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Development of a Synthetic Sediment Graph Using Hydrological Data

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ABSTRACT

A proper and an accurate evaluation of sediment concentration is required for managers and planners for the suitable and effective design of hydraulic structures. The design of most of the soil and water conservation structures is made inaccurately, since the number of studies conducted in the field of sediment temporal distribution is limited. The problem mentioned above is particularly exaggerated in developing countries where more effort is needed in research to achieve appropriate solutions for problems encountered. The main objective of conducting the present research was to develop a model through which the temporal distribution of the watershed sediment i.e. the sediment graph during a storm event can be estimated. The model was developed on the basis of the easily accessible hydrological data of the Amameh watershed in Iran comprising an area of 3712 ha. A water discharge rating curve, precipitation-runoff relationship and sediment rating curves were developed for the watershed study for the completion and refinement of the collected hydrological data. From the Sediment Rating Curve (SRC), it was observed that in most of the cases there was more than one value of sediment discharge for the same value of runoff discharge located at the rising and falling limbs of the hydrograph. Therefore, the development of two separate regression equations for these sets of points was attempted by using regression and confidence area ellipse approaches. The approach based on the hydrological data was then used for the development of a storm-wise temporal distribution prediction model for sediment yield. Based on the results of factorial scoring, it was found that the model developed on the basis of the concept of Unit Sediment Graph and convolution into direct sediment graph using the sediment mobilized could be supposed as an acceptable performed model for the prediction of the sediment graph in the study watershed.

Keywords: Amameh Watershed (Iran), Sediment Mobilized, Sediment Rating Curve, Synthetic Sediment Graph, Unit Sediment Graph.

INTRODUCTION

Soil erosion is a serious cause of concern for soil conservationists, hydraulic engineers and environmentalists world-wide. Eroded soil is a major air and water pollutant, causing many detrimental in-site and off-site impacts. Soil erosion and sediment outflow are the results of very complex processes involving a large number of variables relating to rainfall, soil, topography, vegetation and also management practices. The careful measurement and analysis of such data is a basic pre-requisite for successful planning and design of any soil and water conservation program. Sediment outflow rate is a function of runoff magnitude, which is said to be the response of a watershed system. Although the measurement of inputs and

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outputs of a watershed is difficult to make with absolute accuracy, the mathematical relationships between these variables or parameters can be established with reasonable accuracy.

The use of models in hydrology can be categorized into two classes of assessment (a) of the existing state of the water resources for the prevailing hydrological response and (b) of the watershed and prediction of the future conditions of hydrological response (FAO, 1979). Since sediment modeling is not as mature as pure hydrologic modeling, it needs to be considered in a wider perspective and at greater depth. Different approaches related to sediment modeling have been suggested by several scientists working in this area of research.

The studies in modeling of Sediment Graphs (SG) were started in the 1970's. Sediment transport models or sediment graphs which relate sediment flow rate as a function of time are used for soil erosion control, hydraulic structure design, water resource planning, river morphology, and water quality assessment.

The commonly used technique for the development of the Unit Sediment Graph (USG) suggested by Rendon-Herrero (1978) is applicable only to gauged basins. A form of USG was indeed developed whose standard unit was 1.0 ton (910 kg) for a given duration, distributed over the watershed area, analogous in unit hydrograph analysis to 1.0 in (25mm) of excess (effective) rainfall over the same area (Singh, 1992). During the same period, Williams (1978) developed a model based on the Instantaneous Unit Sediment Graph (IUSG) applicable to un-gauged watersheds that was based on watershed characteristics. The concept of IUSG defined as the distribution of sediment from an instantaneous burst of rainfall producing one unit of runoff was considered to be the product of the IUH and the sediment concentration distribution. Chen and Kuo (1986) proposed a procedure to generate synthetic USG by using the correlation analysis. But the model was only able to synthesize sediment graph from one unit of effective sediment yield from a storm of one-hour duration. Gracia (1996) developed a method for generation of synthetic sediment graph based on the IUH theory for flood prediction and on the convolution integral theory. The method was applicable to wherever physical information i.e. areas, slopes, length of channels and soil type are available. Banasik and Walling (1996) studied the relationship between the lag time of the direct runoff hydrograph and the sediment graph, and the application of the lag times were examined for the estimation of IUSG. They developed the sediment graph model for one of the tributary of the River Exe, River Dart, in South-West England. Kothyari *et al*. (1997) have also applied the kinematics wave equation for estimation of temporal variation of sediment yield for single storm-events in small watersheds through simulation and expression of over land flow and sediment detachment and transport. The literature review showed that most of the pioneering techniques in developing sediment graphs need measured sediment graphs and hydrographs, as well as many other inputs such as the rainfall erosiovity factor and intensity for a specific storm and time parameters of hydrographs are required.

Owing to the lack of availability of hydrologic data, a proper assessment of the hydrological phenomena such as sediment yield using easily applicable and statistically acceptable models is necessary. Under the circumstances, there is the need for a sediment graph model having wide applicability under natural field conditions and requiring only a few and easily accessible input data. The sediment graph models developed based on the physical characteristics of a watershed and precipitation data are a viable and convenient tool for researchers working in this area under actual field conditions since they are the most widely available data in the watershed scale.

The main objective of the present study therefore was to develop a model through which the temporal distribution of the watershed sediment, i.e. the sediment graph, during a storm event can be estimated. The study was conducted in the Islamic Republic of Iran encountering different problems related to soil erosion mainly caused by water and comprising 1648145 km^2 area. The country is almost evenly distributed between mountainous areas and plains with an average precipitation of 365 and 95mm per annum, respectively (Mahdavi, 1992).

MATERIAL AND METHODS

In the present study, an attempt has been made to develop a conceptual model of sediment graph using available hydrologic data. The Amameh watershed, located in the northeast of Tehran and about 40km of it has been selected for development and application of the models. The Amameh watershed which covers an area of 3712 ha is one of the mountainous sub-basins of Jajroud River. It lies between 35°-51′-00″ to 35°-75′-00″ N latitude and 51°-32′-30″ to 51°-38′-30″ E longitude as shown in Figure 1. Some geographic characteristics of the watershed are summarized in Table 1.

The geological formation belongs mainly to the third geologic era. In some parts of the area, Conglomerate, Marls and Schist layers are seen alternatively in a severely folded form. The Quaternary formation also exists only to a limited extent in the collovial and alluvial areas of the watershed. There are twelve rainfall stations located over the entire watershed including ten storage and two recording ones. Of these recording raingauges one of them is situated at the outlet and the other one at the center of the watershed. One more recording raingauge is also available outside the watershed, which was used for climatological analysis.

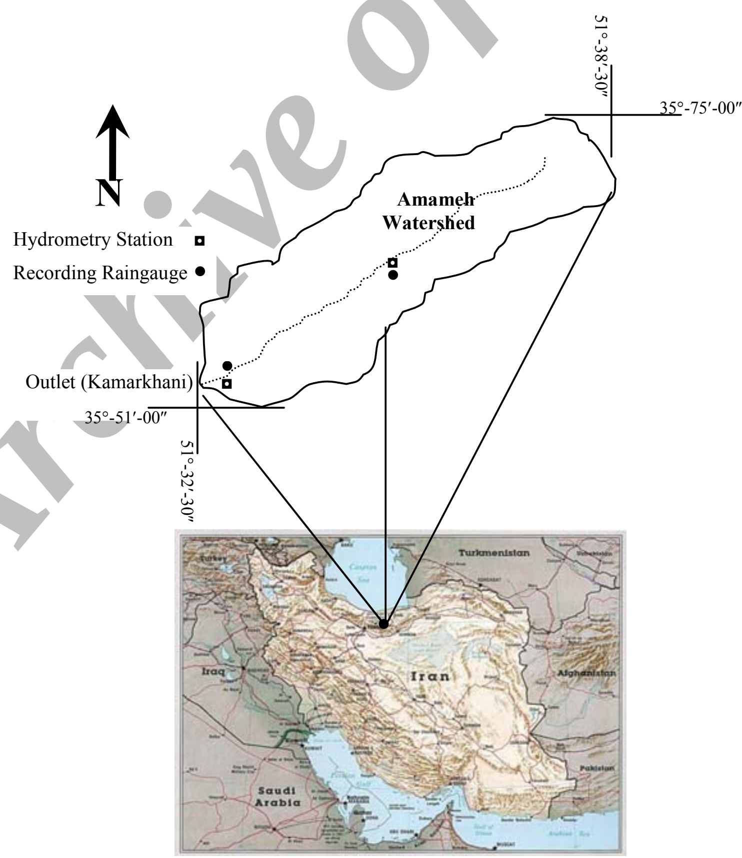

Figure 1. General view and the location of the Amameh watershed in Iran.

Table 1. Geographic characteristics of the Amameh Watershed.

Parameter	Value
Mean elevation (m)	2620
Maximum elevation (m, amsl)	3868
Minimum elevation (m, amsl)	1800
Watershed perimeter (km)	29.50
Drainage density (km/km^2)	3.39
Time of concentration (h)	2.93
Average slope of the watershed (%)	28.50
Average slope of main river (%)	13.80
Length of the main river (km)	13.50
Circularity ratio	1.33
Bifurcation ratio	5.80
Length and width of equivalent rectangle (km)	L=18.98, W=3.57
Length between the centroid and the outlet (km)	6.50

The mean annual precipitation calculated by the Thiessen method and the annual runoff are found to be 848.4 and 504 mm, respectively. Most of the precipitation (almost 73%) falls during the Winter and Spring seasons (December to May). The months of April and September are the wettest and the driest months during the year, respectively.

The annual mean temperature in the area is 8.6°C while the absolute maximum and minimum temperatures are 35 and -24°C, respectively. The least and the highest values of evaporation occur during the months of February and July, respectively. According to the Demarten classification, a very humid climate is dominant over the watershed. Humid and semi-humid climates are found in the lower portions of the area.

There are two hydrometery stations, located at the outlet (Kamarkhani) and the middle of the watershed over the main stream (Baghtangeh). The locations of the stations have been depicted in Figure 1. Both the stations have been equipped with a scale, limnograph (recorder) and a bridge since about 30 years ago. The stream discharge was measured by broad crested weirs and the available stage-discharge relationship. The average long-term discharge at Kamakhani station is 0.575 m^3/s, while the maximum and the minimum observed discharges are 21.2 and 0.01 m^3/s, respectively. The modeling processes have been carried out at Kamarkhani station located at the outlet. More than 80% of the Amameh watershed has been covered by mountainous rangelands.

In order to develop a sediment graph model, the following processes were employed. Based on the availability of data a model has been conceived with sediment mobilized as input. The sediment mobilized which is the direct excess sediment flow to the stream and is analogous to excess runoff (Das, 2000) was obtained from a relationship between sediment mobilized and excess runoff (Sadeghi, 2000). The excess runoff or rainfall excess which is the remaining volume of rainfall that flows out as surface runoff after fulfilling the initial abstractions (Das, 2000) was also estimated by using a most appropriate precipitation-runoff relationship developed for the watershed (Sadeghi *et al*., 2000). The design sediment graph was then obtained by developing a unit sediment graph for which the concept of the average unit sediment graph was conceived in the study. The average unit sediment graph was obtained by using the available hydrological data. The general concepts and assumptions of the unit hydrograph were used for the simulation of the unit sediment graph (Rendon-Herrero, 1978). The assumption of equality for the effective duration of mobilized sediment and the excess rainfall over the entire watershed, as suggested by Rendon-Herrero (1978) and Singh (1992) was also taken to be applicable on the present study. Due to the high degree of affinity between the concepts of generation of runoff and sediment during the effective period of precipitation, the effective duration of 0.5-h, considered as an appropriate duration for an average hydrograph unit in this study. It was also proposed for the derivation of the average USG for the Amameh watershed. Thus, the USG with original 0.5-h effective duration and larger were selected. The USGs with a longer effective duration were converted into 0.5-h USG by using the S-Curve.

The unit sediment graph developed for the T-hour mobilization period, analogous to a T-hour unit hydrograph, was then converted to a sediment graph by convoluting its ordinates with the unit amount of sediment mobilized. The flow chart shown in Figure 2 details the step by step procedure for the development of a design sediment graph model for the Amameh watershed. Since most of the available sediment graphs in the study area are based on discrete data due to

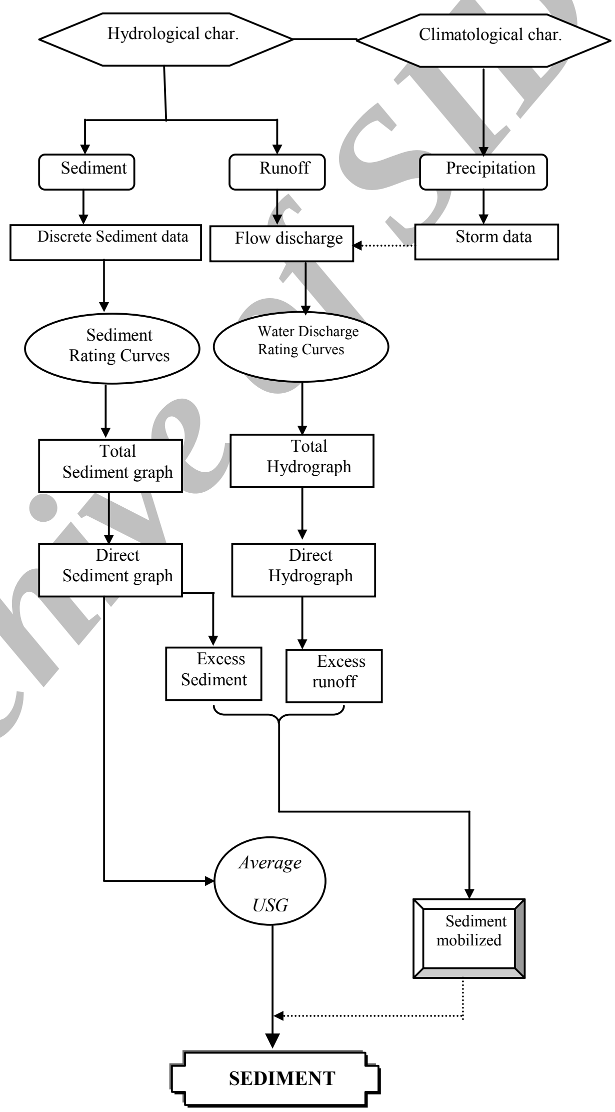

Figure 2. Sediment Graph Modeling in Amameh Watershed.

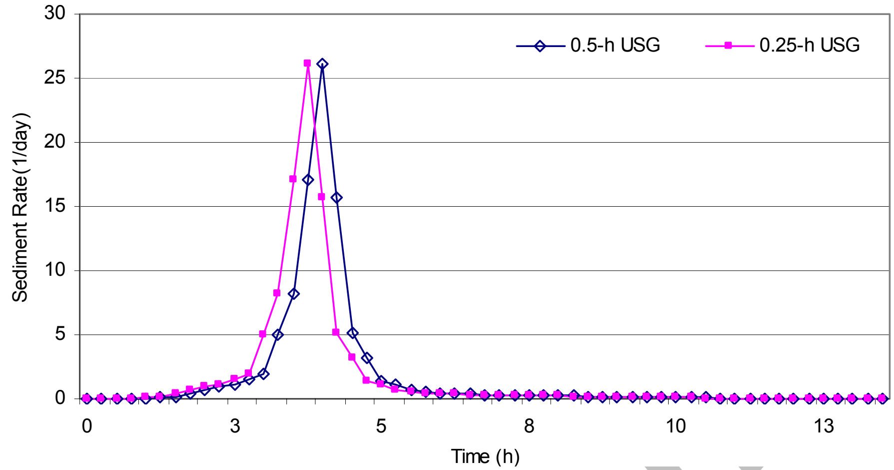

Figure 3. 0.5-h and 0.25-h Unit Sediment Graphs for Amameh Watershed.

unavailability of sediment concentration recording instruments, the continuous sediment graphs were drawn by estimating sediment discharge for the respective flow discharge with the help of separate equations developed for falling and rising limbs (Sadeghi, 2002). The Direct Sediment Graph (DSG) was then obtained by separating the base flow of sediment load from each of the storm-wise continuous sediment graphs and ultimately used for comparison. A new version of MUSLE was further revised for the study area to estimate the values of the sediment mobilized (Sadeghi and Singh, 2001). The average unit sediment graph obtained through analysis of the hydrological data was then convolved to a direct sediment graph by using the values of sediment mobilized and knowing the effective duration of the storm.

The results of modeling were finally compared with the help of qualitative and quantitative approaches. Visual comparison was used for the qualitative evaluation of results whereas the Absolute Relative Error (ARE), Integral Square Error (ISE), Relative Square Error (RSE), Ratio of Error (REO), Bias (Bs) and Correlation of Determination (R^2) were used for quantitative comparison (Sadeghi, 2000).

RESULTS

The validity of the suggested modeling process was ascertained by using eight selected storm events during 1970-1997 for the Amameh watershed based on qualitative and quantitative evaluation parameters. As per the procedure explained earlier, the unit sediment graph and the sediment mobilized generated during each of the incremental segments of effective duration of the rainfall hyetograph were required for obtaining the sediment graph models. The average storm-wise unit sediment graphs for 0.25-h and 0.5-h duration were obtained for the study area and are presented in Figure 3. The following power equation was then developed between sediment mobilized and excess rainfall by using 15 storm events and used for converting USGs into SGs.

$$ES = 8.486ER^{1.628} \qquad (r=0.949) \qquad (1)$$

where ER is excess runoff in mm and ES is excess sediment in tones.

Table 2. Summary of Prediction Performance of the Sediment Graph Model for Amameh Watershed.

Parameter	ARE				ISE	RSE	REO	Bias	R^2 (yield)	R^2 (peak)
	Total yield	Peak rate	Peak time	Base time						
Value	40.56	52.23	55.90	29.61	28.69	1.07	0.29	0.64	0.85	0.60

The sediment mobilized (excess sediment) generated during each of the time increments of effective rainfall duration for various selected storms was obtained. Based on the fundamental principle of the unit hydrograph, the ordinates of a direct sediment graph (SG) were calculated by using the appropriate unit sediment graph for the watershed. The derived USGs were then converted into a direct sediment graph by multiplying the ordinates of USG with the sediment mobilized (Equation 1). If the distribution of the sediment mobilized for all the incremental time intervals during the effective duration of excess runoff was available, then the design direct sediment graph was simulated on the basis of the concepts, of the superposition approach (Subramanya, 2000) used in unit hydrograph analysis. In the case that the distribution of sediment mobilized was not available then the design direct sediment graph was obtained during a single step of convolution.

In order to compare the results of model simulation on sediment graphs, it was observed that the graphs made predictions by using average USG obtained on the basis of hydrological data for different storm events have a sharp peak and a steep rising as well as falling limbs. It, therefore, predicts higher peaks, lesser volumes and shorter times to peak as well as base times in comparison with the respective observed sediment graphs. The general shape of sediment graphs in all of the cases is almost the same. The quantitative evaluation of the performance of the model developed was also carried out on the basis of a number of statistical parameters. The details of its performance as evaluated on the basis of each of the parameters have been set out in Table 2. The model was compared with other models developed using some different approaches and it was implied that the model based on hydrological data stands out from the viewpoint of base time estimation and in terms of the values of coefficient of efficiency, root square error, integral square error and root mean square of error criteria. It was also found that the more accurate the analysis of hyetograph results the more precise the sediment graph.

CONCLUSION

The main objective for conducting the present study was to develop a sediment graph model through which the temporal distribution of the watershed sediment generated during a storm event can be estimated. The model was developed on the basis of the easily accessible hydrological data of the Amameh watershed in Iran. The unit sediment graphs developed for different storms were then obtained and converted to 0.25-h and 0.5-h USGs, and average USGs, for these durations were obtained for the watershed. The direct sediment graph of a storm was then predicted with the help of a superposition technique after multiplying the ordinates of the appropriate T-h USG by the respective sediment mobilized for each time increment. The results of the study revealed that, although the model developed on the basis of hydrological data has not performed perfectly, the predictions have been made within the acceptable range of forecasting of natural and stochastic phenomena. It is therefore suggested that these ettorts be extended to achieve more accurate and easily applicable models.

REFERENCES

1. Banasik, K. and Walling, D. E., 1996. Predicting Sedimentgraphs for a Small Agricultural Watershed. *Nordic Hydrol.*, **27 (4)**: 275-294.
2. Chen, V. J. and Kuo, C. Y., 1986. A Study on Synthetic Sedimentgraphs for Ungaged Watersheds. *J. Hydrol*., **84**: 35-54.
3. Das, G. 2000. *Hydrology and Soil Conservation Engineering*. Printice-Hall of India Private Limited, New Delhi. 489pp.
4. Gracia, S. J., 1996. Generation of Synthetic Sedimentgraphs, Hydrol. Process., **10**: 1181-1191.
5. F. A. O., 1979. *Deterministic Models in Hydrology.* Food and Agriculture Organization of the United Nations, Rome, 75 pp.
6. Kothyyari, U. C., Tiwari, A. K. and Singh, R. 1997. Estimation of Temporal Variation of Sediment Yield from Small Catchments through the Kinematic Method. *J. Hydrol*., **203**: 39-57.
7. Mahdavi, M., 1992. *Applied Hydrology*. 1st volume. Tehran University Publication, Tehran, Iran. (Translation from original Persian), 312pp.
8. Rendon-Herrero, O., 1978. Unit Sediment Graph, Water Resour. Res. **14(5)**: 889-901.
9. Sadeghi, S. H. R., 2000. Some Aspects of Spatial and Temporal Distribution and Development of Prediction Models of Watershed Sediment Yield, Ph. D. Thesis, G. B. Pant University of Agriculture and Technology, Pantnagar, India, 232pp.
10. Sadeghi, S. H. R., 2002. Introducing Two Methods for Development of Sediment Rating Curve Equations in Rising and Falling Limbs of Hydrograph, *National Seminar on Land Management, Soil Erosion and Sustainable Development*, Arak, Iran, 11 pp.
11. Sadeghi, S. H. R. and Singh, J. K., 2001. Prioritization of Sub-watersheds in Generation of Total Sediment Yield using Routing Model, *3rd International Conference on Land Degradation*, Sept. 17-21, Brazil.
12. Sadeghi, S. H. R., Singh, J. K. and Das, G., 2000. Rainfall-Runoff Models for a Mountainous Watershed in Iran, In: *Proc. ICIWM2000*, India.
13. Singh, V. P. 1992. *Elementary Hydrology*. Eastern Economy Edition, New Delhi, India, 973pp.
14. Subramanya, K., 2000. *Engineering Hydrology*, 2nd edition, Tata McGraw Hill Publishing Company Limited, Eighth reprint, New Delhi, India, 392 pp.
15. Williams, J. R., 1978. A Sediment Graph Model Based on an Instantaneous Unit Sediment Graph, *Water Resour. Res*., **14(4)**: 659-664.

تهیه رسوب نگار مصنوعي با استفاده از داده هاي هیدرولوژیکي

س. ح. ر. صادقي و ج. ك. سینگ

چکیده

ارزیابي صحیح و دقیق غلظت رسوب به منظور طراحي موثر و مناسب سازه‌هاي هیدرولیکي براي مدیران و برنامه‌ریزان ضروري است. از آنجایي که تعداد مطالعات مربوط به توزیع زماني رسوب محدود مي باشد لذا طراحي اغلب سازه‌هاي حفاظت خاك و آب با دقت كافي انجام نمي شود. مشکل اشاره شده در کشورهاي در حال توسعه جدي تر بوده و از این رو تلاشهاي بیشتري در راستاي انجام تحقیقات براي حل مشکلات مربوطه در این مناطق ضروري است. هدف اصلي از انجام تحقیق حاضر تهیه مدلي است که با کمك آن بتوان توزیع زماني رسوب آبخیز و به عبارتي رسوب نگارهاي ناشي از رگبارها را پیش بیني نمود. مدل مذکور بر اساس داده هاي هیدرولوژیکي سهل‌الوصول در حوزه آبخیز امامه در ایران به مساحت 3712 هکتار انجام پذیرفت. به منظور تکمیل و پالایش داده‌هاي هیدرولوژیکي از منحني‌هاي تاراژ دبي، روابط بارش-رواناب و منحني‌هاي سنجه رسوب استفاده شد. از بررسي ونده و پایین رونده آب نگار بیش از یك مقدار براي دبي رسوب وجود دارد. از این رو تلاش لازم براي تهیه دو معادله رگرسیوني براي هر یك از دسته داده ها با استفاده از مفهوم رگرسیون و بیضي سطح اطمینان صورت گرفت. سپس دیدگاه مبتني بر داده هاي هیدرولوژیکي براي تهیه مدل توزیع زماني رسوب در طي رگبارها استفاده شد. بر اساس نتایج حاصل از امتیازدهي عاملي مشخص گردید که کاربرد مفهوم رسوبنگار واحد و تبدیل آن به رسوب نگار مستقیم با استفاده از رسوب مازاد از عملکرد مناسب در تخمین رسوب نگارها در منطقه مورد مطالعه برخوردار بوده است.