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Stochastic modeling of sediment load of upper Yangtze river (China)

ZHOU GANGYAN
Bureau of Hydrology, Yangtze Water Resources Commission, Wuhan (430010), China
N. K. GOEL*
Associate Professor, Department of Hydrology, University of Roorkee, Roorkee-247 667, India
V. K. BHATT
Research Scholar, Department of Hydrology, University of Roorkee, Roorkee-247667, India

Abstract
Temporal and spatial sediment load characteristics of Yangtze River, which is Asia's longest river, have been examined in this paper. Annual and monthly sediment load characteristics in temporal domain have been modelled. The annual sediment load data from 1950 to 1990 and monthly sediment load data from 1950 to 1969 have been used. Statistical tests such as turning point test, Kendall's rank correlation test and Anderson's correlogram test have been applied for randomness and trend identification. The periodicity in the sediment load data was analyzed by harmonic analysis and stochastic component was modeled by auto-regressive model.

The results indicate that the annual sediment load series is trend free at 5 percent significance level and the monthly means and standard deviations of sediment load show periodicity. The month to month correlation structure is non stationary. Using AR(1) model for dependent stochastic component 100 years of monthly sediment data have been generated. The monthly means of observed and generated data match almost perfectly.

INTRODUCTION ABOUT SEDIMENT YIELD MODELS

Due to impact of rain and flowing water large quantities of top fertile soil is eroded from the catchment and carried to sea through rivers. Large-scale landslides, earthquakes and other human activities such as cutting of forests, mining, road building and other construction activities accelerate this process. Knowledge of sediment load carried by stream is necessary for the solution of practically all problems associated with rivers. (Garde and Ranga Raju, 1985)

Changes in sediment yield reflects changes in basin conditions including climate, soil erosion rate, vegetation, topography and land use. Fluctuation in sediment load affects many terrestrial and coastal processes including ecosystem responses because nutrients and chemicals are also transported along with sediment load.

Haan et al. (1982), Walling (1988), Singh (1989) and Mathur et al. (1992) have reviewed various sediment yield models. The sediment yield models may be grouped as (i) Em-

* Corresponding Author : Email: goelhy@rurkiu.ernet.in; goelhy@yahoo.com ; Fax: 0091-1332-73560

pirical prediction models (ii) Process based prediction models, (iii) Dynamic simulation models, and (iv) Stochastic models. Stochastic modelling has become major tool in hydrology. It is used for building mathematical models to generate synthetic hydrologic records, to forecast hydrologic events, to detect trends and shifts in hydrologic records and to fill in missing data and extend records (Maidment, 1993). The steps involved in stochastic modeling are identification and removal of significant trend, present in time series, identification and mathematical description of periodicity, identification and separation of dependent stochastic component and in the end modeling of residuals for frequency distribution.

In the present study temporal and spatial sediment load characteristics of Yangtze River, which is Asia's longest river have been examined. Annual and monthly sediment load characteristics in temporal domain have been modelled using stochastic models.

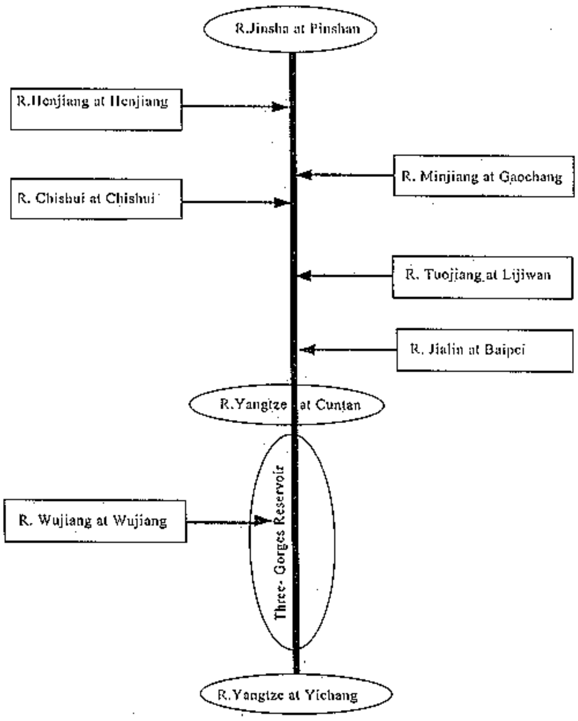

Figure 1 . Sources of sediment load on upper Yangtze.

STUDY AREA AND DATA USED

Yangtze River Basin

The study area comprises Yangtze River basin covering an area of 1.8 billion km^2, which is approximately 1/5 of the total area of China. This vast area is having about 40 percent of the country's total population. The Yangtze valley with mild climatic conditions is having a mean annual precipitation of 1100 mm. The Yangtze valley is the most important agricultural region in the country and agricultural production amounts to 40 percent of the country's total production.

The mean annual run off of Yangtze River is 952 billion m^3 (35 percent of the country's total surface runoff). The sediment concentration is 0.53 kg /m^3 and sediment load is $4.72x10^8$ tons. The large quantity of sediment is resulting in various problems of flood control, power generation, navigation and water supply for industry and agriculture.

Three Gorges Dam

The site of three Gorges dam is 38 km upstream from the Yichang (Fig. 1). It is an exceptionally large water conservation scheme possessing enormous, comprehensive utilization benefits for flood control, power generation, navigation, breeding of aquatic products and water supply. The project consists of a large dam across the river, with total storage capacity of 39.3 billion cubic meters.

The upper reaches of the three Gorges is highly prone to soil erosion and deep gulling because of deep soils, steep topography and special geological characteristics. Mostly the rocks being soft and weak in nature are weathered and result in gravitational erosion and debris flow.

Data

For comprehensive utilization and planning, engineering construction and river regulation in the Yangtze basin, a number of sediment observations (sediment yield, transportation and depositions) are taken by the Hydrology Bureau, Yangtze Water Resources Commission. 126 hydrological stations have been established on the main Yangtze river and its tributaries.

The hydrological data for the three Gorges Project are comprehensive and reliable. The hydrological station at Yichang (near dam site) and at Cutan (at the end of the reservoir) have collected hydrological data over 109 and 94 years respectively. There is regular survey of silting along the Yangtze and more than 40 years of data have been collected for the design of the project.

The following data have been used in the study:
Annual runoff and annual sediment loads from 1950 to 1990 at Yichang hydrologic station; monthly sediment load from 1950 to 1969; the distribution of sediment and composition on the upper reaches of the Yangtze River; the statistical characteristics values of water and sediment on the main Yangtze and its tributaries; and topographic maps and general geology data.

SEDIMENT VARIATION IN THE CATCHMENT

It is observed that the average modulus of sediment transport of Yangtze River is 523 t/km^2/yr. The average erosion intensity is neither high, nor its distribution is uniform in the area; the maximum value is 3000 t/km^2/yr. or more, and the minimum is about 10 t/km^2/yr (Fig.2). The area with modulus of sediment transport less than 200 t/km^2/yr. is 51.2% of the watershed area over Yichang station, and its annual sediment in Yichang. However, area with the modulus of sediment transport greater than 2000t/km^2/yr. is 7% of the watershed area, but the annual sediment load account for 43.0% of the Yichang.

Concentrated distribution of sediment of the Yangtze River mainly comes from the rivers of Jinsha, Mingjiang, Tuojiang, Jialiln, Hengjiang, Chishui and Wujiang, in which the total amount of annual average sediment load of both Jingsha River and Jialin River makes up 72.8% of that in Yichang station, which are regarded as major rivers providing sediment.

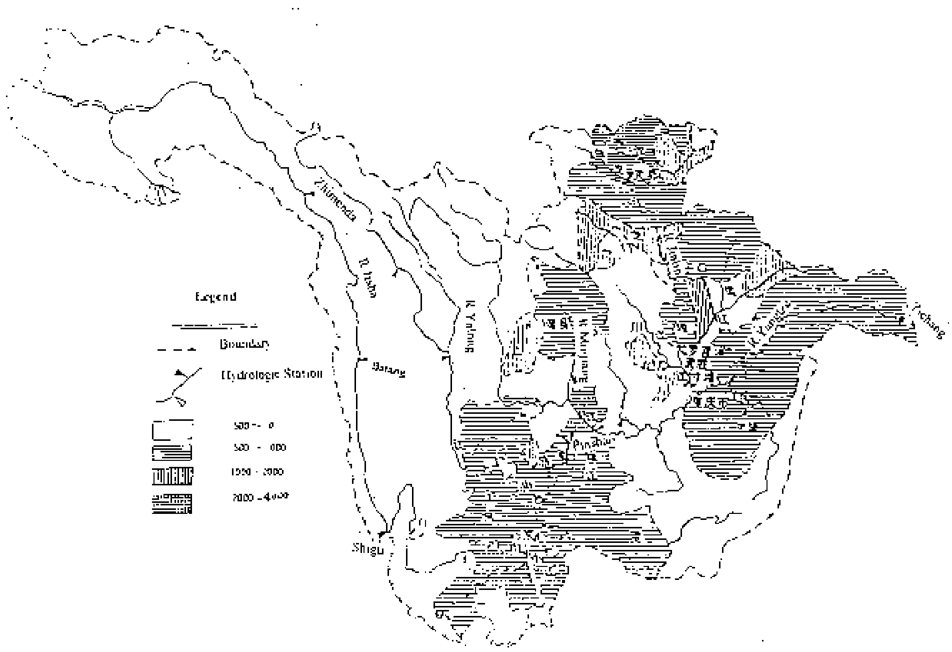

Figure 2 . Distribution of modules of sediment transport in upper Yangtze basin.

The principal area producing sediment to the Jingsha River is the main stream section of the lower reaches (from Dukou to Pingshan), including many small streams with low flows but higher sediment concentration. The sediment concentration in the river to downstream upto Batang decreases along the route. Both Xihan and Bailong River, with little water and high concentration is major sediment producer for Jialin River. But sediment load of Jialin River is less than the Jingsha River.

The variation of suspended sediment concentration and load on Yangtze River is shown in Fig.3. In the upper Yangtze, sediment increases with drainage area, however decreases in the middle and lower sections from Yichang to Hankou, due to large amount of deposition in Dongting Lake. After Dongting sediment load increases slightly. Above Yichang, sediment concentration increases and then decreases, however, sediment load, continue to increase. After Yichang, both sediment concentration and load decrease, this is due to difference in characteristics of the river. The Yangta River above Yichang is a mountainous river with a gravel and rocky bed, steep slope, high velocity with excess transport capacity and there is no exchange between suspended and bed load; the load is controlled by erosion of surface soil. Thus, the variation of sediment concentration and load in this reach is closely related to the sediment yield. Downstream of Yichang the Yangtze is an alluvial river. Regulation, storage and deposition of water and sediment in lakes, especially the Dongting Lake, significantly affect the variartions of sediment concentration and load in this section. 75 percent of the sediment from the four tributaries of rivers, which flow into Dongting Lake, are deposited in the Lake resulting in a decrease in sediment load in downstream of Yangtze. Danjiangkon Reservoir and Poyang Lake also affect the regulation, storage and deposition of silt.

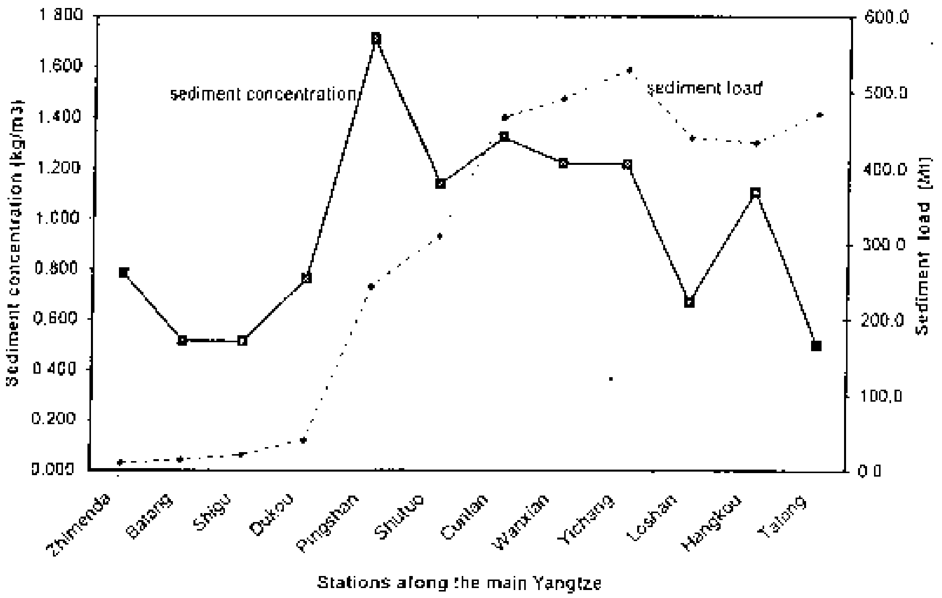

Figure 3 . Sediment concentration and load along the Yangtze basin.

In the main Yangtze, the mean annual suspended sediment load at Zhimenda Statioin in the upstream of Yangtze (Jinsha River) increases from 9.71Million tons (Mt) to 530 Mt at Yichang station. After Yichang it is decreased to 472 Mt at Datong station, a downstream control.

Among the tributaries on the Jialing River, Beibei station has the highest load of sediment (173 Mt.) followed by Gaochang station on the Minjing River with 50.7 Mt. The other major tributaries with high sediment loads are the Wujing River with 32.2 Mt. and the Yalong River with 27.5Mt.

ANNUAL VARIATION OF SEDIMENT

The variation of sediment concentration and transport of runoff throughout the year is determined by the source of sediment. For the Yangtze stem above Yichang, the sediment comes mainly from the erosion of surface soil after precipitation. The distribution of suspended sediment concentration is closely related to the variation of precipitation and runoff throughout the year. The Yangtze River being a flood dominated river, and the major proportion of runoff is concentrated in the rainy season so the trend of runoff hydrograph and sediment graph are similar (Fig.4). However, when there is no or very little precipitation, runoff is derived from ground water, resulting in low sediment concentrations and in lower sediment loads. Sediment load is a function of runoff and sediment concentration therefore high sediment loads only occur when there is a coincidence of both.

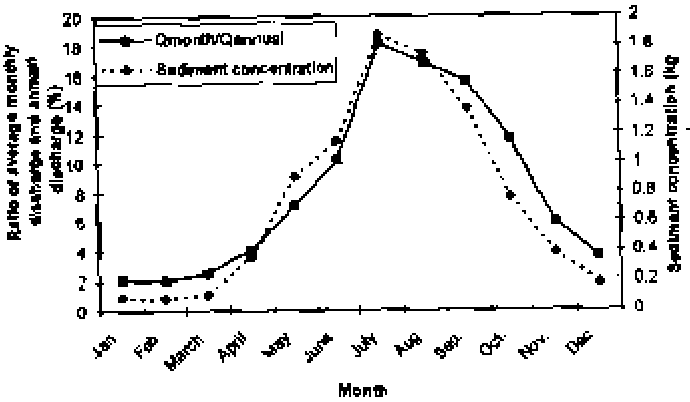

Figure 4 . The variation of sediment concentration and runoff throughout the year.

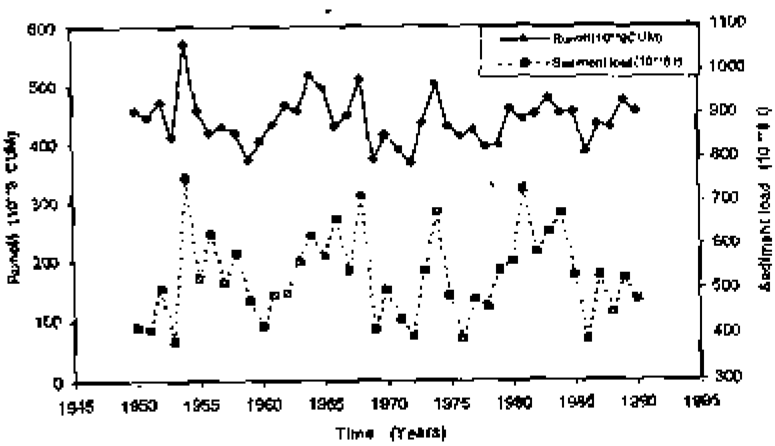

Figure 5 . Discharge and sediment load for Yichang station on Yangtze river.

The annual variation of sediment concentration and load depends on the effect of human activity as well as natural factors, such as precipitation (amount, intensity and regional distribution) and the condition of the underlying surface (geomorphologic pattern, lithologic characters, & soil characteristics). An analysis has been carried out for the annual variation of trend for Yichang station. Other upstream stations on the Yangtze stem are basically similar to Yichang.

Fig.5 shows the hydrograph and sediment load at Yichang from 1950-1990. The mean annul sediment load at Yichang station is 530 Mt. The variation in discharge and sediment basically coincide, with no obvious systematic deviation. There is a good correlation between annual runoff and sediment yield. Accumulated annual runoff has also a direct correlation with accumulated annual sediment load. The observed sediment data indicate that the variation in sediment over the years on the upper reaches of the Yangtze River is irregular over periods, as the high or low values appear alternately.

TREND IDENTIFICATION IN ANNUAL SEDIMENT DATA

Steady and regular movement in a time series, through which the values on the average increase or decrease, is termed as trend. The existence of trend in hydrological series may be due to low frequency oscillatory movement induced by climatic changes or through changes in land use and catchment characteristics.

In certain cases the presence of trend is quite obvious, but often there is doubt whether any suspected systematic effects are significant or not. For this reason, a number of statistical tests for randomness and trend identification have been devised. In present study, turning point test, Anderson's correlogram test, Kendall's rank correlation test, and Regression test for linear trend have been done for annual sediment load series from 1950 to 1990 at Yichang hydrologic station. However, the annual sediment load data are random at 95% confidence level and there is no linear trend in the data.

Table 1 . Statistical parameters of monthly sediment load data (1950-1969).

Month	Mean t/s	Stand. Dev. t/s	Correlation with Previous month
January	0.33	0.13	0.674
February	0.18	0.08	0.535
March	0.56	0.61	0.319
April	2.35	1.73	0.16
May	10.42	8.8	0.078
June	18.5	11.11	0.364
July	59.1	15.69	0.083
August	52.42	18.56	0.305
September	37.13	17.99	0.189
October	14.07	4.67	0.615
November	5.15	2.49	0.556
December	1.28	0.61	0.767

STOCHASTIC MODELLING OF MONTHLY SEDIMENT LOAD

The mean, standard deviation and correlation with previous month were computed for 1950-1969 monthly sediment load data. These parameters (Table 1) clearly show the annual periodicity. An attempt was made to smoothen the observed monthly means and standard deviation by harmonics. The results of harmonic analysis are presented in Table 2 and 3. It may be seen from these tables that even the six harmonics (maximum number of harmonics, which can be fitted to monthly data) are not able to explain the minimum variance (P_{min}) and hence it was considered appropriate to use the observed means and standard deviations.

Table 2. Harmonic analysis for monthly means.

Harmonic Number, j	A_j	B_j	$C_j^2/2$	Variance	Cum.sum	Pmin	Pmax
1	-15.49	-19.79	315.69	447.16	0.706	0.0256	0.9744
2	-2.49	11.55	69.8	447.16	0.8621	0.0256	0.9744
3	3.88	-2.82	11.5	447.16	0.8879	0.0256	0.9744
4	-2.42	1.11	3.6	447.16	0.8958	0.0256	0.9744
5	3	-1.32	5.4	447.16	0.9078	0.0256	0.9744
6	-3.98	0	7.9	447.16	0.9255	0.0256	0.9744

Table 3. Harmonic analysis for monthly standard deviation.

Harmonic Number, j	A_j	B_j	$C_j^2/2$	Variance	Cum.sum	Pmin	Pmax
1	-6.2	-6.76	42.1	52.75	0.7978	0.0181	0.9819
2	-0.97	2.42	3.4	52.75	0.8623	0.0181	0.9819
3	0.84	1.36	1.3	52.75	0.8864	0.0181	0.9819
4	0.71	-1.11	0.9	52.75	0.9029	0.0181	0.9819
5	0.11	-0.58	0.2	52.75	0.9061	0.0181	0.9819
6	-1.49	0	1.1	52.75	0.9272	0.0181	0.9819

Table 4. Statistical parameters of historical and generated data.

Month	Mean		Standard deviation		Correlation with previous month	
	historical	Generated	historical	Generated	historical	Generated
January	0.33	0.31	0.13	0.13	0.674	0.686
February	0.18	0.18	0.08	0.07	0.535	0.667
March	0.56	0.56	0.61	0.62	0.319	0.196
April	2.35	2.38	1.73	1.65	0.16	0.23
May	10.42	10.95	8.8	8.33	0.078	-0.055
June	18.5	19.1	11.11	11.04	0.364	0.379
July	59.1	57.84	15.69	15.58	0.083	0.043
August	52.42	53.16	18.56	19.86	0.305	0.265
September	37.13	34.36	17.99	20.78	0.189	0.163
October	14.07	14.58	4.67	5.01	0.615	0.617
November	5.15	5.28	2.49	2.45	0.556	0.706
December	1.28	1.27	0.61	0.57	0.767	0.795

The monthly sediment load for Yangtze River were generated using AR (1) model considering the correlation structure as non stationary. The model thus becomes equivalent to Thomas and Fiering model (1962). The mean, standard deviation and correlation with previous month of generated data (100 years) and historical data (20 years) are presented in Table 4 and plotted in Figs 6 to 8. It may be seen from Figs 6 to 8 that the statistical parameters of a historical and generated data match almost perfectly and hence the generated sediment load data may be used for further design of Three-Gorge Reservoir system.

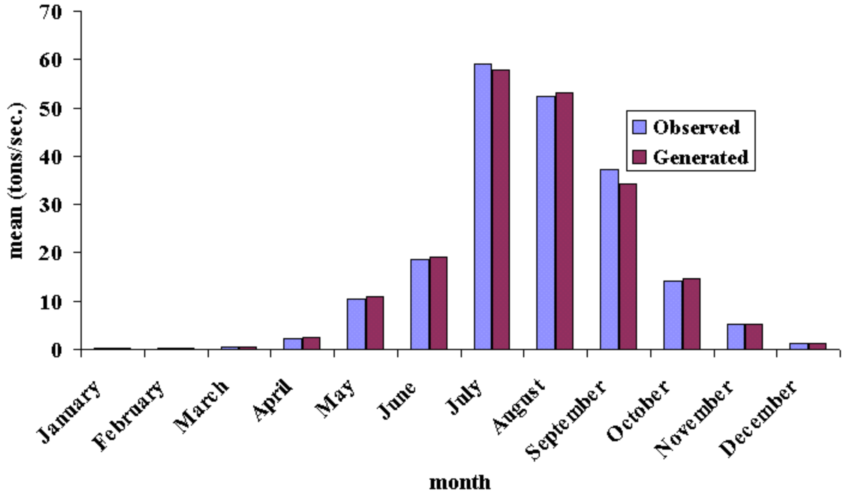

Figure 6 . Observed and generated means of monthly sediment load

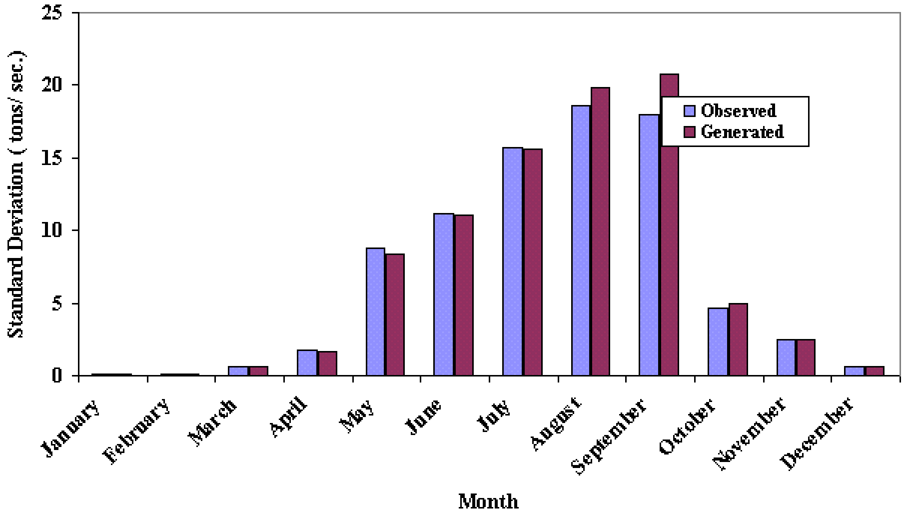

Figure 7 . Observed and generated monthly standard deviations.

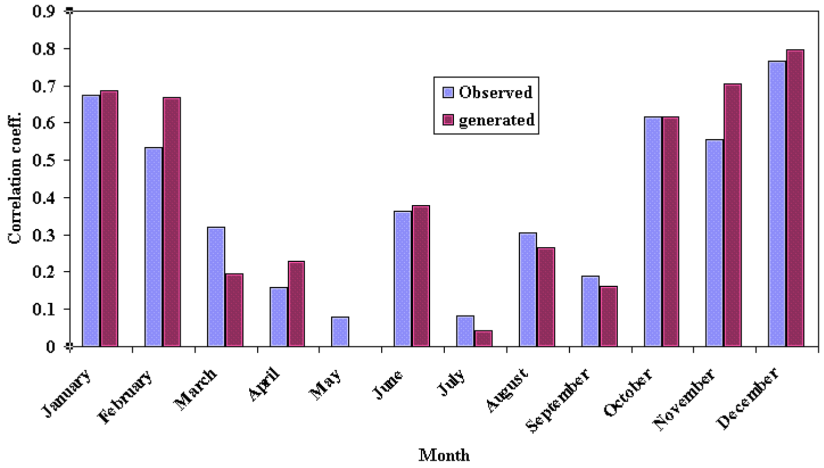

Figure 8 . Observed and generated correlations.

CONCLUSIONS

In the present study an attempt has been made to study stochastic nature of sediment yield, distribution and transport on the upper reaches of the Yangtze River. The following conclusions may be drawn from the study.

The rainfall is the principal factor affecting sediment load. The geological topography is relatively stable for the given region. But human activity has dual effects on increasing and decreasing sediment.

The main source of sediment in the Yangtze River are the Jinsha and Jialing rivers, accounting for 73-90% of the total sediment. Most of the sediment is from the area between the confluence of the Yanlong River and Jinsha River down to Pingshan, and also from the Western Han and Bailon Rivers.

There is no systematic variation in annual sediment load series.

Means and standard deviations of monthly sediment load data show annual periodicity and month to month correlation structure is non stationary.

Monthly sediment load data have been generated using AR(1) model for dependent stochastic component and by taking variable month to month correlation structure. Monthly means and standard deviations of observed and generated data fit almost perfectly well. 100 years generated monthly sediment load data can be used for planning future studies of Three-Gorge Reservoir system.

To minimize sediment load, more intensive soil and water conservation works are required to be taken up in lower reaches of the Jinsha River and on the upper reaches of the

Jialin River which would control 70% of the sediment load, and notably improve the state of sediment load in the upper Yangtze River.

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