National Symposium on Hydrology
Dec.16-18, 1987, N.I.H.,Roorkee

IMPACT OF WATERSHED MANAGEMENT ON HYDROLOGICAL REGIME

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ABSTRACT

There is an increasing urgency towards watershed management with a view to improve upon the land and water resource utilisation. Practices in vogue for watershed management are: cover management, field measures, erosion and conservation structures and water harvesting structures. All the watershed management practices influence the land phase of the hydrologic cycle and are supposed to affect the runoff yield from a basin. This paper presents a comprehensive state of the art information of the impact of watershed management practices generally adopted in a drainage basin on the hydrological regime. Modelling inadequacies in evaluating the impacts is also brought out and a case study is presented.

Introduction

Watershed management is carried out through cover management, i.e. forests, grass or agricultural crops, field measures, such as, bench terracing, contour/graded bunding and erosion control and conservation structures, such as, gully plugs, check dams, revetments, and water harvesting structures. Besides protecting the soil and maintaining its productivity, the above measures are supposed to influence the travel of runoff thereby affecting the quantity, quality and regime of water which is delivered in a stream. The watershed management practices affect changes in watershed retention thus cause alteration in the runoff responses from a drainage basin.

Watershed management programmes are in operation in about 1000 small watersheds (2000 to 5000 ha) in about 35 catchments with total area of 77m.ha. (Das, 1987). Afforestation has been widely used to provide protection against erosion, degradation and improved moisture conditions. Selective deforestation has also been used to give rise to temporary increase in stream flow (Zadroga, 1981). Attempts have been made to evaluate the influence of afforestation on precipitation, water yields and flood peaks on large number of experimental watersheds or small drainage basins. In real life, all categories of soil conservation measures will be used in a watershed and there will be compounding effect due to them on the flow regime from the basin.

The present paper reviews the state of the art information on the effects of afforestation/deforestation and other soil conservation generally adopted in a drainage basin. Majority of watersheds reported are either experimental or small sized. Modelling inadequancies are also discussed and a case study is presented.

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Effects of Afforestation on Precipitation

The impact of afforestation on precipitation has been a subject of dispute for more than a century. Based on his study of American catchments, Zon (1927) had concluded that afforestation increases precipitation by 25%. Voerkov (1952) had concluded that forests increase only the orographic precipitation by 25% and have no influence on cyclonic precipitation. Moore (1910) could not identify any significant influence of afforesation on increase in precipitation. Eitegen (1932) concluded that increase of upto 23% in the raingauge catch may be due to the protection of raingauge because of afforestation and is falsely attributed to increase in actual precipitation. Penman (1963) has concluded that afforestation does not significantly influence the mean basin precipitation. In India, the regions which receive more rainfall are largely forested (Subba Rao and Hilary Raj, 1986). The area under forest in India is approximately 23%. However, the forested areas receive twice as much rainfall as the other areas. The above statistics is perhaps the reason for arguments that forest occupied environments have integrated influence for enhanced precipitation. Verry (1986) also states that based on existing literature, it is false to state that forests increase the abundance and frequency of precipitation.

In this paper, it is presumed that afforestation in conjunction with other watershed management measures only influences the land phase of the hydrologic cycle and its influence, if any, over the amount of precipitation received is not considered.

Effective of Deforestation on Runoff

A large number of publications report the effect of deforestation on the hydrologic regime of a basin. Based on the data of experimental watersheds, Crawford (1966) concluded that a 10% change in potential evapotranspiration can cause upto 30% change in runoff. It is very difficult to generalise the influence of afforestation or deforestation because the amount of evapotranspiration occuring from a watershed is also dependent on the local environments. Burch etal (1987) observed that forested catchments give little runoff; but after forest clearing, runoff initially increases and so do the soil erosion and salinization problems: They concluded that effect of converting forested land to agricultural land use would be to generate high-peak storm flows and large discharge volumes irrespective of antecedant soil moisture conditions. According to the authors, the hydraulic conductivities of the grassland soils were about half of those undisturbed forests. The authors further concluded that conversion of some forests to agricultural lands greatly increases the severity and frequency of storm runoff. Troendle and King (1987) also established significant increase in the annual flows and peak flow from completely deforested basins. They further observed that the potential difference between the gross precipitation entering the system during the winter at the canopy level and net precipitation as indexed by snow-courses on the ground could be quite great. The increase, however, went on decreasing with the subsequent regeneration of forests. Baker (1986) determined annual water yields for three levels of overstorey removal and three levels of strips cut with thinning applied on ponderosa pine watersheds. The increase in water yield in ponderosa pine is less than from what may result from other commercial fir types because pine forests inherently occur on drier sites. The author further indicated that water yield increase from watersheds with northern aspects may be realised with small reductions in forested area and will persist for longer time period as compared to those realised from watersheds with southern exposure. As reported by various authors, net increase in streamflow has been variable depending upon the type of forest cover, mean basin precipitation, steepness of slope, extent of clearance, method used for clearance (Lal, 1981), orientation of forest slopes, etc.

The above observations appear to suggest that one of the best ways of increasing runoff from a basin would be to remove all or part of the vegetative cover of catchment. However, it is not true in case of cloud forests. In catchment covered with cloud forests, deforestation may cause a substantial decrease in water yield; a result of great hydrologic importance especially in the tropics (Zadroga, 1981). In case of cloud forests, the suspended moisture in the atmosphere is intercepted by plant surfaces and precipitation occurs in the form of drip or stemflow even though no rain occurs on adjacent open ground. It is commonly accepted amongst hydrologists that the existence of cloud forest effects runoff regulation. No quantitative analysis has, however, been done to demonstrate regime differences associated specifically with variation in forest cover.

Effect of Afforestation on Runoff

Infiltration capacities of forest land not only exceed rainfall intensities but also absorb overland flow from adjacent natural rock outcrops, agricultural lands and roads (Subba Rao and Hilary Raj, 1986). Overland flow seldom occurs in the forest land even during flood producing rainfall. Planting a bare, eroding site, may take ten years to reach the point where overland flow and erosion practically ceases.

Analysis of the physical properties of soil under forest cover indicated that the surface 10cm of soil has saturated hydraulic conductivity of upto 32m/day (Lal, 1981). The saturated hydraulic conductivity decreases sharply with depth so that 10-20cm zone has a value of about 1.5m/day and the 20-100cm zone a value of about 0.3m/day. The surface layer gets quickly saturated resulting in surface or/and subsurface runoff.

Tennessee Valley Authority conducted experiments on the effects of reforestation on the White Hollow watershed during the latter part of the experiments with those of the earlier period showed that the volume of the flood was not affected, but that flood peaks in summer were markedly reduced, (Hoyt and Langbein, 1955). The effect was rather to spread out the runoff. Numerous experiments were conducted by the Soil Conservation Service (U.S.A.) and Forest Service (U.S.A.) which demonstrated that the rate of soil intake can be increased by improvement in land use and both surface runoff and soil erosion can be decreased. However, floods are made up not only of surface or overland flow but of subsurface runoff as well. Therefore, unless the soil of the area can infiltrate water for long, it may return to the stream as sunbsurface runoff to become part of the floods. During rainstrom shallow zones of saturation may be built up within the soil near the surface and the water infiltrating into this shallow saturated zone will discharge to the channel system much more quickly than water reaching the permanent ground water table.

Das (1986) has shown that forest has effect of modifying infiltration and soil mosture distribution both in its detention and as well as retention storage. Percentage of absorption of incident rainfall ranged from 91 to 100% under forest conditions against 76% under meadow condition. Due to better structural development in the soil mantle under forest, movement of infiltrated water, leading to delayed interflow, is bound to be significant. Increased forest cover is associated with more voluminous and deeper roots which help in large and deeper percolation. The portion of water which enters the soil profile on the watersheds of low order streams (i.e. small watersheds) comes out later into bigger channel system of high order streams as subsurface flow.

The maximum opportunity for soil water storage that the forest can generate at any point is essentially the difference between field maximum and field minimum moisture contents throughout the rooting depth.

Small watershed studies (below 100 ha) in the Soil Conservation Research Stations under Indian Council of Agricultural Research (ICAR) have shown that reafforestation by Eucalyptus at Dehradun could reduce peak by 77% (Das, 1986) while burning, cutting of trees and over-grazing increased peak discharge from various watersheds by 69, 34 and 32% respectively.

While answering questions, based on existing literature,Verry (1986) states that it is usually false; but sometimes it may be true to say that in hill and mountain country, forests conserve water for stream flow. He further adds that it is usually true that forests retard snowmelt, but sometmes it may as well be false. According to him forests cannot prevent floods produced by exceptional precipitation, but may mitigate their destructiveness. The author (Verry, 1986) did not find convincing evidence to conclude that forests tend to equalise stream flow througout the year by making the low stages higher and the high stages lower. There is evidence both in favour and against the above statement. Forests may sometimes aggravate floods by retarding the melting of snow if the snow melt synchronises with.the high intensity rains.

Watershed Management and Hydrologic Responses

Watershed management practices change the watershed retention, thereby tending to alter runoff response of the basin. Based on the data from small watersheds (below 1000 ha) in the Soil Conservation Research Stations under ICAR, it is reported that contour trenching and afforestation reduced peak by 73% while combination of afforestation and gully control works reduced it by 63%. Narrow base terracing or bunding reduced peak by 40% from a 54.63 ha. watershed at Dehradun and reduced runoff by 62% (Das, 1987).

Runoff as percentage of rainfall for a small catchment at Dehradun with 8% slope is reduced from 54.1% for up and down cultivation to 41.2% for contour cultivation (Tajwani, 1981). The author further reports from the experiments at Ootacumund that by adopting contour farming for potato cultivated on 25% slope, runoff was reduced by 55.76%.

Studies conducted at Dehradun showed that a bunded agricultural watershed (12.08 ha.) produced comparatively less runoff and peak discharge as compared to that realised from another unbunded watershed (294 ha.) as is evident from Table 1. Incidentally, bunded areas also gave 10.1% more crop yield than unbunded area. In another experiment at Dehradun, bunding of an agricultural watershed (54.63 ha.) resulted in a 62% reduction in runoff amount and 40% reduction in the peak runoff rate (Tejwani, 1981). The author further reports that in an experiment at Agra, bunding of an agricultural watershed (22.3 ha.) resulted in 45% reduction of runoff.

Analysing the observed runoff data collected from experimental watersheds of ICAR Research Stations at Dehradun and Chandigarh, the values of runoff coefficient 'C' as used in Rational formula were determined. For cultivated fields it ranged from 0.29 to 0.50, pasture 0.15 to 0.45 and forest 0.10 to 0.40. The value of 'C' for rugged Shivalik hills was as high as 0.70 (Das, 1986).

It is obvious that variations in land use management practices will affect the movement of absorbed water through soil profile. In one case study in Lower Bhavani Catchment, the variations in water table heights of the wells lying on the zone of influence of a percolation pond have been studied. As compared to controlled well on the upstream side increase in water table height due to construction of percolation pond ranged from 129% to 35% for wells located at distances from 29m to 689m respectively (Das, 1986). The author further reports that it is a common experience in Maharashtra that nalla plugging and nalla bunding helps in improving water table heights and availability of water from the wells downstream for increasing micro irrigation command.

TABLE 1

Comparison of monthly rainfall, runoff, and peak discharge of bunded and unbunded agricultural watersheds at Dehradun, (Tejwani, 1981)

Month, 1976	Rainfall (mm)	Runoff % of rainfall	Peak Discharge (mm/ha.)
(1)	(2)	(3)	(4)
Bunded sub-catchment			(12.08 ha)
July	527.5	17.1	39.7
August	606.5	22.1	26.2
September	131.5	1.2	1.0
Unbunded sub-catchment			(2.94 ha.)
July	527.5	27.4	47.5
August	606.5	44.8	53.1
September	131.5	15.6	23.1

Hydrologic Modelling and Impact Evaluation

Recent literature of the last wo decades on hydrologic modelling clearly reveals two distinct trends. On one side, there has been the development of conceptual models which purport to be 'physically based' or causal models. On the other side, there has been development of empircal models. System theoretic models (time series models, state space form relationships) also constitute part of empirical models.

Various types of catchment models were developed to simulate the internal description of a watershed with the primary purpose of forecasting river flows. Inspite of the relative sophistication of catchment models, their potential for providing accurate streamflow forecasts, or for extrapolation, i.e., for drawing inferences beyond the range of observation, is not fully realised. Stanford model (Crawford and Linsley, 1966) and Sacremento model (Burnash etal, 1973) belong to this category.

In the words of Klemes (1987), empirical models simply describe the regularity, or pattern, as it manifests itself in the observations, i.e., on the basis of empirical evidence. In other words, while empirical models are only descriptive, causal models are both descriptive and explanatory. It is likely that for discerning a pattern from the historical data, empirical models may perform better.

Main purpose of calibration of a catchment model is to obtain a parameter set which gives best possible fit between the model simulated and observed hydrograph ordinates (estimation criterion) for the calibration period. But there is a big question about the parameter set being unique and conceptually realistic. Also, simple least square criterion used as an objective function may not be the best choice as it does not take into account the stochastic properties of the measurement uncertainties in a realistic manner (Sorooshian and Dracup, 1980). It is difficult to identify a calibration period whose data may be considered representative of the various phenomena experienced by the watershed. Many researchers tend to satisfy this requirement by using as long a length of calibration data as possible. Even this approach has not provided demonstrably superior results (Sorooshian etal, (1983). Moreover, as Sorooshian and Dracup (1980) pointed out, most of the calibration methods tend to emphasize the closeness of fit between the model simulated and observed hydrographs. As such, the resulting parameter set may not be unique and conceptually realistic and may not perform satisfactorily when used for forecasting or impact evaluation.

Ibbitt and O'Donnell (1971) and Johnston and Pilgrim (1976) used many optimisation procedures and have attributed the following reasons for not being able to get unique parameter set for a catchment model:

(a) interdependence between model parameters;

(b) indifference of the objective function to the values of 'inactive' parameters;

(c) discontinuities of the response surface;

(d) presence of local optimum due to the non-convexity of the response surface.

In contrast to conceptual models, the system theoretic models are usually easier to construct and calibrate. These models are strongly criticized for being simplistic as they ignore the nonlinear dynamics of the watershed process. The following paragraph quoted from Sorooshian (1987) puts in proper perspective the problem of the model selection for reproducing the catchment input-output response.

"It has sometimes been argued that, from an engineering point of view, the usefulness of a catchment model (be it conceptual or system theoretic) need not depend on its conceptual realism so much as on its capability to reproduce input-output behaviour. Some researchers have tried to compare certain conceptual and system theoretic models from this point of view. More often than not, the published results have supported the system theoretic models. The reasons for this are probably quite varied and have not been clearly discussed in the literature. Sorroshian (1983) mentioned two important points. First, the state of the art of the parameter estimation in conceptual models has not been adequately refined, whereas the solution techniques available for system theoretic models are comparatively highly efficient. The second reason is that the comparisons are rarely carried out under conditions which would highlight the inadequacies of either type of model. As suggested by Linsley (1982), the most important property of a model (and the least often tested) should be its inherent accuracy, i.e., it should not be a question of prediction accuracy under average or slowly changing conditions, but one of model credibility under extreme or rapidly varying conditions. For example, Kitanidis and Bras (1980) found that under rapidly changing hydrologic conditions, the conceptual SMA-NWSRFS model performed significantly better than an ARMAX (Autoregressive Moving Average with Exogeneous Inputs) linear stochastic model with on-line adaptively estimated parameters and states."

For the purpose of impact evaluation, be it because of watershed management, landuse changes or afforestation-deforestation, the conceptual models should have preference over the system theoretic models because of inherent physical basis of these models provided during calibration emphasis is made both on realising a unique and conceptually realistic parameter set and as well as satisfying the estimation criterion. Fleming (1971) reported the use of Hydrocomp Simulation Program (HSP) to study the effect of forest fire on water yield from Siquoe and Santa Yuez basins. Leaf and Brink (1972) used a conceptual model to study the forest management alternatives in Dead Horse Creek, Colorado. Glymph etal (1971) used USDAHL-70 model to illustrate the utility of the model for evaluating the potentials for influencing water regimes through alternative land use management patterns. However, due to the existing inadequacies in the parameter calibration, the inferences drawn from these models should be used with caution.

Case Study

A mountainous watershed 'Z' (may be named so) having an area of 1040 Sq. Km. having sub-watersheds 'X' with an area of 160 Sq.Km and another sub-watershed 'Y' with an area of 450 Sq. Km were chosen for the study. Soil conservation meaasures consisting of extensive tree plantation, terracing, fencing etc. were undertaken from 1962-63 to 1978-79; though most of the conservation measures were completed during first eight to ten years period. Rainfall-runoff data for the period 1970-83 were analyzed for discerning possible impacts on the

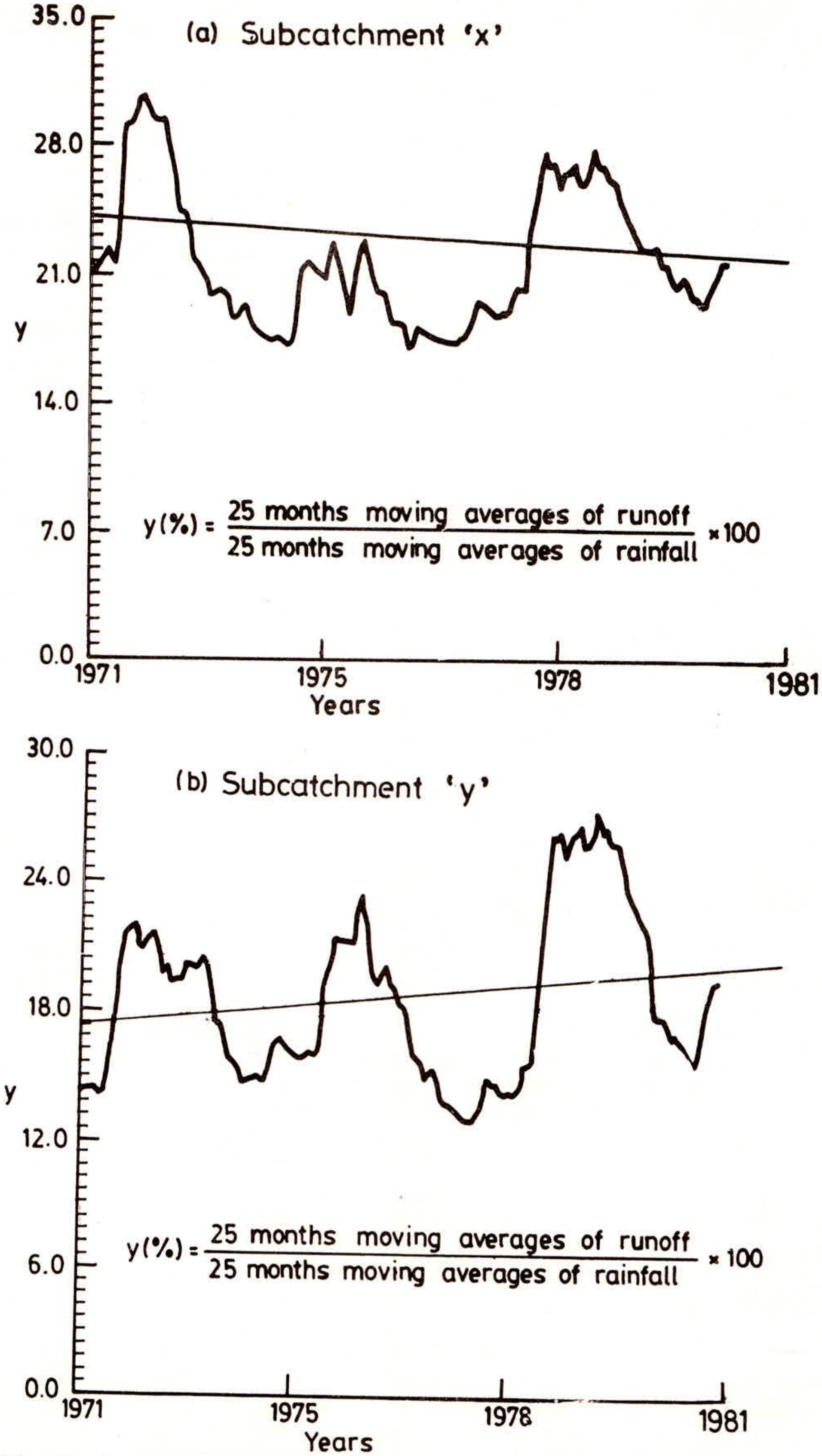

FIG. 1 . ILLUSTRATING IMPACT ON HYDROLOGIC REGIME (a) AT SUBCATCHMENT 'x', (b) AT SUBCATCHMENT 'y'

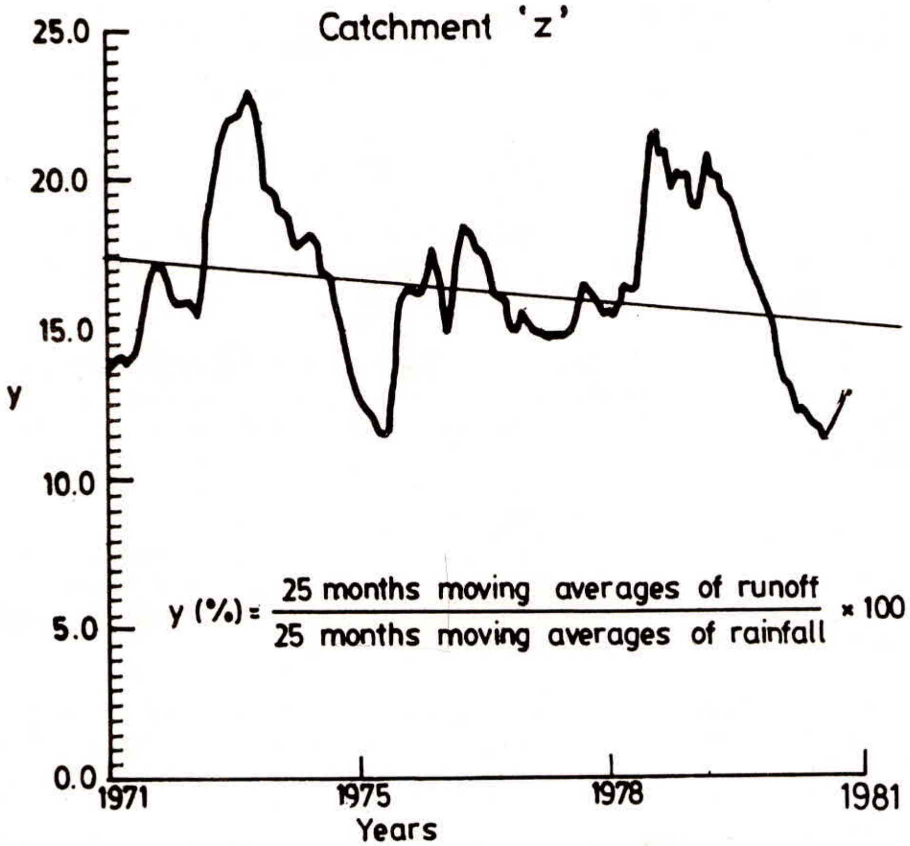

FIG. 2. ILLUSTRATING IMPACT ON HYDROLOGIC REGIME AT CATCHMENT 'z'

hydrologic regime.

Sacramento model was calibrated using the first two years of data (1970-72) and last two years of data (1981-83) for all the three watersheds and model parameters campared. No significant difference in the model parameters could be discerned to which any impacts could be attributed.

Petts and Foster (1985) have reported the use of the ratio of 25 months moving average of runoff to 25 months moving average of rainfall to identifying the impact of land-use practices on river hydrology. Ratios of 25 months moving average of runoff and rainfall were computed for subwatersheds 'X' and 'Y' and watershed 'Z' are plotted in Fig.1(a), 1(b) and 2 respectively. The plot for subcatchment 'X' and catchment 'Z' show a decreasing trend; whereas that for subcatchment 'Y' show an increasing trend.

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