotary type runoff sampler

Table 1. Test results for the runoff sampler

Sl. No.	Flow rate (Q_r), l min^{-1}	RPM	Sample volume (S_v), l min^{-1}	Sampler ratio (S_r)
1.	19.2	21.5	0.070	274
2.	36.6	23.0	0.100	366
3.	49.2	26.0	0.110	444
4.	71.4	30.0	0.120	595
5.	90.6	31.0	0.130	697
6.	109.8	34.0	0.140	784
7.	129.6	37.0	0.142	913
8.	142.0	38.0	0.152	935
9.	168.0	41.5	0.154	1094
10.	174.6	44.0	0.155	1126

Following relationships were obtained.

$$S_r = 35.91 Q_r^{0.66} \quad (3)$$

$$S_v = 0.033\left[\sum_{i=1}^{n}(N - 18.8)\right]^{0.715} \quad (4)$$

Equations (3 and 4) were found to be statistically acceptable at $p < 0.001$, and $r \geq 0.996$. This implies that sampling efficiency decreased in a definite manner with the increase in flow rate. As observed during test it was due to excessive splashing of water out of the sampling cups at larger flow rates. Modification of cups to narrower openings is likely to minimise splashing action, and eventually improve the sampling efficiency of cups at larger flow rates. Further modification and testing of the sampler is therefore necessary for wide range of flow rates and sediment concentrations.

With an additional counting device for number of revolutions of the wheel and modification in design of sampling cups, this sampler will prove to be an useful tool for measuring runoff and soil loss from small watersheds.

ACKNOWLEDGEMENTS

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Installation of monolith lysimeters for evaluation of agricultural hydrology

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ABSTRACT

Data on agricultural hydrology are needed in the solution of many watershed management problems. With the help of monolith lysimeters, complete knowledge of all the components of agricultural hydrologic cycle is possible. Design and construction of a battery of twelve monolith lysimeters installed at Pantnagar University for quantitative evaluation of agricultural hydrology, are discussed. The lysimeters were installed with the help of a drag line. These lysimeters contain the undisturbed soil cores of silty clay loam soil. The inside diameter of lysimeter was kept 112.8 cm to provide an enclosed area of one square meter. The depth of lysimeter was kept 142.0 cm which provides sufficient root zone depth for most of the crops. Each lysimeter is connected with a runoff collector tank and percolate collector tank. Evapotranspiration was determined from water balance equation by accounting for precipitation, irrigation, runoff, storage and percolation. Management and operation aspects of lysimetric setup are also discussed.

Agricultural hydrology in recent years has become a subject of major interest in many fields of activity. A knowledge of water movement over land surface, movement into and through the soil, condensation and absorption of water, evaporation and use of water by crops is necessary in the solution of watershed management problems. Accurate estimates of different components of hydrologic cycle under cropped and uncropped conditions are very important for water resource planning and management. These components can be written in the form of simplified water balance equation as :

$$I + P = D + R + ET + \Delta W \qquad (1)$$

where I is irrigation, P is precipitation, D is deep percolation, R is surface runoff, ET is evapotranspiration and ΔW change in soil water storage. The units of Equation (1) may be expressed in terms of volume or depth of water. Equation (1) permits any one of the above terms to be determined when the others are known. The amount of precipitation and irrigation may be measured by standard means, whereas the measurement of each component of the right hand side of Equation (1) is difficult. Therefore, it is necessary to have such a system through which the different terms of Equation (1) can be measured continuously. Lysimetry in its various froms is the only hydrological method by which complete assessment of all the terms of Equation (1) is possible.

Several types of lysimeters used for various studies have been reported in the literature (Singh 1987). According to the principle of construction, three general types of lysimeters may be used as : (i) Ehermayer type, (ii) filled in type and (iii) monolith, or undisturbed soil block type. In the Ehermayer type, the soil is left in site and a shallow pan or a funnel is inserted at the desired depth to collect the percolate in a measuring tank. There are no side walls, and the soil block in the lysimeter is not separated from the adjoining soil. This type of lysimeter therefore, allows unrestricted lateral movement of soil water and surface runoff and is only used for evapotranspiration studies. Filled in type lysimeter consists of a container with vertical wall, open top, and perforated or closed bottom that provides for percolation. The soil is filled in the correct order of horizons. Since, the physical characteristics of the soil moisture relationship do not represent natural conditions. The monolith lysimeter dombines the desirable features of Ehermayer and filled-in types. In monolith lysimeter a casing of vertical wall is built around a block of soil in and kept in situ. Reliable data of runoff, percolation and infiltration can be obtained by enclosing an undisturbed block of soil. A monolith lysimeter simulates the natural conditions for both qualitaive and quantitative studies. In this paper, design and construction of the12 monolith lysimeters installed at the Crop Research Centre of G.B. Pant University of Agriculture and technology, Pantnagar have been discussed for quantitative evaluation of different components of hydrologic cycle under Nainital *Tarai* Conditions.

Design and construction of lysimeters: The site of the lysimeter installation is in a levelled plot near University Meteorological Observatory. The Pantnagar University (29° north latitude, 79.3° east longitude and 283.83 m elevation from mean sea level) is located in the submontane tract known as *Tarai* about 25 kilometers south of the Siwalik ranges of the Himalayan mountains. The average rainfall in this region is about 140 cm and almost 80 to 90 % of the total rainfall is concentrated during monsoon period from June to September. The soils of this region are alluvial, fairly deep, rich in organic matter and range from clay loam to sandy loam in texture. Different crops like wheat, potato, maize, soybean,

sugarcane and paddy are common in the area. The prevailing wind directions are from east to west in monsoon season and west to east in the winter and summer seasons. A field of several kilometers exists on east and west sides of installation.

Each monolith lysimeter was fabricated in three parts (i) lysimeter casing for taking out the soil monolith, (ii) mild steel rod mesh for supporting the soil monolith during installation and (iii) lysimeter pan for placing the soil monolith over it and collecting the drainage water. The lysimeter casing and pan was made of 3 mm mild steel sheet. The inside diameter of lysimeter casing was kept 112.8 cm to provide a surface area of one square meter. The cross section area of the lysimeter casing is equivalent to 0.0001 hectare which facilitates for quick calculation of different water balance components. The depth of the lysimeter casing was 122 cm. The undisturbed soil enclosed by lysimeter casing provide sufficient effective root zone depth for most of the crops grown in Nainital *Tarai* region. The bottom of the lysimeter casing was kept open in the beginning. The diameter of mild steel rod mesh was kept 112.8 cm. The m.s. rod used in fabricating the mesh were spaced at 10 cm interval. The diameter of the m.s. rod was 1.2 cm. The diameter of the lysimeter pan was 115 cm, and one angle iron of 2.54 cm size was welded along the top periphery of the pan. A slightly bigger diameter for the lysimeter pan than the casing was kept so that the bottom of the casing fits well in the pan. The bottom of the pan was closed. The height of the lysimeter pan was kept 20 cm. A circular design of lysimeter was chosen because of ease in its construction, and less cost as compared to a rectangular design. A circular design has an advantage as the wall of the lysimeter can be kept at a minimum thickness for a given strength of material. Moreover, uniform sinking of circular lysimeter casing and its removal from the ground are easier than a rectangular lysimeter.

An angle iron of 2.54 cm size was welded arond the periphery of the lysimeter casing to avoid any denting or bending of rim during the process of sinking or installation. The lower edge of the casing was bevelled to faciliate sinking. One more angle iron of 2.54 cm size was also welded at a distance 20 cm above the bottom of lysimeter casing. Eight rings of 10 cm diameter of 1.25 cm thick were welded at equal distances on the angle iron for facilitating in the lifting of soil monolith and installing it. One runoff pipe of 1.8 cm was fixed at a distance of 8 cm from the top of casing. Similarly one percolate pipe was also welded at the bottom of lysimeter pan. Fig. 1 shows the constructional details of lysimeter casing and pan. The inside as well as outside surfaces of lysimeter casing and pan were coated with paint to retard rust.

Installation of lysimeters: A silty clay loam soil was selected for obtaining the undisturbed cores for lysimeters, because this soil series covers a large areas of Nainital *Tarai* region. Physical and chemical properties of the soil are given in Table 1. Water table in this soil series

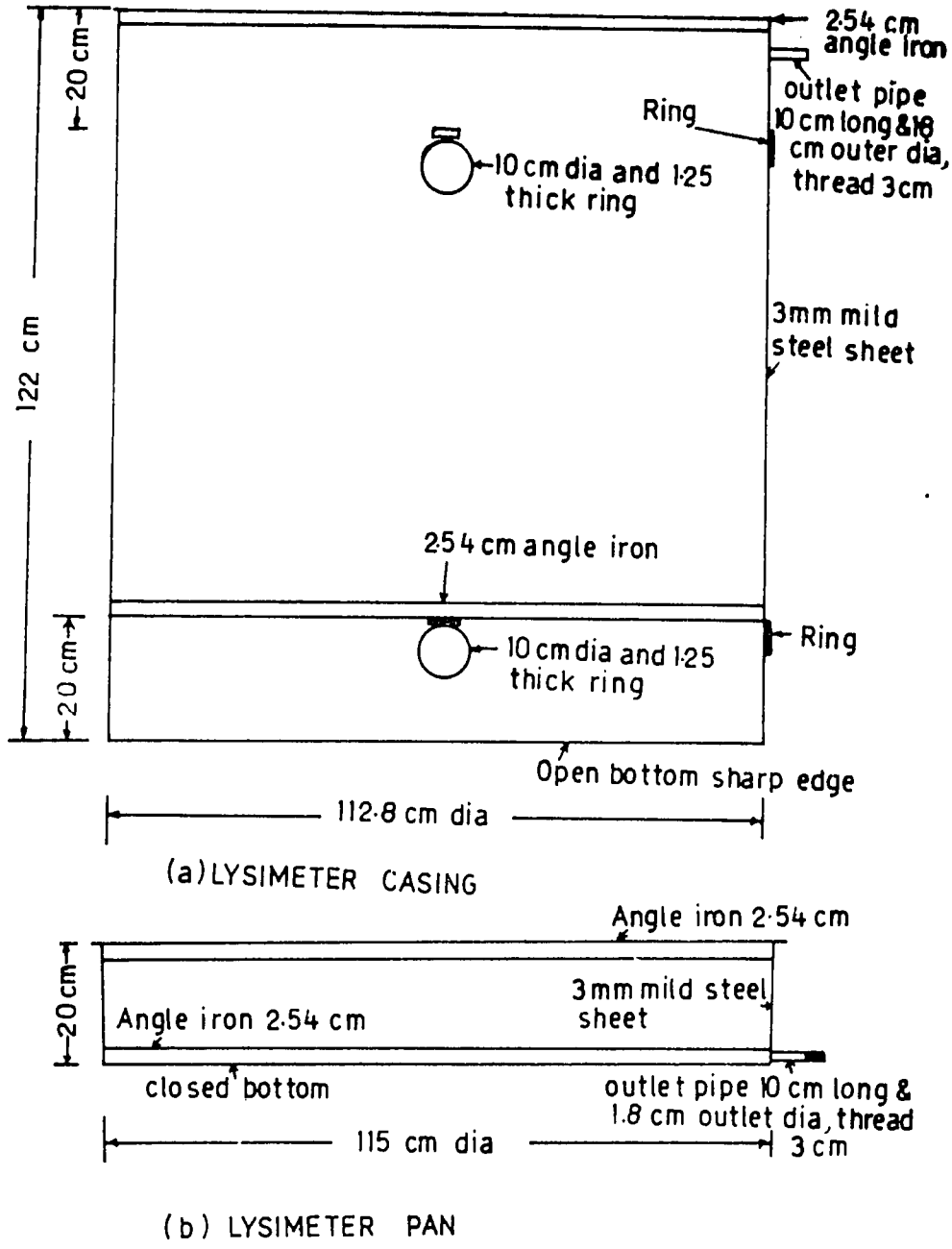

Fig. 1 Construction details of lysimeter casing

is shallow. Shallow water table posses some problems in installation of lysimeters. Therefore, the installation site was selected on a higher elevation at a little distance from the excavation site.

Table 1. Physical and chemical properties of soil

Soil Property	Value
A. Physical	
Mechanical composition, %	
Sand (2.00 - 0.02 mm)	10.0
Silt (0.02 - 0.002 mm)	61.3
Clay (> 0.002 mm)	28.7
Texture	Silty clay loam
Moisture content at field capacity, %	31.5
Moisture content at wilting point, %	12.0
Bulk density, mg m^{-3}	1.34
B. Chemical	
pH	8.10
Electrical conductivity, sm^{-1}	0.036
Organic matter, %	2.60
Available P, mg kg^{-1}	8.50
Available K, mg kg^{-1}	93.0
Exchangable cations, meq 100 g^{-1}	
Ca	12.20
Mg	6.65
K	4.23
Na	1.24

For obtaining the soil monolith, the empty lysimeter casing was placed at a levelled soil surface. Wooden planks and G.I. pipes were placed at the top of casing. The casing was lowered by putting earth filled sacks on the planks. The sinking of the casing was further facilitated by removing the soil around the casing. The casing was sunk upto the level of runoff pipe, and thus, net soil depth in casing was about 110 cm. Because of shallow water table at a depth of 1 m at the

excavation site the 15 cm layer at the bottom of casing was saturated.

The water was removed from the pit before taking out the soil monolith. The monolith block of soil was separated from the soil below it with the help of a 1.2 cm size of wire rope and a 35 h.p. tractor. A loop of the wire rope was placed along the periphery of the bottom of the monolith and pulled slowly by the tractor. Due to pulling of the wire rope the bottom of the soil monolith was sliced uniformly and no soil was removed from the monolith. An attempt was made to pull the lysimeter casing vertically from the ground with the help of a dragline but soil core slipped from the casing, therefore casing could not be lifted from the ground vertically.

In order to remove the monolith casing from the pit it was laid horizontally in the pit with the help of a tractor and a wire rope. The casing was laid horizontally to avoid slipping of soil. The wire rope was wrapped on the top of the lysimeter and then pulled slowly with out any jerk. In this process no soil was disturbed. Top and bottom sides of soil monolith was tightly wrapped with the help of straw, grasses, empty sacks and ropes in such a manner that no soil is removed during lifting of the monolith casing. The monolith casing was lifted from the pit with the help of a dragline, and placed in a tractor trolley. Before removing the casing the dragline rope was properly balanced with the help of 8 rings fixed in the casing. This method worked very well in this situation and no slipping of the soil inside the lysimeter casing occured on the removal of lysimeter casing from the ground. The lysimeter casings were brought at the installation site by a tractor trolley. The speed of the tractor was kept low and care was taken to avoid any jerk in the transit.

A large pit was made at the installation site to accommodate 5 lysimeters in it. The excavated soil of the pit was kept in the correct order. A concrete foundation was made for the installation of the lysimeters. A slope of about 5 % was kept while constructing the foundation. This slope was provided so that the drainage water collected in the bottom of lysimeter may be drained out by gravity flow. After placing the lysimeter pan on the concrete floor, a filter bed consisting of 10 cm of graded gravel and 8 cm of sand was kept at the bottom of the pan. In the pan, glass wool was also placed at the inlet of the drain pipe to avoid any choking by soil particles. As the percolate collector pipe was kept at a 5 percent slope, additional suction at the bottom of lysimeter to improve drainage was not provided. In order to avoid slipping of the soil monolith from the lysimeter casing in a vertical position mild steel rod mesh was welded at the bottom of the soil monolith. The welding was done when the lysimters were laid in a horizontal position.

After welding of the mesh at the bottom of the casing it was raised vertically with the help of the dragline. Then the casing was lifted by the dragline and was placed over the pan slowly and without any jerk so that the casing may prop-

erly fit into the pan. The casing was also properly levelled with the help of a dumpy level. About 2 cm depth of casing bottom was inserted inside the lysimeter pan. Thus total height of the lysimeter was 140 cm in which 110 cm was soil and 10 cm gravel and 8 cm sand. The gap between the lysimeter casing and the pan was welded. After welding, lysimeters were tested for water proofness by filling it with water upto the rim. A percolate collector pipe made of pvc having the inner diameter of 2 cm was connected at the bottom of the monolith lysimeter. The pipes were embeded in the 20 cm layer of the sand for protection. After connecting the percolate pipe, the large pit in which the 6 lysimeters were installed was filled up with the soil in the same order as was excavated. The soil in the pit was saturated many times during the filling process. The rim of the lysimeter protruded 10 cm above the soil surface so that no surface runoff water may enter into the lysimeter. Fig. 2 shows the layout of the lysimeter installation. There are four rows containing three lysimeters each. This provides either four treatments with three replications or 6 treatments in duplication. The area outside the lysimeter is used as a buffer area for each treatment.

Measuring systems in lysimeters: Pruitt and Angus (1960) and Harrold and Dreibelbis (1967) have reported different measuring systems for lysimeter installation with an underground room or a tunnel below the lysimeters. The main limitations of these installations are that a large area around the lysimeter is disturbed in order to contstruct the underground tunnel. The cost of installation, maintenance and repairs of underground tunnel may be high. Moreover, in an area receiving heavy rainfall and shallow water table conditions, like Nainital *Tarai* the construction cost may further be added for waterproof walls of an underground room. In order to avoid the construction of an underground room this lysimetric setup was instaled at a place where elevation difference is about 2.3 m between two adjacent plots. On the uphill plot the lysimeters were installed and on the downhill plot all measuring systems were established (Fig. 3).

In hydrological balance studies, determination of surface runoff is not very difficult. However, there are two major components of water balance equation which can not be easily determined, namely evapotranspiration and deep percolation. Determination of these components is essential in order to obtain a quantitative data of water use by the different crops. These lysimeters were designed for measuring the following different components of the hydrological cycle:

Measurement of runoff: Fig. 4 shows the placement of runoff collection tanks. The surface runoff from each lysimeter was piped to separate runoff collector tank where the water accumulates for measurement. The runoff pipe of 1.8 cm inner dia made of pvc was connected 8 cm below the rim of the lysimeters to runoff collection tank at a 5% slope. For regulating the runoff one stop cock is

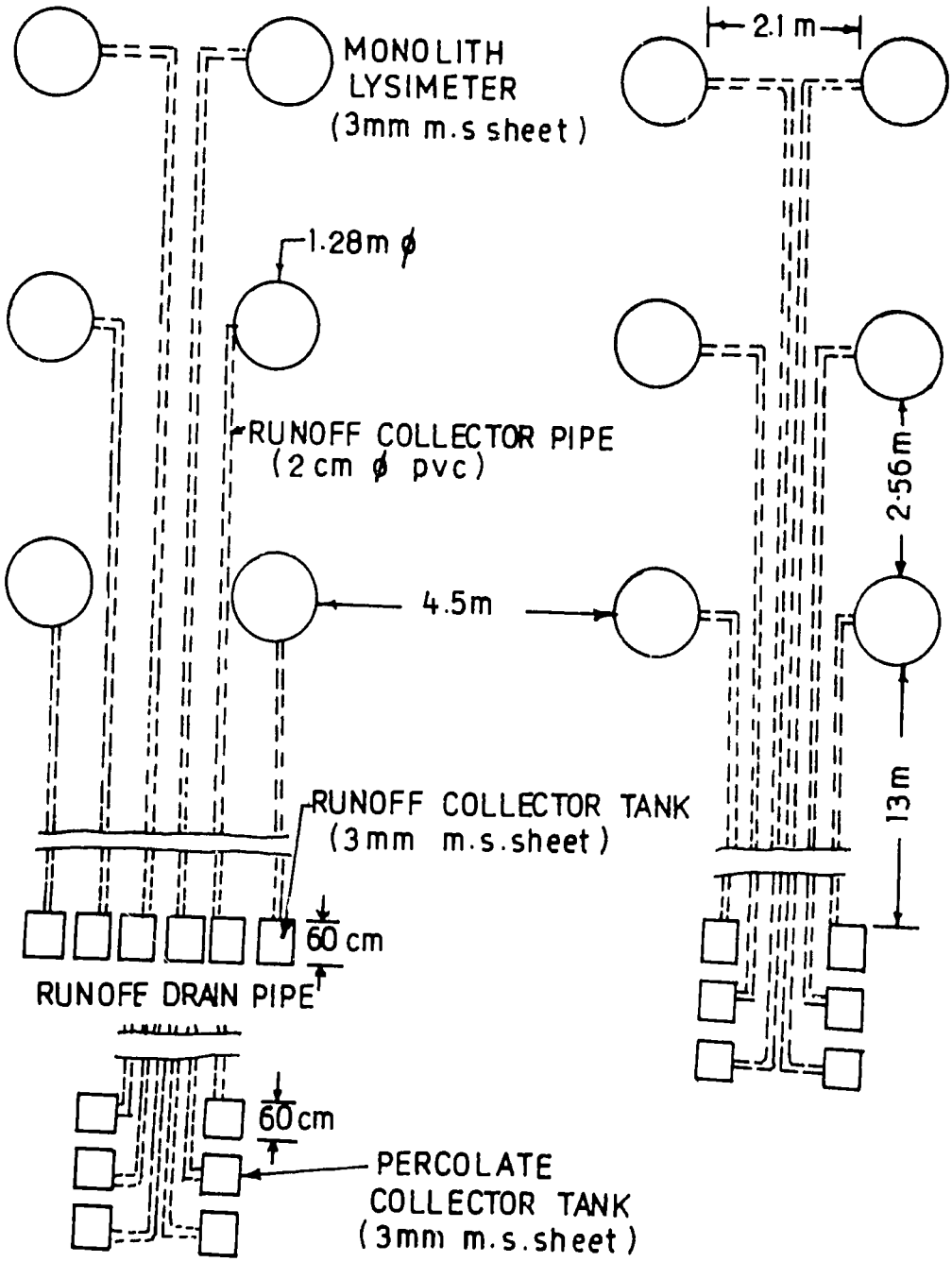

Fig. 2 Layout of Monolith lysimeters

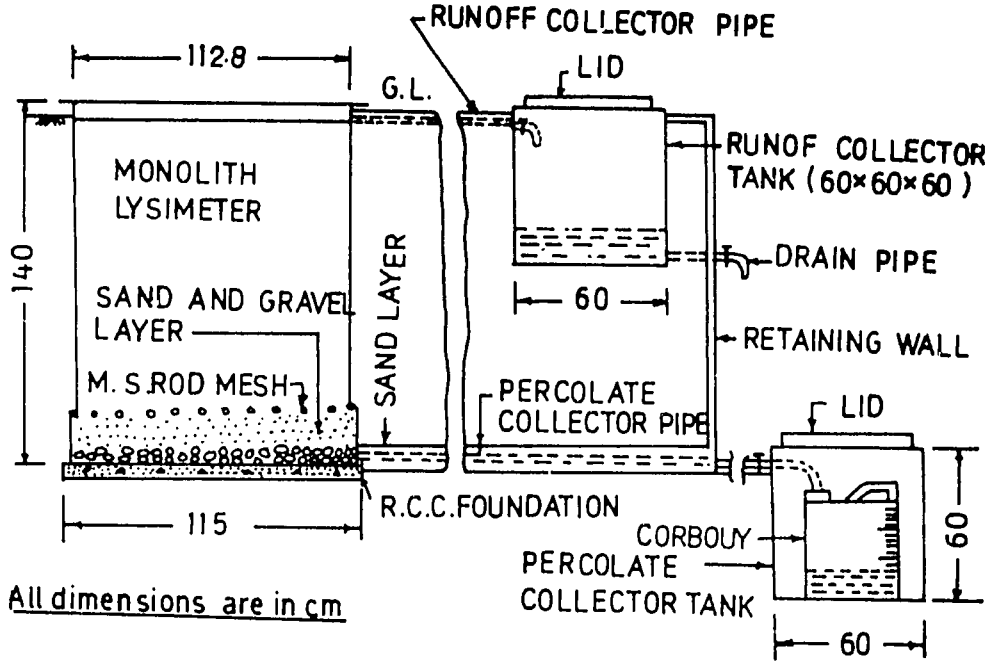

Fig. 3 Measuring system of deep recolation and surface runoff in monolith lysimeter

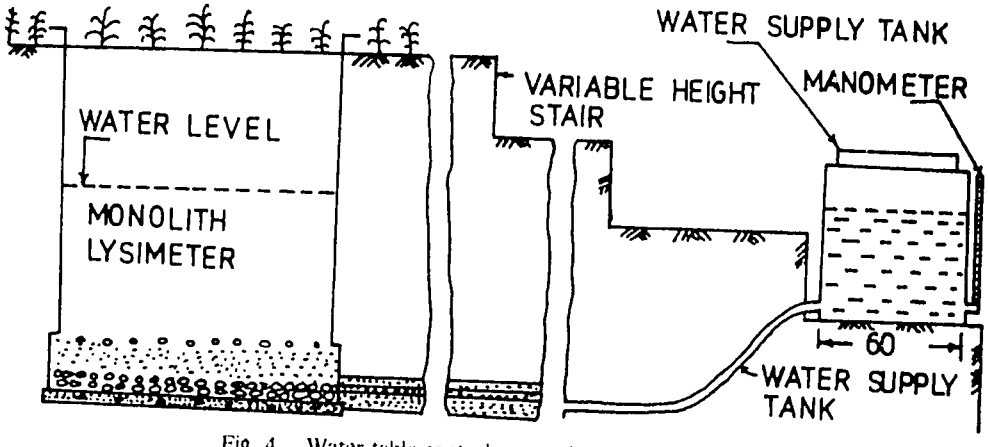

Fig. 4 Water table control system in monolith lysimeter

fixed at the end portion of each runoff pipe. The runoff collector tanks were made of 3 mm mild steel sheet. The dimensions of these tanks were 0.6 m by 0.6 m and 6.6 m deep. Each tank was covered with a lid to prevent rain and evaporation. Each runoff tank consists of a drain pipe fitted with a drain cock, so that water accumulated in the runoff tank maybe drained off after measurements.

Measurement of percolation: Deep percolation beyond the root zone of the crop occurs due to frequent rainfall or regular irrigation. Each lysimeter is equipped to measure continuously deep percolation. Percolation water that reaches bottom of the lysimeter through the soil is drained by a pvc drain pipe of 1.8 cm diameter to percolate collector tank separately for each lysimeter. The dimensions of percolate collector tank are same as that of runoff collector tank. Fig. 5 shows the measuring system for deep percolation and runoff in monolith lysimeter.

Measurement of evapotranspiration: Values of evapotranspiration can be obtained by rearranging the equation (1) as follows :

$$ET = I + P - D - R - \Delta W \qquad (2)$$

Over long enough periods, at the beginning and at the end at which the soil water content does not differ markedly soil moisture storage changes need not be considered. Singh and Shukla (1978) have described complete procedure for measurement of evapotranspiration by non-weighing type lysimeters. Potential evapotranspiration can be determined accurately from this installation. For checking the actual evapotranspiration values of crops, two mechanical weighing types of lysimeters were installed in the same field. One floating lysimeters as described by King et al. (1956) is already in operation in the same plot. By placing calibrated gypsum blocks and tensiometers at different depths in the lysimeters the changes in soil moisture content can be obtained. Continouous soil water content in thelysimeters can also be measured with the help of neutron moisture meter.

Measurement of upward water flux: The soils of Nainital *Tarai* region are characterized by shallow water table conditions. The water table in the hydrologic cycle represents the phase of water in the soil water system at which pressure is atmospheric. The soil immediately above the water remains saturated and is termed as the zone of capillary fringe has a pressure less than the atmospheric pressure. The moisture moving upwards into the soil from the shallow water table is called as the water flux which is a significant phenomenon particularly in those irrigated areas where quality of water is good. In order to measure the upward water flux a provision was made to maintain the desirable depth of water table in monolith lysimeters.

The lysimeters site has a unique feature of elevation difference between two adjacent plots. On the uphill plot the lysimeters were installed and on the down

hill area a step down platform was made. The water supply containers were placed on step down platform as shown in Fig. 6. The platform was located in a position such that water in the water supply container maintained at a specific level would also maintain the desired water table in the lysimeters. The dimensions of water supply containers are 0.6 m by 0.6 m by 0.6 m deep. A graduated vertical glass manometer was fixed by the side of the container to record the amount of upward water flux from a desired water table depth. A properly fitted lid on the top of water supply container was fixed to prevent the evaporation and rain.

Management and operation of lysimeters: It is essential that the surface of the lysimeter should be representative of the surrounding area and lysimeter itself should be indistinguishable from the surrounding area. In this installation considerable border area is maintained, around the lysimeters which is planted, fertilized, watered and managed in the same manner as lysimeters. Various agricultural operations were made in the lysimeters at the same time and at the same intensity as in the adjacent fields. However, the heavy implements used in the cultivation of adjacent farm fields could not be used in lysimeters. Hand tools were used for different operations in the lysimeters.

To meet the demand of water for crop use in the lysimeters an irrigation pipe line was laid nearby lysimetric set up. The irrigation system has the provision for regulating water with the help of wheel valve such that the required quantity of water can be applied in each lysimeter. The water was applied through a small pipe fitted in the main pipe line. Precautions have been made to apply water only at the ground level so that the foliage is not wetted. Surrounding field was irrigated by a tube well installed nearby lysimetric setup. Surface irrigation systems of border and check basin are used for irrigation in the adjacent fields.

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Water balance study in a small ground water basin

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ABSTRACT

Water balance study is an appropriate technique for evaluation of ground water potential and planning its use. A small ground water basin of 10,917 ha was selected in catchment of the Pariyat, a tributary to the Narmada near Jabalpur of Madhya Pradesh. In the present study, different components of water balance equation namely rainfall, consumptive use, ground water draft, irrigation, runoff from the basin and subsurface inflow and outflow were estimated. Aquifer and soil characteristics in the basin were determined. Estimated fluctuation of water table was compared with the observed fluctuation in open wells. The estimated value was more than the observed value by about 30 %.

Increasing demand of water for agriculture and domestic purposes, necessitates study of the availability of water resources for their scientific use. Many researchers (Raghava Rao et al. 1969, Saksena 1980, Anonymous 1983) have estimated ground water recharge assuming some percentage of rainfall. It needs to incorporate all aspects, of the hydrologic cycle in depth. Experiences of large scale irrigation have proved the ill effects of over irrigation, viz. saline and water-logged lands. It is, therefore, the next logical step to analyse situation of ground water, where from water could be utilized conjunctively with surface water within practically feasible limits. Studies were made for watershed of the Pariyat tank to estimate each component of the water balance equation logically and to formulate a procedure for similar work in other watersheds.

MATERIALS AND METHODS

The catchment of the Pariyat tank was selected for water balance study. The total area of watershed is 10,917 ha and it is located at about 35 km from Jabalpur on Jabalpur-Dindori road (Fig.1). It is situated between longitudes 80° 10' to 80° 20' E and latitudes 23°10' to 23° 27' N in the toposheet 64 A/4 of Government of India.

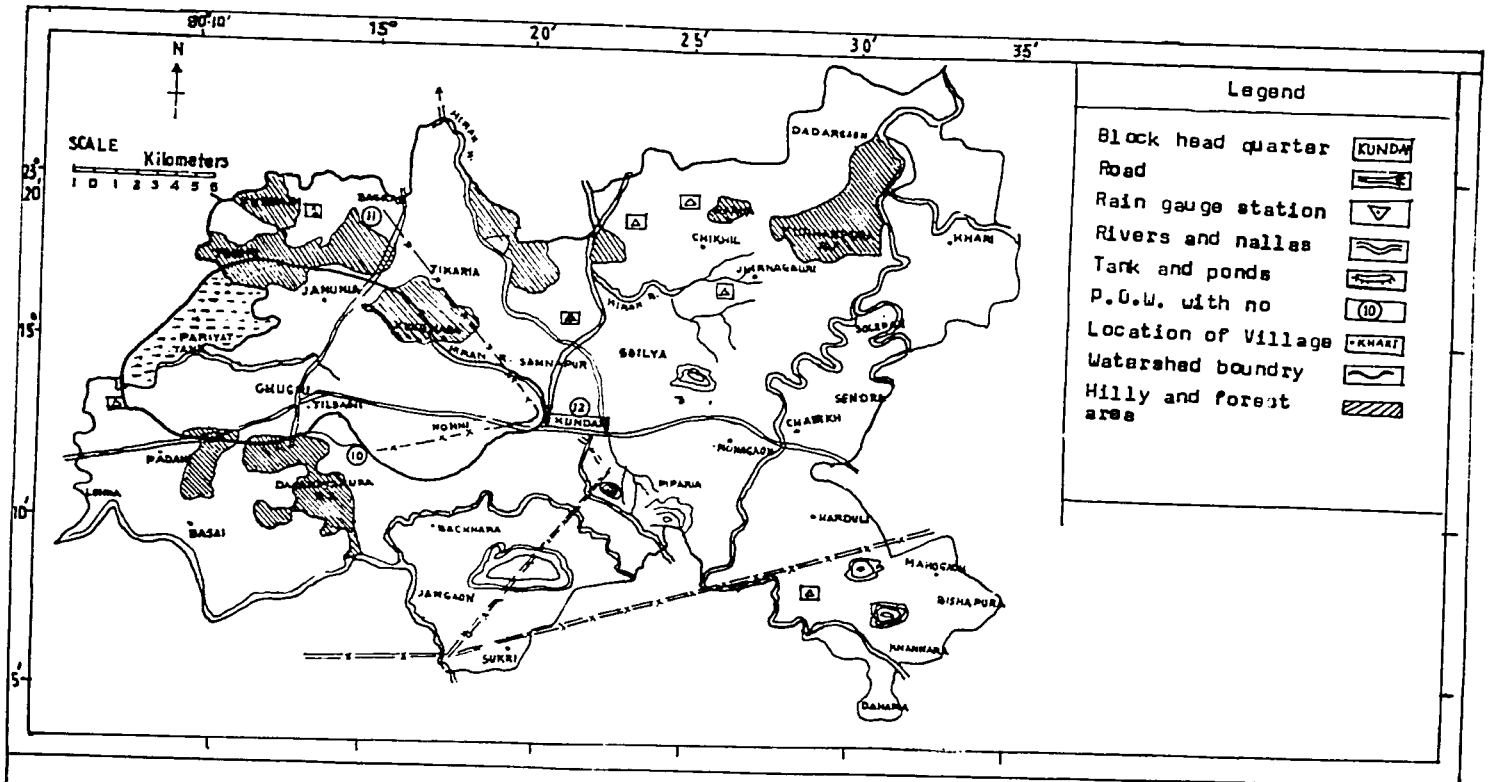

Fig. 1 Index map of project area of water balance study

Information on watershed characteristics were collected from different sources. Rainfall data recorded at headworks of the Pariyat tank were used.

Since there is no runoff gauging station situated in the watershed, runoff from the watershed was calculated by balancing inflow and outflow of the reservior.

Evapotranspiration for different crops and vegetative covers of the watershed was estimated by modified Penman equation. Ground water draft was estimated using open wells data and the norms adopted by the Directorate of ground water survey, Madhya Pradesh (Anonymous 1983 b).

Time-draw down and recovery tests were conducted in open wells at four different locations in the watershed. Specific yield of the well and permeability of aquifier were estimated using Slicher's formula. Observations of water table were used to prepare water table contours of the watershed.

Change in ground water storage was estimated for the pre and post-monsoon periods and compared with the observations of water table for the same period in the open wells.

RESULTS AND DISCUSSION

The average annual rainfall during 1974-87 was 1.400 m with the minimum and maximum values of 0.530 to 2.240 m respectively. Ninety percent of the annual rainfall occurs before 15th October. The highest and lowest temperature recorded was 47.7^{0}C and 1.2^{0}C respectively.

The topography of watershed is undulating with slope ranges from 2 to 8% except in the forest areas. The watershed is fern-leaf shaped with form factor and compactness coefficient, as 2.930 and 1.496, respectively. The drainage density based on available 1:253440 scale toposheet is found to be 993 m km^{-2}. Drainage pattern of the area is shown in Fig. 2.

Texture of the soil differs in different parts of the watershed. It varies from clay to sandy loam with soil depth ranging between 0.30 and 3.20 m. The weighted average depth of soil was taken as 1.00m.

Topography: Fifteen percent of the total area of watershed is under reserve forest. Area under cultivation is 5010 ha. The crops grown are paddy, sorghum, pigeonpea, kodo and kutki in kharif season and wheat, gram, lentil, mustard and niger in rabi season. Detailed land use of the watershed is presented in Table 1.

Hydrologic book keeping equation: The most widely used form of ground water balance equation (Raghunath, 1983) is as below:

$$R + Iq + Si = Qq + Se + Et + Dgw + \Delta Gws$$

Where,

R = recharge in ground water due to rainfall

Iq = inflow into the basin from other basins

Si = influent seepage from other basins

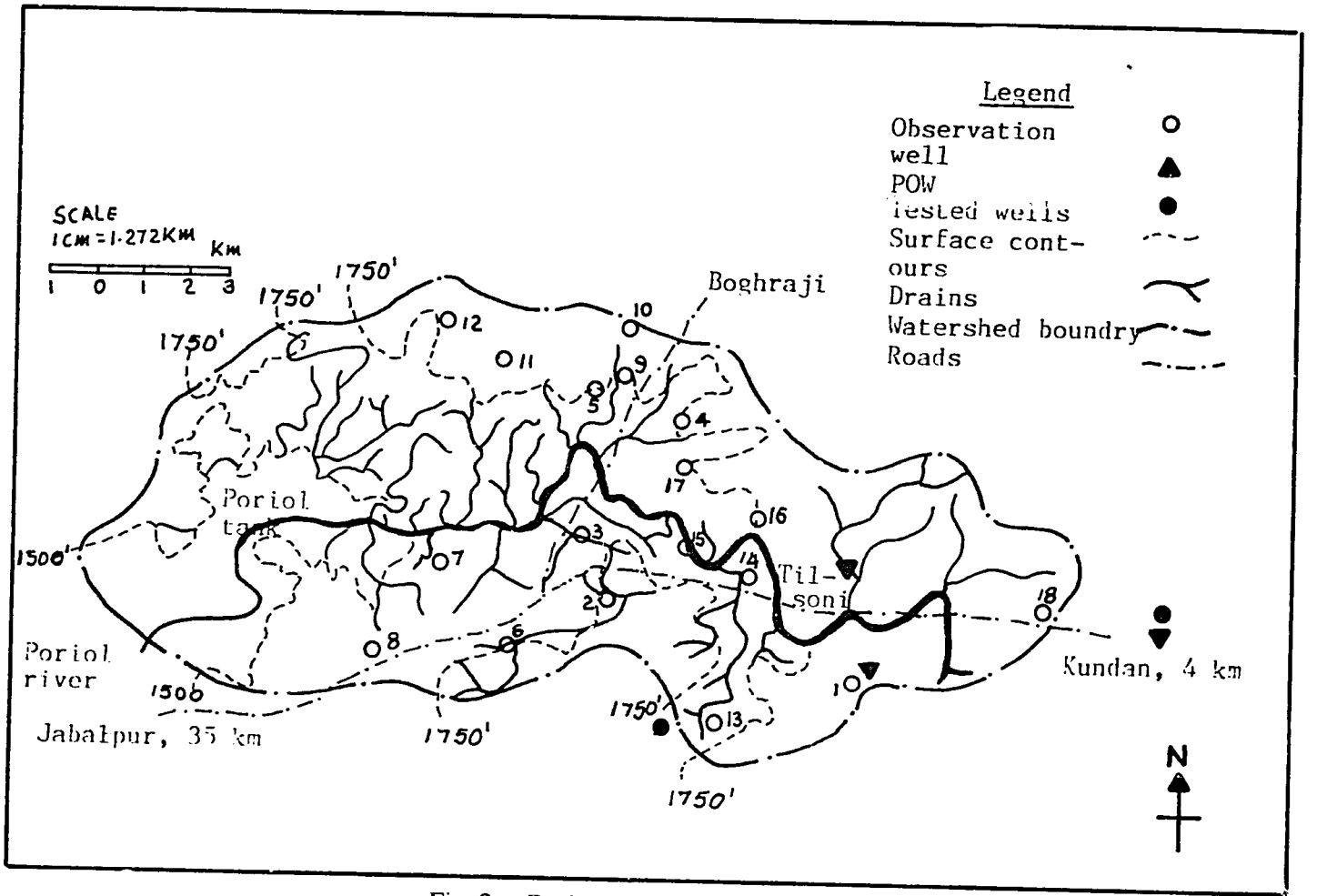

Fig. 2 Drainage pattern in Pariyat watershed

Table 1. Land use in the Pariyat watershed

Particulars	Value
Total geographical area	10917 ha
Area under reserve forest	1837 ha
Permanent pasture	1179 ha
Area not suitable for cultivation	244 ha
Fallow land	2647 ha
Cultivated area	5010 ha
Area under kharif crops	3724 ha
Area under rabi crops	1893 ha
Double cropped area	607 ha
Cropping intensity in kharif	74%
Cropping intensity in rabi	36%

Qq = outflow from the basin to other basins

Se = effluent seepage from streams

Et = evapotranspiration from the watershed in direct contact with the aquifer

Dgw = draft from ground water

ΔGws = Change in ground water storage

Small stream in general are influent as well as effluent depending upon the stage of flow in the streams. If it is assumed that seepage from influent streams is balanced with effluent streams, it may not have much effect on accuracy of estimates. Other components were estimated as given below.

Recharge due to rainfall: Recharge of ground water from rainfall is determined by equation

$$R = Pr + Ro + Sms$$

Where,

Pr = precipitation over the watershed

Ro = runoff from the watershed

Sms = Storage of moisture in soil profile

Total rainfall occuring over the watershed from the 15th June to October, 1987 was 0.998 m. Using daily records of stage, ouflow and evaporation from the tank daily runoff was obtained. Cumulative rainfall and runoff for the period under study (15th June to October 15th) is presented in Fig. 3. Runoff component is estimated to be 25.6647 × 10^6 m^3 which is equivalent to a depth of 0.235 m over the entire watershed.

Considering the soil texture and average depth of soil, weighted average moisture storage in soil profile is taken as 0.08 m. The resultant recharge due to rainfall comes to be 0.683 m.

Subsurface inflow and outflow: As observed from the water table contour of pre-monsoon period, 1981, as shown in Fig. 4, the ground water divide has a slight deviation from the surface water divide. It indicates that some outflow is taking place from northern and south-western bounderies of the watershed. This outflow is estimated by using Darcy's equation. Permeability of the aquifer material was found to be between 7.8 and 21.5 m^3 day^{-1} m^{-2} which gives an average value of 15 m^3 day^{-1} m^{-2}. Water table gradient in south-west direction was calculated as 1.68% whereas it is 5.30% in case of Northern side. Considering the average depth of water bearing strata as 4.5 m, total outflow in both the directions is esitmated to be 5.843 × 10^6 m^3.

Evapotranspiration: Estimated values of evaportanspiration per day for standard meteorological weeks for main crops are presented in Table 2. Total evaportranspiration from the watershed was estimated to be 37.93 × 10^6 m^3.

Table 2. Evapotranspiration of major crops of the Pariyat watershed, m × 10^3 day^{-1}

Standard week	Paddy Early	Late	Standard week	Gram	Wheat
26	–	5.7	41	–	–
27	–	5.3	42	–	–
28	4.8	5.0	43	1.3	–
29	4.8	4.8	44	1.5	–
30	4.8	4.9	45	1.4	–
31	4.9	4.9	46	1.5	1.1

32	4.4	4.5	47	1.8	1.5
33	4.2	4.2	48	2.0	1.5
34	4.7	4.8	49	1.9	2.1
35	4.9	4.9	50	2.2	2.5
36	4.9	4.5	51	2.5	2.7
37	4.9	5.0	52	2.9	2.9
38	5.1	5.2	1	3.0	3.0
39	5.2	5.3	2	3.0	3.2
40	4.7	4.8	3	2.8	3.2
41	4.7	4.8	4	2.4	3.3
42	4.7	4.7	5	2.1	3.3
43	4.4	4.4	6	2.0	3.2
44	4.2	4.2	7	1.6	2.0
45	3.5	3.2	8	1.3	1.5
46	3.1	2.4	9	1.1	0.9
47	–	2.8	10	–	0.9
			11	–	0.61

Ground water draft: There are 55 open wells in the watershed; 40 of them are used for domestic purpose and 15 are irrigation wells. Total draft from the wells is estimated to be 0.1812×10^6 m^3.

Change in ground water storage: All the components estimated above were converted into equivalent depths over the entire watershed and are presented in Table 3. It shows, the net recharge to ground-water body is of the extent of 0.280 m. Weighted average fluctuation of the water table was found to be 2.20 m. Assuming a specific yield of aquifer meterial as 10%, average fluctuation of 2.20 m reflects a change in ground-water storage by 0.220 m. Thus, there is a gap of 0.060 m between estimated and observed change in ground- water storage. The season behind it may be misappropriation in assigning values to one or more components responsible for the same. It indicates the necessity of further refinement in the study of these components through careful and accurate measurements/estimates.

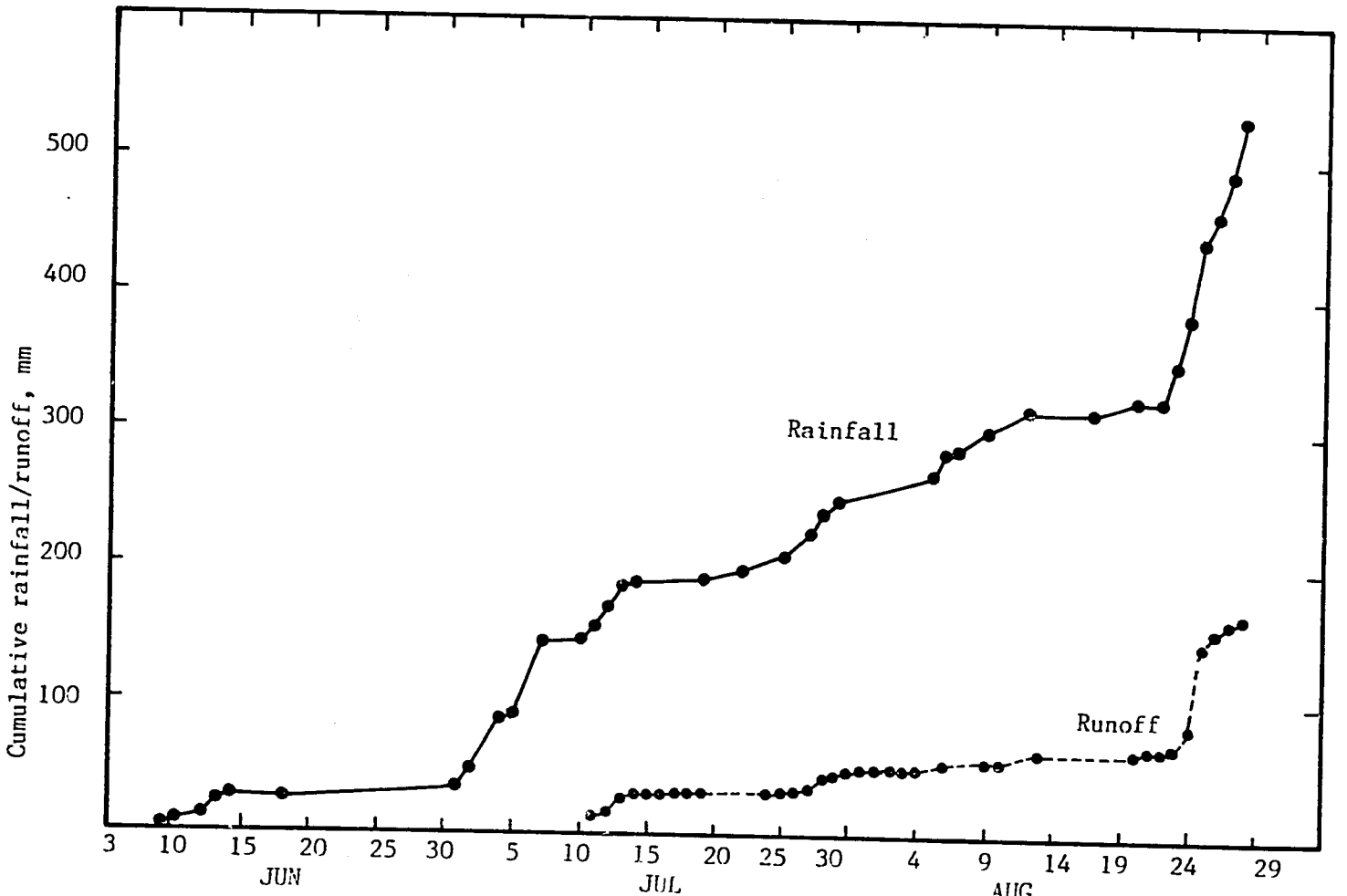

Fig. 3 Cumulative rainfall and runoff for the Pariyat watershed

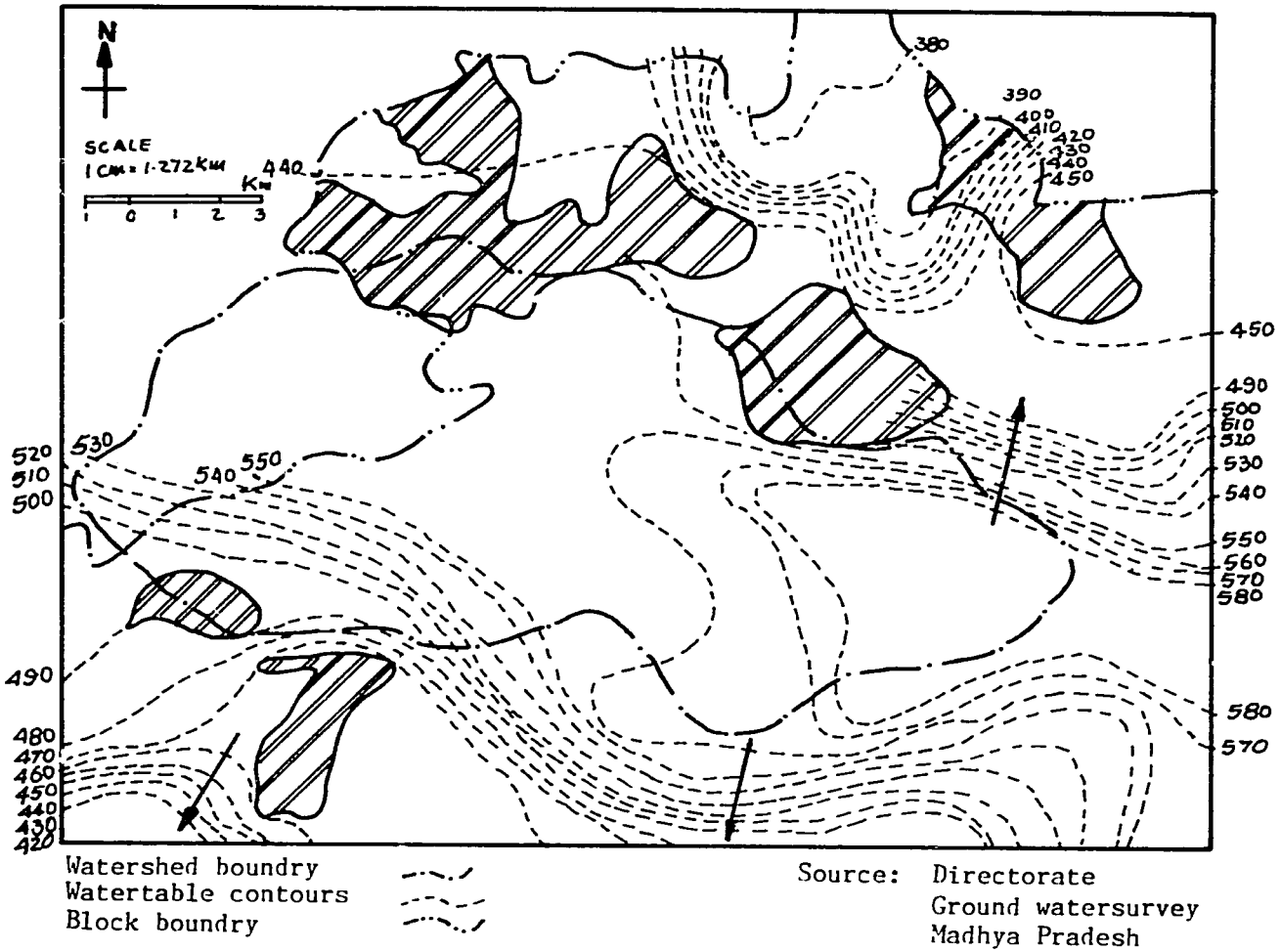

Fig. 4 Water table contours in Pariyat watershed, May 1981

Table 3. Estimated values of components of water balance for the Pariyat watershed, 15th June - 15th October

Components	Estimated/measured depth over the watershed, m
Rainfall	0.998
Runoff	0.235
Evapotranspiration	0.347
Groundwater draft	0.002
Moisture storage in soil profile	0.080
Subsurface outflow	0.054
Net recharge	0.280

Ground-water exploitation: Although there is good recharge available to the ground-water, the present utilization is hardly one percent of utilizable amount. Considering the depth of strata and the type of formation viz. Deccan traps, basalts and sandstone below the soil depth, the total watershed area is demarcated as a zone where ground-water can be exploited by using dugwells only. The average depth and diameter suggested for dug wells is 15 and 5 m, respectively.

As a matter of fact ground water table continues to deplete during post-monsoon period even with very insignificant utilization of ground water. It is, therefore, wise to utilize it for the crop production. The net recharge if determined based on water table fluctuation is of the extent of 0.220 m. considering 50% of the net recharge as utilizable water and irrigation efficiency as 70%, about 84 ha-m water can be made available for irrigation. This amount is sufficient to irrigate about 1900 ha of rabi crops and thus, the intensity of crops may be doubled for rabi season. Irrigated area may further be increased by providing check dams on the main river. Fortunately this part is already under progress.

ACKNOWLEDGEMENTS

The above study has been carried out at college of Agricultural Engineering under All India Co-ordinated Research Project on optimising the ground-water utilization through wells and pumps. The authors duly acknowledge the facilities provided by J.N. Krishi Vishwa Vidhyalaya, Jabalpur, and Indian Council of Agricultural Research, New Delhi. Co-operation in data collection by departments of Agriculture, Irrigation and Revenue at Jabalpur is also duly acknowledged.

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Integrated approach to watershed and command area development

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ABSTRACT

An integrated approach to pinpoint the role of small watershed hydrology in rainfed agriculture is presented. A systems approach is presented in three phases consisting of preliminary survey, data collection and control measures using socio-economic status and attitudes of the farmers. Emphasis is laid on the need for co-operative venture and the Government's responsibilities through a case study of Tabageria Irrigation Co-operative Society Ltd. Economics of existing and the improved allocation of land through multi-goal systems approach clearly indicated why the Government's goal of production and labour maximization are not achieved when the farmer is considering cultivation as an industry to maximize profit. Another case study has been appended to focus the design criteria for percolation ponds in particular and tanks in general. Economic analyses are made for different capacity ponds and crop allocations, keeping in view water balance. No doubt the design and capacity evaluation is location specific, but the methodology is universal. The study clearly denounces the present policy of fiscal constraints.

Having about 100 m ha area under rainfed agriculture and with the declared emphasis of VIII five year plan on rainfed agriculture based on agro-climatic zones, it is time to find a suitable approach to achieve the required goal of increasing the agriculture production. Table 1 shows the present state of the country's land resources. Lot of reasons have been already listed by researchers for these results (Bali 1986, Sarkar et al. 1987), while pointing out towards an integrated approach to watershed and command area development using systems approach with due consideration to the social and physical factors involved in the process.

Table 1. Status of land resources in India

Description	Area, m ha
Total geographical area	328
Cultivated area	
Rainfed	100
Irrigated	40
Forest	
Total	67
Actual	35
Problematic agricultural land	
Ravines and gullies	3.90
Salinity and alkalinity	7
Shifting cultivation	2.80
Torrents and stream banks	0.25
Coastal sandy lands	1.63
Desert	18.69
Water logged areas	5.99
Flood affected areas	40
Annually flood affected area	8
Problematic riverine lands	2.48
Drought hit area	260
Disastrously drought hit area	20

Source : Statistics on soil conservation in India, Ministry of Agriculture, ovt. of India, New Delhi, 1986.

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Objective of the approach : The objective of this paper is concerned with reduction and elimination of rural poverty on a permanent basis. The relevance and benefits of command area development lie in increasing food production, using new technologies; stabilize farm income and spread it evenly round the year, reducing seasonal shortages; and checking urban migration. It is true that methodology is universal and at present, uses the standard procedures irrespective of whether the area is irrigated or rainfed but the plea in this paper is for a search for analysis and understanding of ideas with practical applications to acheive the objective.

Concept of integrated approach using systems methodology : Systems methodology refers to the holistic approach of studying the system as an entity made up of all its components and interrelationships, together with the relationships between the system and its environment. The systems methodology, in contrast with the traditional research approach, is oriented to first specify the target and then assessing the alternative ways of reaching it. Consistent with this definition the integrated approach to watershed and command area consists of three major elements, each of which represents several steps. The integrated approach considers:

i) preliminary survey as a process involving separated but closely linked steps of basic information survey so as to decide upon the local needs.

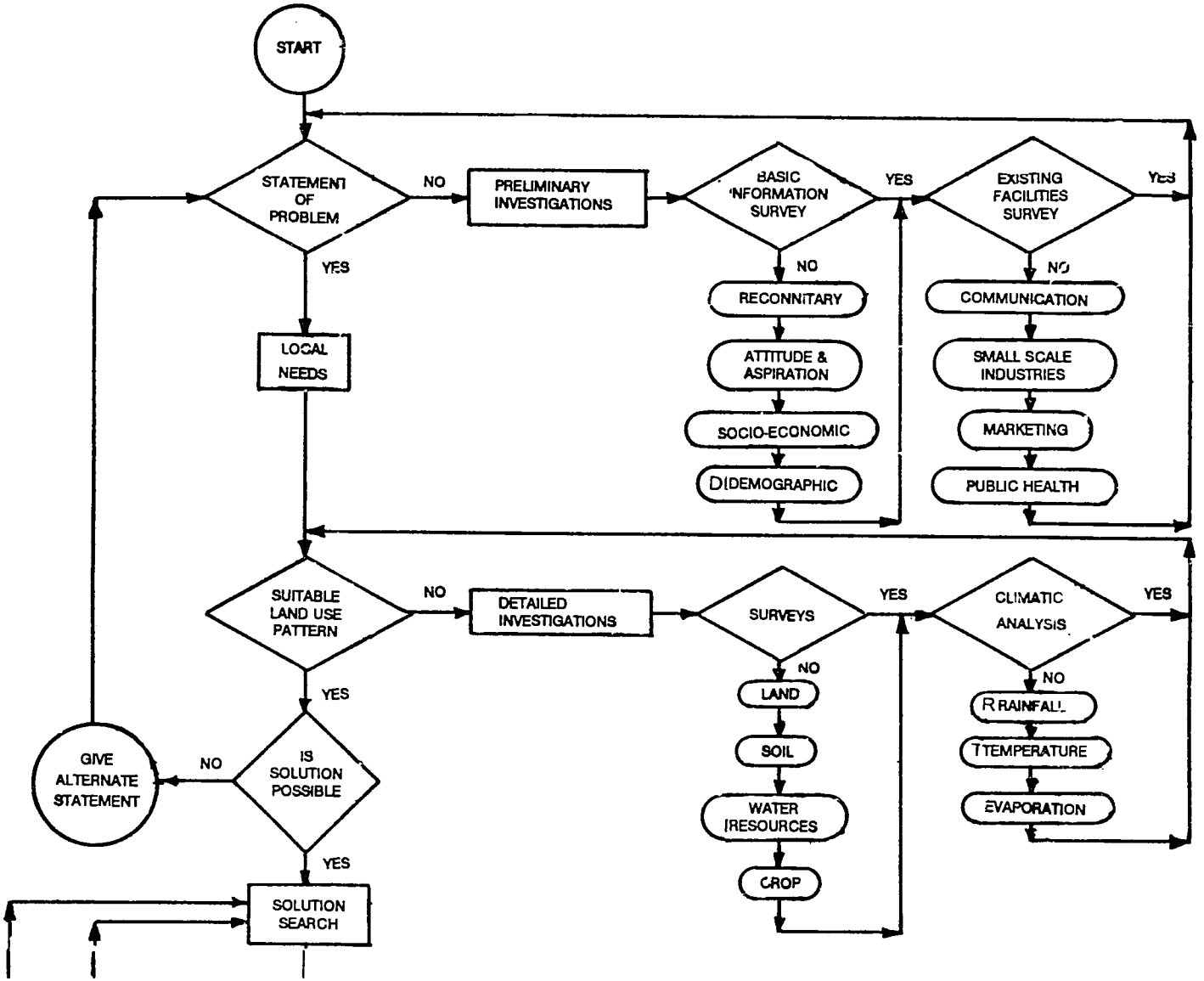
ii) detailed survey as a process which, after consideration to the local needs and the available resources gives the first breakthrough to the problem.

iii) watershed and command area development plan as a planned system of control measures and implementation tools.

Fig. 1 presents the flow chart of the integrated approach to watershed and command area development as sequential steps of planning and design process with monitoring and feedback of information to earlier steps. Looking at watershed and command area development as a sequential process helps us to understand how planning and implentation should be meshed if the development has to be effective. For example, lessons learned from the performance during the implementation stage would be useful to make appropriate revisions in the same or similar development programmes.

Preliminary survey : In this approach, the very first step is to decide the local needs on ths basis of basic information survey, which includes reconniter, socio-economic, attitude and aspirations, alongwith marketing facilities, small scale industries, communication and public health. There are two important points to be made about this way of looking at the watershed and command area development. The first is, the plan so developed will be need based and secondly as a consequence there will always be a possibility of full cooperation from the actual users themselves in the implementation of the programme.

Detailed survey : On the basis of local needs and the detailed survey of soils, crops suitable for that area, land type, water resources, agro-industry potential and the climatic conditions a suitable land use pattern must be developed. The entire area needs to be subdivided into various types of existing or prospective major land uses such as: agriculture, grazing, agro-foresty, commercial forest, protection forest etc. Of course, for each of these types, there may be multiple uses. For example, a commercial forest may also be used for grazing, wild life and recreation etc. With such detailed surveys available for each type of given land use, the identification of control and conservation measures becomes easier.


START
STATEMENT OF PROBLEM
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PRELIMINARY INVESTIGATIONS
BASIC INFORMATION SURVEY
YES
EXISTING FACILITIES SURVEY
YES
YES
NO
RECONNITARY
ATTITUDE & ASPIRATION
SOCIO-ECONOMIC
DIDEMOGRAPHIC
NO
COMMUNICATION
SMALL SCALE INDUSTRIES
MARKETING
PUBLIC HEALTH
LOCAL NEEDS
SUITABLE LAND USE PATTERN
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DETAILED INVESTIGATIONS
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GIVE ALTERNATE STATEMENT
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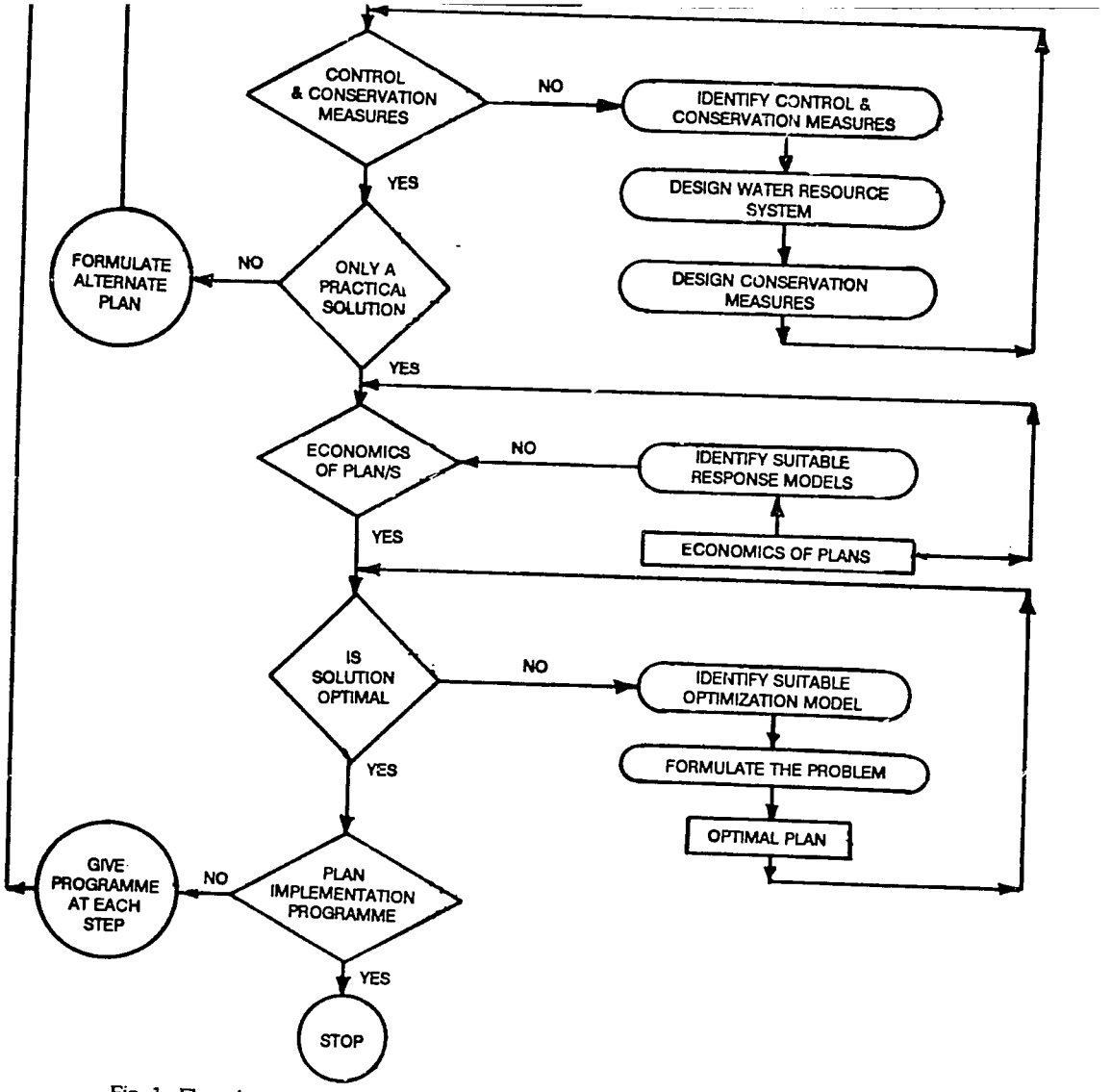

Fig. 1 Flow chart of integrated approach to watershed and command area develop-

Control measures and implementation program : With the help of identified control and conservation measures, the action plan should be prepared. In case of agriculture this would include quantity and time patterns of inputs such as water, fertilizer, labour and machinery along with their methods of application and the design of conservation measures like the water conveyance system, erosion control structures, stream bank protection measures.

At this stage, the economics of the development programme should be worked out. For assesing the land use returns, suitable crop response models should be selected. An optimal plan should be selected from the alternate plans using the standard optimization techniques.

APPLICATION OF THE APPROACH

Each of three major elements of the approach represents a set of several activities. In this paper, two typical case studies are presented in abstract form to illustrate the approach for which details can be found in the appended references.

Case study of Tabageria Irrigation Co-operative Society Ltd. (West Bengal): The site selected for the study is Tabageria, a small village in shaldhari watershed situated about 40 km from IIT, Kharagpur. The culturable area of the village is 151.6 ha. It has a population of 713, which suffers from utter poverty even though 44% of the population is educated. Most of the area is monocropped and faces the risk of innundation. Soils are clayey (45.6% clay and 41.9% silt). The area consists of 3067 plots, of which 82.33% has area less than one-tenth of a hectare. The source of irrigation water is a tubewell with a discharge rate of 58 $l\ s^{-1}$.

Based on the preliminary and detailed survey, a suitable agronomical package was developed after preparing the time schedule for application of irrigation and fertilizer. Economics of the plan was worked out, but, while testing the optimality of plan by using standard linear programming (LP) it was observed that labour shortage at the time of sowing of paddy and irrigation water shortage at critical weeks posed major constraints while nitrogen and potash posed minor constraints (Tripathi and Rao 1985). To overcome this, it was seen that due to staggering of the sowing time of the crops, water and labour requirement constraints could be avoided succesfully to a great extent. Table 2 presents the alternate plan features for different goals of profit, production and labour maximization cases.

As is evident from Table 2, the first three alternate plans have their own profits but in case of a compromise plan which will augment all the three goals, there is no clue. Thus later on Mangraj et al. (1985), demonstrated the advantage of using Fuzzy LP technique over simple LP method. The final results are also presented in Table 2. It is very interesting to note that Fuzzy LP model gives 100% land use and lowest investment. Thus, in view of the financial structure, it is encouraging to use Fuzzy technique

Table 2. Alternate plan features of development plan of Tabageria Irrigation Co-operative Society Ltd. by using different optimization models

Description	Land alloted, ha	Land use, %	Investment, Rs.	Profit, Rs.	Production, '000 kg	Labour, No.
Linear programming model						
a) Profit maximization	448.53	98.60	16,22,762	13,57,004	13,301	57,044
b) Production maximization	446.00	98.10	18,42,356	9,07,786	15,876	69,319
c) Labour maximization	450.65	99.10	18,29,697	8,27,350	14,684	69,985
Fuzzy linear programming model	454.80	100.00	16,08,029	10,58,104	14,550	61,645
Per cent gain over minimum	1.96%	—	12.72%	27.90%	9.40%	8.07%
Per cent loss over maximum	Nil	—	Nil	22.00%	8.35%	11.80%

in land allocation although there is a decrease in profit, production and labour when compared to their respective maximum obtainable.

Case study of percolation pond near village Collapatti, Dharmapuri (Tamil Nadu) : The most advanced agricultural states of India are facing either groundwater undermining or water logging problems due to miss management of water. In fact, in some parts of Tamil Nadu, groundwater is getting depleted in an accelerated manner. This case study provides an integrated plan to minimize groundwater depletion and maximize production. The selected pond is located at a distance of 7 km from Dharmapuri district of Tamil Nadu on the eastern side of Collapatti village. The pond lies in the upper catchment area of Kambainalar sub-basin, at foot of hillock, which forms the ridge line of the sub-basin.

The catchment area of the pond is 2850 ha and has a leaf shape. The existing capacity of the pond works out to 21,615 m^3. The length of embankment with surplus weir is 80 m and the top width is 2 m. the upstream and downstream side slopes are 2.5:1 and 2:1, respectively and the upstream slope is given a stone rip-rap. The water spread area is 0.99 ha at full tank level.

On the basis of preliminary and detailed investigations it was found that the runoff volume is very high as compared to the existing capacity of the pond. Therefore, it was proposed (Rao, 1987) that four alternate plans with different increased capacities of the percolation ponds be prepared so as to cover more area under irrigation. Table 3 presents the economics of alternate plans in brief. It reveals that the existing capacity has already increased the net returns of the command area by 20 % when compared to the pre-pond condition. It is also expected that the four alternate plans will increase the total returns by 42, 56, 75 and 100% respectively, when compared to the pre-pond condition.

The proposed approach is both a diagnostic and a planning tool which basically relies on disaggregation of the development programme into different specific stages that can be analyzed separately. The approach also enables one in isolating specific parts of the development programme for examination in detail. For example, the case study of Tabageria Irrigation Co-operative Society Ltd. shows that the major emphasis is placed on finding a suitable optimal programme. While the other case study of percolation pond clearly shows the monetary limitations in plan implementation although the required resources i.e. irrigation water is available in ample quantity. The optimality test can also be applied to the percolation pond's case study to find the best solution.

Table 3. Economics of alternate plans for development of percolation pond near Collapatti village (Tamil Nadu)

Description	Capacity of pond, m^3	Area, ha	Cost, Rs.	Return, Rs.	Increase, %
Pre-pond period	Nil	19.65	Nil	51,056	Nil
Existing pond case	21,615	22.83	—	61,335	20
Plan I	50,000	26.53	43,420	72,457	42
Plan II	1,00,000	27.75	63,178	79,673	56
Plan III	1,50,000	29.97	78,890	89,089	74
Plant IV	2,00,000	32.00	95,720	1,02,239	100

* indicates the per cent increase in the returns when compared to the pre-pond condition

Since, in this paper major concentration is placed on highlighting the important issues related to the preparation of watershed and command area development plan, the main points can be summarized as below :-

1) There should be an integrated approach in development of any plan considering the social and physical factors,

2) Stress should be laid on more number of small areas (either a small watershed or a command area of water resource) so that the plan is more aceptable and gives the best results irrespective of whether the area is irrigated or rainfed as demonstrated by the case studies.

3) More emphasis should be given to conjuctive use of water i.e. surface water and ground water so that the natural balance is maintained while at the same time reducing the hazard of water logging, salinisation etc.

4) Priority should be given to minor irrigation works, like percolation ponds, which are quick maturing and are labour intensive and provide the only means of irrigation in several chronically drought affected areas.

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Rain water management for stabilising productivity of drylands

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ABSTRACT

Keeping the importance of rain water in dryland agriculture in view, considerable research efforts to workout suitable practices for rain water and soil conservation have been made in the All India Coordinated Research Project for Dryland Agriculture. These research results are summarised in this paper. The results suggest that the runoff and soil loss vary with crop and cropping system. Mechanical structures, though cost intensive, are quite effective in reducing soil loss. Vegetative barriers have also been found fairly effective, economic and operationally feasible, however, more studies in this direction are needed. Off-season tillage is another practice which increases rain water conservation leading to higher crop yields. Use of surface mulches reduces loss of conserved soil moisture and helps in getting higher crop yields.

Presently drylands occupy about 100 m ha of the total cultivated area of 143.8 m ha in the country. These areas are spread over almost all major soil types which vary considerably in physical and chemical properties resulting in varied moisture situations. The quantum of rainfall differs from arid to humid situations and is highly erratic in distribution frequently resulting in scarcity as well as excess moisture conditions. Both these situations lead to unstable productivity of drylands.

Soil and runoff losses in different cropping systems: The effect of different cropping systems on loss of soil and rain water has been studied at different centres. At Rajkot the runoff and soil loss were recorded in different systems for 5 years at three slopes. The data summarised in Table 1 show maximum loss of soil and rain water in sole pearl

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millet and minimum in spreading groundnut. Similar studies at Indore showed that the runoff was 53.7% in fallow field and 56.6% in maize + soybean intercropping system and minimum in sole soybean (31.6%). Soybean + pigeonpea and sorghum + pigeonpea systems recorded runoff to the tune of 36.9 and 45.3%, respectively. At Bangalore centre, the soil loss and runoff from different crops have been studied for 6 consecutive years from 1982-83 to 1987-88. The results set out in Table 2 show that maximum loss of soil and rain water was in fallow and minimum in maize. The main reason for lower values of runoff and soil loss with maize at Bangalore is attributed to the management practices where each row was earthed up and made into a ridge. The study with cotton + greengram and sorghum + pigeonpea intercropping systems was conducted in vertisols at Akola for 3 years from 1983-84 (Table 3). The results show that loss of both soil and rain water was almost equal in the two intercropping systems.

Table 1. Runoff and soil loss in different cropping systems in relation to slope at Rajkot (average of 5 years)

Cropping system	Soil loss, Mg ha^{-1} at slope, %				Runoff, % at slope, %			
	0.5	1.0	1.5	Mean	0.5	1.0	1.5	Mean
Sole groundnut (Spreading, GAUG-10)	0.39	0.74	0.83	0.65	21.4	26.3	30.2	26.0
Sole groundnut (Bunch, GAUG-1)	0.68	0.99	1.01	0.89	24.7	29.9	32.0	28.9
Sole pearl millet (BJ-104)	1.23	1.59	1.74	1.52	33.6	31.1	36.9	33.9
Pearl millet (BJ-104) + pigeonpea (UPAS-120)	1.16	1.47	1.52	1.38	27.8	31.3	34.1	31.1
Groundnut+pigeonpea (GAUG-1) (UPAS-120)	0.93	1.20	1.31	1.15	24.9	30.9	32.5	29.4
Mean	0.88	1.20	1.28		27.8	29.8	33.2	

Table 2. Runoff and soil loss under different crop canopies at Bangalore during 1982-83 to 1987-88

Crop	Mean rainfall, m	Runoff, %	Soil loss, Mg ha^{-1}	Yield, Mg ha^{-1}
Fallow	0.460	33.17	7.59	
Groundnut	0.465	36.16	8.41	1.24
Finger millet	0.460	29.66	6.33	2.03
Maize	0.460	15.92	3.30	2.75

Table 3. Effect of cropping systems on runoff and soil loss at Akola (average of 3 years 1983-84 to 1985-86)

Cropping system	Runoff, m^3 ha^{-1} year^{-1}	Soil loss, Mg ha^{-1}	Yield, Mg ha^{-1}
Cotton + greengram (B 1007) (Kopergaon)	15.5	0.40	0.62 + 0.29
Sorghum + pigeonpea (CSH-1) (C-11)	14.9	0.35	1.86 + 0.53

Soil and moisture conservation practices: The various practices of arresting loss of soil and runoff involve construction of bunds, grass strips and other barriers on the contours. The excess water held by the bund, without the provision for proper drainage may lead to breaking of structures and formation of new gullies. This especially true in a high-rainfall situation. But in a low rainfall condition, the runoff is effectively arrested by contour bunds (Table 4). A surplussing arrangement with grades in bunds need to be provided to drain excess water.

Table 4. Runoff from total rainfall (%) as influenced by land treatments on alfisols of Bangalore

Practice	High rainfall (1.10 m)	Low rainfall (0.65 m)	Average
Field bunds	20.1	14.1	15.9
Contour bunds	19.4	7.4	12.0
Graded bunds	12.7	12.7	12.7
Graded border strips	17.0	6.3	10.2
Bed-furrow system	24.2	14.6	16.7

Land levelling, bench and zingg terracing etc. are various land shaping approaches. The levelling process avoids ponding of water in troughs and provides uniformity in soil moisture. A very cautious approach is needed in case of highly heterogeneous shallow soils. The spatial variability of the surface soil depth is of high order in drylands due to erosion. Any atempt to level such lands exposes the low fertility sub-soil and reduces yields. In inceptisols at Agra and in entisols of Hoshiarpur, attempts were made to mildy shape the land surface. This helped the crops, more so under low rainfall situation (Table 5). Zingg terracing with scooping, at Bijapur gave higher sorhgum yield whereas compartmental bunding showed promise at Kovilpatti (Table 6).

Table 5. Effect of land shaping on crop yield, Mg ha^{-1}, at Hoshiarpur and Agra

Land shaping	Hoshiarpur Wheat + chickpea mixture	Agra Pearlmillet Rainfall, m	
		0.32	0.66
Natural	1.05	1.34	2.22
With land shaping	1.65	1.63	2.31

Table 6. Effect of land shaping on the yield of sorghum

Centre	Treatment	Yield, Mg ha^{-1}
Bijapur	Zingg terracing	0.89
	Zingg terracing + scooping	1.01
	Compartmental bunding	0.88
	No land treatment	0.67
Kovilpatti	Control	1.14
	Compartmental bunding	1.72

Different land treatments are studied in different soil and rainfall situations. The results suggest that 'bed and furrow', system increases the runoff over other systems. Therefore, suitable only for higher rainfall vertisol areas where drainage may be a problem. A modified version of graded line cultivation is recommended for light and medium soils with a grade of 0.2-0.6 %. The bunds (0.6 m^2 cross section area) are laid to provide the line of cultivation. This helps in natural drainage and also provides more opportunity for water entry into the soil. This system is more acceptable to farmers as no special implement is required. The effects of different treatments on runoff and soil loss on crop yields are summarised in Tables 7 and 8.

Table 7. Effect of land treatments on soil loss and runoff

Centre	Particulars	Flat on grade	Bed and furrow on grade
Jodhpur	0.020 m rainfall		
	Runoff, mm	0.2	2.2
	Soil loss, Mg ha^{-1}	0	0.007
	0.070 m rainfall		
	Runoff, mm	4.2	9.9
	Soil loss, Mg ha^{-1}	0.038	0.135

Hyderabad	0.010 m rainfall		
	Runoff, mm	0.02	0.94
	Peak rate, m^3 sec^{-1}	0.01	0.01
	0.040 m rainfall		
	Runoff, mm	0.15	1.42
	Peak rate, m^3 sec^{-1}	0.01	0.01
	0.080 m rainfall		
	Runoff, mm	0.60	2.97
	Peak rate, m^3 sec^{-1}	0.03	0.05
Solapur	Fallow-sorghum system		
	Runoff, mm	19	90.0
	Soil loss, Mg ha^{-1}	0.318	0.148
	Greengram-sorghum system		
	Runoff, mm	7.3	34.0
	Soil loss, Mg ha^{-1}	0.208	0.049

Table 8. Effect of land configuration system on average yield of crops

Location	Soil type	Crop	System	Yield, Mg ha^{-1}	
				Control	With land configuration
Bangalore	Alfisols	Finger millet	Graded border strip (0.1% grade)	2.28	3.35
Anantapur	Alfisols	Groundnut	Dead furrow at 3.0 m	0.68	0.75
Hyderabad	Alfisols	Sorghum+ pigeonpea	Flat on grade and ridging later	2.45+0.58	2.91+0.72
Akola	Vertisols	Sorghum	Broad bed and furrow	1.69	2.13
Bellary	Vertisols	Sorghum	Graded furrowing	0.21	0.28

Dehra Dun	Entisols	Maize + rice (2 : 1 row ratio)	Inter plot water harvesting	0.97+1.0	1.14+1.21
Jodhpur	Aridisols	Pearl millet	Inter plot water harvesting	1.85	2.80

Mechanical structures to control soil and water loss occupy space which is not available for cultivation. Growing hedge rows along the contour (vegetative barriers) helps not only to reduce soil and water loss but also provide some fodder during the off season (Table 9). Such practices alone as well as along bunds is getting popular in small size fields. Another practice, viz., vertical mulch using crop stubbles at regular interval, provides barrier for water flow. These barriers have been found useful in vertisols (Table 10).

Table 9. Effect of live bunding on crop yield

Centre	Crop	Treatment	Yield, Mg ha^{-1}
Bijapur	Groundnut	Traditional bund	0.82
		Live bund	
		Sesbania aculeata	1.10
		Glyricidia	1.04
		Leucaena	1.08
		Vetiveria	0.72
		Perennial pigeonpea	0.68
Akola	Cotton	Control	0.80
		Ridge and furrow	0.92
		Live bund (*Vetiveria*)	0.97
	Sorghum + pigeonpea	Control	2.0+0.24
		Ridge and furrow	2.13+0.26
		Live bund (*Vetiveria*)	2.0+0.24
	Greengram	Graded bund	0.41
		Live bund(*Leucaena*)	0.44

Table 10. Effect of vertical much (4 m wide) on crop yield

Centre	Crop	Yield, Mg ha^{-1} Control	Vertical mulch
Akola	Sorghum + pigeonpea	2.0+0.24	2.4+0.29
	Cotton	0.80	1.03
Bellary	Sorghum	0.83	1.18
			1.20*

* 8 m wide

Tillage: Tillage has considerable influence on in situ conservation of rain water. The experiences show that 'off-season' tillage keeps the field open for entry of rain water resulting in better moisture conditions and better crop performance (Table 11). The advantages of off-season tillage are greater in sub-normal rainfall years.

Table 11. Effects of off-season tillage on yields, Mg ha^{-1}

Tillage	Hyderabad (Alfisols) Sorghum (3 years)	Castor bean (2 years)	Varanasi (Entisols) Barley (3 years)
Without off-season tillage (farmers' practice)	1.87	0.32	1.37
With off-season tillage (Improved system)	2.60	0.38	1.57

Primary tillage helps in extending available time for seeding by atleast 4 days over the usual 3 days after soaking rains in Alfisols of Hyderabad due to better intake of moisture. In vertisols of Solapur the available moisture was increased by breaking the soil clods into smaller fractions. At different centres, deep tillage with tractor was tested against farmers' traditional shallow tillage practice with a

country plough. The results set out in Table 12 show a definite increase in yields of a variety of crops with deep tillage along with an increase in soil moisture utilisation. However, the water use differences were not very high in low rainfall situations. Anantapur results also suggest that the effect of deep tillage lasts for 2 to 3 years.

Table 12. Effect of shallow (traditional) and deep (tractor) tillage on crop yields

Centre	Particulars	Crop yields, Mg ha^{-1} Shallow	Deep
Bhubaneswar	Rice (2 years)	0.62	0.71
Ranchi	Maize	0.85	1.45
	Rice	3.12	3.47
	Wheat	2.48	2.53
Bangalore	Groundnut	1.18	1.20
	Finger millet	2.72	2.87
	Maize	3.54	4.23
	Pigeonpea	1.23	1.56
	Sunflower	1.09	1.00
Hyderabad	Sub-normal season		
	Sorghum	1.74	1.81
	Pearl millet	0.10	0.15
	Castor bean	0.38	0.43
	Sunflower	0.81	0.89
	Pigeonpea	0.25	0.29
	Normal season		
	Sorghum	2.66	2.95
	Pearl millet	1.94	2.23
	Castor bean	0.78	1.27
	Above normal season		
	Sorghum	2.61	2.65
	Pearl millet	1.60	1.63
	Castor bean	0.78	1.27

Rakh-Dhiansar	Maize	0.45	1.24
Hoshiarpur	Maize	2.22	2.30
	Wheat	2.38	2.55
Bhubaneswar	Rice (2 years)	0.62	0.71
Varanasi	Barley	1.33	1.57
Agra	Barley	1.74	2.17
Rajkot	Pearl millet	1.98	1.81
	Sorghum	2.11	1.81
	Groundnut	0.48	0.45
	Sunflower	1.10	1.04
Anantapur	Direct effect		
	Castor bean	0.64	0.88
	Pigeonpea	0.90	1.17
	Pearl millet	1.20	1.54
	Groundnut	0.42	0.44
	Residual effect		
	I year		
	Castor bean	1.01	1.30
	Pigeonpea	0.91	1.18
	Pearl millet	0.77	1.03
	Groundnut	0.86	1.17
	II year		
	Castor bean	0.51	0.86
	Pigeonpea	1.03	1.50
	Pearl millet	0.49	0.74
	Groundnut	0.57	0.82
	III year		
	Castor bean	1.28	1.51
	Pigeonpea	0.52	0.74
	Pearl millet	0.02	0.03
	Groundnut	1.33	1.42

Surface mulches: Surface mulching aims at slowing the movement of soil water vapours into the atmosphere. This aspect has been studied in detail at different centres. Of the various materials studied, soil mulch and organic mulch are of importance in Indian context. Some of the results are presented in Table 13.

Table 13. Effect of surface mulches on crop yield, Mg ha^{-1}

Crop	Centre	Mulch treatment			Material used
		No mulch	Dust mulch	Organic mulch	
Sorghum	Solapur	0.78		1.27	Dry grass
				1.04	Sorghum stubble
	Bellary	1.08	2.55	1.36	Stubbles
	Kovilpatti	0.53	0.63	0.94	Sorghum stubbles
				0.82	Pearl millet stover
				0.66	Paddy stover
		0.92	1.03	1.12	Sorghum stubble
				1.11	Pearl millet stover
				1.35	Groundnut husk
	Bangalore	1.20	-	1.85	Stover
				2.36	Polyethylene
Pearl millet	Agra	1.72	-	2.70	Blackgram stover
Maize	Varanasi	0.45	0.58	0.57	Wheat straw
				0.52	Weed stubbles
	Rakh-Dhiansar	1.85	-	2.16	Wheat straw
				2.33	Sarson trash
	Udaipur	0.80	-	1.20	Wheat straw

Finger millet	Bangalore	1.25	-	1.34 1.46	Stover Polyethylene
Setaria	Bangalore	1.13	-	1.26	Stover
Groundnut	Rajkot	1.09	1.18	1.27	Pearl millet husk
Sunflower	Bangalore	0.66	-	0.75	Stover
Wheat	Jhansi	0.96 1.54	- -	1.68 1.79	Stover Grass
	Rewa	1.34	-	1.64	Paddy stover
	Rakh-Dhiansar	2.65	-	3.03 3.09	Branker leaves FYM layer (1.5 cm)
Barley	Agra	1.93	-	2.53	Blackgram stover
Chickpea	Arjia	0.35	0.44	0.46	Farm residue
Safflower	Arjia	0.89	1.18 1.28 (soil stirring)	0.94	Sorghum stover
Rice-barley	Varanasi	3.89-1.25	3.96-1.47	3.72-1.36	Wheat straw
				4.17-1.60	Safflower husk
Maize-wheat	Hoshiarpur	3.48-2.54	-	4.06-3.38	Basoti mulch (*Adhatoda vasica*)

It is evident from these results that this practice has very little place in crop production during the rainy season. However, in post-rainy season mulches have an important role to play as it can carryover moisture for a short time or can be conserved for a subsequent crop.

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Watershed modelling for yield assessment

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ABSTRACT

Assessment of water yield in a basin is basic to the design and operation of an irrigation project. Very often the streamflow data series are not available for making such an assessment. Under such circumstances stream flow records can be generated by transforming the rainfall records, which are usually available, into runoff using some appropriate models. The models employed for such purpose vary from empirical models to conceptual water balance models. A comparison between the performance of an empirical model and a water balance model is attempted in the present paper.

There are numerous existing and proposed irrigation schemes in India where yield assessment is desired for their optimal design and operation. In most of these schemes, especially the minor irrigation schemes, sufficiently long sequence of streamflow observations may not be available. Consequently transformation of rainfall into runoff or basin yield is resorted to. Empirical relationships, such as that of Binnie's, are usually employed for such transformations. The empirical relationships do not encompass the dynamic nature of the hydrological processes of the basin. With the wide availability of computing power and better understanding of hydrological processes, it is imperative that the old methods of yield assessment need to be replaced with better scientific methods capable of representing the rainfall-runoff transformation process more realistically.

Continuous water balance models or conceptual models are such tools which have the capability of incorporating the hydrologic processes going on in the catchment for accurate assessment of the yield. One such model is the tank model. This model has been used on the Banchhor tank catchment of Madhya Pradesh. The

results obtained by the Tank model have been compared with those obtained using the Binnie's method for yield assessment.

MATERIALS AND METHODS

Tank model : The tank model (Sugawara et al. 1984) is a continuous water balance model. It is a simple model having small computational requirements and can be run on a personal computer. The data requirements of the model match with the data usually available on small catchments.

Structure of the model : Tank model is composed of four or less tanks stacked vertically. These tanks are modelled to produce different components of the total response, e.g., the surface runoff, interflow and base flow.

A soil moisture structure is defined in the top tank to simulate the fluctuating soil moisture status of the top soil profile. The lower tanks have no soil moisture structure as they are believed to be saturated at all the timings.

The top tank has two soil moisture storages, namely, a primary soil moisture and a secondary soil moisture storage. The capacities of these storages are expressed as S1 and S2, respectively (Fig. 1). The input of rainfall enters the top tank first and fills the primary soil moisture. If the status of the primary storage is represented by XA, then as long as XA < S1 the total quantity will be stored in primary soil moisture storage. But as XA exceeds S1 the surplus, i.e., (XA-S1) will become the free water which will subsequently infiltrate or discharge through outlets as shown in Fig.1. In other words

when XA < S1

$$XP = XA; \; XF = 0$$

and when XA < S1

$$XP = S1; \; XF = XA - S1$$

where, XP - primary soil moisture content; XF - primary free water content; and S1 - primary soil moisture content

There is a secondary soil moisture storage which is situated along side the primary soil moisture storage. Water transfer takes place between the primary and secondary storages, as shown in Fig.2, with respect to their relative affinity. This transfer can be expressed as

$$K2 * (XP/S1 - XS/S2)$$

Where, K2 - a constant, dependent on soil type; XS - secondary soil moisture content; and S2 - secondary soil moisture capacity

The water transfer will be from primary soil moisture storage to secondary soil moisture storage if the above expression is positive and vice versa.

When the primary soil moisture storage is not saturated, transfer also takes place from the free water in the lower

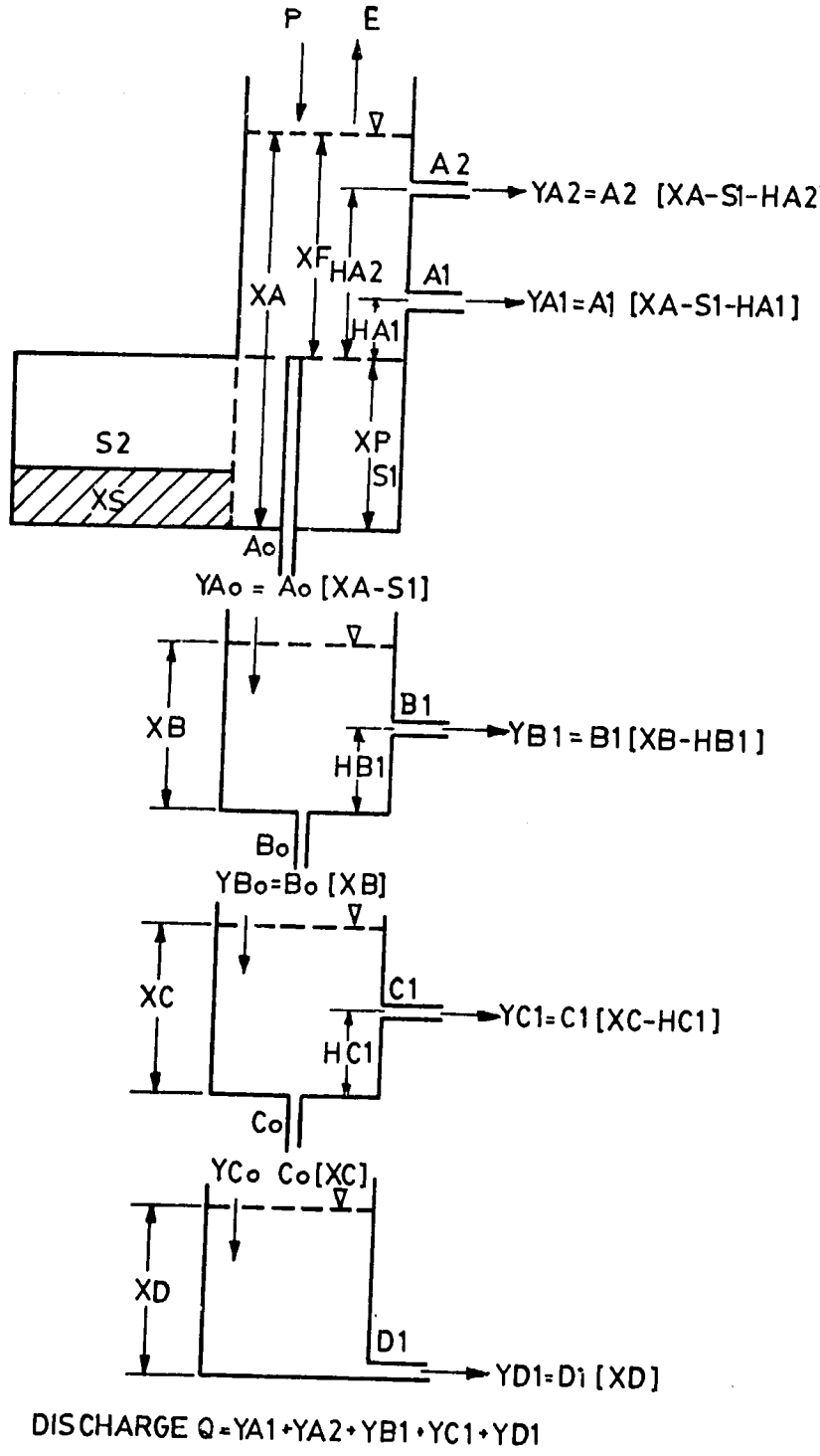

Fig. 1 Detailed structure of the tank model

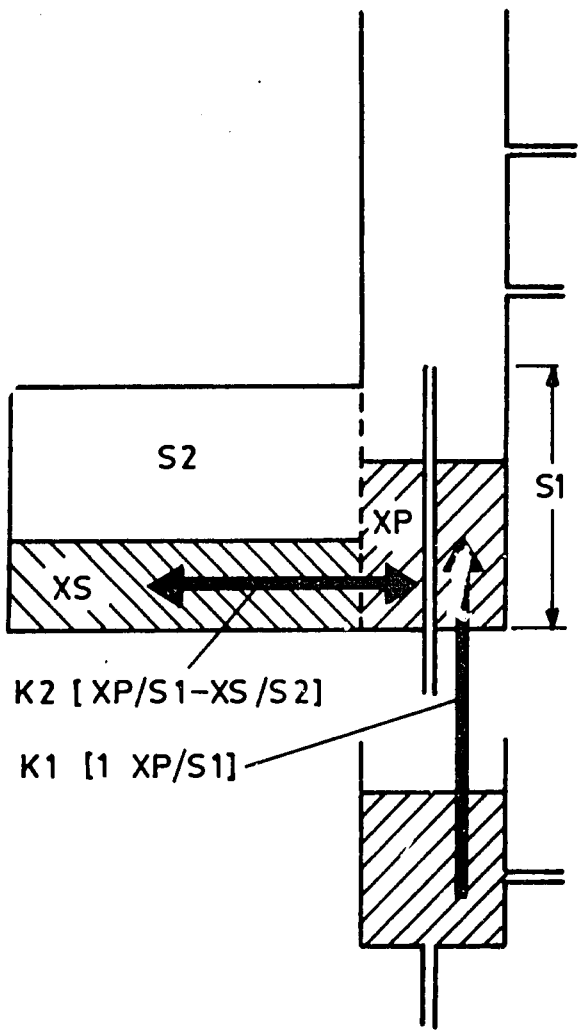

Fig. 2 Illustration soil moisture transfer

tank. This transfer is only one directional and is governed by

$$K1 * (1 - XP/S1)$$

where K1 - a constant, dependent on soil type.

In the above expression, one can see that the transfer to primary storage will be zero when XP = S1, i.e. saturation of primary soil moisture; and will be maximum when XP = 0, i.e., it is completely dry.

The tanks are labelled A,B,C and D from the top and the free water in each tank discharges partly through the side outlet(s) and partly infiltrates through the bottom outlet to the next lower rank. The top tank A has two side outlets and all the other ranks have one side outlet. Every tank except the bottom tank D has a bottom outlet. The amount of runoff from the side outlets and the infiltration from the bottom outlets per unit time is proportional to the head of water at the outlet. The runoff coefficients for each tank, i.e., A1, A2, B1, C1 and D1; the infiltration coefficients for each tank, i.e., HA1, HA2, HB1 and HC1 as shown in Fig.1 are some of the model parameters which need to be evaluated. Besides these basic parameters, some adjustment factors are also incorporated in the model to provide more flexibility. These adjustment factors help in treating the input to the model in a distributed manner in time and space. A detailed description of the model parameters and the adjustment factors is given by Gosain et al. (1987).

Data requirements and calibration : The process of determining the values of model parameters and the adjustment factors for a particular catchment is known as model calibration. The model calibration can be accomplished by either of the three possible techniques, manual, semi-automatic or automatic. Out of these, manual technique is more reliable because of the interaction of the model parameters and is adopted in this study.

In the manual calibration, an initial set of model parameters is selected and the model is run to get the model output. The model (simulated) output is compared with the observed output and changes are made in the model parameters such that the discrepencies between observed and simulated output are minimised. The number of trial runs needed to calibrate the model are reduced considerably if a good initial parameter set is selected. Moreover, a good understanding of the model is also necessary for proper and efficient calibaration of the model.

The tank model requires the data on mean daily station rainfall and potential evapotranspiration. In the event that daily potential evapotranspiration data is not available, the mean monthly potential evapotranspiration data may be used. For calibration of the model, a continuous record of runoff data for about two years is also required.

Banchhor catchment : The Banchhor tank was constructed under minor irrigation scheme in the District of Raisen (Madhya Pradesh). The Banchhor tank is located at longitude 77° 46′ and latitude 23° 13′ N. The tank has a catchment area of 14.76 km^2, which comprises of mainly two types of forest areas as shown in Fig.3. About 35% of the area is covered with fairly dense mixed jungle of mainly sagvan and bamboo and about 55% of the area is covered with dense jungle of mainly gurjaina. The remaining 10% of the catchment area is submerged by the tank.

Data availability : There is one ordinary raingauge located at the dam site at Banchhor. Daily rainfall data recorded at this station is available from 1972 to 1986. Another ordinary raingauge, in the near vicinity but outside the catchment area, is located at Sudra. Seven years of daily rainfall data from 1980-1986 is available at Sudra. Recorded mean daily yields in million cubic feet are available from 1972 to 1986. These yields are converted to m^3 sec^{-1} for use in the model. Mean monthly potential evapotranspiration values for the area are also available.

Calibration of model for Banchhor catchment : Manual calibration procedure has been adopted for this study. It involves selecting initial model parameter set and operating the model using the daily rainfall data, daily discharge data, mean monthly evapotranspiration data, and the initial contents of the storages. Plots of observed and simulated discharges are compared for updating the model parameters such that the discrepencies between observed and simulated data yield values are minimised. In order to ensure proper simulation, a number of trial runs are made. Parameter sets A,B and C for three of the trial runs on year 1975 are given in Table 1.

Table 1. Tank model parameters selected for different calibration runs and the final set of parameters adopted for simulation

Parameter name	Triai A	Trial B	Trial C (Final)
S1	20.0	50.0	30.0
S2	150.0	350.0	350.0
HA1	15.0	30.0	30.0
HA2	25.0	55.0	45.0
Ao	0.12	0.12	0.12
A1	0.20	0.15	0.25
A2	0.35	0.35	0.35
HB1	15.0	15.0	15.0
Bo	0.0	0.03	0.01
B1	0.15	0.08	0.15
HC1	0.0	0.0	0.0
CO	0.0	0.0	0.0
C1	0.0	0.0	0.0
HD1	0.0	0.0	0.0
DO	0.0	0.0	0.0

D1	0.0	0.0	0.0
K1	2.0	2.0	2.0
K2	15.0	15.0	15.0
CE	0.6	0.65	0.65

The recorded and simulated monthly yields (mm) for odd years using the parameter sets A, B and C are summarised in Table 2. It may be observed that the basin yields as obtained from the model are quite sensitive to some of the model parameters and change drastically by adjusting these parameters.

Table 2. Results of calibration runs for odd years with parameter sets, A, B and C

Month	Item	1973	1975	1977	1979	1981	1983	1985
June	QO	0.000	0.004	0.000	0.000	0.023	0.000	0.000
	QSA	0.000	0.004	0.000	0.000	0.061	0.000	0.000
	QSB	0.000	0.000	0.000	0.000	0.015	0.000	0.000
	QSC	0.000	0.000	0.018	0.000	0.039	0.000	0.000
July	QO	0.320	0.064	0.035	0.004	0.050	0.007	0.000
	QSA	0.324	0.147	0.114	0.001	0.039	0.094	0.008
	QSB	0.170	0.022	0.028	0.001	0.000	0.005	0.000
	QSC	0.244	0.049	0.056	0.012	0.003	0.024	0.000
Aug.	QO	0.521	0.285	0.416	0.023	0.227	0.265	0.351
	QSA	0.412	0.393	0.415	0.061	0.184	0.569	0.423
	QSB	0.267	0.239	0.332	0.011	0.105	0.373	0.252
	QSC	0.318	0.289	0.394	0.029	0.139	0.445	0.301
Sept.	QO	0.236	0.252	0.350	0.000	0.025	0.201	0.209
	QSA	0.239	0.275	0.340	0.000	0.016	0.263	0.298
	QSB	0.176	0.194	0.307	0.000	0.016	0.210	0.207
	QSC	0.191	0.229	0.324	0.000	0.020	0.229	0.246
Oct.	QO	0.012	0.005	0.000	0.000	0.000	0.002	0.142
	QSA	0.012	0.025	0.000	0.000	0.000	0.052	0.137
	QSB	0.012	0.023	0.005	0.000	0.000	0.027	0.091
	QSC	0.011	0.023	0.000	0.000	0.000	0.035	0.102
Year	QO	1.089	0.609	0.801	0.037	0.325	0.476	0.702
Sum	QSA	0.986	0.843	0.869	0.098	0.299	0.978	0.866
	QSB	0.625	0.477	0.675	0.017	0.134	0.615	0.550
	QSC	0.744	0.590	0.793	0.060	0.202	0.734	0.649

QO Observed discharge, m
QSA Simulated discharge with parameter set A, m
QSB Simulated discharge with parameter set B, m
QSC Simulated discharge with parameter set C, m

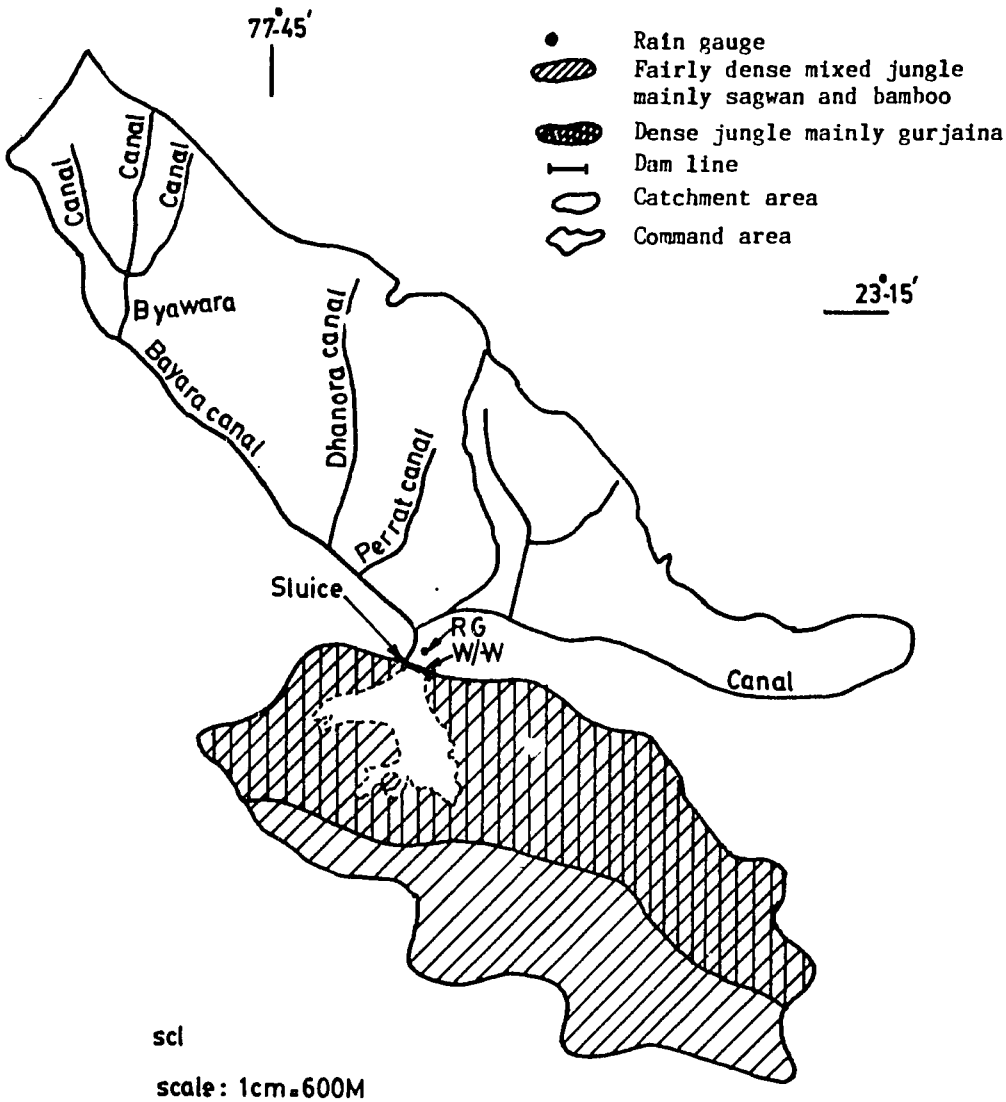

Fig. 3 Map of Banchhor catchment along with command area

It may also be observed (Table 2) that parameter set C gives a good simulation for majority of the years. However, the parameter sets A and B simulate some particular years better than those obtained by using parameter set C. This may appear anomolous due to the fact that the catchment characteristics have not changed and, therefore, the yield response of the basin should also not change. But there may be some extraneous reasons resulting in unusual basin response. These are discussed in the following section.

RESULTS AND DISCUSSION

After finalising the model parameter set through calibration, the model is run on the continuous basis. Continuity is maintained by adopting the contents of the stores at the end of the year as the starting contents for the following year. The simulation results are summarised in Table 3.

Table 3. Simulation using Banchhor rainguage data with the final set of model parameters, C for odd years

Month	Item	1973	1975	1977	1979	1981	1983	1985
June	RN	0.039	0.167	0.164	0.154	0.195	0.036	0.032
	QO	0.000	0.004	0.000	0.000	0.023	0.000	0.000
	QS	0.000	0.000	0.018	0.000	0.039	0.000	0.000
July	RN	0.561	0.309	0.316	0.092	0.222	0.332	0.329
	QO	0.320	0.064	0.035	0.004	0.050	0.007	0.000
	QS	0.224	0.049	0.056	0.012	0.003	0.024	0.000
Aug.	RN	0.540	0.466	0.563	0.186	0.277	0.656	0.502
	QO	0.521	0.285	0.416	0.023	0.227	0.266	0.351
	QS	0.318	0.289	0.393	0.029	0.139	10.445	0.301
Sept.	RN	0.207	0.326	0.291	0.000	0.129	0.280	0.371
	QO	0.236	0.252	0.350	0.000	0.025	0.202	0.209
	QS	0.191	0.229	0.323	0.000	0.020	0.230	0.247
Oct.	RN	0.000	0.030	0.025	0.000	0.000	0.085	0.165
	QO	0.012	0.005	0.000	0.000	0.000	0.002	0.142
	QS	0.011	0.023	0.001	0.000	0.000	0.035	0.102
Year	QO	1.088	0.609	0.801	0.037	0.325	0.476	0.702
Sum	QS	0.744	0.590	0.792	0.060	0.202	0.734	0.649

RN Total monthly rainfall, m
QO Observed monthly discharge, m
QS Simulated monthly discharge, m

On close examination of Table 3, one can observe that some yield values are not practically possible. For example, a yield of 0.520 m for August 1973 from the monthly rainfall of 0.540 m seem to be unusually high and on the other hand for the month of August 1983 a yield of 0.266 m has been recorded against the monthly rainfall of 0.656 m, which seems to be too low. These anomalies may either be associated to extreme variability of rainfall in the area or to erroneous discharge measurements at the site.

In order to minimise the effect of variability of rainfall over the catchment area, simulation exercise is also done by taking the rainfall data at Sudra (a raingauge available in the vicinity of the catchment) into account. The rain gauge at Sudra is assigned the same weightage as that installed at Banchhor bund and the parameter set C is used for simulating the yields from 1980 to 1986, period for which rainfall data for Sudra is available (Table 4). It is observed that the simulation for six out of seven years has definitely improved by taking another raingauge into account. It confirms that there is some variability in rainfall of the catchment. This has also been confirmed by analysing the daily rainfall and yield data. There are some patches available where the yield has been shown but there is no recorded rainfall in the immediate past. This yield may be due to the rainfall occurence in the upstream areas of the catchment which could not be recorded.

Table 4. Simulation using one and two raingauge stations in order to show the impact of rainfall variability in the catchment

Month	Item	1980	1981	1982	1983	1984	1985	1986
June	QO	0.041	0.023	0.002	0.000	0.000	0.000	0.002
	QS1	0.042	0.039	0.000	0.000	0.000	0.000	0.000
	QS2	0.057	0.081	0.000	0.000	0.000	0.000	0.015
July	QO	0.040	0.050	0.020	0.007	0.013	0.000	0.882
	QS1	0.014	0.003	0.023	0.024	0.074	0.000	0.650
	QS2	0.011	0.004	0.027	0.047	0.037	0.038	0.739
Aug.	QO	0.416	0.227	0.484	0.266	0.514	0.351	0.305
	QS1	0.209	0.139	0.424	0.445	0.544	0.301	0.211
	QS2	0.236	0.188	0.499	0.549	0.521	0.423	0.192
Sept.	QO	0.056	0.025	0.067	0.202	0.002	0.209	0.000
	QS1	0.079	0.020	0.043	0.230	0.029	0.246	0.000
	QS2	0.094	0.019	0.051	0.316	0.016	0.219	0.000
Oct.	QO	0.000	0.000	0.000	0.002	0.000	0.142	0.000
	QS1	0.000	0.000	0.000	0.035	0.000	0.102	0.000
	QS2	0.000	0.002	0.000	0.027	0.000	0.115	0.000
Year	QO	0.553	0.325	0.572	0.476	0.529	0.702	1.189
Sum	QS1	0.345	0.202	0.491	0.734	0.647	0.649	0.862
	QS2	0.399	0.295	0.577	0.939	0.574	0.794	0.946

QO Observed monthly discharge, m

QS1 Simulated monthly discharge, m, using one rainguage station (Banchhor)

QS2 Simulated monthly discharge, m, using two rainguage stations (Banchhor and Sudra) with equal weightage

Flow duration analysis is performed over observed annual yields and the simulated yields using these methods. Flow duration curves of observed and Binnie's yield are given in Fig.4. Fig.5 gives the flow duration curves for observed yield and the yield obtained using Tank model with one raingauge station (Banchhor) whereas Fig. 6 illustrates the improvement obtained in the yield by using two rain gauge stations in the Tank model for only seven years (1980-86). It is evident from these figures that the performance of the Tank model is much better in comparison to the Binnie's method. Even with single rain gauge the Tank model simulates the above 50% dependability level (Fig.5) yields much better than those of Binnie's method. There is remarkable improvement in Tank model's performance by using an additional rain gauge for only part of the data and above dependability of yield get closely simulated (Fig.6).

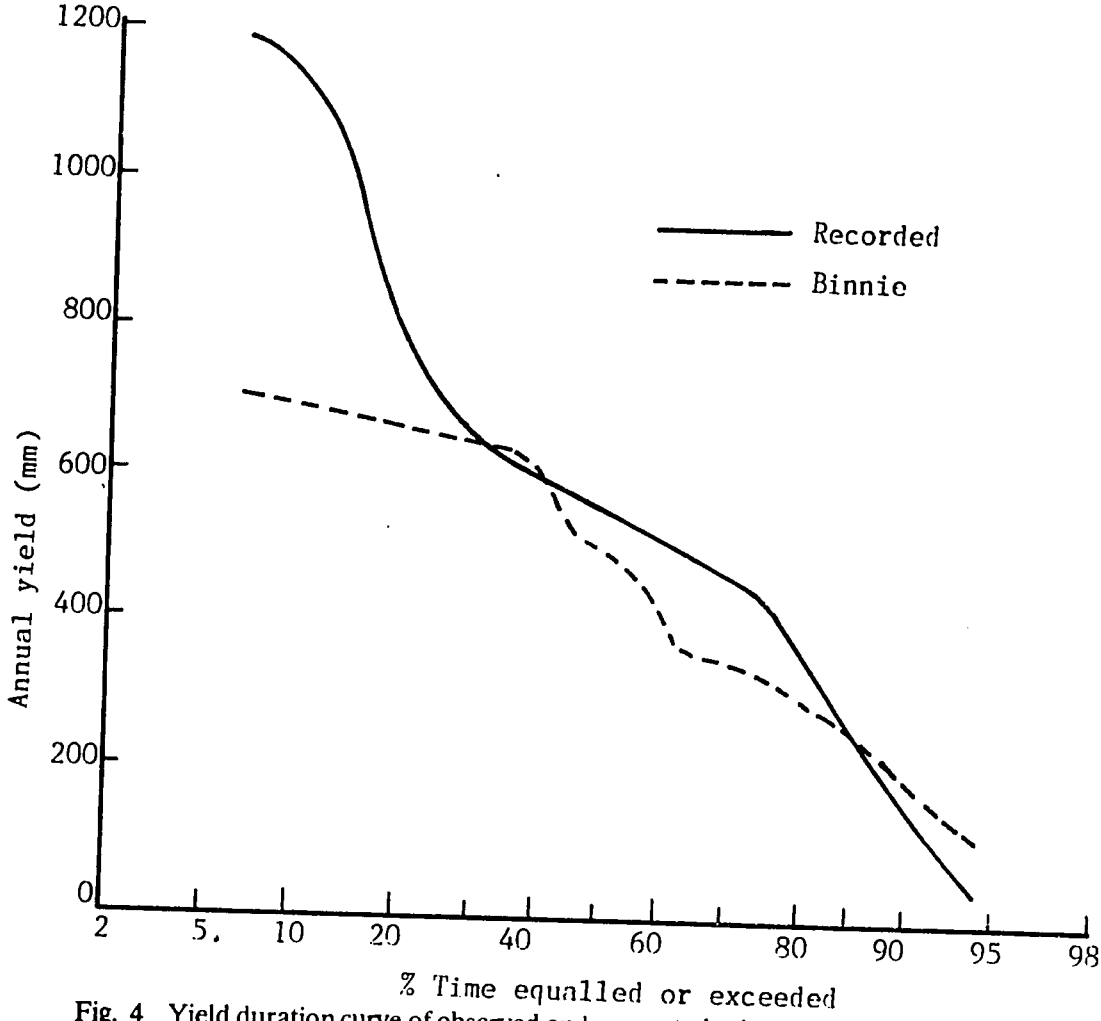

Fig. 4 Yield duration curve of observed and computed values obtained using Binnie's method

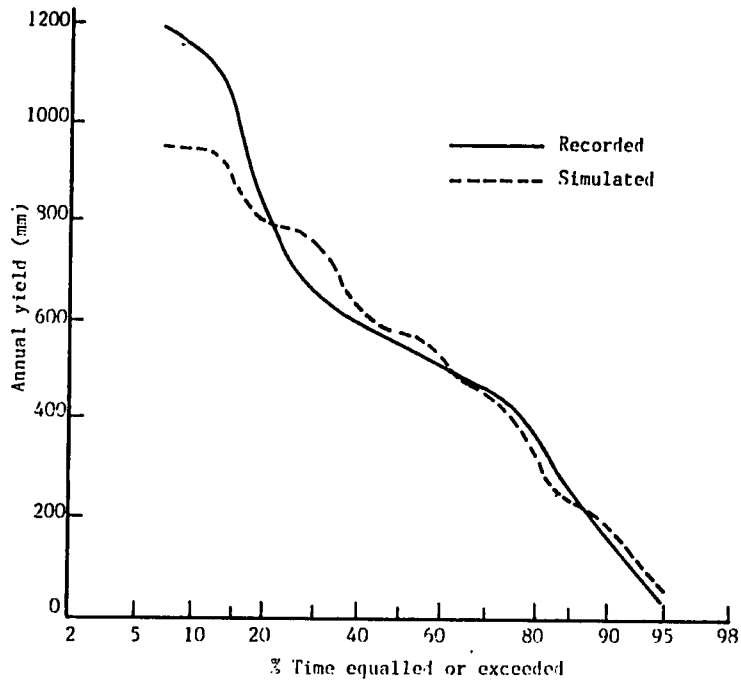

Fig. 5 Yield duration curves of observed and simulated values obtained using tank model with one raingauge data

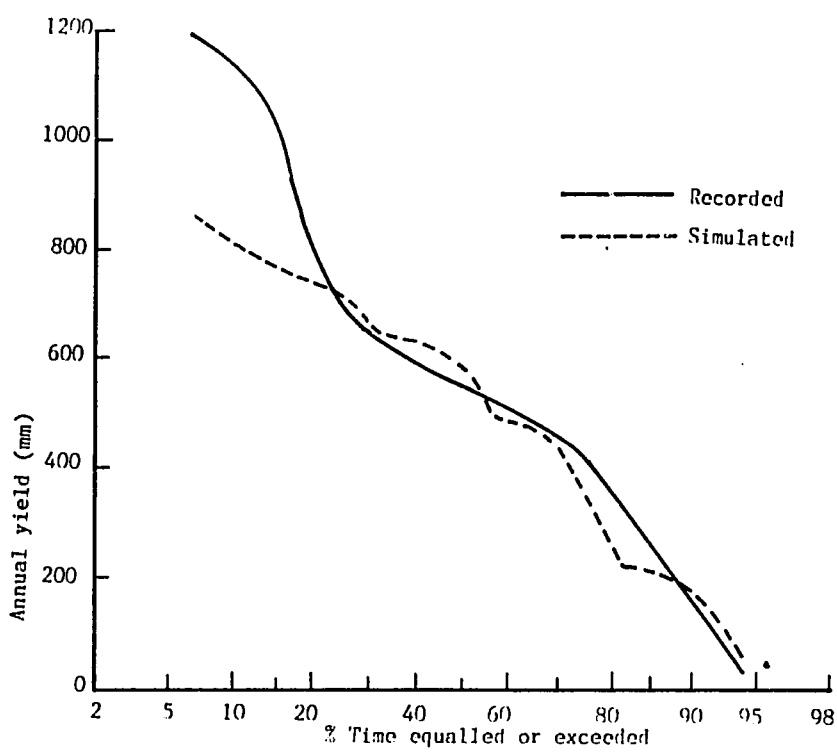

Fig. 6 Yield duration curves of observed and simulated values obtained using tank model with two raingauge data

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Rainwater management for crops in rainfed Kandi belt of Punjab

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ABSTRACT

Investigations were carried out in the rainfed area of Northern Punjab on the management of rainwater both in situ as well as with farm ponds. Early maturing local maize-wheat in the sandy loams and sunnhemp (for mulching)-wheat in loamy sands are the most suitable cropping systems in the area. Minor land grading, field bunding, excess water disposal, sowing of maize across the slope and making ridge and furrow by ploughing between rows after a month of maize sowing were found most suitable in situ water conservation measures in sandy loam soils. Land smoothing and growing sunnhemp across the slope for mulching were found viable in loamy sand soils. The lowest assured weekly, periodical and seasonal runoff amounts were estimated and studied at different probability levels. Both periodical and seasonal runoff distributions were found suitable for tank design. The tasseling-silking stage of maize and pre-sowing stage of wheat were found to be the most critical stages for supplemental irrigation. The monetary returns of presowing irrigation to wheat was 3.5 times more than that of maize. Portable diesel engine pump sets with PVC pipes were found most suitable for tank based supplemental irrigation. A comprehensive computer programme was used for designing tanks of inverted truncated pyramid shape having square base and 1:1 side slope, and to compute its cost and expected available water at time of irrigation. The benefit-cost ratio of the tank designed on the best probability levels of estimated seasonal runoff to give presowing irrigation to wheat is more than that designed on estimated runoff for different periods and varies from 0.85 to 4.56 for 1 to 100 ha watershed area.

Presently, only a small portion of the average annual rainfall is actually used for crop production in many rainfed areas because of various factors like rain-

fall distribution in time and space, soil characteristics, cropping pattern, lack of technology and economic constraints.

Information on rainfall analysis, in situ rainwater conservation, estimation of runoff, supplemental irrigation and design of farm ponds/tanks were reviewed. It was found that available information in literature is not adequate to design complete rainwater management system for rainfed agriculture. Keeping this in view investigations on efficient use of rainwater were carried out in Northern Punjab.

A rainfed belt of Punjab known as Kandi which covers nearly 4800 km^2 was choosen for this study. This belt lies at the foot hills of lower Shivaliks and extends into the adjoining states. The major crop area has undulating topography and is badly dissected by numerous seasonal streams. Soils are highly eroded and low water retentive. The soils of the Kandi belt are loamy sand and sandy loam. Small watersheds of 1 to 100 ha were considered in this study. Maize-wheat and fallow/green manuring-wheat + gram mixture are recommended cropping sequences in sandy loam and loamy sand soil, respectively (Singh et al. 1983).

Rainfall distribution : The rainfall data for 27 years (1960-1986) were analysed for weekly and seasonal totals. Incomplete Gamma distribution was used to estimate weekly rainfall amount at different probability levels varying from 10 to 90 % . To test the fit of Gamma distribution, variance ratio test was applied. The pan evaporation data for 21 years (1961-81) were analysed for weekly pan evaporation and was used for computing potential evapotranspiration of main rainfed crops i.e. maize and wheat.

The average annual rainfall of the study area is 0.889 m out of which 0.703 m occur during monsoon season (June to September) and 0.186 m occur during winter season (November to April). However, weekly rainfall distribution is erratic. Weekly rainfall is low during later part of Kharif season. During rabi season reliability is below 40 %. Selection of crops and varieties which can tolerate moisture stress and adoption of in situ moisture conservation measures to mitigate moisture stress become very important for such area. There is considerable rainfall above PET value during July and August with reliability upto 70% which can be conserved in soil profile or in ponds.

Onset of Effective Monsoon (OEM) and Critical Dry Spells (CDS) for planning supplemental irrigation were evaluated using the criteria developed by Verma (1987). As per new criteria the OEM falls in 27th week for the recommended crops of the area. The results were verified with actual sowing weeks in the case study area for the years 1971 to 1986. It was found to be in close agreement with actual sowing time.

The CDS for maize are 13 days during early vegetative stage between standard week No. 31 and 33 and 11 days during tasseling-silking stage. The probability of a week to be critically dry at the

early vegetative stage, (week No. 31 to 33) varied from 14.8 to 22.2 % whereas the probability at tasseling-silking which is most sensitive, varied from 57.1 to 65.6 %. The chance of providing supplemental irrigation to maize at first critical stage (less sensitive) is only 18.5 % compared to 55.5 % probability of giving irrigation at second critical stage (most sensitive). Full benefits of supplemental irrigation at first and second critical stages (a rain within a week after irrigation results in partial benefit of applied water) to maize can be obtained in 20 and 80 % of the years respectively. The chances of planning a presowing irrigation to wheat in both the soils, which is essential in 96.3 % cases, are 100 % with full benefit of irrigation.

In situ water conservation measures : The technical and economic feasibility of different in situ rainwater conservation methods was evaluated for large scale adoption. The information and data required about technology, materials and finance for evaluation of soil conservation masures were collected from the Punjab Agricultural University, local industries and State Govt.'s offices. Current prices/costs (1987) were used for analysis and evaluation.

The most viable soil and water conservation measures for sandy loam soils are land grading, terracing, field bunding and safe water disposal system. Other in situ moisture conservation measures include off season tillage, medium deep ploughing at the onset of monsoon, ploughing between maize rows (locally called halod) and contour cultivation. For loamy sand soils, where only one crop is taken (rabi), simple land smoothing and growing sunnhemp for in situ mulching are suitable in situ water conservation measures. Other soil and water conservation measures like contour/graded bunding, conservation bench terracing, contour trenching, tied ridging, mulching etc. are not feasible in this area. Winter rains, being light, do not produce any runoff. In situ water conservation measures are, thus, required only during Kharif.

Estimated runoff : The in situ water conservation measures cannot conserve all rainwater and therefore runoff is bound to occur. This runoff can be stored in tanks for supplemental irrigation. The design of tanks requires reliable estimation of surface runoff volume from cropped area treated with in situ water conservation measures, is not available. The only alternative is to estimate runoff from daily rainfall record. The runoff curve number method (U.S. Soil Conservation Service, 1964), which is also known as hydrologic soil cover complex number method and based on recharge capacity of watershed is used to estimate runoff from rainfall. The method is widely used in India and daily rainfall-runoff equations were developed for all types of soils (Govt. of India 1972). A computer programme (Verma 1987) based on runoff curve number method was used to estimate weekly and seasonal runoff from daily rainfall records (1960-1986). The lowest assured weekly, periodical (week Nos. 24-35 and 36-39)

and seasonal runoff amounts were estimated at different probabilities (20 to 90 %) using incomplete Gamma distribution for the study area.

The estimated lowest assured runoff was used for tank design. Weekly distribution was not useful due to its low reliability. A tank designed to irrigate maize at its second critical stage (tasseling-silking) can utilize runoff occuring upto week No. 35 whereas a tank designed for presowing irrigation to wheat can utilize entire monsoon runoff. The runoff distribution for two periods and for the season is given in Table 1. The data showed that considerable amount of runoff can be harvested from sandy loam and loamy sand catchments even after adoption of in situ water conservation measures. During the period between week No. 36-39, the runoff amount and reliability are very low. After irrigating maize in 35th week, probability of collecting more water as runoff from late monsoon rains to provide a presowing irrigation to wheat is less than 40 %.

Table 1. Lowest assured runoff for two different periods and complete monsoon season from cropped catchment with in situ water conservation measures

Probability level, %	Estimated runoff amount, m			
	Sandy loam			Loamy sand seasonal
	Standard week 24-35	36-39	Seasonal	
20	0.141	0.014	0.148	0.092
30	0.108	0.006	0.119	0.073
40	0.088	0.002	0.100	0.056
50	0.067	0.000	0.083	0.044
60	0.053	0.000	0.068	0.034
70	0.039	0.000	0.054	0.025
80	0.027	0.000	0.041	0.016
90	0.015	0.000	0.027	0.007

In sandy loam soil having maize crop, average seasonal estimated runoff was reduced from 0.197 m under traditional method of farming to 0.099 m when land development works (land grading, terracing and field bunding) and other in situ water conservation measures like medium deep tillage, halod and contour cultivation were practiced. Similarly, in loamy sand soil average seasonal estimated runoff was 0.108, 0.057 and 0.039 m in case of traditional fallow, land smoothing and sunnhemp mulching and land development and sunnhemp mulching, respectively.

Runoff storage tanks : Excavated tanks lined with polyethylene (200 micron) at bottom and brick-cement on sides have been found suitable for Kandi region (Verma et al. 1984). The computer programme developed by Verma (1987) was used to design appropriate runoff storage tanks and to study their economic feasibility. The tanks of inverted truncated pyramid shape having square base and 1:1 side slopes and lined with polyethylene sheet of 200 micron burried under 20 cm thick soil at bottom and brick-cement (7.5 cm thick) on sides were designed for different catchment areas varying from 1 to 100 ha at different probability levels of lowest assured runoff. The tanks were designed to have a maximum water depth of 5 metres. The main criterion used for designing tank capacity was the availability of tank full water after accounting seepage and evaporation losses from collection period to the time when irrigation is given to maize in 35th week or at the end of monsoon in 39th week. Sediment storage capacity of 2 m^3 ha^{-1} $year^{-1}$ was considered for 5 years and it was assumed that sediment will be removed after every 5 years.

The equivalent annual cost of tank construction assuming 10 % interest rate and 40 years expected life of tank and expected available water at the time of irrigation were computed. The main cost of tank included excavation cost as a function of tank width (lead), bottom and side lining cost and costs for inlet and spillway structures. Annual land productivity cost was also considered for the land occupied by the tank. It was found that initial cost of tank construction was Rs.13.2, Rs.7.8 and Rs.5.9 per m^3 (at 1987 prices) for tanks of one thousand, ten thousand and hundred thousand m^3 capacity, respectively.

The probability levels which lead to lowest cost per unit of available water at the time of irrigation varied from 40 to 80 % for various catchment sizes varying from 1 to 100 ha in both the soils. In all the cases under study, the probability level of tank design increased with increasing catchment size. The computed data for tanks in sandy loam soils, given in Table 2. indicated that when tanks are designed on the basis of runoff for different periods to irrigate maize in 35th week, the expected available water in tank varied from 67 to 72 % of the capacity for small tanks in watersheds below 10 ha. This value goes upto 77 to 78 % for bigger tanks. These tanks can be used to irrigate maize in 56 % of the years. In the rest 44 % of the years expected available water for presowing irrigation to wheat is 37 to 54 % of the capacity for small tanks in watersheds below 10 ha. For bigger tanks it is 61 to 64 % of the capacity. In case of tanks, designed on the basis of seasonal runoff for giving presowing irrigation to wheat, expected available water in 44th week is 50 to 69 % of the capacity for small tanks in watersheds below 10 ha. This value goes up to 71 to 77 % for bigger tanks. The data in Table 2 also showed that about 54 % of the watershed area can be irrigated once with 0.05 m water.

Table 2. Expected water in tanks at the time of irrigation and benefit-cost ratio of supplemental irrigation from the tanks in sandy loam soils in Kandi region

	Tanks, designed to irrigate maize in 35th week				Tanks designed for presowing irrigation to wheat in 44th week		
Watershed area, ha	Total tank capacity, m^3	Expected available water, m^3 35th week	Expected available water, m^3 44th week	Benefit-cost ratio	Total tank capacity, m^3	Expected available water in 44th week, m^3	Benefit-cost ratio
1	470	315	174	0.85	494	249	1.60
5	2710	1823	1307	1.43	2477	1563	2.66
10	4401	3192	2401	1.76	4125	2854	3.24
20	6694	5212	4066	2.01	8643	6159	3.78
30	10168	7909	6318	2.20	13210	9515	4.00
40	13678	10637	8628	2.31	13369	10213	4.16
50	17207	13381	10972	2.36	16828	12908	4.27
60	20722	16108	13297	2.41	20366	15707	4.36
70	24266	18863	15668	2.45	23833	18410	4.42
80	27797	21604	18022	2.48	27341	21168	4.47
90	31315	24329	20354	2.50	30907	24004	4.52
100	34878	27101	22762	2.53	34383	26718	4.56

Tanks were also designed on seasonal runoff basis for watersheds in loamy sand soils to give presowing irrigation to wheat. The tanks' capacity in loamy sand soils was 62 % of that in sandy loam soils for same watershed area.

Lifting, conveyance and application of tank water: Selection of a suitable lifting, conveyance and application system for supplemental irrigation with tank water for each location is very important as water application is done only once in a year for a limited period of 7 to 10 days. For the recommended crop and in situ water management practices in the area drip irrigation is not feasible and only sprinkler and surface irrigation methods are technically feasible. Though sprinkler irrigation system is ideal for application of limited 0.05 m supplemental irrigation on undulating light soils of the area, it is

not viable economically. Based on 1987 prices, cost of the sprinkler sets of 2, 5 and 10 ha capacity with different pipes made up of alluminium, PVC and HDPE varied from Rs. 4500 to Rs. 7450 per ha. This is very high because only one supplemental irrigation is possible and operational costs are to be added to this. There is no possibility for custom hiring the system in this area.

Surface irrigation through graded furrows made for in situ moisture conservation while doing halod, is suitable for irrigating maize without incurring any additional expenditure. For giving presowing irrigation to wheat, furrows on grade made by desi plough are suitable for applying 5 cm water. Conveyance of water from the tank to the field under gravity is economical in the hilly areas where slopes are high. On flat slopes (about 2 %) the cost of laying underground pipeline for getting water by gravity was analysed. It was found to be costly, costs varying from Rs. 29000 to Rs. 43000 for 5 m drop (250 m length). Moreover, it was found to be difficult to apply water at distant places (250 m away from the tank) crossing fields of other farmers.

Lifting water from tanks with electric motor pump is not feasible because electric connection is not possible for short time. Small diesel engine pump set of 5 to 10 HP power has a great promise because it can be used for other works on the farm like maize shelling and wheat threshing. Only 17 % of the time of the diesel engine is needed for lifting water for supplemental irrigation. Open channels are not suitable in this study area for conveyance and distribution of water and underground pipeline which works as main line costs Rs. 3081 to Rs. 5552 per ha on current prices. The portable PVC pipeline was found to be more economical and suitable.

The costs of complete system of supplemental irrigation, assuming the tank at the centre of the area to be irrigated, were analysed considering the current as well as the trend of price rise. The equivalent annual cost of a supplemental irrigation of 5 cm was found to be Rs. 390, Rs. 331 and Rs. 298 per ha with diesel engine pump sets of 5, 7.5 and 10 HP power size, respectively. The unit cost of irrigation decreased with increasing pump set size upto 10 HP.

Supplemental irrigation to rainfed crop : The available data for Kandi region were analysed for determining the average response of one supplemental irrigation to maize and wheat at their most critical stage in terms of grain and straw yields. The yield increase due to one supplemental irrigation at most critical period was expressed as equivalent annual monetary value using 1987 procurement prices of maize and wheat. The price growth rates were analysed on the basis of procurement prices from 1971-72 to 1987-88. The results of this analysis were used for selection of tank design and comparing costs and benefits of supplemental irrigation systems.

The most critical stage for supplemental irrigation to maize and wheat are tasseling-silking and crown root initiation, respectively. But pre-sowing irrigation is necessary for germination and

good plant stand of wheat. The average response to one supplemental irrigation is 0.04 Mg ha^{-1} of maize when applied at tasseling-silking stage and 0.077 Mg ha^{-1} of grain and 0.13 Mg ha^{-1} of straw in case of wheat when irrigation is given at presowing time.

The annual monetary returns of a supplemental irrigation are Rs.528 ha^{-1} and Rs.1668 ha^{-1} at current prices for maize and wheat, respectively. In terms of equivalent annual return (for the whole life of tank) it is Rs. 1147.3 ha^{-1} for maize and Rs. 4023.2 ha^{-1} for wheat. The net equivalent annual return of supplemental irrigation is Rs. 963.7 ha^{-1} for maize and Rs.3379.5 ha^{-1} for wheat.

Benefit-cost ratio of supplemental irrigation from the tanks : An irrigation system is viable only when benefit-cost ratio is more than one. In this study cost of tank construction and lifting, conveyance and application systems and returns from one supplemental irrigation to maize and wheat were analysed in terms of equivalent annual worth. The benefit-cost ratios are given in Table 2.

The benefit-cost ratios of tanks designed on seasonal runoff basis for presowing irrigation of wheat is almost double than that of tanks designed on the basis of runoff for different periods for a supplemental irrigation to maize and varies from 1.6 to 4.56 for tanks in sandy loam watershed between 1 to 100 ha. The benefit-cost ratio increased as the capacity of tank increased.

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Short Communication

Water balance of agricultural watersheds

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Water is a major constraint to agricultural production and watersheds are major focus for resource development and utilization. Five agricultural watersheds on vertisols were selected at Central Research Station, Punjabrao Krishi Vidyapeeth, Akola, to study water balance. The watersheds varied in shape and land slopes area ranging from 5.5 to 9.4 ha.

The study was conducted from May 1980 to April 1981. Sorghum, pigeonpea, chillies, cotton, blackgram, sunnhemp were grown as inter or sole crop in monsoon and post monsoon season. Part of the area in one of the watershed remained fallow. Profile soil moisture was monitored during the study period. Surface runoff measurements were made on each watersheds and ground water changes were recorded using 23 open wells and 5 piezometers. Rainfall and open pan evaporation data were collected from the meterological station of the research station.

The average seasonal runoff was 12 % of total 0.654 m season rainfall. The change in ground water levels, H, were obtained for study period with respect to driest month, May, as a reference. Actual evapotranspiration was estimated using crop coefficients for various crops and daily pan evaporation observations. estimated total evapotranspiration from June to September, 1980 was 0.458 m and total soil moisture storage during the period was 0.089 m.

Following equation was used to obtain water balance for the period June 1 to September 30:

$$P = R + ET + U \pm Ss \pm Sg$$

where P is the precipitation, R the surface flow, Ss changes in soil moisture and Sg changes in ground water storages. The sub surface flow was assumed to be negligible. Sg was computed as a product of ground water charge, H and gravity yield, Yg. The gravity yield in percentage, Yg, for each observation was computed using the relationship

$$Y g = 100 (P-R-ET \pm Ss)/H$$

Based on above results it was concluded that during analysis period of June to September, 70 % rainfall was utilized by soil and plant evaporation and 12 % rainfall resulted into surface flow. The estimated average gravity yield was approximately 8.8 and 2.2% of ground water fluctuation during June to September excluding and including profile soil moisture charges, respectively.

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Short Communication

Hydrologic planning of small watersheds: An approach

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Contour bunding has proved efficient in checking soil erosion and reducing run-off, but has never been critically examined with regard to its impact on productivity. Often the size of bunds is such that they occupy a considerable area resulting in loss of production. Further, the moisture retained by the bunds and the upstream burrow pits is not productively utilised. Quite often the accumulated moisture simply evaporates, this loss being especially serious in semi-arid areas where the average precipitation in a spell often matches or falls short of the average evaporation rates.

The concept of hydrological planning needs to be reevaluated on the basis of an approach that aims at improvement of primary productivity. This note presents an outline of such a possible alternative.

The watershed (or sections of it) could be divided into two kinds of areas - an uplying runoff portion and a lowlying infiltration portion, with a different but integrated set of measures for each portion as outlined below.

In the uplying portion, the approach would be to bring about substantial erosion control, but without reducing runoff substantially and without loss in production alternatives. This could well be achieved by small, graded bunds over which suitable grasses could be established, and one or more rows of trees planted downstream of the bunds in order to utilise the water percolating into the ground. The bunds need only to be slightly graded to achieve substantial control of erosion without reducing runoff substantially. The grasses and trees provide the alternative production to counterbalance the production lost on account of the area devoted to erosion control. The run-off from this uplying area could then be suitably channelled to the lowlying portion where the main thrust would

be directly that of soil amelioration and storage capacity of the soil and to utilise effectively the moisture thus stored.

Several considerations and directions of further investigation also follow from this alternative approach. First, is the need to optimise the ratio of the uplying catchment area to the lowlying infiltration area as part of the hydrological planning for the watershed. This, however, cannot be divorced from the other considerations, those of optimising the production from biomass species and their distribution between the different areas.

Grasses, with their shallow root zones, short growth periods and their capacity for regeneration may prove suitable to the uplying catchment areas. However, their productivity per unit of water utilised is low, especially when high winds and unfavourable temperatures lead to high evaporation conditions. By contrast, many tree crops have the capacity to produce greater quantities of biomass per unit of water utilised, especially in a multi-tier system where early canopy closure and resultant micro-climate and wind-shielding effects introduce stabilising factors against adverse wind and temperature conditions. Also, since tree crops offer a much wider range of products, it would be possible to achieve greater levels of useful products and income per unit of biomass produced. It has now been fairly clearly demonstrated that such multi-tired systems increase soil infiltration and storage capacities by establishing and reproducing humus forming conditions. Trees, especially multi-tier systems are, therefore, more suitable to the low-lying infiltration areas.

From a systemic point of view, rational hydrological planning also necessitates an investigation of methodologies to estimate the quantum of water that can be effectively utilised by different species and varieties and also its relation to the quantity of water infiltrated into the soil with various treatments. There is also a need to take into consideration primary productivity in terms of total dry matter along with the proportion of the harvestable (in the sense of directly usable) component for different varieties and species. The differences can be substantial and will affect the optimal ratio between the two types of area outlined above. Several grasses and field crops may require as much as 300 kg of water per kg of dry matter produced with a harvestable component as small as 0.4, while some trees may require as little as 140 kg correspondingly with as much as 0.8 harvestable.

In arid and some semi-arid areas, the amount of runoff from the uplying areas may be just sufficient to replenish the improved soil storage available after soil amelioration. As we go towards higher rainfall regimes it may become possible with the above approach to have supplementary post-monsoon surface storages based on the directed runoff from the uplying catchments that may support, on an environmentally sustainable basis, a much higher level of primary biomass productivity.

It is generally believed that productivity of natural grassland or tree-stands is limited by the availability of utilisable water. However, recent studies from Sahel and other semi-arid areas indicate that after a certain minimum level of production is reached, it is mainly the nutrient and not the water that is the limiting condition. In that case the concentrated tree-biomass in the lowlying area may be able to serve a double purpose with a limited application of external inputs. Depending on the extent to which the biomass from the stand is to be recycled, with a limited quantity of chemical nutrients and supplementary irrigation in the initial establishment period, it may provide between 15 and 20 Mg of dry biomass per ha per year, a substantial portion of which could provide low cost nutrient input for intensively cultivated areas provided practices are made suitable to organic inputs.

In some areas, though probably very few in number, erosion processes may be so severe that it may not be possible to achieve substantial erosion control without drastically reducing runoff. However, even in such areas, it may be advisable to treat full erosion control as a long-term goal and concentrate measures in the first instance on checking or attenuating erosion processes. This is because once a biomass based process of watershed development is under way it has the potential of generating the resources and the materials necessay for effective erosion control. In fact, with the approach outlined here, the first priority is to build up a base of local resources and materials on the basis of the proposed biomass strategy which can then help to overcome the severe resource constraint that purely protective or conservatory programmes face today. Without radical reevaluation of underlying concepts it is most likely that programmes aimed at erosion control and reducing runoff will continue to have an adverse effect on primary productivity, to face indifference or hostility on part of the local population, and to face severe resource constraints.

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Short Communication

New material and techniques for watershed structures

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The note is divided into two sections. The first section describes the new materials and techniques and the second section outlines their specific applications to small watershed development.

NEW MATERIALS/TECHNIQUES

Geocrete : Geocrete are flyash admixed low cost concretes, constituted of local low grade aggregates and low cement content (of the order of 50 kg m^{-3}). The ample flyash content would provide high proportions of paste of cement and fine material and thereby ensure workability and low permeability. The reinforcing materials for geocrete would mainly be synthetic polymers or suitably treated natural fabrics and small timber. The behaviour of geocrete is similar to that of bentonite admixed plastic concrete used extensively in cut off layer earthen dams. Although the strength of geocrete is low, of the order of 10 kg cm^{-2}, the use of reinforcement enables higher strengths to be realised in critical zones.

When geocrete is used for gravity structures the basic design requirement is weight and the stresses are generally low. Greater deformabilities are also required to ensure freedom from cracking. Geocrete is therefore eminently suited for gravity walls, foundation rafts, aprons for hydraulic structures and protective works for erosion control. By virtue of its low deformation modulus geocrete is compatible to low modulus reinforcing materials such as synthetic polymer, bamboo/natural-fibre or small timber.

Experience of roller compacted concrete construction and extensive studies on characteristics of roller compacted concrete have brought out clearly that concretes with low cement content have adequate durability and have sufficiently low permeability. Higher water contet can be used thereby reducing the requirements for compaction since lower strengths will be acceptable.

Geomembranes: Recent development in membrane technology have made it possible to use membrane of superior performance. The imroved low cost membranes are constituted of films reinforced by woven PP/HDPE slit-tape fabrics of high strength commonly used for bagging applications. By bonding non-woven filter fabric, friction of the membrane with regard to the soil base or concrete cover can be improved. This enables the membranes to be used successfully for sloping surfaces. The bonding of bitumenous emulsions or elastomers such as PVC or butyl rubber would be used for field jointing. The tear resistance of the membranes is significantly high and has the clear cost advantages.

Filter fabrics : Non-woven filter fabrics are a new category of synthetic materials which have controlled size of opening and permeability. Geofabrics can be used effectively for drainage and seepage control functions and their use would facilitate control of uplift and thus help to bring down the cost of many structures where heavy load of a thick concrete apron is needed to resist uplift pressures. When filter materials of required quality cannot be obtained, seepage control can be achieved by use of filter fabrics. Placement of filter in narrow widths and thin layers along slopes would also be facilitated by use of fabrics.

Ferrocement : This is a versatile composite material which admits control of geometry and thereby optimising design. By using ferrocement in conjunction with bricks and clay tiles the thickness can be reduced. The impact strength of ferrocement members can be increased by incorporation of synthetic fibres. Addition of fibres would improve the capacity of the members to withstand handling stresses. The ferrocement members being thin have greater flexibility and would thus be used with advantage for buried pipes, culverts flumes. Application possibilities for ferrocement consist of impervious septum for crib dams outer covers of water delivery hosepipes.

In the proposed application of ferrocement the cement content is optimised without compromising workability and permeability by use of super platicisers. There is a further scope for reducing cement content by adding flyash and a high grade pozzolana consisting of amrophous silica produced by controlled burning and grinding of rice husk ash. Adequate durability would be assured by using galvanised or polymer coated wiremesh and eventually it should be possible to use synthetics or natural fibre coated with synthetic elastomers.

Reinforced soil : This technique is a new development and over the last 10 years use of reinforcement is increasing especially for gravity structures and treatment of foundations. A traditional example of reinforced soil is sand filled gunny bags used to build temporary walls. With a better understanding of the theory, the requirement of reinforcement has been optimised. Although a great majority of reinforced soil structures have been used for granular materials and thousands of structures exceeding 10 m height

have been built of sandy soils, reinforced soil walls of clay have recently been constructed successfully. Reinforcement of synthetic polymers in the form of fabric or grids is placed in layers and the ends of the fabric or grid are anchored into the facing elements. The role of the reinforcement must therefore extend beyond the probable failure surface. Range of application of reinforced soil systems can be extended by use of stabilised soil or geocrete in view of their cohesion characteristics and increased angle of internal friction.

The cost of studies and examples furnished herein are all based on prices of indigenously available materials.

Reinforced soil constructions can be used for gravity walls and water retaining structures and for caps of embankments to bring down the cost of embankment or to raise existing embankments.

Applications

1. Timber crib dams can be used as check dams for groundwater and erosion control and as spillways of small tanks.
2. Reinforced membranes and fabrics can be used to prevent leakages from existing and new reservoirs.
3. Pipeline technologies can be radically modified by using low cost lay flat tubings of reinforced membranes for diameters of 100 to 400 mm. Woven fabric reinforcement of the membrane brings down the synthetic material consumption drastically and ensure water tightness while damage from ultravoilet (UV) degradation, vandalism and burrowing animals would be overcome by providing cover of optimising ferrocement or clay-tile-bamboo and natural fibre composite depending on the size of the pipe.
4. Cement asbestos composites can be substituted by natural fibre-cement with strategic use of synthetic fibres and meshes and ferrocement.
5. Technology for burried pipes can be radically changed by using covers of geotextiles and geogrids to relieve the load on the pipes. The pipe cost can be drastically reduced by using the multihinged ferrocement clay lime composite construction. This technique could very well be used for conveyance of effluent and waste water to treatment facilities and to recycle waste water for tree plantation thereby eliminating the health hazard.
6. Ferrocement can be used for tanks within the house as well as overhead tanks. Ferrocement construction can be optimised by use of clay tiles and small timber and of membranes for water tightness.
7. Low cost irrigation delivery system can be developed using the low cost pipes and irrigation delivery system with moving lines.
8. Use of filter fabrics may also improve the performance of infiltration system. Sandy beds of nallas could be provided with check dams and a set of low cost clay tiles or ferrocement pipes protected with filter fabrics.

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Short Communication

Development of synthetic unit hydrograph for small watershed in Aravalli hill range of Rajasthan

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The small watersheds are largely ungauged and availability of hydrologic data for small watershed is a major constraint for rainwater management. Depending upon physiographic similarity, the synthetic unit hydrograph from gauged watershed may be used to predict hydrologic characteristics of ungauged watershed.

A small watershed of 143.3 ha at the college demonstration and training farm was selected for conducting the study on development of synthetic unit hydrograph. Twenty two linear aspects of channel system and areal and relief system of physiographic characteristics of watershed were determined. Forty two significant stage hydrographs of the watershed for the period 21 June 1982 to 9 August 1987 were selected for development of synthetic unit hydrograph. The duration assigned to a unit hydrograph is the duration of net effective rainfall. The deviation of ± 5% in storm duration was allowed and unit hydrographs of various duration were developed. The unit hydrographs from several storms of same duration were averaged to arrive single typical unitgraph for the watershed. The peak values of unit hydrographs, the time to peak from beginning of runoff, and time base of runoff hydrographs were averaged. The average unit hydrograph was, then, sketched with computed values so that total runoff volume under the graph is 1 cm. The synthetic unit hydrographs following Snynder, Clark's Soil Conservation Service (SCS), and Central Water Conservation (CWC), India methods were developed.

It was observed that Synder's approach can be well applied for small watershed hydrology. Some modifications were made for arriving the time base of unit hydrograph and peak discharge equations in SCS method for the small watershed. CWC method determines only synthetic peak discharge and lag time. Since base length can not be determined by CWC method, it can not be applied for development of synthetic unit hydrograph for small watersheds. The Clark's method, perhaps, is not applicable to small watershed since the time of concentration in many cases is less than 30 minutes (27.1 min. in present case) because wave storage effect is negligible in the stream.

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Short Communication

Quantification of erosion and runoff with cropping management practices for watershed modelling

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Government of India has recently initiated the transfer of dryland technology on the basis of agricultural watersheds for improved resource management to conserve and utilize the rainfall which, when integrated with soil and improved crop production systems, will increase productivity and assure dependable crop harvests.

In India most of the watersheds in arid and semi-arid areas are ungauged and very limited hydrological data are available. Therefore, simulation experiments could be a means to obtain emperical answers provided a mathematical model could be developed based on the data. For efficient management of rainfall, prediction of both peak and total runoff are essential. It is also important to predict soil loss from cultivated areas and to evaluate change due to changes in farming practices.

A study to quantify runoff and erosion with cropping and management practices for watersheds modelling was initiated. Replicated Wischmeier plots having dimensions of 6m × 12 m on a slope of 4% were adopted. The treatments were fallow, alfalfa grass grown in rows of 15 cm up and down the slope, barley grown along and across the slope in 15 cm rows.

To simulate rainfall storms of low, medium, and high intensity, specially made different sized sprinkler nozzles were used. Rainfall intensities of 12.5, 22.5 and 38.1 mm h^{-1} with 40, 45, 60, 75, 90 and 120 minutes duration were generated with the help of a moving wheeled sprinkler system specially set up for the purpose. The corresponding runoff and soil loss data for all durations of each intensity were measured. Respective precipitation, depth of ground water fluc-

tuation, soil moisture status by neutron probe, and gravimetric method were also determined. Soil physical characteristics and crop yields required for the analysis and interpretation of data were also determined systematically. The following are the salient findings:

1. Runoff and soil loss were significantly reduced by the surface cover (crop) and management practices.

2. Rates of runoff and soil loss increased significantly as the density and crop canopy decreased.

3. High rainfall intensities and durations increased runoff and soil loss more than crop and land management treatments.

4. The relationship between erosion and runoff was found to be linear.

5. High intensity and longer duration rainstorms resulted in high rates of runoff occurring uniformly over the entire basin, resulting in increased peak flow and volume discharge.

6. Hydrographs developed from runoff characteristics for all the treatments adopted a pattern commonly obtained under situations of short duration and intense rainfall.

7. Analysis of the data, suggested that a unit hydrograph model could be used to predict runoff from ungauged watersheds receiving short duration but intense rainstorms. The model could comprise both synthetic as well as the data based unit hydrographs.

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Short Communication

Hydrology based model for prediction of runoff and sediment yield with limited data for agricultural watersheds

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Measurement of water erosion of soil is expensive and difficult. Therefore indirect estimations are made for various purposes. A study was conducted in one sub-watershed of G.R. Halli watershed, Chitradurga district (Karnataka). The runoff and soil loss during 1985 and 1986 were recorded and the records were extrapolated for 1981-84 using following procedure.

The double exponential Gumbel distribution was used for estimating rainfall amount (monthly or daily) for different return periods using 15 years (1971-85) rainfall records of Chitradurga. The slope length and gradient factor, LS factor in Universal Soil Loss Equation, was computed using average watershed slope and length. Kirpatch formula was used for calculating time of concentration. Anticedent moisture index (AMI) regressions were developed for API < 25 mm and API 25 to 50 mm, respectively, when Y is daily runoff (mm) and X is daily rainfall (mm). The runoff recorded for 1981-84 was extrapolated using above equations.

The watershed storage, St, (mm) was estimated using the expression

$$St = 5\,Xr + 10Yr - 5Yr\,(5Xr/Yr+4)\ ^{**}\ 0.5$$

where Xr is rainfall (cm) and Yr is runoff depth (cm) respectively. The SCS curve number, CN, was calculated as 1000/ (10 + St/2.54). The peak rate of runoff, qp ($m^3\ Sec^{-1}$), was estimated using the relationship

$$DP = 0.0208\,A\,Yr/(0.06\,Tc + TC)$$

where A is watershed area (ha) and Tc, the time of concentration (h). The modified universal soil loss equation was used for estimating the sediment yield as

$$Y = 11.8\,(Q \times qp)^{0.56}\,KCPLS$$

where Y is sediment yield (Mg), Q the storm runoff rate (m^3), K the soil erodibility factor, and C and P are crop management, LS the slope length and gradient factor, and erosion control practice factors, respectively. The soil loss data were extrapolated for 1981-84 since the watershed was undisturbed prior to 1985. The probability distribution of curve number, daily runoff volume, peak rate of runoff, and annual soil loss were calculated.

The threshold value of rainfall to cause runoff was estimated as 14 mm and 22 mm for API > 25 and API 25-50 mm, respectively. The estimated computed curve number varied widely (52.8 - 82.3) with an average of 69.5 and highest estimated peak rate of runoff was 1.122 cumce from 120 ha watershed. The maximum estimated observed soil loss was 2.2 Mg ha^{-1} during the year 1981 where as in 1986 soil loss was 0.69 Mg ha^{-1} which demonstrates that soil and water conservation measures effectiveness. The information provided in the paper can be used for estimation of runoff and soil loss when limited data is available.

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Short Communication

Effect of land management practices on small watershed hydrology

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Water conservation is one of the most important production factors in the state of Rajasthan. The Aravalli mountain range divides the state into arid and semi-arid region. Poor water conservation practices have lead to inadequate vegetation cover which was resulted into accelerated erosion. Only 9 % area is occupied by forest and vast area is covered under baren hills and plains. Various land management practices are in vogue but requires investigations before recommending for the region.

Two experiments were conducted at the college farm during 1980 and 1981. Two micro watershed (28 m^2 catchment) on 16 percent land slope were treated with five trenches each (3× 0.6× 0.5 m size) and natural vegetation during 1980. One micro watershed was fenced (FMW) whereas uncontrolled grazing was allowed on other micro watershed (UFMW). Runoff and sediment yield were measured on both micro watersheds. Second degree logarithmic equations between accumulated rainfall and accumulated runoff, accumulated rainfall and accumulated sediment yields were regressed. During 1981 two small watersheds (1.06 ha, 19.3% slope and fenced; 2.95 ha, 5.7% slope and unfenced) were monitored for runoff and sediment yield. Both watersheds were under staggered contour trenches, tree plantation and natural grasses. Necessary corrections were applied by considering runoff and sediment per unit area and ratio of time of concentrations for area and slope, respectively. Multiple linear regression analysis were performed between runoff as dependent variable and rainfall amount and intensity as independent variables.

The average runoff yield from UFMW was 1.4 times to that of FMW. The average ratio of runoff from unfenced small watershed (UFSW) was 4.4 times in comparison to fenced small watershed (FSW). The average sediment yield from UFMW was 1.2 times to that of FMW whereas UFSW resulted into seven fold increase in sediment yield to that of FSW. Analysis of 30 years (1956-1985) rainfall records suggest that approximately 35% additional rainfall can be conserved by subjecting catchment area to staggered contour trenching under protected vegetation cover.

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Short Communication

Land management practices for small agricultural watersheds

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The land management practices for erosion control and water conservation have a significant influence on the hydrological behaviour of a watershed. The land management could consist of engineering, forestry, and agronomical practices. These measures influence the watershed hydrological behaviour depending upon the extent of application of these measures and catchment area under them.

The land management practices in an agricultural watershed could consist of measures like contour trenching and aforestation, bench terracing, graded bunding, ridge and furrows, contour planting and strip cropping, pasture development, and stream bank and gully erosion control etc. The effect of each of these measures on runoff and sediment production in conjunction with land uses within a watershed need to be known.

The changes in behaviour of a watershed can be assessed by actual measurement of runoff and sediment, empirical approaches, and modelling and simulation. Actual measurements of watershed discharge and sediment yield, though more accurate, can serve as information for analysing similar situation but are costly, time consuming, and are impracticable for every situation. The empirical and statistical procedure have been developed to predict the peak rate and total volume of runoff. More commonly used methods are: rational method, Cook's Method, curve number method, and coaxial correlation method. The empirical methods, though serve specific purpose for which they have been developed, are not based on physical proceses occuring in the watershed and does not provide precise information when watershed consists of several changing land use changes.

With the availability of computers,

a large number of modelling and simulation approaches for studying watershed behaviour have been developed. These simulation models take into consideration the hydrologic processes and require the basic data about the watershed under consideration.

Over a watershed several types of land uses and soil types may be involved and mixture of conservation measures are required. The planning of different conservation measures can be undertaken using linear programming approaches.

The linear programming model may be stated as follows:

$$\text{Maximize/minimize } Z = \sum_{i=1}^{n} CiXi$$

Where Xi is the level of activity i which has to be determined in order to minimize or maximize the objective function of Z. In this particular case Xi could be the area allocated to different land treatment practices, Ci is a coefficient which may represent cost per unit area of each practice that is to be adopted for water yield or sediment coming from particular land unit.

The constraints can be presented as follows:

(i) water yield constraints

$$aij\ X\ i \geq bj \qquad j = 1,2,....n$$

(ii) sediment yield constraints

$$dij\ X\ i \leq ej$$

Where aij and dij represent the water yield and sediment yield coefficients and b and e represent the minimum water yield and maximum sediment yield expected in the storage facility. Other necessary constraints for the situations under consideration can be imposed. In developing the model, the information relating to each of the land management practices in terms of costs, runoff and sediment yields should be known.

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Short Communication

Watershed based land development for efficient soil and water conservation in red soils of southern Karnataka

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Failure of crops, as a result of floods and droughts in all regions of the country are common. A need for proper scientific approach to conserve all resources for optimising crop production is wanting. Watershed-wise assessment of water potentials, study of recharge process, and water balances are required to be done before taking up large scale development works. The management of the watershed should be done on integrated approach, to achieve optimum benefit and minimise the risk. Model watershed development studies involving the entire complex of development and management of resources in agricultural production have been initiated since 1983 onwards in the state of Karnataka.

The studies conducted at the dryland agrcultural research project at Bangalore centre, on red soils, on slopes of 1-3 per cent indicated that:

(i) On an average, the loss of water through runoff is 24 to 36 percent of the annual rainfall and it may be somewhat less when larger catchment area is considered.

(ii) The runoff is of very high order when the soil is compact and crusted.

(iii) The system of ridges and furrows across slope reduces the runoff losses to a large extent, as compared to flat sowing.

(iv) The ridges and furrows are stable and are retained till the next tillage season.

(v) Graded border strip of land development is the most efficient method of land development for moisture conservation. This is suitable for lands with 1-3% slope having deep soils. A gradient of 0.2% may be adopted upto a length of 100 to 150 m.

(vi) Graded ridges and furrows may be adopted for widely spaced crops like maize. A grade of 0.2 to 0.4% may be adopted.

(vii) Broad ridges and furrows (bedding) system serves the purpose of moisture conservation as well as drainage of excess runoff water.

Favourable responses from farmers due to impact of the soil and water conservation works are likely to be obtained when land development is taken up as an integral part of watershed development. The cost of Rs. 500-700 per hectare towards land development can be recovered by farmer within 2-3 crop harvests. Best use of land and water resources is also possible with this type of land development. Large scale development trials on watershed basis have been taken up in Karnataka State for adoption.

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The Indian Journal of Dryland Agricultural Reasearch and Development is a periodical published *quarterly* for the publication of records of orginal research in different disciplines of agriculture, viz., agronomy, soil science, soil water conservation, farm machinary, plant breeding, economics, statistics, agrometeorology, agricultural extension, operational research etc., pertaining to efficient land use systems, and cognate sciences for dryland conditions. Invited articles from well recognized scientists, summarizing the existing state-of the Art on a particular theme or topic will also find a place. Short communications based on one year's data containing outstanding original research information are also accepted for publication.

Contributions are welcome from all scientists of all countries working for increasing the productivity of drylands.

2. Submission of manuscripts and conditions of acceptance

Manuscripts, written in English should be sent to the Secretary Indian Society for Dryland Agriculture Research and development, Central Research Institute for Dryland Agriculture, P.O. Saidabad, Hyderabad-500 659, Andhra Pradesh, India. Except in case of invited articles contributions from the members of the society will be considered for publication in the Journal. At least one of the authors must be a member of the society. It is also understood that the authors have obtained approval of the Head of their Department/Faculty/Institute in cases where such approval is necessary.

Manuscripts including illustrations be sent in duplicate and final form, fully checked for all typographical and other errors. Communication of a paper will be taken to imply that the material has not previously been published and is not being communicated for publication elsewhere.

All papers are critically reviewed, by expert referees/editorial board members. On their advice, the Chief Editor accepts or rejects the paper, or returns the manuscript to the author or the first author (in case of a paper having more than one author) for revision.

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Typescripts : Manuscripts should be typed on one side of the bond paper/good quality

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Title : The title should be short, specific and informative. It should identify the content of the article. The name(s) of author(s) should be written on the next line after the title of the paper followed by address of the institution where the research was done. Change of address should be given as foot-note.

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Illustrations : These are expensive to print and their number should be kept to a minimum. Illustrations which are of good quality and are essential for a clear understanding of the paper can be accepted. Line drawings should be clearly drawn in black India ink on smooth but tough paper. These should be of the size : width 12 cm × height (preferably 9 cm, to a maximum of 18 cm). Figures meant for reduction should have multiple dimension of the above size. Line drawings and photographs should have legends, which should also be supplied on a seperate sheet. They should preferably not be folded or creased.

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SPECIAL ISSUE ON THE ROLE OF SMALL WATERSHED HYDROLOGY IN RAINFED AGRICULTURE

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