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ORIGINAL PAPER

An effective dynamic runoff-sediment yield modeling for Shakkar watershed, Central India

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Abstract

Modeling of the watershed runoff and sediment yield method is very variable and nonlinear in nature. The Shakkar watershed of the Narmada river basin, Central India, has been taken under the study. The linear dynamic (LD), nonlinear dynamic (NLD), and logarithm dynamic (LogD) sediment yield prediction models based on the concept of determining and assigning the varying weightings to the antecedent events for the runoff-sediment process were developed for the watershed. The data set (1990–2005) model was developed only by using active daily runoff data, together with the antecedent runoff index (AQI) and antecedent sediment yield index (ASYI). Due to the high value of R^2 (over 60%), the linear, nonlinear, and logarithm dynamic model was discovered to be appropriate for the field of research. The Nash-Sutcliff efficiency (NSE), mean absolute error (MAE), and Willmott's index (WI) were employed to assess the performance of the models. The results showed that the NLD model was found better than linear and logarithm models. These models had Nash-Sutcliff efficiency (NSE = 92.69, 64.93, 79.66), mean absolute error (MAE = 5744.20, 12,618.83, 0.02), and Willmott's index (WI = 0.98, 0.88, 0.95) correspondingly. Hence, the NLD model can be used for predicting sediment. In order to take the right conservation steps in the watershed to minimize the sediment load in the reservoir to boost the lives of the structure, the forecast for the sediment yield is of great importance.

Keywords Sediment yield · Runoff · AQI · ASYI · Daily dynamic model

Abbreviations

LD	Linear dynamic
NLD	Nonlinear dynamic
LogD	Logarithm dynamic
AQI	Antecedent runoff index
ASYI	Antecedent sediment yield index
NSE	Nash-Sutcliff efficiency
MAE	Mean absolute error
WI	Willmott's index
Q	Runoff
S	Sediment
SY	Sediment yield
MT	Metric Tonne
m^3/s	Meter cube per second
k_0, k_1, k_2, k_3	Regression coefficient
R^2	Correlation coefficient

Introduction

Research on rainfall and runoff produced sediment-based problems would be very helpful in knowing the broad issue of soil degradation and soil erosion in an agricultural nation like India, where there are growing pressures on soil and water resources from the inhabitants (Renard 1980; Dhruv Narayana and Babu 1983; Meshram et al. 2019a, b). The need for accurate information on watershed runoff and sediment yield has grown rapidly during the past decades because of various watershed management programs for conservation,

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development, and beneficial use of all natural resources including soil and water (Flaxman 1972; Walling 1977; Garde and Kothari 1987; Meshram et al. 2018a; Gudino-Elizondo et al. 2019).

The watershed runoff and sediment yield production method from the watersheds are very complicated (Meshram et al. 2018b). The time and spatial variability are extremely nonlinear. The event-based modeling has an important position in the watershed management and development (Meshram et al. 2018c). Many models have been created particularly for the rainfall run-off phase, such as black box, conceptual, and physically based models. On the other side, very few model for exact estimation of sediment graph from the storm events.

Due to different catchment leadership programs for conservation, development, and useful exploitation of all natural resources, including soil and water, the need for precise data of runoff and sediment yields has been increasing quickly over the previous few centuries (Meshram et al. 2018d). Hydrology is aimed at improving infiltration in soil for all watershed management programs, controlling excess runoff, handling, managing, and utilizing runoff for useful purposes, and reducing soil erosion for land conservation reasons. Therefore, the prerequisite with watersheds requires that the watershed is understandable and that the output of runoff and sediment is determined.

The dynamic aspect of hydrological procedures ensures that the dynamic model represents the faster and more accurate watershed runoff and sediment yield process (Gajbhiye et al. 2015). Dynamic model is the input-output model that takes into account the impacts of previous occurrences in the memories of the system (Ahmadi and Molladavoodi 2018; Cordier et al. 2020; Wang et al. 2019). In the past research, these models were provided equivalent weight for each preceding event. Dynamic systems for the estimation of annual daily sediment yield (Kumar 1993) and the annual runoff volume (Kumar and Das 1998) were created for a Himalayan watershed in India by studying the impacts of the watershed memory. However, each previous event may have a different impact on this incident. The first immediate preceding event can influence the production more than the second preceding event and so on. Two antecedent indices, the AQI and the ASYI, were chosen as independent factors in this research to determine the varying effects of consecutive events.

Different scientists in the distinct region of India have developed a dynamic model of watershed runoff and sediment yield. Kumar and Das (2000) have been trying to develop a dynamic model of daily runoff and sediment yield for Ramganga (India). For the Naula Watershed Ramganga basin (India), Pyasi and Singh (2001) developed a weekly sediment yield dynamic model. In their research, the models focused on the idea to determine and assign the variable weighting to antecedent runoff, and sediment occurrences were created for both linear and nonlinear annual sediment yield forecast. The new model of linear regression was developed by Panigrahi (2007) to estimate sediment yield, with known value of runoff for Odisha watersheds. For the Kushinagar Watershed of the Vamsadhara Rivers Catchment, Orissa (in India), a dynamic model of the sediment yield was developed by Ranjan et al. (2011).They developed linear and nonlinear sediment yield prediction models depending on the idea of determining and attributing the different weight to the antecedent event for the precipitation-runoff sediment method. For the Barakar River basin, Jharkhand (India) Giridih watershed, which considers current runoff and previous levels of runoff and sediment yield as the input variable, established nonlinear (loglog transformed) sediment yield model, to assess the catchment sediment yield on a daily basis. The coefficient of multiple regressions for the nonlinear dynamic model was 0.873.

The effects of rainfall and runoff on sediment yield, in the watershed system, are a complex process. The yield of sediments at any time depends not only on the present rainfall and runoff values but also on the previous rainfall, runoff, and sediment yield values, i.e., the data in the system's memory. Therefore, the sediment yield from a catchment at any time is a cumulative result of the existing rainfall and runoff values and preceding rainfall, runoff, and sediment yield values. So it seems logical that a dynamic model is likely to reflect the rainfall-runoff cycle better.

Generally, the runoff was considered an important input variable in the creation of sediment yield models. Nevertheless, it has been observed that the yield of sediments at any time depends on the extent of the generation of sediments and the subsequent transport of the eroded soil to the outlet of the watershed. The cycle of sediment generation is governed by the characteristics of rainfall, runoff, and catchment, while the cycle of transportation is primarily affected by runoff parameters and characteristics of the watershed including the configuration of the watershed fluvial system. Therefore, it is felt that the inclusion of the rainfall in the sediment yield modeling method will aid in a more objective evaluation.

Our exploration can produce enormous data, which can assist water resource engineers in dealing with more successful soil and potential designs for water protection in the basin. To classify areas that should be prone to erosion, the use of dynamic modeling and runoff data plays an important role in developing new methodologies for managing soil erosion with a more competent solution. Nevertheless, the understanding of the abovementioned facts in the basin has still been discussed, and so far, no such scientific tests have been published for a basin. Consequently, the findings of this study are novel and significant for the authorities concerned on water resources.

In the present analysis, an attempt was made to establish a dynamic sediment yield model to estimate the sediment yield from a catchment on a regular basis, considering both rainfall and runoff as the input variables. The model was implemented on a Shakkar watershed of the Narmada River basin (Fig. 1), to test its applicability and capacity to estimate and generate daily sediment yield for the catchment.

The rest of the paper is organized as follows. The "Materials and methods" section provides the material and methods, and the third section provides the results of the three dynamic models generated using the runoff and sediment dataset. Finally, the last section provides findings and concluding remarks for closing the paper.

Materials and methods

Study area

The present study was conducted in Gadarwara gauging station, one of the gauged watersheds of the river Shakkar (Fig. 1). The Shakkar River is a major stream of the Narmada River. Shakkar watershed lies between 22° 23′ N latitude and 78° 52′ E longitude. The total catchment area of this watershed is 2220 km^2. The topography of the watershed is undulating. The climate of the Shakkar watershed is dry except during the monsoon season. Rainfall mainly occurs during June to October by the southwest monsoon. The soil in the watershed can be classified into clay to loamy texture. The collection of the hydrological data at the Gadarwara station was started in the year 1990 by the Central Water Commission (CWC), Bhopal. The daily runoff, sediment data from 1990 to 2015 were collected for the study. Sediment flow is mainly confined to the monsoon period of June–October, so models were tested for the monsoon period only. The statistical parameters of runoff and sediment data have been shown in Table 1.

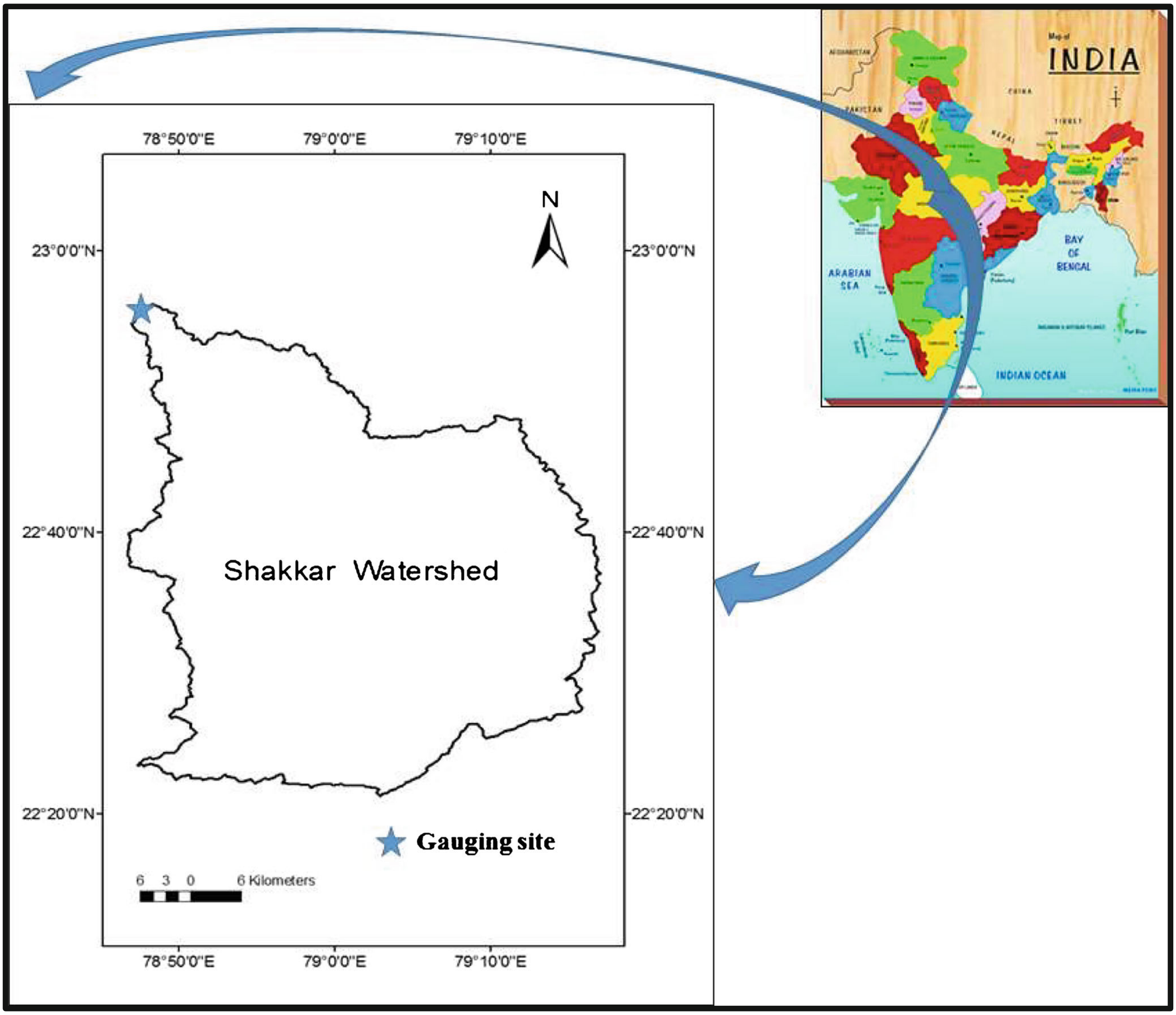


Fig. 1 Location map of the study area

Table 1 Statistics of runoff and sediment yield in the Shakkar watershed

Data	Period	Length of data	Minimum	Maximum	Median	Mean	Standard deviation
Runoff (Cumec)	June–Oct (1990) to June–Oct (2015)	3945	0	5850	42.33	109.91	271.03
Sediment yield (MT)	June–Oct (1990) to June–Oct (2015)	3945	0	2,682,247.08	263.53	10,131.12	68,135.42

Basic statistical attributes of monsoon (June–October) runoff, sediment yield for the period of 25 years (1990–2015) of Shakkar watershed, were analyzed, such as mean, median, and standard deviation (SD) (Table 1). The mean and SD of the runoff data was 109.91 and 271.03 cumec, respectively. In the case of sediment data, these values were 10,131.12 and 68,135.42 MT over the period of 1990–2015. The scrutiny of runoff and sediment data records showed that the maximum runoff and sediment were 5850 cumecs and 2,682,247.08 MT correspondingly. Figure 2 displayed the flow diagram of the technique.

Model development for runoff-sediment process

Considering the watershed as a lumped system (black box), the causative factors such as runoff (Q), AQI, and ASYI can be treated as input to the system and sediment yield as the output. The mathematical expression of sediment yield can be functionally represented as Eq. (1):

$$SY = f[Q, AQI, ASYI] \tag{1}$$

where *SY*= sediment yield (MT), *Q*= Runoff (m^3/s), *AQI*= antecedent runoff index (m^3/s), *ASYI*= antecedent sediment yield index (MT).

Equation (1) can be represented in the linear form as Eq. (2):

$$SY = \mathscr{k}_0 + \mathscr{k}_1 Q + \mathscr{k}_2 AQI + \mathscr{k}_3 ASYI \tag{2}$$

where $\mathscr{k}_0$, $\mathscr{k}_1$, $\mathscr{k}_2$, and $\mathscr{k}_3$ are the regression coefficients.

Nonlinear forms were then tested to improve the performance of the linear dynamic model. A nonlinear dynamic sediment yield model is defined as Eq. (3):

$$SY = \mathscr{k}_0 Q^{\mathscr{k}_1} AQI^{\mathscr{k}_2} ASYI^{\mathscr{k}_3} \tag{3}$$

A nonlinear relation in the form of the logarithmically transformed variables can be expressed as Eq. (4):

$$\ln(SY) = \mathscr{k}_0 + \mathscr{k}_1 \ln(Q) + \mathscr{k}_2 \ln(AQI) + \mathscr{k}_3 \ln(ASYI) \tag{4}$$

where antecedent runoff index (*AQI*) and antecedent sediment yield index (*ASYI*) calculated as Eqs. (5) and (6):

$$AQI = \sum_{j=1}^{m} Q_j \mathcal{Y}_j \tag{5}$$

$$ASYI = \sum_{j=1}^{m} SY_j \mathcal{Y}_j \tag{6}$$

where Q$_j$ = daily runoff in the jthday before the day under consideration (m^3/s), SY$_j$ = daily sediment yield in the jthday before the day under consideration (MT), m= an integer, $\mathcal{Y}_j$ = the weightage of the preceding events, which can be estimated by following Eq. (7) (Ojasvi et al. 1994)

$$\mathcal{Y}_j = \frac{exp\left[-\frac{j-1}{m}\right]}{\sum_{j=1}^{m} exp\left[-\frac{j-1}{m}\right]} \quad (j = 1, 2, 3 \ldots\ldots m) \qquad \sum_{j=1}^{m} \mathcal{Y}_j = 1 \tag{7}$$

The iterative process including the trial and error method was used to work out the appropriate value of m for the study area and the value of m that gives the highest value of the multiple regression coefficient (R^2) is selected for the study area. In the present study, m ranging from 2 to 7 has been tried and m = 3 has been found to yield the highest value of multiple regressions ($R^2 = 0.997$). Thus, the weight assigned to preceding three daily events prior to the day under consideration was established using Eq. (6), 0.4484, 0.3213, and 0.2303.

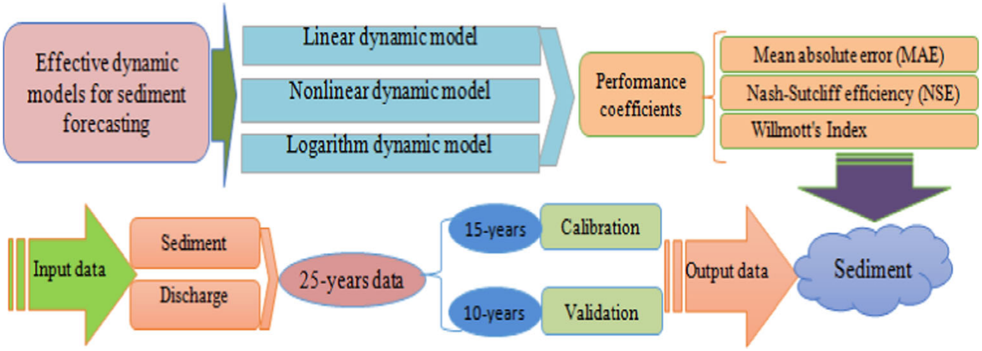


Fig. 2 Flow diagram of the technique

Parameter estimation

Data have been evaluated in Windows edition 16.0 using the SPSS Statistical Package. One-way multivariate analyses were used to depart from the runoff, sediment yield, AQI, and ASYI factors for multi-step regression. In the case of runoff-sediment yield relationship, sediment yield was the dependent variable, and runoff, AQI, and ASYI were the independent variables.

Qualitative evaluation of model performance

In this paper, three error measures were utilized to assess the quality of prediction models (Eqs. 8–10): mean absolute error (MAE), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), and Willmott's index (WI) (Willmott 1981).

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |(P_i - Q_i)| \tag{8}$$

$$NSE = \left| 1 - \left[\frac{\sum_{i=1}^{N} (Q_i - P_i)^2}{\sum_{i=1}^{N} (Q_i - \bar{Q})^2} \right] \right|, \quad -\infty \le NSE \le 1 \tag{9}$$

$$WI = \left| 1 - \left[\frac{\sum_{i=1}^{N} (Q_i - P_i)^2}{\sum_{i=1}^{N} \left(|P_i - \bar{Q}| + |Q_i - \bar{Q}| \right)^2} \right] \right|, \quad 0 \le WI \le 1 \tag{10}$$

where n is the total number of data; Q_i and P_i are the observed and predicted sediment data, and $\bar{Q}$ is the average of observed data.

Results and discussion

Water is normally the medium involved in the process of producing and transporting sediments. The yield of sediments in the watershed system is linked with runoff processes. Since hydrological processes are of dynamic nature, better are the dynamic models. In the perspective of Central India, therefore, it is necessary to develop sediment yielding dynamic models of prediction.

Model development for runoff-sediment yield process

The daily sediment yield prediction models based on watershed runoff and sediment yield processes were developed for the Shakkar watershed. The three dynamic models (linear, nonlinear, logarithm) were developed by considering the daily dataset 1990–2005. The linear, nonlinear, and logarithm dynamic models (Eqs. 2, 3, and 4) were calibrated using the monsoon period data of Shakkar watershed, Central India. Making use of the corresponding Q, AQI, and ASI, the sediment yield was calculated by the above three models (Eqs. 11, 12, and 13). Parameters k_0, k_1, k_2 and k_3 were determined by the least square optimization technique. The estimated values of k_0, k_1, k_2, and k_3 along with R^2 of the dependent and independent variable are given in Table 2.

For the linear dynamic model, the coefficients were $k_0 = 0.0024$, $k_1 = 112.01$, $k_2 = 0.0005$, and $k_3 = 0.80$. For the nonlinear dynamic model, the coefficients were $k_0 = 0.0024$, $k_1 = 0.87$, $k_2 = 0.0005$, and $k_3 = 0.99$, whereas, in the logarithm dynamic model, the coefficients were $k_0 = 0.066$, $k_1 = 1.29$, $k_2 = 0.032$, and $k_3 = 0.11$. In the calibration, the three dynamic models (linear, nonlinear, and logarithm) performed differently with R^2 equal to 0.72, 0.78, and 0.76 correspondingly. This shows the applicability of all three models. The linear, nonlinear, and logarithm models developed by 1990–2005 datasets are (Eqs. 11–13):

$$SY = 0.0024 + 112.01(Q) + 0.0005(AQI) + 0.80(ASYI) \qquad R^2 = 0.72 \tag{11}$$

$$SY = 0.0024Q^{0.868}AQI^{0.0005}ASYI^{0.99} \qquad R^2 = 0.78 \tag{12}$$

Table 2 Estimated values of regression parameters linear dynamic model, nonlinear dynamic model, and logarithm dynamic model and coefficient of determination (R^2) for the dependent and independent variables

Regression parameters	Sediment yield dynamic model					
	Linear model		Nonlinear model		Logarithm model	
	$SY = k_0 + k_1Q + k_2AQI + k_3ASYI$	R^2	$SY = k_0Q^{k_1}AQI^{k_2}ASYI^{k_3}$	R^2	$\ln(SY) = k_0 + k_1 \ln(Q) + k_2 \ln(AQI) + k_3 \ln(ASYI)$	R^2
k_o	0.0024	0.67	0.0024	0.93	0.066	0.79
k_1	112.01		0.868		1.29	
k_2	0.0005		0.0005		0.032	
k_3	0.80		0.99		0.105	

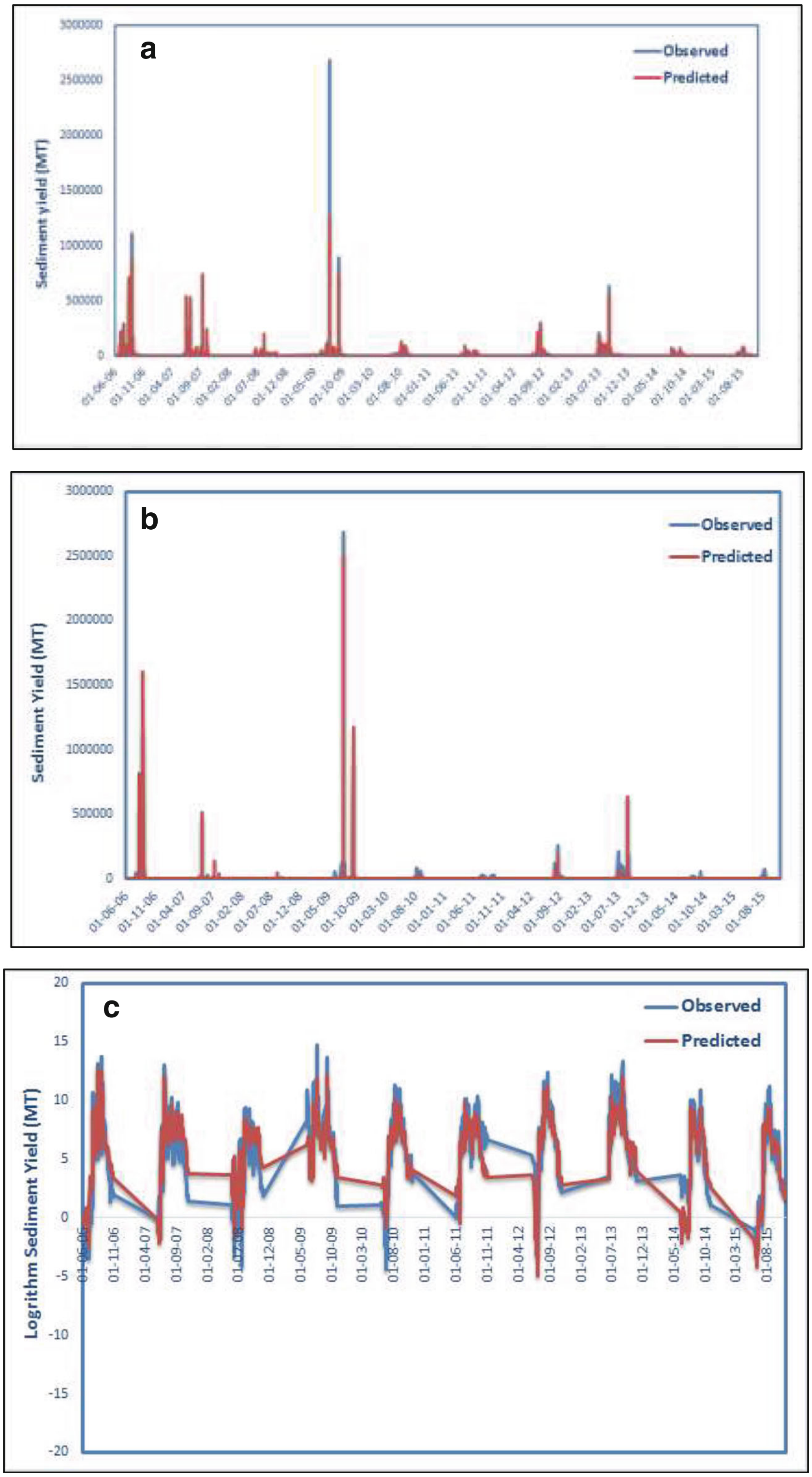
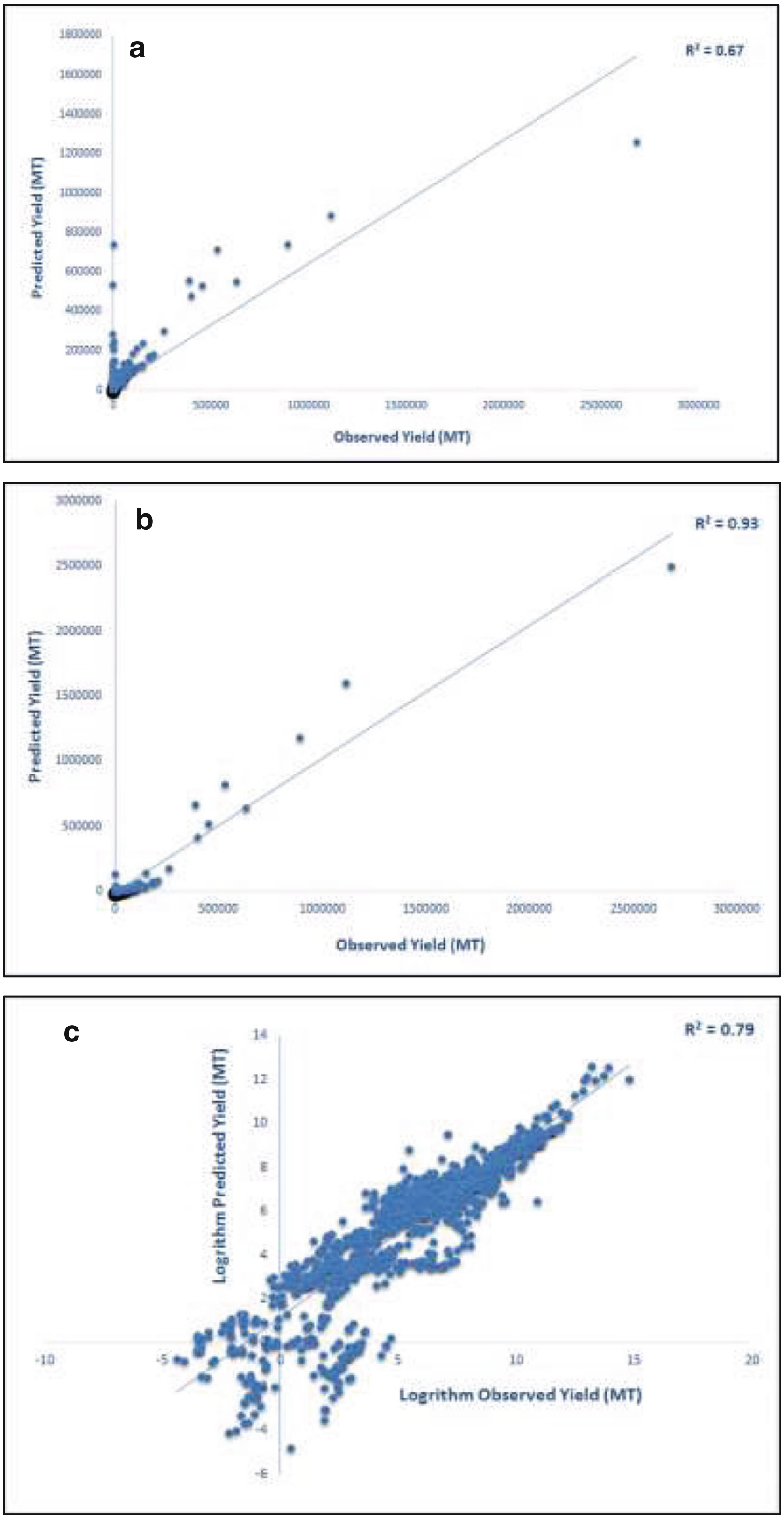


Fig. 3 Comparison of observed and predicted sediment yield using the data set (2006–2015). **a** Linear model; **b** Nonlinear dynamic model; **c** Logarithm dynamic model

$$\ln(SY) = 0.066 + 1.29\ln(Q) + 0.032\ \ln(AQI) + 0.109\ln(ASYI) \qquad R^2 = 0.76 \tag{13}$$

All the three dynamic models (linear, nonlinear, and logarithm) were tested and verified for their applicability for the study area by applying them on the daily sediment yield data series individually for successive years. The comparison of the observed value and predicted value through the developed model using the second data set (2006–2015) is presented in graphical form through Fig. 3(a–c) along with the graphical validation as shown in Fig. 4(a–c) respectively and the correlation coefficient (R^2). The values of qualitative parameters for

Fig. 4 Validation of the developed sediment yield prediction model: **a** Linear model; **b** Nonlinear dynamic model; **c** Logarithm dynamic model



model developed using the data sets of 1990–2005 are also given in Table 2. It was observed that the model performs well for the prediction of daily sediment yield data which is the necessity for a successful soil conservation program. Kumar and Das (2000) also found that dynamic model for watershed runoff and sediment yield predicts daily sediment yield. Similar analyses have been carried out by Kumar (1993) and Kumar and Das (1998, 2000).

Model validation for runoff-sediment yield process

All the linear, nonlinear, and logarithm dynamic models were validated for the daily runoff-sediment yield data series from the years 2006 to 2015**.** For validation, the above-optimized parameters (k_0, k_1, k_2, and k_3) were used for predicting sediment yield (using Eqs. 11, 12, and 13). The predicted sediment yield was compared with the observed sediment yield, for all the linear, nonlinear, and logarithm dynamic models (Fig. 4a–c). The value of the (R^2) coefficient of determinations for all the models was observed to be 0.67, 0.93, and 0.79 respectively.

The resulting NSE, MAE, and WI are shown in Table 3. The values of NSE, MAE, and WI of linear models were found to be 64.93, 12,619, and 0.88; of the nonlinear model were 92.69, 5744, and 0.98; and of the logarithm model were 79.66, 0.0162, and 0.95 respectively (Table 3). Validation statistics of all the best-fit all models were found to satisfy the criteria of a good model (Table 3). Therefore, on the basis of this performance test, it can be said that the nonlinear model was the best fit dynamic model among linear and logarithm model.

Despite the fact that dynamic models have been applied and demonstrated promising applications in many fields of scientific research, still there are some notable challenges that were attributed to dynamic models. For example, the temporal variability of hydrological processes and their influence on the water balance are observed and modeled through the comparison of a stationary (time-invariant parameters) and dynamic (time-variant parameters) model. Since conceptual models are the most adequate option for a data-scarce basin, the dynamic model is more robust than the stationary one (Toledo et al. 2015). The system dynamic model developed with STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) is a useful tool to estimate soil hydrological processes and water use in a eucalypt plantation (Ouyanga et al. 2016).

Table 3 Performance evaluation of linear, nonlinear, and logarithm dynamic model

Watersheds	NSE	MAE	WI
Linear dynamic model	64.93	12,618.83	0.88
Nonlinear dynamic model	92.69	5744.20	0.98
Logarithm dynamic model	79.66	0.02	0.95

As the literature review shows that the accuracy obtained with the help of a linear model is not sufficient, a nonlinear technique should be used. If, within the given class of problems, a rigorous nonlinear hydrodynamic model is available, it is likely to outperform most of the nonlinear models of other types (conceptual or black box system models) (Amorocho 1967; Papazafiriou 1976). There is no unique model to be superior to others in all cases and the performances of different models may be different according to the condition of each hydrological watershed. Therefore, the combination of different dynamic models (linear, nonlinear, and logarithmic) is tested and verified.

Conclusions

In this research, the aim was to create runoff-sediment yield dynamic models by incorporating the input parameters runoff (Q), the AQI, and the ASYI. All the dynamic models (linear, nonlinear, logarithm) were developed for rainfall-runoff sediment yield process for Shakkar watershed, Central India. For runoff-sediment yield process, all three models developed were performed satisfactorily. The dynamic models developed by assigning the varying weightage to antecedent events were found suitable for the study area. The results showed that the NLD model was found to be better than the linear and logarithm models. These models had Nash-Sutcliff efficiency (NSE = 92.69, 64.93, 79.66), mean absolute error (MAE = 5744.20, 12,618.83, 0.02), and Willmott's index (WI = 0.98, 0.88, 0.95) correspondingly. The watershed fluvial scheme is maintained with powerful storage material on a daily basis. The AQI and ASYI independent variables have a considerable influence on sediment yield forecast.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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