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Adib1, Arash; Foladfar, Hesam; Argashi, Nastaran

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Application of Fluvial-12 model for calculation of maximum deformation in cross sections of tidal rivers (the Karun River in Iran)

Arash Adib1
Shahid Chamran University of Ahvaz, Irán
arashadib@yahoo.com

Hesam Foladfar
Iran Water & Power Resources Development Company, Irán

Nastaran Argashi
Iran Water & Power Resources Development Company, Irán

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Abstract:

In tidal rivers design return period is multiplication of return periods of floods and tidal flows. This research considers the down stream of the Karun River in southwest of Iran as case study. For calibration of Fluvial-12 model, the deformations of river cross sections from 1996 to 2013 were measured by surveying. Using of the Ackers – White (1973) equation eventuates the best fitness between calculated deformations by Fluvial-12 model and observed deformations. This equation is an appropriate sediment transport equation for river beds and banks that their materials are silt or fine sand such as the most of tidal rivers in the world. For design return period N years, the highest erosion occurs at flood return period N years and tidal flow return period 1 year. At cross sections near the mouth of the river the highest sedimentation occurs at flood return period 1 year and tidal flow return period N years but at cross sections far from the mouth of the river the highest sedimentation occurs at flood return period N years and tidal flow return period 1 year. Because sedimentation occurs at flood cycle of tide at near the mouth of the river, tidal flow that its velocity is low causes sedimentation. On the other hand, erosion occurs at ebb cycle of tide and fluvial flow intensifies ebb velocity toward the mouth of the river therefore fluvial flow causes erosion at the whole length of the river.

Keywords: combined return period, erosion, the ackers – White (1973) equation, sedimentation.

Introduction

Tidal rivers have important role for the human societies. These rivers join to seas and ships can arrive to them and carry agricultural and industrial products to cities and large factories. Changes of the cross sections of tidal rivers can prevent from ships moving and damage to the economy of countries.

The largest tidal river is the Karun River in Iran. The mouth of the Karun River was the most important war zone in Iran and Iraq war (1980 to 1988). This part of river seriously damaged during this war. Therefore sedimentation and erosion is an important problem in the mouth of river. Tidal and fluvial flows are two basic factors that influence on changes of the cross sections of tidal rivers. The separation of effects of these factors is a required task for river engineers and designers.

This research has two aspects:

1) Interaction between the tidal and fluvial flows:

Author notes

arashadib@yahoo.com

Some researchers studied about this subject and they applied different methods for this problem.

Using from analytic method as Vongvisessomjai and Rojanakamthorn (1989), utilizing numerical models as Sobey (2001) and applying stochastic methods for studying interaction between the tidal and fluvial flows as Samuels and Burt (2002).

Also researchers applied artificial neural networks and optimization methods for simulation tidal and fluvial flows, salinity, sediment transport and etc in the tidal rivers. Liang, Li, and Sun (2008) developed three Back-Propagation Neural Network models in order to improve the accuracy of prediction and supplement of tidal records. Pashova and Popova (2011) applied different Artificial Neural Networks (ANNs) (multilayer Feed-Forward (FF), Cascade-Feed-Forward (CFF), Feed-Forward Time-Delay (FFTD), Radial Basis Function (RBF), Generalized Regression (GR) neural networks and Multiple Linear regression (MLR) methods) for tidal prediction model at the town of Burgas in the western Bulgarian Black Sea coast during 1990–2003. Remya, Kumar, and Basu (2012) applied a preliminary empirical orthogonal function (EOF) analysis in order to compress the spatial variability into a few eigenmodes, so that Genetic Algorithm (GA) could be applied to the time series of the dominant principal components (PC). Adib and Nasiriyani (2016) used of ANN and GA method for determining tide velocity, ebb velocity and variation of water surface elevation by tidal flow. Adib and Jahanbakhshan (2013) applied two perceptron ANNs and Levenberg–Marquardt training method for determination of suspended sediment concentration. They applied GA for increasing regression coefficient and decreasing MSE. Adib and Javdan (2015) applied ANN and GA methods for calculation salinity concentrations in tidal rivers too. Singh (2014) illustrated that applied optimization methods for evaluation of seawater intrusion management in coastal aquifers and tidal rivers can be classified to five categories: linear programming, nonlinear programming, genetic algorithms, artificial neural networks, and multi-objective optimization models.

2) The changes of geomorphologic characteristics of rivers:

Some scientists researched about different aspects of the geomorphologic changes in rivers as effects of construction of hydraulic structures, effective parameters on formation of the braided rivers, the geomorphologic effects on discharge and water surface elevation and etc. Legleiter (2014) used geostatistical methods and variogram models for evaluation of topographic changes of longitudinal profile and cross sections of river. Saleh, Ducharne, Flipo, Oudin, and Ledoux (2013) utilized HEC-RAS one-dimensional model in the Seine River of France and showed that effects of longitudinal profile of the bed river and geomorphological irregularities are more than effects of cross-sections shapes on water surface elevation in river.

Delhomme, Alsharif, and Capece (2013) studied characteristics of 37 oxbows of the Caloosahatchee River in South Florida of U.S.A. and observed that width of oxbows increased and water depth increased in the exterior of oxbows and decreased in the interior of oxbows in both 1978 and 2011. Li, Millar, and Islam (2008) developed a two dimensional hydrodynamic-morphological model for studying about gravel transport and river morphology in the Fraser River of British Columbia, Canada. Frascati and Lanzoni (2010) used time series analysis in meandering rivers. They applied this nonlinear method for studying about the spatial series of local curvatures and the time series of long - term channel sinuosity. Lofthouse and Robert (2008) studied about meander morphology in southern Ontario of Canada. They evaluated relation between riffle–pool morphology (sequence length and amplitude) and planform curvature. Dai, Yang, and Cai (2008) showed that construction of dams reduced sediment discharge in the Pearl River of southern China. Zámolyi, Székely, Draganits, and Timár (2010) investigated about effects of neotectonic activity on sinuosity changes of the Danube River in the westernmost part of the Little Hungarian Plain from 1840 to now. Lazarus and Constantine (2013) developed a generic theory for sinuous flow patterns in landscapes. They showed that flow resistance relative to surface slope controls channel sinuosity. Constantine, McLean, and Dunne (2010) showed that sporadic changes in the capacity of river sections or the installation of natural dams and the occurrence of sudden flood surges could be the causes of cutoff formations. Güneralp and

Marston (2012) investigated about the stages of meanders formation by hydrodynamic forces and geometric pattern changes during meander formations. Smith, Morozova, Pérez-Arlucea, and Gibling (2016) studied about effects of the E.B. Campbell Dam of Canada on the Saskatchewan River such as changes of river cross sections and sediment discharge. The considered length was 108 km from the dam. Haghighi, Marttila, and Kløve (2014) developed a new combined river impact (RI) index. This index can show effects of dam construction on flow in rivers. Casado, Peiry, and Campo (2016) evaluated effects of dam construction on geomorphic and vegetation changes in the Sauce Grande River of Argentina. For this purpose, they considered downstream and upstream of river before (1961 to 1981) and after (1981 to 2004) dam construction. Termini (2016) did experiments in a meander flume and evaluated effects of vegetation on flow velocity pattern and bed shear stress along a high-curvature bend in flume. Vegetation increases turbulent in flume. Wei, Blanckaert, Heyman, Li, and Schleiss (2016) studied about effects of different parameters on secondary flow in sharp bends. They observed that secondary flow is not dependent to Froude number at range 0.1 to 0.5. Also secondary flow magnitude increases with increasing of bed roughness in strong curvature and decreases with increasing of bed roughness in mild curvature. Jing et al. (2013) developed a two- dimensional numerical model for calculation of sediment transport and bed deformation in meandering rivers. They applied this model in the upper reach of the Yellow River of China.

Schook, Rathburn, Friedman, and Wolf (2017) investigated about displacement of meanders of the Powder River in Montana of U.S.A. during 1830 to 2014. They utilized tree rings, aerial imagery and cross sections of river and observed that displacements decreased because flood peaks reduced. Mao, Picco, Lenzi, and Surian (2016) used of virtual velocity approach in two rivers of Italy, the Tagliamento and Brenta Rivers, that the material of bed of these rivers is gravel. They evaluated sedimentation, erosion and morphological changes after the floods.

This research utilizes Fluvial-12 software for determination of the deformations of river cross sections. This software shows sedimentation and erosion in different points of each cross section. The tidal flow changes very gradually whereas the fluvial flow changes very quickly. Erosion occurs at rapid changes of flow whereas sedimentation occurs at gradual changes of flow. This research verifies this subject.

Also interaction between two phenomena is a very complex problem. Design return period is a combination of return periods of two flows. Therefore this research uses of a conventional method for combination of two return periods. Conventional method assumes that combined return period is multiplication of two return periods.

Material and methods

The Karun River

The Karun River is the largest river in Iran and this river has the most volume of water among Iran's rivers. The downstream of the Karun River is selected for this research.

The upstream of this reach is Ahvaz, the centre of the Khuzestan province, and its downstream is three branches junction of Khoramshar. The length of this reach is 188.760 km. There are no major tributaries in this reach. The tidal limit of the Karun River locates at Darkhovein (at a distance of 135 km from Ahvaz). Figure 1 illustrates the selected reach.

The peak flow discharges are shown in Table 1 for different return periods.

The tidal elevations are illustrated in Table 2 for different return periods.

The indicator flood hydrograph at the upstream and the tidal elevation curve at the downstream are illustrated in Figure 2 and 3.

The annual mean temperature and precipitation in Ahvaz are 25ºC and 215 mm. Also the annual mean temperature and precipitation in Khoramshar are 25ºC and 181 mm.

The conventional method for determination of design return period and introducing Fluvial-12 software

In the conventional method, it is assumed that flood and tidal flow are two independent phenomena. If two phenomena are independent, the return period of their intersection will become multiplication of their return periods, according Equation 1 and 2.

$$P\ (A \cap B) = P\ (A)*P\ (B) \qquad (1)$$

(1)

$$T\ (A \cap B) = T\ (A)*T\ (B) \qquad (2)$$

(2)

where:

T is return period (year) and P is probability ($P = 1\ T^{-1}$). Therefore conventional method considers different combinations of return periods of flood and tidal flow for producing of the design return period. These combinations are flood with 1 year return period and tidal flow with N years return period, flood with N years return period and tidal flow with 1 year return period, flood with N/2 years return period and tidal flow with 2 years return period and etc.

N is return period of design return period.

TABLE 1.
The peak flood discharges vs different return periods in Ahvaz.

Return period (year)	1	2	5	10	20	25	50	100
Peak discharge of flood (CMS)	2507	2802	3961	4606	5142	5297	5735	6118

TABLE 2.
The tidal elevations vs different return periods in three branches junction of Khoramshar.

Return period (year)	1	2	5	10	20	25	50	100
Tidal elevation (m)	3.09	3.18	3.35	3.46	3.56	3.6	3.7	3.8

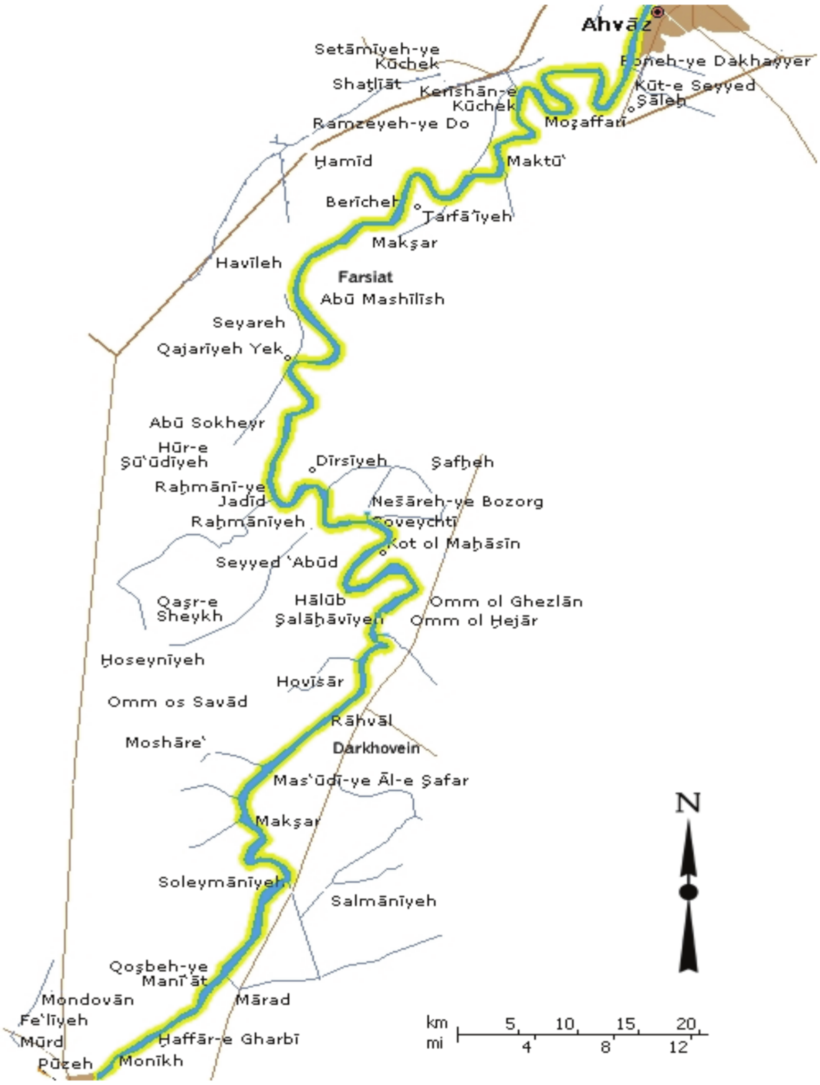

FIGURE 1.
Map of selected reach of the Karun River in Iran.

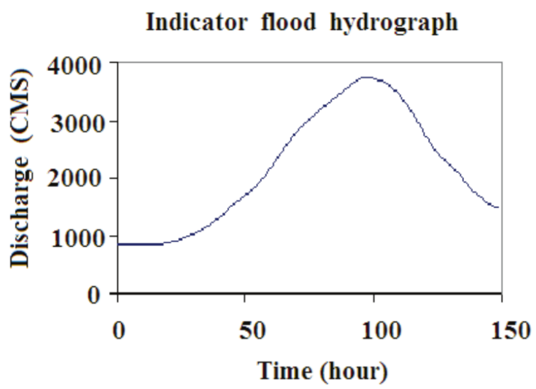

FIGURE 2.
The indicator flood hydrograph at the upstream.

Fluvial-12 software was developed by Chang (1972). This model is an unsteady model for erodible channels and can simulate channel bed scour and fill, width variation, and changes in bed topography induced by the curvature effect (Chang (1998). This software uses different total load equations (for example The Ackers – White [1973] equation). The Ackers – White (1973) Equation 3 is:

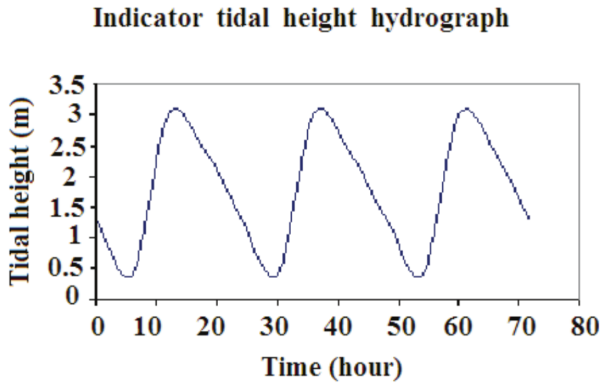

FIGURE 3.
The indicator tidal height cycle at the downstream.

$$D_{gr} = D_{50}\left(\frac{g(S_S - 1)}{\upsilon^2}\right)^{1/3} \qquad (3)$$

(3)

where:

D_{50} is mean diameter of sediment particles (mm), g is gravity acceleration (m s^{-2}), S_S is sediment specific gravity, υ is water kinematic viscosity (m^2 s^{-1}) and D_{gr} is dimensionless sediment diameter, according Equation 4.

$$F_{gr} = \frac{V_*^{\,n}}{\sqrt{gD_{50}(S_S - 1)}}\left(\frac{V}{\sqrt{32}\,\log(10\,h/D_{50}}\right)^{1-n} \qquad (4)$$

$$n = 1 - 0.56\log(D_{gr})$$

(4)

where:

$V_* = (ghs)^{0.5}$ is shear velocity (m s^{-1}), h is flow depth (m), s is the slope of river, V is flow velocity (m s^{-1}) and F_{gr} is particle mobility, according Equation 5 at 10.

$$G_{gr} = c\left(\frac{F_{gr}}{A} - 1\right)^{M} \qquad (5)$$

(5)

$$c = 10^{\,2.79\log(D_{gr}) - 0.98[\log(D_{gr})]^2 - 3.46} \qquad (6)$$

(6)

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \quad (7)$$

(7)

$$M = \frac{6.83}{D_{gr}} + 1.67 \quad (8)$$

(8)

$$G = \gamma_W QX \quad (9)$$

(9)

$$X = \frac{G_{gr} D_{50} S_S}{h\left(\frac{V_*}{V}\right)^n} \quad (10)$$

(10)

where:

G_{gr} is the dimensionless sediment transport rate, G is the sediment transport rate (Ton day^{-1}), Q is flow discharge (m^3 s^{-1}), γ_w is specific weight of water (N m^{-3})

Performance criteria

The used Performance criteria are:

Root mean square error (RMSE), according Equation 11.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{ci} - X_{oi})^2} \quad (11)$$

(11)

where:

X_c is calculated value of parameter, X_o is observed value of parameter and n is number of observations.

Correlation coefficient (R^2), according Equation 12:

$$R^2 = \frac{\sum_{i=1}^{n}(X_{ci} - \overline{X_c})(X_{oi} - \overline{X_o})}{\sqrt{\sum_{i=1}^{n}(X_{ci} - \overline{X_c})^2 (X_{oi} - \overline{X_o})^2}} \quad (12)$$

(12)

The value of RMSE should be close to zero and R^2 should be close to one.

The stages of research methodology are illustrated in Figure 4.

Results and discussion

Preparation of the inputs of Fluvial-12 model and calibration of model

145 cross sections of the considered reach were prepared by the KWPA (Khuzestan Water & Power Authority) in 1996. Distance between consecutive sections was 0.5 to 2 km. A number of these cross sections are illustrated in Figure 5.

The Manning's coefficient was considered 0.022 and 28 the river meanders were introduced to Fluvial-12 model. Distances of these river meanders to three branches junction of Khoramshar are 49-178 km. Radius of these river meanders are 106.15-361 m.

For calibration of Fluvial-12 software, dominant discharge for transportation of suspended sediment was determined. For this purpose, it is utilized sediment-flow discharge rating equations. These equations are shown at follow for different hydrometric stations, according Equation 13 and 14:

$$y = 0.0143x^{2.166} \text{ for Ahvaz} \quad (13)$$ (13)

$$y = 0.0193x^{2.1462} \text{ for Farsiat} \quad (14)$$ (14)

where:

x: Flow discharge ($m^3\ s^{-1}$) and y: Sediment discharge (Ton day^{-1}).

By using of these equations, dominant discharge is almost equal to 800 CMS. The KWPA prepared the soil grading curves for Ahvaz, Farsiat and Three branches junction of Khoramshar hydrometric stations (Figure 6).

Figure 6 states that materials of river bed and bank is silt and fine sand (non cohesive sediment). Therefore sediment transport equations of fluvial-12 software can be applied in considered reach. These equations were developed for non cohesive sediment. Also, this figure shows that sediment grain size in three branches junction of Khoramshar is more than other hydrometric stations.

The best equation for calculation of variations of cross sections of this river (from 1996 to 2013) is the Ackers – White (1973) equation (determined by calibration of Fluvial-12 software). Table 3 illustrates results of the model calibration for different equations and Table 4 expresses performance criteria for different equations.

Table 3 and 4 show below result.

1) Results of using of the Ackers – White (1973) equation are similar to results of other equations in Ahvaz. But using of this equation improves results in Farsiat and especially in Khoramshar. The reason of this subject is increasing of the grain size of river bed and river banks in Khoramshar. Results of the Ackers – White (1973) equation is suitable for silt and fine sand.

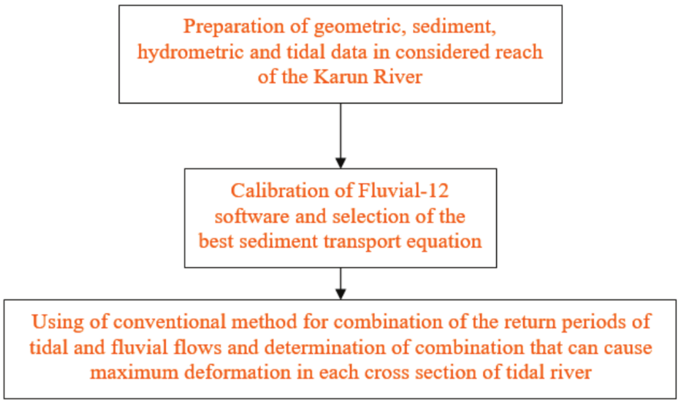

FIGURE 4.
A brief flowchart of research methodology.

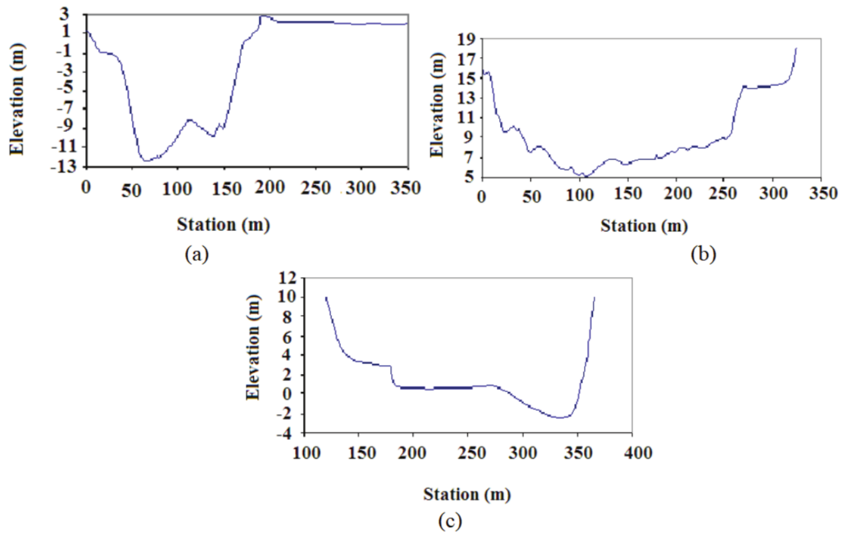

FIGURE 5.
The cross sections of considered reach a) Ahvaz b) Farsiat (60 km at downstream of Ahvaz) c) Three branches junction of Khoramshar.

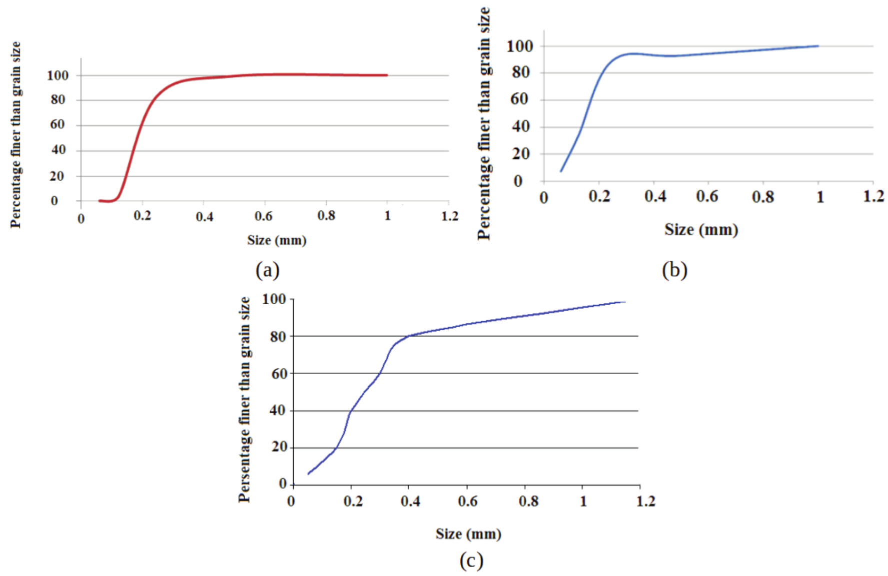

FIGURE 6.
The grading curve soil a) Ahvaz b) Farsiat c) Three branches junction of Khoramshar.

Comparison between observed cross sections (in 2013) and calculated cross sections by Fluvial-12 and the Ackers – White (1973) equation can be seen in Figure 7.

Figure 7 illustrate that fluvial-12 software can simulate deformation, sedimentation and erosion; very accurate at different parts of tidal river also results of this software at near the mouth of river are more accurate than those of software at other parts of tidal river.

Determination of maximum erosion and sedimentation based on combination of flood and tidal flow return periods

Considered design return period is 100 years in this research. Six combinations were evaluated for combination of return periods flood and tidal flow (flood 100 years and tidal flow 1 year, flood 1 year and tidal flow 100 years, flood 50 years and tidal flow 2 years, flood 2 years and tidal flow 50 year, flood 20 years and tidal flow 5 years and flood 5 years and tidal flow 20 years). The obtained results for these combinations are shown in Table 5. In this table, the calculated maximum depth of erosion and sedimentation by Fluvial-12 software and the Ackers – White (1973) equation has been stated for some points of river.

Table 5 shows below results:

1) The combination of flood with return period N years and tidal flow with return period 1 year causes the maximum erosion depth in different parts of river. Also this combination causes the maximum sedimentation depth in most parts of river.

2) The combination of flood with return period 1 year and tidal flow with return period N years causes the maximum sedimentation depth in parts of river that are near to the mouth of the river.

Tidal elevation hydrograph changes very gradually whereas flood hydrograph changes very quickly. Erosion occurs at rapid changes of flow whereas sedimentation occurs at gradual changes of flow.

3) Because river slope is low (average slope is almost 0.0001), the erosion depth is less than the sedimentation depth. The velocity of flow is low in the considered reach and flood overflows to flood plains (reduction of power flow). Also because of construction of several dams at upstream of Ahvaz (distance between the nearest dam to this region and Ahvaz is more than 200 km) floods strongly erode the bed and

banks of river at upstream Ahvaz (increasing of sediment load of flow and reduction of potential of flow for sediment transport) and eroded materials settle in considered reach during flood.

4) In the mouth of the river, tidal flow has the governing role. Therefore the tidal flow causes the maximum sedimentation. But changes of tidal flow have gradual nature and have not potential power for erosion of the bed and banks of river.

5) At the upstream of river, flood has the governing role. Sedimentation and erosion are dependent to flood discharge.

6) At the middle part of reach, the interaction between tidal flow and flood strongly reduces flow velocity. Tidal flow acts as a barrier against flood and flow is almost stationary in this part of river (121.87 km from Ahvaz). Therefore sedimentation depth has maximum value. Also backwater occurs in this part and developed disturbance increases erosion within little distance of the point that its sedimentation depth is maximum. In this part erosion depth has high value (119.577 km from Ahvaz).

TABLE 3.
Results of calibration Fluvial-12 software for different equations in hydrometric stations.

Equation	Ahvaz	Farsiat	Khoramshar
	Mean difference between calculation results and observed data (cm)	Mean difference between calculation results and observed data (cm)	Mean difference between calculation results and observed data (cm)
Graf, 1970	11.4	2.1	4.8
Yang, 1973-1986	11.4	2.3	4.1
England – Hansen, 1967	11.4	2.1	4.2
Parker, 1982	11.4	2.3	4.9
Ackers – White, 1973	11.4	1.6	1.2
Meyer-Peter-Muller, 1948	11.4	2.3	4.9

TABLE 4.
Performance criteria of calibration Fluvial-12 software for different equations in hydrometric stations.

Equation	Ahvaz		Farsiat		Khoramshar	
	R^2	RMSE (cm)	R^2	RMSE (cm)	R^2	RMSE (cm)
Graf, 1970	0.983	5.12	0.99	1.25	0.982	2.21
Yang, 1973-1986	0.992	5.09	0.986	1.34	0.984	1.97
England – Hansen, 1967	0.978	5.14	0.991	1.21	0.986	2.1
Parker, 1982	0.985	5.08	0.982	1.37	0.975	2.34
Ackers – White, 1973	0.992	5.08	0.996	0.97	0.998	0.81
Meyer-Peter-Muller, 1948	0.987	5.1	0.984	1.4	0.98	2.38

TABLE 5.
The calculated maximum depth of erosion and sedimentation by Fluvial-12 software for different combination of flood and tidal flow return periods (F is flood and T is tidal flow).

Distance from Ahvaz (km)	Maximum depth of erosion (mm) (Corresponding combination)	Maximum depth of sedimentation (mm) (Corresponding combination)
66.83	37 (F100 T1)	197 (F100T1)
119.577	433 (F100T1)	855 (F100T1)
120.573	108 (F100T1)	518 (F100T1)
121.87	225 (F100T1)	985 (F100T1)
123.2	74 (F100T1)	400 (F1T100)
123.84	9 (F100T1)	172 (F100T1)
167.51	62 (F100T1)	157(F100T1)
185.5	62 (F100T1)	85(F1T100)

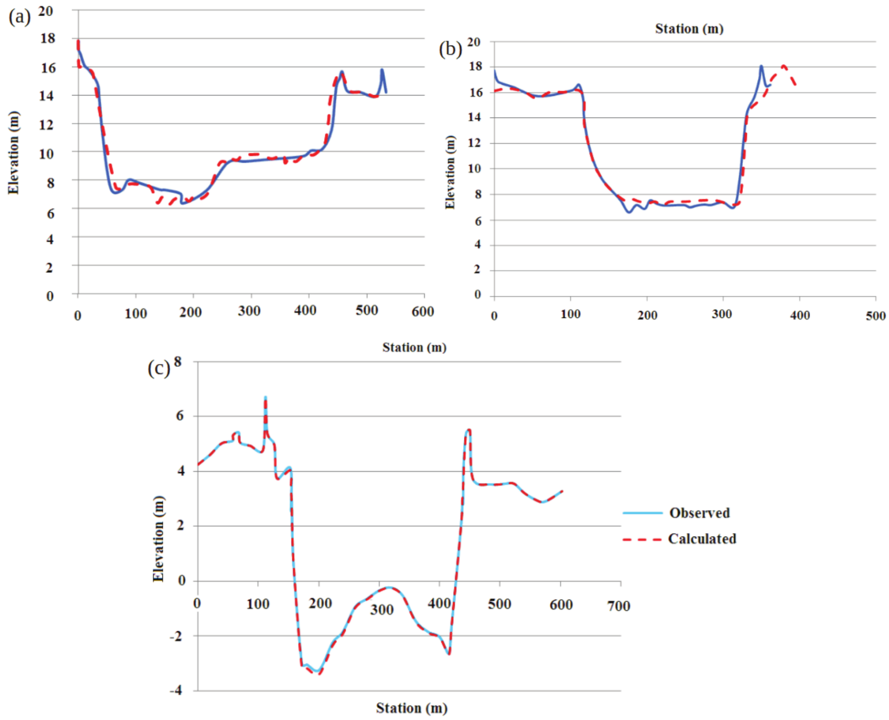

FIGURE 7.
Comparison between observed cross sections (in 2013) and calculated cross sections by Fluvial-12 and the Ackers – White (1973) equation a) Ahvaz b)Farsiat c) Three branches junction of Khoramshar.

Conclusion

Unlike non tidal rivers, determination of a combination of return periods of flood and tidal flow that can cause maximum erosion and sedimentation depth is a very important problem in tidal rivers. This combination changes in different parts of tidal river. Effective factors can change length of tidal limit in river. These factors are large or small domain of tidal height variations, the value of flood discharge, slope of river and effects of dam construction.

This research shows that erosion is dependent to the value of flood discharge and sedimentation in the mouth of the river is dependent to tidal height variations. Because of interaction of flood and tidal flow, the maximum value of sedimentation and erosion occur in the middle part of river (the tidal limit boundary).

Also, calibration of the fluvial-12 software shows that the best sediment transport equation is the Ackers-White (1973) equation. This equation is appropriate for rivers that material of their bed and bank is silt and fine sand such as the considered reach. Because of tidal flow governance, increasing of flow depth and reduction of flow velocity and slope of river, the performance criteria improve at downstream of considered reach.

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