Asian Journal of Scientific Research

ISSN 1992-1454

Asian Journal of Scientific Research 1 (1): 32-40, 2008
ISSN 1992-1454

Use of the Fuzzy Method for Determination of Sediment Balance and its Role on the Morphological Changes in Meandering Rivers

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Abstract: In this study the basic theories of development of the meanders in rivers are described and categorised and the role of sediment balance on the morphological changes in these types of rivers is investigated using the fuzzy method. A supervised clustering fuzzy algorithm was applied to determine the sediment balance in a meandering river. The capability of the fuzzy method in recognition of the sediment transport trend was first checked using two analytical problems and the approved algorithm was then applied to recognise the trend of sediment transport and balance for Karoon River, the largest river in Iran. The predicted results obtained from the fuzzy model were compared with the sediment balance results for three sediment measuring sites along a 140 km reach of Karoon. This research has shown that the sediment balance along the research area was negative before construction of Karoon dam and as a result the bank erosion was continued at that period and after dam operation the sediment transport capacity of the river has decreased and now the river is in sedimentation conditions. The result of this research study was also that sedimentation occurs at the outer banks for this situation and as a result the river sinuosity index decreased and radius curvature of river increased.

Key words: Fuzzy method, sediment transport, river morphology, meandering rivers

INTRODUCTION

Morphology is a part of science in which the effective parameters on the form and behaviour of the rivers systems are generally investigated. For instance, some of these parameters are sediment and hydraulic characteristics, river cross sections and plan, bed slope and bed longitudinal profile (USARmy, 1993, 1994).

Meandering rivers are apparently consisted from a series of consecutive bends connected by the reaches with different lengths. The bed slope in meandering rivers is generally small and as a result the sediment carrying capacity along the rivers is low and also the main parts of sediments are fine (silt and clay). The general form of the river cross section is trapezoidal and along the bends the cross section would change to a semi triangular form. Along the two consecutive bends the cross section is generally rectangular with lower depth and larger width. Meandering rivers are usually sinusoidal form in plan due to the special form of the velocity profile along the flow direction and transverse to the flow direction. The forms and locations of the meander bends are not fixed and the pathway is always changing with time, with the bank erosion being a main cause for the wider path and changing in the wave latitude and longitude of the curvature (Julien, 2002).

The problems related to the meander of a river are very complex and may be considered from two view points. The first one is the mechanism of the meandering phenomenon due to the mechanical and hydraulic parameters such as amplitude and direction of flow velocity and the second one is the role of the sediment transport processes in the morphological changes (Przedwojski *et al*., 1995).

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A river with sediment load more than its capacity left lots of sediment behind and this causes unbalanced river system and as a result the meandering feature forms along the river. If all parameters disturbing the flow conditions are eliminated, the shape of the channel will remain constant. The main cause for the meandering processes in a river is the flow direction, velocity components and bank caving phenomenon. The meandering feature in a river is primarily started by the flow disturbance parameters and is developed during floods. Some of the scientists believe that the meandering phenomenon in rivers happens by higher bed slopes (Przedwojski *et al*., 1995) or by higher shear stresses and energy dissipation on banks or by fine suspended sediments (Leopold *et al*., 1964).

In recent years due to the huge eulargement in sophisticated computers, the computational models with the intensive mathematical iterations are widely used in river engineering. Among these new methods, genetic algorithm, artificial neural networks and fuzzy logic algorithm are increasingly applied to the different problems in nature. Bardossy *et al*. (1990) applied the fuzzy logic method in hydrology. Horikawa *et al*. (1992) and Keller *et al*. (1992) developed the fuzzy models for specifying and classifying different algorithms. Capra (1994) used this new method to drought classification. Russel (1996) developed a fuzzy model to optimise the reservoir dam operation and compared the results with the corresponding results obtained from the linear optimisation program. He concluded that there is not significant difference between these two methods. Sherstha *et al*. (1996) also applied fuzzy method to model the reservoir dam operation. Kashefipour *et al*. (2005) developed a neural network model for predicting caliform bacteria along the Scotland coastal waters. Nayak *et al*. (2005) developed a neurofuzzy model for the short term flood forecasting. Vernieuwe *et al*. (2005) used a Takagi-Sugeno fuzzy algorithm to determine the precipitation-runoff relationship. Kisi (2005) used a neurofuzzy algorithm for modelling suspended sediment transport processes. El Kadi and Paquier (2006) applied a fuzzy logic algorithm to model the effect of sediment transport for morphological changes during a flood event for Ha!Ha! River.

The main aim of this research study is to investigate the role of sediment balance on the meandering development processes using a fuzzy logic algorithm. This model enables the river engineers and environmental managers to predict the probable displacement of meanders and morphological changes along the rivers and as a result they would be able for making the best decisions regarding river banks' protection projects.

MATERIALS AND METHODS

Research Area

Karoon River, the largest river in Iran with an average annual discharge of 643 m^3 sec^{-1}, located in the south west of Iran in Khoozestan province. This river is an alluvial river with fine sediments in bed and due to too many known and unknown factors is a meandering river. Figure 1 shows the research area and its situation in Iran. The operations of two big dams at the upstream of the tributaries of this river during the past forty years and also development of the water resources within the Khoozestan plain during the recent years have made a very unstable river and the meandering bends of the Karoon river immigrate each year, with a large bank erosion left behind. Recent researches have shown that the flow capacity and conveyance factor of this river has extremely reduced (Al-e-Yasin, 1999).

Aerial photos and satellite images show that too many small and large islands have formed along this river, mostly at the north and south of Ahvaz city during the recent years. These islands not only have reduced the conveyance capacity of the river but also increased the floods risks around this city. Observations have also shown that too many intakes along the river have serious problems due to sedimentation and erosion.

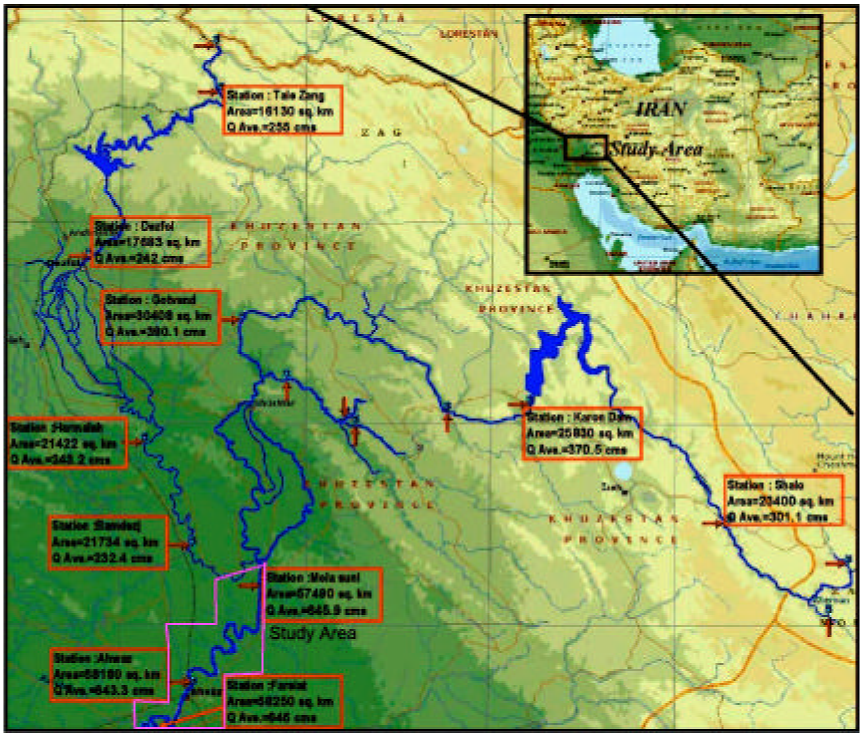

Fig. 1: The location of Karoon River and the research area

In this study the fuzzy method has been deployed to investigate the sediment balance along a 140 km reach and the aerial photos, satellite images and topography maps were used for investigating of the physiographic characteristics of the meanders.

Data

The data used in this research study were daily average discharge and daily average sediment discharge taken in some days of a year during 1952-1996 at 3 survey sites along the considered research reach. These sites were Mollasani (located 80 km in the north of Ahvaz), Ahvaz Site and Farsiat (located 45 km in the south of Ahvaz). The situations of these sites have also shown in Fig. 1.

The coordinates of the selected points in river plan along the left and right banks of river were taken from topographic maps (1/50000), aerial photos provided in 1955, 1964 and Landsat-TM satellite images provided in 1990, 1991, 1998 and IRS-LIS satellite images provided in the year 2003.

Sediment Balance Estimating Method

For the sediment balance the measured suspended sediment values at the mentioned survey sites were used and by applying a fuzzy clustering method an algorithm was introduced. In this method the simultaneous measured discharge and sediment discharge were used. It is usual to apply a regression analysis for estimating the suspended sediment discharge however, the fuzzy method has too many advantages in comparison with the traditional statistical and regression analysis methods. These advantages may be listed as follows.

- The time dependence and physical conditions of data collecting such as the base flow or flood discharge conditions and wet and dry periods for rivers are not recognized by the traditional regression analysis.

- Each data has the same effect on the trend of the best fit line in regression analysis. Since the most data are usually collected during the base flow discharge of rivers and the effects of floods in transporting sediments are much more than the normal conditions, thus more errors may happen in estimating the sediment transport using regression analysis. The restrictions of using these types of models would be clear when the river is out of the normal regime due to the operation of new dams, new hydraulic structures and so on.
- In regression analysis there is no difference in wet and dry years.
- In traditional method the time variation of sediment concentrations is not considered.
- Sometimes choosing one best curve line passing through measured data is not possible and the data are experimentally divided into two or more regions.

Supervised Fuzzy K-mean Clustering Method (Javaheri, 2005)

In this method the number of clusters is determined according to the domain conditions of the measured data. The number of clusters would be somehow that changing the sediment transport algorithm is possible. For a suitable sediment transport algorithm the following items are considered:

- For a specified discharge (Q) which has happened at a time t, searching for the corresponding sediment discharge (Q_S) will be taken place in a discharge range of Q±ΔQ and time t±Δt.
- In this method Q would be considered as the center of the cluster. Therefore, in fuzzy method for any variable the desirable searching area in the clusters could be selected.
- In this method Q_s is determined in daily form using the discharge Q within any proper period. Therefore, in the fuzzy method the effect of wet and dry periods, construction and operation of the new hydraulic structures such as dams is considered in the trend of sediment transport.

The variable time is defined as:

$$t_i = y_i+(m_i-1+d_i/30)/12 \qquad (1)$$

where, y, m and d are year, month and day, respectively. t_i is the recording date of Q and Q_s. In this case the function of the fuzzy dependence for a discharge Q_j in time t_j is written as:

$$W_{ij} = e^{-C_1(Q_j-Q_i)^2-C_2(t_j-t_i)^2} \qquad (2)$$

where, W_{ij} is the dependence degree of Q_j measured at time t_j to the observed Q_i measured at time t_i. The coefficients C_1 and C_2 show the fuzzy measure of the system and are determined as follows: If $Q_j = Q_i$ and $t_j = t_i$ then $W_{ij} = 1$ and if $Q_j = Q_i \pm \Delta Q$ or $t_j = t_i \pm \Delta t$ then $W_{ij} \cong 0$. Since in this research the membership function has been selected as a power function (Eq. 2), then the minimum value of W_{ij} could not exactly reach to zero and it is usual to choose a very small value close to zero. Thus,

$$e^{-C_1(Q_j-Q_i)^2} = O(10^{-5}) \qquad (3)$$

and

$$e^{-C_2(t_j-t_i)^2} = O(10^{-3}) \qquad (4)$$

The function O shows the approximation degree of the coefficients C_1 and C_2. According to Equations 3 and 4 these coefficients can be calculated as

$$C_1 = \frac{5}{\Delta Q^2} \text{ and } C_2 = \frac{3}{\Delta t^2}$$

The amounts of ΔQ and Δt are calculated according to the number of clusters and existing data. This method bounds the searching domain for estimating a discharge of Q_{sj} between Q±ΔQ and t±Δt and the sediment discharge variation algorithm is determined using the variation of discharge with time. By determination of the coefficients C the amount W_{ij} for each Q_j for all observation data (i = 1,2,….,n) could be calculated and normalized as follows:

$$SumW_j = \sum_{i=1}^{n} W_{ij} \quad (6)$$

and

$$W_{ij}^N = W_{ij}/SumW_j \quad (7)$$

and as a result the estimated sediment discharge for Q_j measured at time t_j is obtained:

$$Q_{Sj} = \sum_{i=1}^{n} W_{ij}^N Q_{Si} \quad (8)$$

The total yearly sediment transport is calculated using the estimated daily sediment discharge as:

$$Q_{S-annual} = \sum_{j=1}^{365} Q_{Sj} \quad (9)$$

For a year the sediment balance may be carried out using the estimated sediment discharge for each day.

To show the capability of the fuzzy method in estimating a variable an example is shown in Fig. 2. In Fig. 2 the results of this method are compared with the results of traditional regression analysis and the assumed data.

Since the sediment discharge is not measured for all days during a year, whereas the discharge is recorded in daily form at the hydrometric survey sites, sediment discharges at the considered sites were estimated in daily form using the above mentioned procedure and the yearly results are summarised in Table 1. The sediment balance has been also carried out for the years before and after the operation of two big reservoir dams namely Dez and Karoon and the results are appended to Table 1.

Physiographic Studies of Meanders

To investigate the spatial situations of the meanders a few statistical parameters such as maximum, arithmetic mean, minimum, variance and the geometric characteristics of river plan including: top width of the river, curvature radius and center line deviation angle of river were determined. Although all statistical formulations are as defined in the literature, some of them according to the special research area were modified as follows (Przedwojski *et al*., 1995):

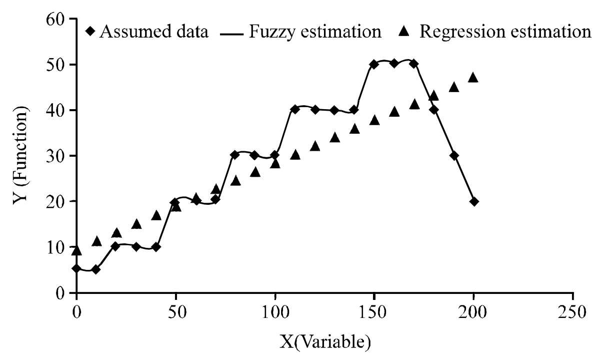

Fig. 2: Comparison of the results obtained from the fuzzy method and regression analysis with the assumed data as an example

Table 1: Annual and periodic sediment discharge from the considered stations using the fuzzy method (million ton)

	Mollasani			Ahvaz			Farsiat			
Year	Annual	Total	Average	Annual	Total	Average	Annual	Total	Average	Remarks
1952	ND			10.486			ND			
1953	ND			44.676			ND			
1954	ND			35.816			ND			
1955	ND			37.529			ND			
1956	ND			39.242			ND			
1957	ND	ND	ND	27.786	335.6	28.0	ND	ND	ND	
1958	ND			30.117			ND			
1959	ND			15.120			ND			
1960	ND			34.884			ND			
1961	ND			28.268			ND			
1962	ND			20.420			ND			
1963	ND			11.291			ND			Starting of Dez dam operation
1964	ND			27.188			ND			
1965	ND			28.711			ND			
1966	ND			19.119			ND			
1967	11.678			29.382			ND			
1968	37.254			62.200			ND			Total
1969	4.333			6.531			ND			sediment
1970	11.617	189.3	17.3	19.878	377.8	28.2	ND	ND	ND	transported
1971	23.320			63.053			ND			in Ahvaz
1972	7.450			8.945			ND			was more
1973	18.185			21.351			ND			than
1974	17.027			19.347			ND			Mollasani
1975	34.846			45.150			ND			
1976	6.937			6.249			ND			
1977	16.608			20.694			ND			Starting of Karoon dam operation
1978	9.586			11.676			ND			
1979	20.307			31.537			ND			
1980	17.629			17.747			ND			
1981	20.530			13.041			ND			Total
1982	12.387			12.899			ND			sediment
1983	4.907	166.5	15.1	8.223	161.4	14.7	ND	ND	ND	transported
1984	4.999			6.337			ND			in Ahvaz
1985	16.385			12.194			ND			was less
1986	21.949			18.775			ND			than
1987	25.713			21.334			ND			Mollasani
1988	12.136			7.595			ND			
1989	17.973			16.323			10.324			
1990	8.348			8.233			08.118			
1991	46.517			32.031			28.336			Total
1992	90.742			50.766			29.168			sediment
1993	2.175			3.709			05.091			transported
1994	22.932	242.9	27.0	21.864	159.5	17.7	19.139	124.8	13.9	in Ahvaz
1995	31.733			14.769			13.423			was less
1996	4.582			4.502			03.534			than
1997	29.432			19.569			13.343			Mollasani
1998	6.473			4.007			04.693			and more
										than Farsiat

ND: No Data available

If the average value of the geometric characteristics along a reach of river between the points I and I+1 is calculated using $X_{ave} = (X_{i+1}+X_i)/2$ for I = 1,..,n then the other statistical parameters are calculated as:

$$\bar{X} = \frac{\sum_{i=2}^{n} \ell_i X_{ave}}{\sum_{i=2}^{n} \ell_i} \quad (10)$$

Table 2: Statistical analysis of the geometric river plan parameters

Year	2003	1998	1991	1990	1964	1955
Top width						
Min.	94.7	103.9	109.3	107.2	88.4	62.0
Ave.	265.7	261.8	313.5	288.8	275.6	300.8
Max.	757.3	689.7	862.7	741.1	828.5	939.8
St.Dev.	96.9	84.0	126.4	108.8	99.4	129.1
Center line curvature radius						
Min.	138	117	133	112	113	80
Ave.	2607	2409	2234	2273	1909	1993
Max.	601449	1805390	1824909	705287	25566869	253378
St.Dev.	4.007	3.813	3.58	3.73	4.123	3.456
Center line deviation angle						
Ave.	-2.49	-2.42	-2.44	-2.47	-2.43	-2.42
St.Dev.	1.11	1.07	1.08	1.07	1.08	1.05
Ratio of top width to curvature radius						
Min.	0.000	0.000	0.000	0.000	0.000	0.000
Ave.	0.210	0.210	0.260	0.250	0.300	0.270
Max.	2.730	2.350	3.570	2.850	3.170	3.800
St.Dev.	0.290	0.280	0.340	0.360	0.380	0.360

$$S_x^2 = \frac{\sum_{i=2}^{n} \ell_i \left(X_{ave} - \bar{X}\right)^2}{\sum_{i=2}^{n} \ell_i} \tag{11}$$

where, l_i is distance between the points I and I+1 and $\bar{X}, S_x^2$ are arithmetic mean and variance of the parameters, respectively. The results of the statistical values are summarised in Table 2. It should be noted that the results in this table are taken from too many points selected from aerial photos and satellite images during the years 1955 to 2003.

RESULTS AND DISCUSSION

For the years 1952 to 1966 the ouly survey site was Ahvaz and it is not possible to be confirm about the sediment balance results however, if the same sediment transport assumed for Mollasani Station (1967-1977), it can be seen from Table 1 that the sediment balance during 1952-1977 was negative and mostly erosion was happened between these two stations. On the other hand the operation of Dez dam has had not significant effect on the river regime. According to Table 1 during 1967-1977 an amount of 1.199×10^8 ton sediments was transported from the region between Mollasani and Ahvaz to the downstream boundary of this region. For the next two periods, 1977-1989 and 1989-1998, as can be seen from this table the sediment balance in this region was positive. During these years totally 8.85×10^7 ton sediments was left between these two stations. These results show that the operation of Karoon dam was significantly effective on the river regime. Comparison of the transported sediments for the stations Ahvaz and Farsiat for the last period shows an amount of 3.47×10^7 ton sediments deposited in this area. Each year generating and developing of the islands from upstream of Ahvaz to the downstream of this city confirms these balances. It should be noted that the construction of some bridges over Karoon River along Ahvaz city in recent years could be another main cause for changing the river regime.

From Table 2 it can be seen that the maximum river width in the research zoon was 940 m in 1955 and 757 m in 2003. The average width of the river along the research area was 301 m for the year 1955 and 266 m in 2003 and the minimum values of river width were 62 and 95 m for the years 1955 and 2003, respectively. It seems that the Karoon river width decreased with time during the considered

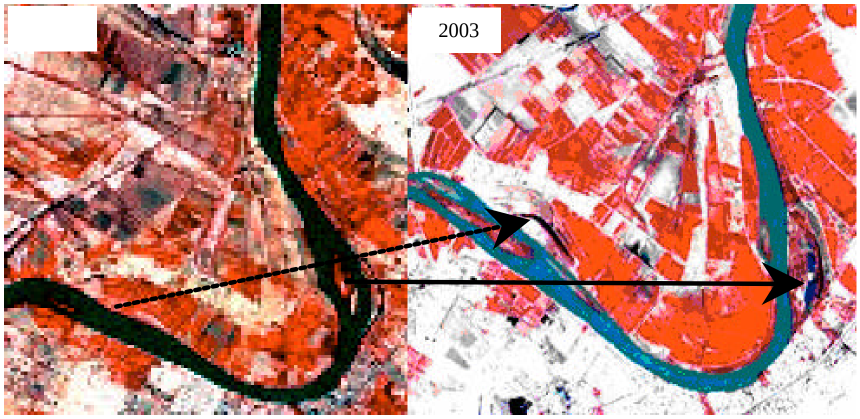

Fig. 3: Comparison of the satellite images for the years 1998 and 2003 for two meanders of Karoon River

periods. The average center line curvature radius varied from a minimum of 1909 m in the year 1964 to an amount of 2607 m in the year 2003. The other statistical parameters related to the curvature radius in this table show an increasing trend in this geometric factor. As can be seen from Table 2 the ratio of B/R (width to the curvature radius) decreased by the time during the years 1955 to 2003. These results show an adverse trend of the developing of the meanders. On the other hand the sinuosity of the river in plan was decreased.

As it was shown the sediment balance was positive in the research area (Mollasani to Farsiat) and as it was mentioned too many small and large islands were generated during the considered periods. These islands mostly are along the outer banks with small curvature radiuses. A precise inspection of the satellite images confirms that although the primary forming of these islands were close to the inner banks but by the time they were developed towards the outer banks (Fig. 3) and by the connection of these islands to the banks the curvature radius decreased during these years. Deposition of sediments in the front of intakes along the river is another fact to confirm this phenomenon. Therefore, in designing of the intakes positions these results should be considered by the designers.

CONCLUSIONS

According to the results of sediment balance for Karoon River it was fonnd that any human disturbances on the nature such as constructing bridges, dams, etc. may significantly affect the river regime. It was also fonnd that the fuzzy method is able to accurately estimate the sediment loads for the missing periods.

ACKNOWLEDGMENT

This research project was funded by The Office of Vice-Chancellor for Research of Shahid Chamran University of Ahvaz, Iran.

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