Evaluating the Effects of Dam Construction on the Morphological Changes of Downstream Meandering Rivers (Case Study: Karkheh River)

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Abstract—**The establishment of stability in rivers is dependent on a variety of factors, and yet the established stability can be interrupted at any moment or time. One factor that can strongly disrupt the stability of rivers is the construction of dams. For this study, the identification and evaluation of morphological changes occurring to the Karkheh River, before and after the construction of the Karkheh Dam, along with determining the degree of changes to the width and length of the downstream meanders of the river, have been performed with the assistance of satellite images and by applying the CCHE2D hydrodynamic model. Results show that under natural circumstances the width of the riverbed increases downstream parallel to the decrease in the slope angle of the river. The average width of the river was reduced from 273 meters to 60 meters after dam construction. This 78% decrease in river width has made available 21 hectares of land across the river bank per kilometer length of the river. In the studied area, the average thalweg migration of the river is approximately 340 meters, while the minimum and maximum of river migration measured 53 and 768 meters, respectively. Evaluations reveal that nearly 56% of the migrations pertain to the western side of the river, while over 59% of these migrations take place outside the previous riverbed. By average, each year, the lateral migration rate of the river is 34 meters in the studied area which signifies the relevant instability of the region.**

Keywords-erosion; dam; meander; morphology; CCHE2D hydrodynamic model.

I. Introduction

After the construction of any dam, the fluvial regime of the river is subjected to consequential change and its system or pattern of erosion may undergo metamorphosis. Dam construction alters the amount of sediment production, retention and transportation of the sediments in the system. This causes changes in the pattern of erosion and thus can alter the channel's morphology in both short and long term periods. It can further change the morphological qualities of the bed and banks, which influence the amount of water transportation and the rise and fall in the elevation of the bed, ultimately resulting in the spread of flooded regions surrounding the river. All of the above can be attributed to the produced effect of morphological changes occurring to the river. The change in the direction of meanders is one of the most prominent problems regarding the instability of rivers. This change in the meander direction can seriously threaten the success of projects that are aimed at controlling floodwater. The threat can be explained by the fact that as meanders change their course and migrate, some installations such as levees and lateral flood-controlling installations tend to lose their functionality [1]. In sections of meanders, there is a high gradient of change in the distribution of velocity along the length of the river, when considering the water velocity of the inner bend of the meander towards its outer bend. Due to the continuous change in the bend's radius of curvature, fluvial parameters are more complex in meander sections than in straight river sections [2].

In [3], authors stated that the most important feature of fluvial structure in meandering rivers is the inverted vortex direction of secondary flow cells at the peak of curvature, considered before and after the occurrence of flood. The intensity and direction of vortex for these secondary flow cells have a significant effect on the morphology of the bed and banks, besides affecting the distribution of flow velocity along the length and across the width of the river. In [4], 20 meandering reaches were analyzed over a 128-km-long river reach located in the middle part of the Karoon River, Iran. The results of a paired t-test showed that river width and meander neck length have significantly changed during the study period (1989–2008), with an increase of + 3.5 m for width and a decrease of 274 m for length. In [5], it was suggested that the feedback mechanism between in-channel sedimentation and bank erosion may affect channel morphology. Here, the pattern of the bar area, bank erosion, and morphology of the gravel-bed Dunajec River upstream from the Czorsztyn Reservoir, constructed in 1997 in southern Poland were analyzed from aerial images (1982–2012). In [6], authors examined spatial variation in channel morphology and bed sediment character upstream and downstream of four run-of-river dams in Illinois. Results show that the four dams do not create major discontinuities in channel morphology or sediment character.

Silt/clay content of bed material at the four sites is higher upstream of the dams than downstream, but this size fraction generally is a minor component by weight of the sediment samples collected. An applicable instance whereby satellite images are used for study is the assessment of geometrical changes that occur to the meanders over a period of time. Usually, as the rivers reach a flooded state, the water level rises and progresses more towards the banks. Eventually, after the flooding ensues, various sizes of patches of land alongside the river become immersed in water. The repetitive evaluation of satellite images provides a convenient means for the discrimination of geometric changes to the river.

The amounts by which a dam affects the morphology of the downstream river, is largely dependent on the strategy of the dam and the features of the downstream river. Examples of studies in this field include the long term changes in the bed of the Rio Grande River as a result of establishing irrigation installations [7-8], geometrical, hydraulic changes in the downstream of the Hapcheon Dam [9], the effect of daily pulses of flow that originate from the dam on the Hwang River [10], evaluating the effect of the Englebright Dam on the downstream morphology [11] and evaluation of the effect of functionality of the Keystone Dam on the morphology of the Arkansas River [12]. It appears that the first research on the geomorphologic changes of rivers resulting from the construction of dams was conducted by Petts in the late 1970s which significantly influenced the future of relevant research in the field [13-14]. Dams can influence the fluvial pattern and the sediment load of the river. Upstream the reservoir of dams, the local groundwater level rises. Rivers that feed a reservoir deposit their load in their beds in the vicinity of the reservoir and as forms of delta inside the reservoir bed. Sedimentation reduces the slope of the riverbed and increases the elevation of the bed, thereby increasing the risk of flooding. In addition to the change in the length and width of the river channel, the occurrence of erosion in subordinate streams and in the stream's origins can be greatly influenced by changes in the basal ground level of the channel [5-18]. In [19], authors described the geometric shape of the river as a reflection of its discharge, sedimentation and the hydrological conditions of the flow. Their research focused on the role of a unit factor in evaluating the geometric pattern of the river, but seldom considered systematically the geomorphic conditions and geological setting of the river, altogether, along its route. In [20], authors applied the model of meander migration in the southern river of Virginia and compared the development and migration of meanders within the alluvial domains of sandy beds and rocky beds. The research showed that over 45% of regions the erosion model predicted to be eroded would eventually then actualize in field observations of erosion. In [21], authors evaluated the mechanism of cutoff formation along the length of big meanders by considering the topography of the floodplain and its floodwater dynamics. Their research claimed that reasons such as rapid changes in the capacity of river sections, which commonly result from the construction of dams and the sudden surge of floodwater, can generate meander cutoffs. In [22], authors assessed the stages by which morphodynamic meanders are formed. The mechanism of meander formation based on hydrodynamic forces was discussed along with realizing the patterns of change in the geometry of meanders. In [23-25], the corriolis effect on the making of meanders under laboratory conditions was simulated

This research aims to evaluate how the construction of the Karkheh Dam affects morphological changes in the downstream meandering section of the Karkheh River. For this purpose, morphological changes of the Karkheh River before and after dam construction was evaluated by satellite images, along with determining the degree of changes to the length and width of river meanders downstream the Karkheh by assistance of the CCHE2D hydrodynamic model. In this research, evaluations are made regarding the effects of dam construction on the hydraulic features and morphological characteristics downstream the Karkheh River. In this method, the changes in hydraulic shapes of the river between two stations, namely Pay-e-Pol and Abdolkhan (downstream the Karkheh Dam) were modeled by the CCHE2D model and the transition in plane and cross-section was considered in addition to the morphological changes in the river during the time span between the years 1996 and 2011 which were determined based on making comparisons between the relevant satellite images. The Karkheh Dam is the biggest dam in Iran and in the Middle East which was completed for exploitation in 2002. This dam is one of the world's biggest earth dams, which is located 22 kilometers north-west of the city of Andimeshk in the Khuzestan province of Iran. The Karkheh River is the third biggest river in Iran in terms of discharge, after the Karoon and Dez Rivers.

II. DISTRICT OF STUDY

In order to simulate the fluvial pattern for the purpose of analyzing the hydraulics of meanders, a section of the Karkheh River (downstream the Karkheh Dam and the hydrometric station of Pay-e-Pol) was selected for this study. Figure 1 displays the location of the Pay-e-Pol station on the Karkheh River, and Figure 2 shows the district selected for this study on the river.

Fig. 1. The location of the Pay-e-Pol station on the Karkheh River.

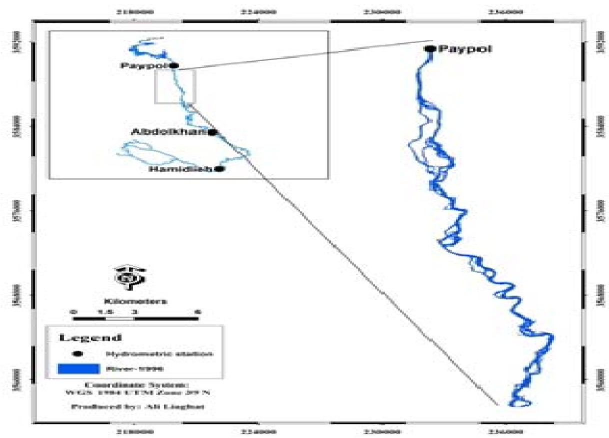

Fig. 2. Location of the selected domain of study for the Karkheh River.

III. METHODS AND MATERIALS

The stages of this research were: (i) to find the hydraulic processes of the flow and to determine its relevant features, besides simulating the transportation of sediments in the Karkheh River through the application of the CCHE2D software and the calculations of hydraulic parameters pertaining to the flow and the transportation of sediments; (ii) to compare the results obtained by simulations of the model of hydrodynamic sections and that of the identical spots, before and after the construction of the Karkheh Dam (via the assistance of satellite images) with the aim of determining the effects of dam construction on the river; (iii) to calculate the length of the river as it contributes to the river's instability and to show the morphological condition of the river, before and after dam construction. Equations pertaining to flow, herein, concerned open flow channels which are relevant to the essentials of shallow waters. Therefore, the influence of fluvial vertical motion is not so much important in this circumstance, and for this reason the averaged two-dimensional equations are of suitable precision and functionality which address the depth of a river in most cases of simulating the hydraulics of the flow. The averaged equations used for the depths of the fluvial system for its turbulent flows are presented as the equations in the CCHE2D model [24]:

Continuity equation of flow:

$$\frac{\partial Z}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}=0 \quad (1)$$

Equations of momentum (movement):

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial z}{\partial x}+\frac{1}{h}\left[\frac{\partial(h\tau_{xx})}{\partial x}+\frac{\partial(h\tau_{xy})}{\partial y}\right]-\frac{\tau_{bx}}{\rho h}+f_{cor}v \quad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial z}{\partial x}+\frac{1}{h}\left[\frac{\partial(h\tau_{yx})}{\partial x}+\frac{\partial(h\tau_{yy})}{\partial y}\right]-\frac{\tau_{by}}{\rho h}+f_{cor}u \quad (3)$$

In these momentum equations, especially in (2), the Reynolds stresses can be predicted with the help of the Boussinesq hypothesis according to the following [25]:

$$\tau_{xx}=2v_t\frac{\partial u}{\partial x} \quad (4)$$

$$\tau_{xy}=\tau_{yx}=v_t\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \quad (5)$$

$$\tau_{yy}=2v_t\frac{\partial u}{\partial y} \quad (6)$$

It is necessary to grid the environment for the discretization of partial differential equations governing the model in relation to water and sediments via numerical methods (Figure 3). The process involves gridding the selected domain via the CCHE2D Mesh Generator Model by algebraic and numerical methods. Then, the produced grids is assessed by the MDO and ADO functions. After calibrating and assessing the grids, it was observed that the environment gridded with i=30 and j=200 displayed less error in comparison with gridding by other values of 'i' and 'j'. Table I demonstrates the precision of gridding. Generally, grids are more precise when the values of the MDO and ADO functions are less.

TABLE I. CALIBRATING AND ASSESSING THE PRODUCED GRIDS.

No.	(i) value	(j) value	Function (ADO)	Function (MDO)
1	20	200	9.46	8.23
2	15	300	5.32	6.30
3	30	200	1.12	2.40

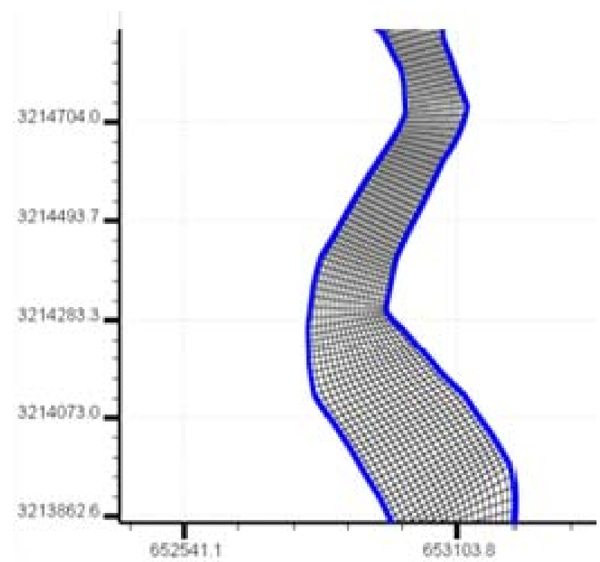

Fig. 3. Type of the produced grids of the selected domain.

A. *Analysis of the daily discharge hydrograph of the flow in the model*

One of the most important factors in determining the mechanism of floodwater hydrograph combinations and the condition of a river system at times of flood is the temporal delay between the peak discharge of floodwaters of upstream and downstream districts of the river which directly affects the peak discharge of the overall floodwater. The peak of floodwater hydrograph is important in terms of hydraulic conductivity, regardless of the volume of floodwater hydrograph, which posit the peak discharge of the hydrograph as the base for the engineering of river installations and designs. For this purpose, the relevant scale and condition of the river under critical situations of flooding which indicate the degree to which the surrounding lands of the river become flooded and immersed in water are factors determined by the peak discharge of the floodwater hydrograph. However, the influential factor affecting the erodibility of the riverbed and banks is mostly the long-term effect of discharge within a specified amount of time.

In this research, the hydrograph of flow discharge pertaining to a time span of three consecutive years was obtained from the hydrometric station upstream the river, and its information was regarded as the input data for the model. A three-year time span was considered for the time preceding the construction of the dam, and a three-year time span was studied to consider the condition after dam construction. The pre-construction period of three years was from September 1993 to August 1996, and the post-construction period of three years was from September 2008 to August 2011. This pattern of time-span selection has been practiced in previous research too [26]. Figure 4 shows the hydrograph of three consecutive years before and after the construction of the Karkheh Dam.

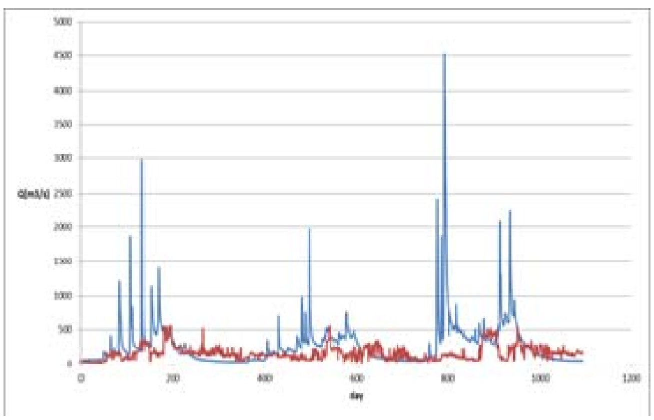

Fig. 4. The hydrograph of three consecutive years before and after the construction of the Karkheh Dam.

Determination of Manning's roughness coefficient can be done by the d50 value of materials which constitute the structure of riverbed and banks. The Strickler equation is also involved in the relevant calculations.

$$n = 0.047\, d_{50}^{\frac{1}{6}} \qquad (7)$$

Where n is Manning's coefficient value, d50 is the average size of alluvial particles (m). The method of calibrating the surface level of water was applied for calibration and assessment of the model. To correlate the calculated amount of sediment discharge with the actual amount of sediment discharge, it was supposed that the Manning coefficient which was obtained from the calibration of surface water level remains valid for this stage too. Accordingly, it was realized that the calculated values matched quite suitably with the actual values observed in the experimental field. Table II displays the Manning coefficient in the model for various domains.

B. Correlations between flow discharge and sediment discharge, the amount of suspended load and bed load in the CCHE2D model

The equation that best fits the optimum curve congruent with the data of flow discharge and sediment discharge of the Jelogir and Pay-e-Pol stations can be presented as in the following formula. The formula (8) is used for sediment data pertaining to the time before the dam was constructed, and formula (9) is used for sediment data of after when the dam was constructed [27, 28].

$$Q_s = 0.032 Q_w^{2.4027} \qquad (8)$$

$$Q_s = 0.0364 Q_w^{2.357} \qquad (9)$$

Where Q_w is the flow discharge in m^3/s and Qs is the sediment discharge expressed in ton/day.

TABLE II. MANNING'S ROUGHNESS COEFFICIENT OF THE RIVER BEFORE AND AFTER THE CONSTRUCTION OF THE DAM.

Reach No.	Distance from Pay-e-Pol st. (km)	Manning's roughness coefficient in 1996	Manning's roughness coefficient in 2011
1	12.3	0.034	0.035
2	20.1	0.039	0.039
3	30.9	0.038	0.040

The transportation of materials in a river occurs in the form of bed load and suspended load, in either case it depends on the size of particles and the velocity or other qualities of the flow. The presence of various kinds of sediments (sand, silt and clay) in the alluvial system is partially due to the process of selective transportation wherein particles are arranged in their movements. This leads to the fact that the process is related to the selective motion of various sediment particles which have an incipient motion that is nearly equal to the shear stress in the bed, but which the particles can be extensively transported when a higher degree of shear stress rules. Accordingly, (10) and (11) can be used for the input data of bed load and suspended load in the CCHE2D model [27, 28].

$$Q_w = 0.1102 BL + 5.7932 \qquad (10)$$

$$Q_w = 48.37 SL + 7.2085 \qquad (11)$$

Where Q_w is the flow discharge measured in m3/s and BL is the bed load and SL is the suspended load expressed in ton/day.

C. Grain size gradation of bed load sediments

The relationship between grain size of sediments and the hydraulic conditions of the flow was determined by the help of the flow discharge diagram in relation to the percentage of three different types of sediment particles in the bed load, namely gavel, sand and fine grains. The composition of sediment particles of the Karkheh River was 93.26% sand, 4.63% gravel and 2.08% of fine grains (silt-clay). Figure 5 shows the diagram of gradation for average grain size of sediment particles in the studied district of the Karkheh River. In the studied district of the river, the Karkheh River exhibits diverse widths along its course and sections. The river is very wide in some sections (having an extensive floodplain) and has tall banks in some other sections. Therefore, in most occasions, massive floodwaters may partially stream off the river's main course and thus cause errors in the measurement and documentation of the floodwater by downstream hydrometric stations. But to solve this problem, a wide domain of river sections was selected which also included the river's floodplain. Under these circumstances, the model can yield actual and logical results on a two-dimensional basis.

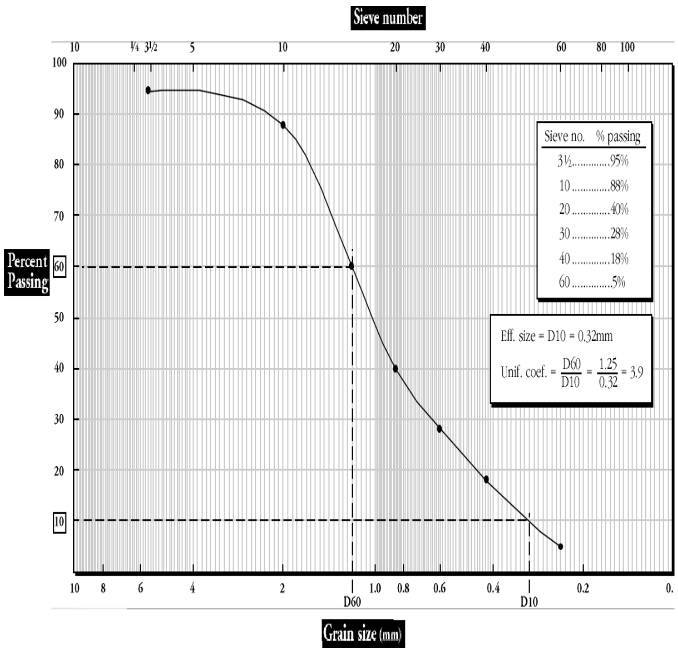

Fig. 5. The diagram of gradation for average grain size of sediment particles.

IV. RESULTS AND DISCUSSION

It is common knowledge that rivers are influenced by various factors and variables that cause them change in their dimension, direction and pattern. These changes have temporal and geographical dimensions and are affected by the discharge of flow and sediments, the features of input sediments to the system and grain size of the bed materials (of river bed and banks). Metamorphosis of rivers can be gradual and continuous in the long-term approach, or it can be sporadic and sudden if considered under certain circumstances in the short-run [29-31]. The results of these changes in this research are as follows:

A. *Changes to the widths of the river*

By measuring the widths of the riverbed obtained by results of the model in different seasons through the course of the river, the trend of change for the widths of the riverbed can be achieved. Under natural conditions, the widths of the riverbed increases towards the downstream of the river's course, parallel to the decline in the river's slope angle along the length of the river. Figure 6 and Table III show that the width of the river has been reduced considerably because of dam construction. The overall domain of the studied district measured 31 kilometers long. There were 34 sections considered along the district, and the summarization of results is presented in 6 domains (Table III). The average widths of the river before dam construction was 273 meters, its maximum and minimum widths were 589 and 75 meters, respectively. The average widths of the river became 60 meters after dam construction, the maximum and minimum of widths after dam construction were 86 and 30 meters, respectively. Therefore, by an approximate reduction of 78% in the widths of the river, nearly 21 hectares of land, per each kilometer of river length, was released from floodwater. This value pertains to the floodwater with a return period of two years.

TABLE III. AVERAGE WIDTHS OF THE RIVER BEFORE AND AFTER THE CONSTRUCTION OF THE DAM.

Average widths of river (m)		Distance end of reach from Pay-e-Pol st. (m)	zone
2011 year	1996 year		
51.4	219.4	5138	1
60.3	423.1	10852	2
57.4	289.1	15085	3
61.2	191.6	20060	4
57.3	215.9	25111	5
71.9	291.0	30982	6

B. *Changes to the plane of the river and lateral migration*

When there occurs a considerable change in the amount of flow discharge and sediment load in a meandering river, the plane of the river also undergoes considerable change as a consequence, over the specified amount of time. In Table IV, the migration of the river's thalweg is shown in addition to its direction and status in comparison with the primary conditions of the riverbed. In the studied district, the average thalweg migration of the river is approximately 340 meters, and its maximum and minimum are 768 and 53 meters, respectively.

TABLE IV. THE THALWEG MIGRATION OF THE RIVER BEFORE AND AFTER THE CONSTRUCTION OF THE DAM.

Sum thalweg migration input and output old riverbed (m)		Sum thalweg migration with the primary conditions (m)		Average thalweg migration (m)	Distance end of reach from Pay-e-Pol st. (m)	zone
Right direction	Left direction	Input old riverbed	Output old riverbed			
2855	2283	2850	2288	68.4	5138	1
0	5714	1633	4081	408.5	10852	2
3004	1229	2244	1989	356.9	15085	3
3706	1269	2366	2609	430.5	20060	4
5051	0	2281	2770	373.0	25111	5
3464	2407	3768	2103	369.4	30982	6
18080	12902	15142	15840	-	–	SUM

Figure 6 shows the changes in plane and the lateral migration of the river in the studied domain, and Figure 7 shows the diagram for thalweg migration of the river. Results show that over 51% of migrations occurred to the west side of the river, and over 58% of these migrations took place outside the old riverbed. The analysis of results shows that there is an average lateral migration of 34 meters occurring to the river each year, in the studied district, which signifies the instability of the region.

Fig. 6. The changes in plane and the lateral migration of the river in the studied domain.

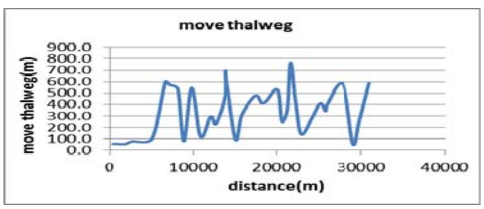

Fig. 7. The diagram for thalweg migration of the river

C. Changes to the longitudinal profile and the level of riverbed

The slope angle along the length of the river is first controlled by the conditions and features of topographic and geological characteristics of the watershed region. The slope, however, would change gradually as a result of erosion and disintegration of materials. With increasing the slope value the erosion level of the river bed will be increased and visa versa (because of the velocity of water). This concludes to a condition that the slope of the river becomes the summation result of water flow effects and the influences of topographic and geological parameters (Figures 8 and 9).

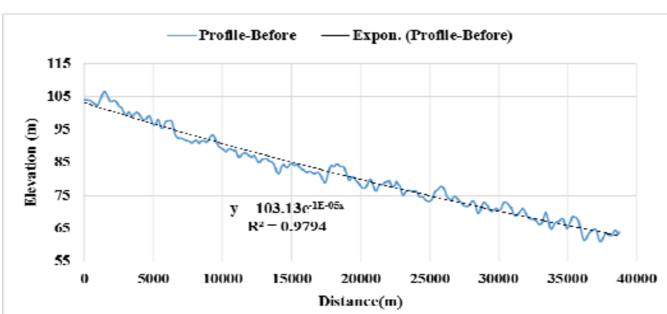

Fig. 8. Changes to the longitudinal profile before the construction of the Dam.

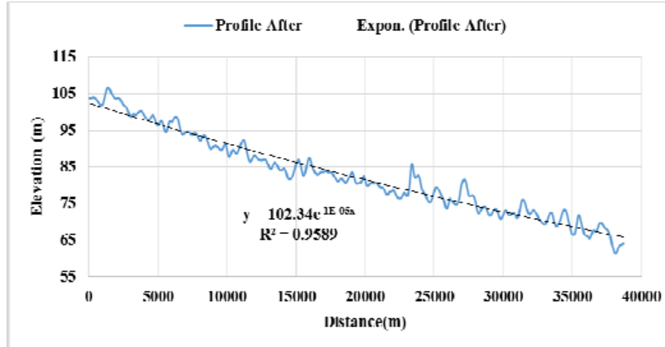

Fig. 9. Changes to the longitudinal profile after the construction of the Dam.

The equations for the longitudinal profile of the studied district, before and after dam construction, can be expressed as in (12) and (13), where El is the height of the riverbed (m), and D is the distance to the Pay-e-Pol station (m).

$$EL = 103.13 e^{-1E-05D} \quad (12)$$

$$R^2 = 0.9794$$

$$EL = 102.34 e^{-1E-05D} \quad (13)$$

$$R^2 = 0.9589$$

D. Changes to the cross-section of the water level

To illustrate the cross-section of the water level, the results of the model's performance was derived correspondingly in a congruent manner regarding the period preceding dam construction and the period after it. By comparing the cross-section of the floodwater between the pre-construction and post-construction periods, it is evident that the level of water in the river has declined in most sections, because of dam construction. Figures 10 and 11 show that in both cases of pre- and post-construction periods of the dam, the fluctuations in the river's depths are sporadic in relation to the distance from the station, but generally these changes exhibit a trend of increase in the river's depths by the longer distance from the station, in both cases of pre and post construction periods of dam construction. One reason for this increase in the river's depth can be explained by the reduction in the river's slope angle and the occurrence of sedimentation downstream the selected domain of the river.

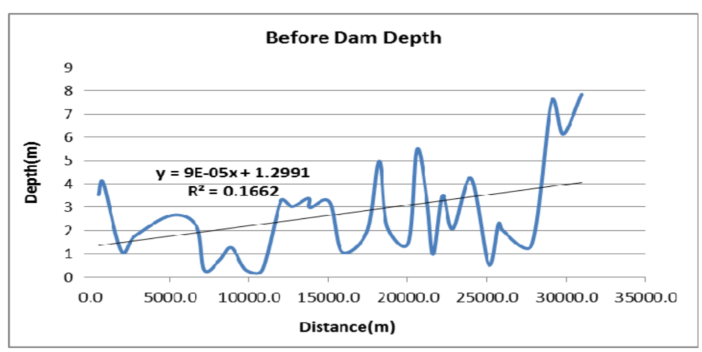

Fig. 10. Changes to the cross-section of the water level before the construction of the Dam.

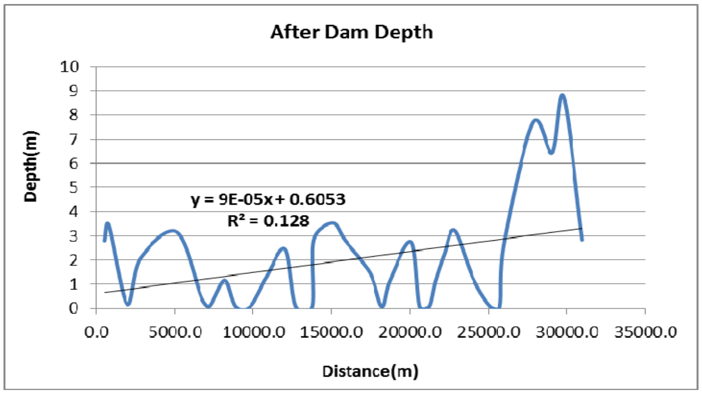

Fig. 11. Changes to the cross-section of the water level after the construction of the Dam.

V. CONCLUSIONS

Metamorphosis of rivers can be gradual and continuous in the long-term approach, or it can be sporadic and sudden if considered under certain circumstances in the short-run. Under natural conditions, the widths of the riverbed towards downstream the river's course is increased, when the river's slope angle decreases. In this case, significant changes occurred after the construction of a dam. The average widths of the river reduced from 273 meters to 60 meters. By an approximate reduction of 78% in the widths of the river, nearly 21 hectares of land, per each kilometer of river length, was released from floodwater. This value pertains to the floodwater with a return period of two years. In the studied district, the average thalweg migration of the river is approximately 340 meters, and its maximum and minimum are 768 and 53 meters, respectively. Results show that over 51% of migrations occurred to the west side of the river, and over 58% of these migrations took place outside the old riverbed. There is an average lateral migration of 34 meters occurring to the river each year, in the studied district, which signifies the instability of the region. With respect to the assessment of the model's results, the bed profile of the river has thus reached a relative degree of stability, and the channel's slope angle is not significantly different when comparing between 1996 and 2006. Therefore, dam construction did not have a considerable effect on the general changes to the slope angle along the length of the river. The equation for the longitudinal profile of the studied domain of the river, before and after dam construction, is expressed in two exponential functions with coefficients of R^2=0.96 and R^2=0.98 which shows the reduction of the river's slope angle towards downstream the river and correlates with the Shulitz equation for changes in the slope angle along the river's route. The fluctuations in the river's depths are sporadic in relation to the distance from the station, but generally these changes exhibit a trend of increase in the river's depths by the longer distance from the station, in both cases of pre and post construction periods of dam construction. Results suggest that the studied region of the Karkheh River is characterized by instability, in between the distance from the Pay-e-Pol station up to 40 km downstream of it. Therefore, future changes to the course of the river are anticipated to happen in the studied district. Results pertaining to the migration and movement of various sections of the river also confirm the strong likelihood of change that can occur to the river's course in the future.

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