Dynamic Model of Daily Runoff-Sediment Yield for a Himalayan Sub-Catchment of Ramganga River

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Abstract: Runoff sediment yield process is dynamic in nature. To model this process, consideration of antecedent status of input and output variables is important, and this status depends to a great extent on the memory content of the watershed system. In this study, an attempt has been made to develop a dynamic model of daily runoff and sediment yield considering the memory content of the watershed system. The developed model was applied on the uppermost Himalayan catchment of Ramganga river comprising an area of 1010 square kilometres. The model estimated and predicated values of daily sediment yield were found to be in good agreement with the measured values of daily sediment yield from the area.
Keywords: dynamic model, runoff, sediment, ramganga, memory content, himalayan catchment

1 Introduction

Natural systems and their relationships are dynamic, where the output has the effects of the memory of the system. The runoff-sediment yield process in a catchment is also a dynamic relationship. Runoff is the main carrier of eroded material to the outlet of a watershed and the portion of the eroded material which moves along with runoff in suspension is called suspended sediment or washload. The measurement of actual sediment outflow from an area is an expensive and time consuming process. As an alternative technique, mathematical models are used to assess the sediment outflow. The models employed for sediment outflow assessment need to be fairly accurate and adoptable under the actual field conditions. Various models which are in use for estimation of sediment yield, viz. Wischmeier and Smith (1965), Williams (1975) etc. have been developed considering the watershed system either as static or memory less. These relationships apart from being complex are empirical in nature, and do not provide a true representation of the natural process. The development of a dynamic relationship, based on the memory content of the watershed system, is likely to provide a better representation of the runoff-sediment yield process. It has been observed in Canada that a first order dynamic model on monthly basis and a second order dynamic model on daily basis adequately describes the sediment yield process with runoff as the input (Sharma *et al.*,1979). Jackman (1993) developed rainfall-runoff models on daily basis by assessing the dynamic response characteristics of river flood. At Pantnagar, dynamic models were developed by considering the effects of the watershed memory to estimate daily runoff volume by Kumar & Das (1998) and daily sediment yield by Kumar (1993) and Kumar & Das (2000) for a Himalayan watershed in India.

In the present study, an attempt has been made to develop a dynamic sediment yield model, considering runoff as the only input variable to estimate the sediment yield from a catchment on a per day basis. The model was applied on a Himalayan sub-catchment of the Ramganga river, called in this study as Naula watershed (Fig.1), to test its applicability and capacity to estimate and generate daily sediment yield for the catchment.

2 Description of study area

The watershed considered for this study, called as the “Naula watershed”, is the catchment upstream to the Naula gauging station of the Ramganga river (Fig.1). It consists of two gauged sub-catchments and a small area drained by small rivers and streams. The Naula watershed selected for this study comprises an area of 1,010 km^2, where the maximum and minimum elevations with undulating irregular slopes range from 3,112 to 792 m above the mean sea level. The watershed is located between 29° 44′ N and 30° 6′ 20″ N latitude and 79° 6′ 15″ E and 79° 31′ 15″ E longitude in the Ranikhet forest subdivision of Ramganga river catchment (Uttaranchal, India). The watershed is located in a Himalayan sub-tropical area and has a sub-temperate climate with a mean annual temperature of 30℃ and a mean minimum temperature of 18℃. The precipitation in the watershed occurs mainly in the form of rainfall from the middle of June to the end of September with a mean annual rainfall of 1015 mm. Hydrologic data of the watershed is collected by the Divisional Forest Office (Soil Conservation) Ranikhet.

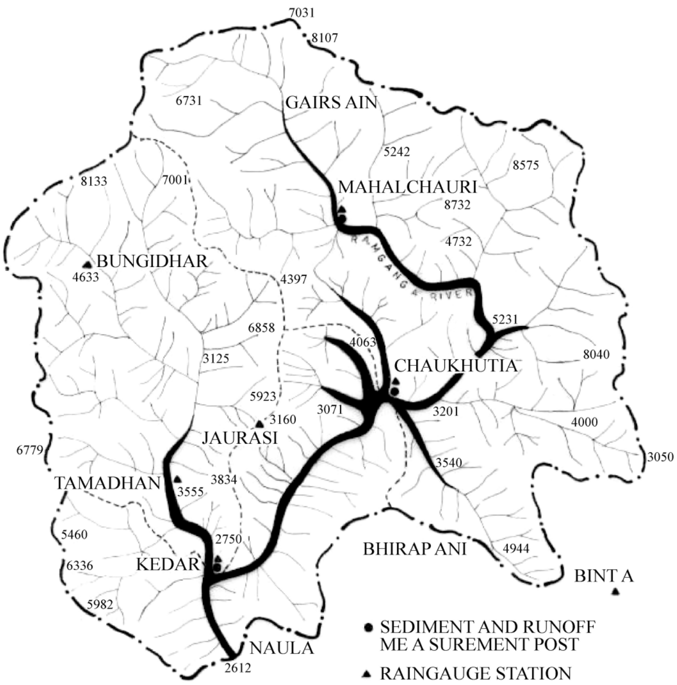

Fig.1 Naula watershed

3 Conceptualization of model

The basic concept involved in the development of a model representing the dynamic process of runoff-sediment yield is based on the fact that the watershed system exhibits its inbuilt memory. Invariably, for the conceptualization of system models for sediment yield processes, the watershed is considered to be a lumped system or a black box, where no consideration is to be given to the physical processes operating within the system. The effects of runoff on sediment yield is a dynamic process in the watershed system. The sediment yield at any time is dependent not only on the present values of the runoff, but also on the previous values of runoff and sediment yield, *i.e*, the data which are in the memory of the system. Such situations are particularly true in cases of large catchments, where the eroded soil takes a considerable time to travel to the outlet. The runoff which is still in the watershed's fluvial system may either gain in suspended sediment due to land slides or channel scour, or lose it due to deposition on the channel bed, depending on the nature of flow parameters. The sediment yield from a catchment at any time, therefore, is a combined effect of the present runoff values and the previous values of the runoff and sediment yield. Thus, logically a time variant dynamic model is likely to be a better representation of the rainfall-runoff process. The functional form of such a process can be described as,

$$S_t = f(Q_t, Q_{t-1}, Q_{t-2}, ...Q_{t-n}, S_{t-1}, S_{t-2}, ...S_{t-n}) \quad (1)$$

where S is the daily sediment yield, Q is the daily runoff and subscripts t, t–1, *etc*. denote the time at respective lags in days. The above equation falls in the multiple input-single output (MISO) category, since it has a single output in response to a number of input variables.

4 Development and calibration of model

To develop the conceived model, at first, a preliminary study was conducted on the study watershed, where it was observed that the sediment yield on a day is the combined effect of runoff on that day, and runoff and sediment yield of the five previous days. Accordingly, for this watershed, a time lag of five days was considered for the development of functional relationships between input and output variables of the model.

Linear dynamic model

To begin with for the development of the model (Eqn 1), at first the model structure was considered to be linear. The basic structure of a linear dynamic model for a lag of five days is described below:

$$S_t = A_0 + \sum_{i=1}^{6} A_i Q_{t+1-i} + \sum_{i=1}^{5} B_i S_{t-i} \quad (2)$$

In the above equation, A_0, A_i, and B_i are the model coefficients. The values of these model coefficients and their respective level of significance were determined by using the techniques of multiple regression analysis. A linear dynamic model applicable at the 5% level of significance was then obtained, which was of the following form:

$$S_t = 0.00221Q_t - 0.000613Q_{t-2} - 0.00103Q_{t-3} + e_t \quad (3)$$
$$(R^2 = 53.5\%)$$

where S is the daily sediment yield in ha-cm, Q is the daily runoff in ha-m. The model in Eqn (5), however, yielded a poor value of coefficient of multiple determination R^2 equal to 53.5 %. At the same time, in this model the previous sediment yield terms were not found to be significant at the 5% level of significance.

Non-linear dynamic models

To improve the value of coefficient of multiple determination and the performance of the linear dynamic model (Eqn 3), non-linear forms of it were then tried. It was observed that a non-linear model with log transformed data provided much better results. A dynamic non-linear sediment yield model with log transformed data is described as,

$$\ln S_t = \ln A_0 + \sum_{i=1}^{6} A_i \ln Q_{t+1-i} + \sum_{i=1}^{5} B_i \ln S_{t-i} \quad (4)$$

The values of model coefficients of the equation were similarly determined as in case of the linear model. After eliminating the non significant terms, the following non-linear dynamic model consisting of variables significant at the 5% level of significance was obtained.

$$\ln S_t = -6.70 + 3.22 \ln Q_t - 2.33 \ln Q_{t-2} + 0.542 \ln S_{t-1} + e_t \quad (5)$$

The coefficient of multiple determination R^2 for the non-linear dynamic model in Eqn (5) was obtained as 80.1% as compared to 53.5% in case of linear dynamic model, which is fairly acceptable in case of sediment yield models, as such models represent a very complex hydrologic process.

5 Error component (e_t)

The composition of the developed model can be divided into two components, namely, the deterministic and the stochastic. The deterministic component consists of terms obtained through a multiple regression analysis, and the stochastic component represents the error values e_t which may have accrued due to faults during sampling, measurement and recording of the data. The magnitude of independence and randomness of values for e_t were tested by computing the auto-correlation functions (*ACF*) and the autocorrelograms. The series is considered to be a randomly distributed and independent white noise series when the ACF are not significantly different from zero, or are within the limits of twice the standard error (*SE*) of the series (Kottegoda,1980). The residuals, *i.e.*, the difference between measured and predicted values of daily runoff, and their ACFs at different lags were calculated. It was observed that the values of calculated ACFs were within the twice of the standard error value of the residual sediment yield series at the 5% level of significance. This gave that, the series for e_t is an independent, randomly distributed and cannot be modeled. Therefore, the error component was dropped from the main model, and the final model which represents the rainfall-runoff-sediment yield process of the study watershed was expressed as:

$$\ln S_t = -6.70 + 3.22 \ln Q_t - 2.33 \ln Q_{t-2} + 0.542 \ln S_{t-1} \quad (R^2{=}80.1\%) \tag{6}$$

6 Model testing and validation

The developed non-linear dynamic model (Eqn 6) was tested on the daily data series of the years 1980-82 to check its performance. The estimated values of daily sediment yield from the model were compared with the corresponding values of measured daily sediment yield for the monsoon months of these years. The applicability of the model was checked by applying it on the data series of the years 1979 and 1983 respectively, which were not considered for the development of the model. It was found that for all the four monsoon months (June-September), the values of daily sediment yield predicted by using the model were in good agreement with the corresponding values of measured sediment yield. The model was also used to synthetically generate a daily sediment yield data series for future by using the past measured daily runoff data and the model predicted values of daily sediment yield as the input information, through a step regression technique. Graphical comparison of measured, predicted and synthetically generated values of daily sediment yield for the month of August, 1983 as shown at Fig. 2. It was observed that the model predicted and generated values of daily sediment yield compared fairly well with the corresponding measured values of daily sediment yield. The coefficient of multiple determination of the model was found to be 80.1%, which indicated that the model is able to explain more than 80% of the variability in the sediment yield estimation. Thus, the model was considered to be a good representation of the runoff and sediment yield process of the Naula watershed.

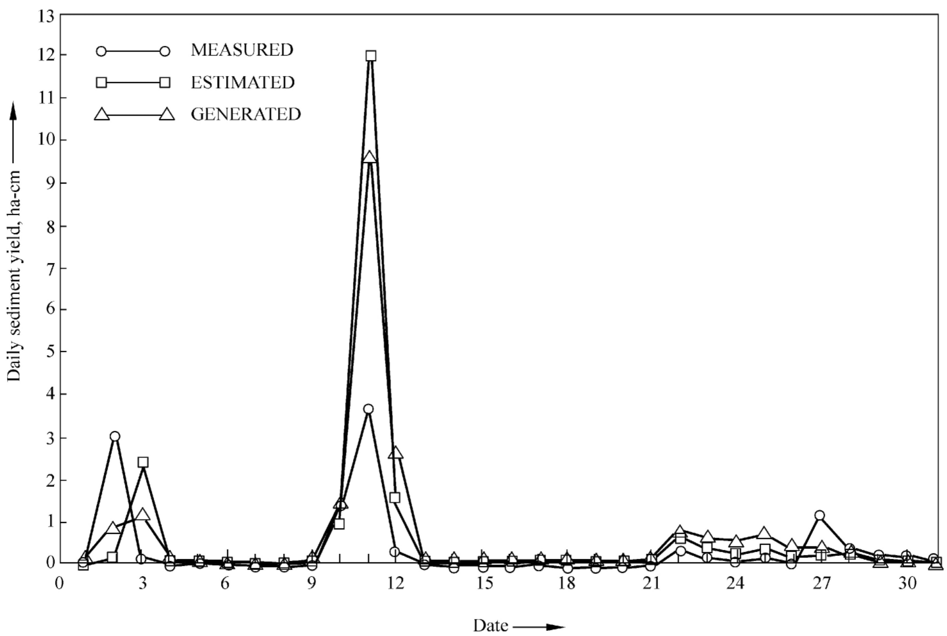

Fig.2 Measured, estimated and gener ated daily sediment yield for August, 83

7 Conclusion

An input-output time invariant dynamic model has been developed to represent the daily runoff-sediment yield process in the Naula watershed of Ramganga river catchment in the Himalayan region of Uttaranchal (India). The coefficient of multiple determination for the model was found to be 80.1%. The model estimated and synthetically generated values of daily sediment yield were found to be in fair agreement with the corresponding measured values. The error component present in the model has been found to be an independent and randomly distributed white noise.

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