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THE EFFECT OF STREAM POWER IN THE INSTABILITY AND MORPHOLOGICAL CHANGES OF HAJI ARAB RIVER, BUIN ZAHRA (QAZVIN PROVINCE, IRAN)

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Abstract:
The stream power is one of the important river variables which is used in morphological analysis. Therefore, the stream power determines both erosion and deposition. This research examines the stream power, instability and morphometric changes of the channel using the annual geomorphic energy (AGE) in Haji Arab River in Buin Zahra (Qazvin Province). The AGE is calculated by integrating the relationship between the excess specific stream power and discharge using a flow duration curve. The AGE values for each reach should be either positive or negative. Therefore, according to the differentials in AGE values, depositional and erosional reach are determined. In this paper, the results of the AGE method were compared with the rapid geomorphic assessments (RGA), including the channel stability indicators (CSI) model and OSEPI index. Also, the RHS method based on the field works was used to identify depositional and erosional geomorphic landforms. Comparing the results of the AGE with rapid RGA indices, shows that results of the OSEPI are more consistent with the erosional and depositional status of the reaches, based on the AGE. Spatial variations in lithology and structure, when combined with the course of the Haji Arab River indicate that channel morphometry locally reflects geological factors that have caused slope differences in different reaches. The calculated AGE values at different cross-sections have significant variability, reflecting characteristic local variation in bed slope, cross-section geometry and bed-sediment composition.

Key words: Annual geomorphic energy (AGE), Stream power, Erosional., Depositional., Haji Arab River

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INTRODUCTION

Rivers are the best geomorphic landscapes because of the relationship between the system of forces and the landforms (Chorley *et al*., 1984). The rivers are constantly changing in terms of dimensions, forms, direction, and pattern due to their mobility and dynamic characteristics. In characterizing broad-scale instability, according to the Lane's relationship (Lane, 1955), the variables of water discharge, channel slope, bed material load and median size of the bed material have the greatest effect.

The equilibrium of river system would be disrupted by these changes, would cause new equilibrium conditions and can impact upon channel morphology. For example, if the volume of the sediment, supplied to a reach over a given time, is less than the capacity of the reach to transport a volume of the sediment through, then erosion of the channel boundary is a probable outcome, which could lead to persistent channel instability through bed scour and/or channel widening, dependent on relative erosion differences between bed and bank materials). Lateral instability can also be a secondary response if bed lowering increases bank height, sufficiently to initiate mass instability (Darby *et al*., 2007). Conversely, if sediment supply is greater than the transporting capacity, then sedimentation processes are more likely to predominate with potential for channel instability through aggradation and/or channel narrowing. Additional complex responses to channel instability include accelerated rates of lateral mobility in meandering rivers (Newson, 1992; Hooke, 2003) and channel widening as flow is deflected around maturing sediment bars.

The Riparian zone affected these changes and are always exposed to the risks such as instability of beds and bank. Changes of the river geometric pattern, bed instability and erosion of river banks will cause damage to agricultural lands and facilities. Also sediments caused by bank erosion, reduce the dam capacity and disrupt hydrological conditions of the streams. Therefore, identifying geomorphic and geological phenomena that change the geometric pattern of the river and the instability of the bed is essential.

The variables affected of the river morphology are river patterns (meandering, braided and straight channels), geometric and hydrodynamic characteristics of river bends, bed and banks material, stream hydrological variables and factor of shear stress (Minghui *et al*., 2010; Tokaldany *et al*., 2007). Changes of the internal and external components of river system affect the stability of a river.

Knowledge about the sediment transport and channel sensitivity to erosion or deposition is very essential for river management. During the past decades, various methods and models have been presented to investigate and calculate the rate of sediment transport in rivers and to identify their geomorphic effects. Lane's approach remains a qualitative, 'indicative' treatment of potential channel instability that is not necessarily a reliable predictor of the 'type' of morphological response, e.g., bed scour, bank erosion, bar formation or some combination thereof (Soar *et al*., 2017). A decade ago, in the UK, the most widely applied approach for assessing sediment-related problems in rivers within their wider, drainage basin context is the fluvial audit (Sear *et al*., 1995; Thorne *et al*., 2010). In this approach, the focus is not on the reach-scale (or sub reach-scale) influences and impacts, it provides also no quantitative measure of the relative scale of channel instability between the reaches. This is also the case for other broad-scale assessment methods (for a review see Belletti *et al*., 2014). Another available approach to investigate sediment transfer and channel stability in river basins are the morphodynamic models. The resources required to run the morphodynamic models at a basin scale are often prohibitive in terms of time, data, personnel costs, demanding computational requirements as well as the specialized expertise necessary to develop and calibrate these models. The sediment transport equations employed in these models are still, unfortunately, a subject to high levels of uncertainty (Soar *et al*., 2017). According to this issue, in order to avoid uncertainties related to the calculation of sediment transfer loads, it is possible to use the annual available energy (Downs *et al*., 2018), as a comparable alternative to the annual sediment load to describe the reaches in terms of river channel stability and the potential for a morphological change (Soar *et al*., 2017).

The concepts of energy balance and budget in river science are well established. For example, disequilibrium in energy is a central component of the river continuum concept (Vannote *et al*., 1980), whereby uniformity of energy expenditure in river systems helps to explain the stability and diversity of stream communities. A direct link between downstream imbalances in river energy and the erosion, transfer and deposition of sediment was presented by Mackin (1948) and Leopold and Bull (1979). The geomorphological performance was subsequently linked to a stream power by Bull (1979), with aggradation and degradation attributed to sustained periods below and above the critical power for bedload transport, respectively (Soar *et al*., 2017). Reinfelds *et al*. (2004) and Jain *et al*. (2006) showed how abrupt changes in channel slope along a watercourse, and thus discontinuities in power, can lead to changes in the average rate of sediment transport and storage. These studies provided guidelines for the application of stream power in the identification of morphological adjustment at the reach scale. One such approach to emerge is the stream reach equilibrium assessment method (ST:REAM) of Parker *et al*. (2015), where specific stream power is applied as an index of sediment discharge and balances between adjacent reaches.

The stream power is one of the important river variables which is used in a morphological analysis. The concept of stream power is the amount of water energy, flowing through the river cross-section to perform some geomorphic work, especially the amount of sediment transport and channel geomorphic patterns in general (Bagnold, 1977). Variation of the stream power changes the balance of sediment transport and the amount of sediment load, and creates the bed morphological features (Hafez, 2000). So, it should be noted that the stream power and the potential energy of the river are basically related to each other (Kale, 2007). The potential energy of flowing water causes the stream power in alluvial channels, due to slope and gravity.

The sedimentation process in a reach of the river can reduce sediment transport; hence, it will increase the stream power and dominate the erosion in the downstream reach, and this erosion causes instability and damage to the infrastructures (Wallerstein *et al*., 2006).

Increasing the stream power will increase the incision and the river capacity to transport and causes the channel erosion. Therefore, the stream power determines the erosion and deposition (Eaton and Church, 2011). Also, the distribution pattern of the stream power identifies the threshold of the morphological changes of the channel (Nupur *et al*., 2014; Buraas *et al*., 2014). Bizzi and Lerner (2015) have examined the total stream power and specific stream power of the river to determine the dominate processes of the channel, especially erosion processes. Soar *et al*. (2017) quantified the geomorphological channel stability and potential of morphological adjustment, based on auditing stream energy.

This research examines the stream power changes in relation to the morphometric changes of the channel, using the AGE in Haji Arab River in Buin Zahra (Qazvin Province). This river is a gravel bed river with variety of patterns (meandering, braided and straight channels) and different types of bed sediments (sand, pebble and cobble). It is necessary to study the morphology of this river, in order to channel management and river restoration, erosion control, and understanding the current conditions and the potential changes in the future.

REGIONAL SETTING

The Haji Arab River flows through the southwest of Buin Zahra city in the Qazvin Province of Iran. The

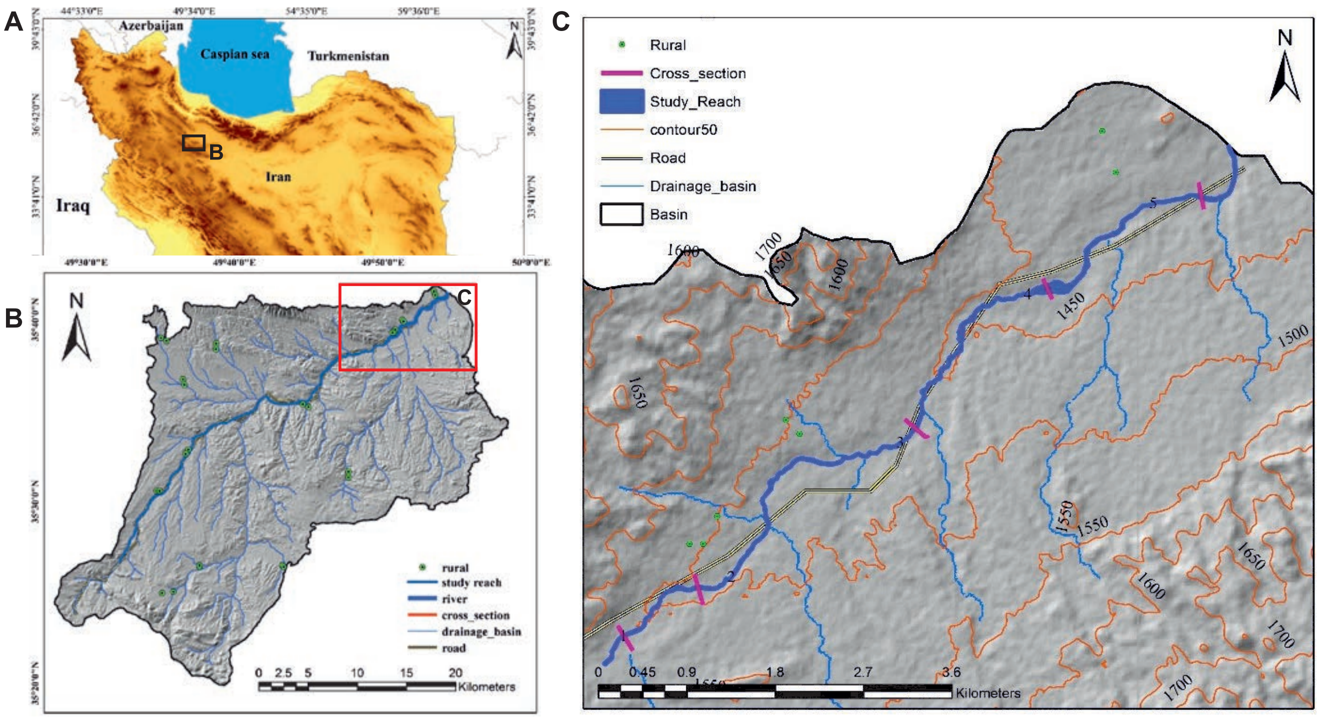

Fig. 1. Location map of the Haji Arab river (A); location of studied catchment in Iran(B); map of the Haji Arab catchment (C); location of studied reaches catchment (D).

river drains an area of 130.6 km^2. The river has two main branches named Nusrat-Abad and Chenaqchi, and originates from the Ziarat Belghi Mountain, 2600 m high, in the central mountain range of Iran. The study area was located in the lower Haji-Arab River basin. The study reach is 10 km, flowing within the villages of Rudak, Rostam Abad and Yerjan (Fig. 1). This region has a relatively dry and semi-arid climate. The average annual precipitation is around 274.8 mm. (Haji Arab station) and the maximum and minimum average temperature of the area is 37.5ºC and -3.5ºC, respectively. The mean annual discharge is 0.62 m^3/s 1981–2019 (Haji Arab hydrometric station).

The study area is located in the south of Boein-Zahra city (Qazvin Province) which is a portion of the Urmia-Bazman Magmatic Belt in the Central Iran Structural Zone. In this area, the Cenozoic (mostly Eocene and younger) volcanic and pyroclastic rocks are incised by a plutonic body.

MATERIAL AND METHODS

The AGE was used for investigating the role of shear stress and stream power changes in relation to the morphometric changes of the channel in the Haji Arab River. In fact, the concept of flow continuity was used to study the AGE difference in a short river reach. Therefore, a reach 10 km long of this river was selected, and 5 reaches were determined according to the channel morphology (width, depth, channel slope, sediment size and planform), so that the geomorphic energy of each reach is measured and compared to the previous reach.

The cross-sections data such as width, depth and channel slope should be obtained by field surveys to calculate the AGE. Also, particle size distribution of bed sediment was measured by pebble counts and shovel samples methods (Kondolf and Piégay, 2003). Finally, based on the data of the hydrometric station, the flow duration curve is provided and the median discharge of each discharge classes is obtained. The flow velocity and the flow rate in bankfull discharge was measured using the current meter device and Manning's Equation, respectively (Eq. 1).

$$Q = \sum_{k=1}^{3} \left(\frac{A_k R_k^{0.67} S^{0.5}}{n_k} \right) \qquad (1)$$

where Ak is cross-section area (m^2), Rk is hydraulic radius (m), S is channel slope through the reach, n_k is the Manning's coefficient of roughness (the roughness coefficient was calculated using the Cowan's method).

First, the specific stream power at each reach was calculated for identifying the AGE. Specific stream power (ω) in units of watts per unit area (W·m–2) is defined as (Eq. 2):

$$\omega = \rho_w gQS/W \text{ or } \omega = \Omega/W \qquad (2)$$

where, ω is the specific stream power (w/m^2), Ω is a total stream power per unit of channel length and in watts per meter (wm^{-1}), ρ_w is density of water (1000kg/m^{-3}), g is gravitational acceleration (9/81 m/s^2), Q is discharge (m^3/s), S is energy slope or bed slope (m/m) and W is water surface width (m) (m^3/s).

Excess specific stream power, ωe (W·m^{-2}), is determined by subtracting a measure of the critical specific stream power, ωc (W·m^{-2}), required for the initiation of sediment transport, from the total specific stream power (Soar *et al.*, 2017) (Eq. 3):

$$\omega e = \omega - \omega c \qquad (3)$$

The critical stream power concept is developed further in river energy audit scheme (REAS) to account for the range of grain sizes present on the bed. This is achieved through the summation of excess specific stream powers ($\omega - \omega$ci) for the median grain size of each size class, *i*, found on the bed using the standard Krumbein phi scale multiplied by its decimal frequency of occurrence, *Pi*. Thus, excess power, ωe (W·m^{-2}), for a grain size distribution of '*n*' classes is expressed as (Soar *et al.*, 2017) (Eq. 4):

$$\omega_e = \sum_{i=1}^{n} P_i\,(\omega - \omega_{ci}) \qquad (4)$$

Ferguson (2005) reanalyzed Bagnold's critical power equation and presented equation 5 to calculate the critical specific stream power for sediment particle size class, based on Andrews' research (1983), regarding the effect of hiding particles (Soar *et al.*, 2017).

$$\omega_{ci} = 0.113 d_{50}^{1.5} \log\left[\frac{0.73}{S}\left(\frac{d_i}{d_{50}}\right)^{0.4}\right]\left(\frac{d_i}{d_{50}}\right)^{0.6} \qquad (5)$$

where ω_{ci} is critical specific stream power for sediment particle size class i (W·m^{-2}), d_{50}, d_i, and S are the median particle size in the bed material (mm); the median particle size in size class i (mm) and the channel slope (m/m), respectively. The power of 0.6 is the factor of hiding particles, which replaces the critical depth term in the Bagnold equation.

The AGE is calculated by integrating the relationship between the excess specific stream power and discharge using a flow duration curve. Therefore, the flow frequency histograms are obtained based on the hydrometric stations data for each cross-section. Then, the excess specific stream power is used to calculate the stream energy of the cross-sections to perform geomorphological work. For each cross-section, the excess specific stream power for the median discharge in each discrete class in the flow frequency histogram is calculated and then multiplied by the water surface width to give the excess total stream power for that discharge class, a measure of bulk energy for the cross-section.

The excess amount of specific stream power for sediment particle size class (Eq. 3) are multiplied by their respective discharge's decimal frequency of occurrence and finally summed for '*m*' discharge classes (Eq. 6) to yield total excess stream power for all discharges combined, *Ωe*: (Soar *et al.*, 2017).

$$\Omega_e = \sum_{j=1}^{m} F_j W_j \left[\sum_{i=1}^{n} P_i\,(\omega_i - \omega_{ci})\right] \qquad (6)$$

where, *Fj* is the decimal frequency of occurrence of each discharge class *j*, *Wj* is channel width for each discharge class and *ωj* is corresponding specific stream power (W·m–2).

The calculated values is watts per unit of channel length, which can be converted into the annualized quantity of excess energy AGE by multiplying the number of seconds in a year. It would be better to express the resulting numbers in units of kilowatt hours (kWh) per unit length.

After calculating the AGE in each of the reaches, the differentials in AGE of successive reaches in the downstream direction is calculated (Eq. 7). The AGE balance of the studied reaches is calculated in the way that the AGE values of the reaches is subtracted from the AGE values of the upstream reach (r decreases in the downstream direction) (Soar *et al.*, 2017).

$$\Delta AGE_{(\mathrm{r})} = AGE_{(\mathrm{r}\text{-}1)} - AGE_{(\mathrm{r})} \qquad (7)$$

It should be mentioned the first reach from upstream will not have a balance because it will not be possible to compare with the AGE values of an upper reach. The AGE values for each reach should be positive or negative. A positive value indicates that the reach has less energy than upstream reach (energy deficit and depositional reach) and a negative value indicates that the reach has greater energy compared with upstream (energy surplus and erosional reach). Therefore, according to the differentials in AGE values, depositional and erosional reach are determined.

So far, various techniques such as direct measurement, remote sensing techniques, sedimentology and biological evidence have been used by researchers to evaluate channel erosion (Hosseinzadeh *et al.*, 2020). In this paper, the results of the AGE method were compared with rapid geomorphic assessments (RGA) techniques including the channel stability indicators (CSI) model, and Oklahoma Ozark stream bank erosion potential index (OSEPI) (Heeren *et al.*, 2012). Also, the RHS (River Habitat Survey) method based on the field works has been used for identifying depositional and erosional geomorphic landforms.

RESULTS

The erosion phenomenon and sediment transport is one of the important hydrodynamic processes that affects many hydrodynamic systems such as drainage basins, rivers, coasts, ports, dams, bridges, roads, fields and construction facilities.

The study reach of Haji Arab river is 10 km (divided to 5 cross sections and the first reach from upstream will not have a balance) which is flowing within the villages of Rudak, Rostam Abad, and Yerjan. The data is obtained by field observations and hydrometric data of Haji Arab gauging station. The location of the cross sections was selected away from bridges and other structures that could have misrepresented the study and modeling process. Also, the selected cross sections are different in terms of pattern (Fig. 2).

Characteristic of the studied cross-sections: The first cross-section is located at a distance of 1.88 km from Yerjan village. The second cross-section is located above Yerjan village and is about 1.5 km away from the center

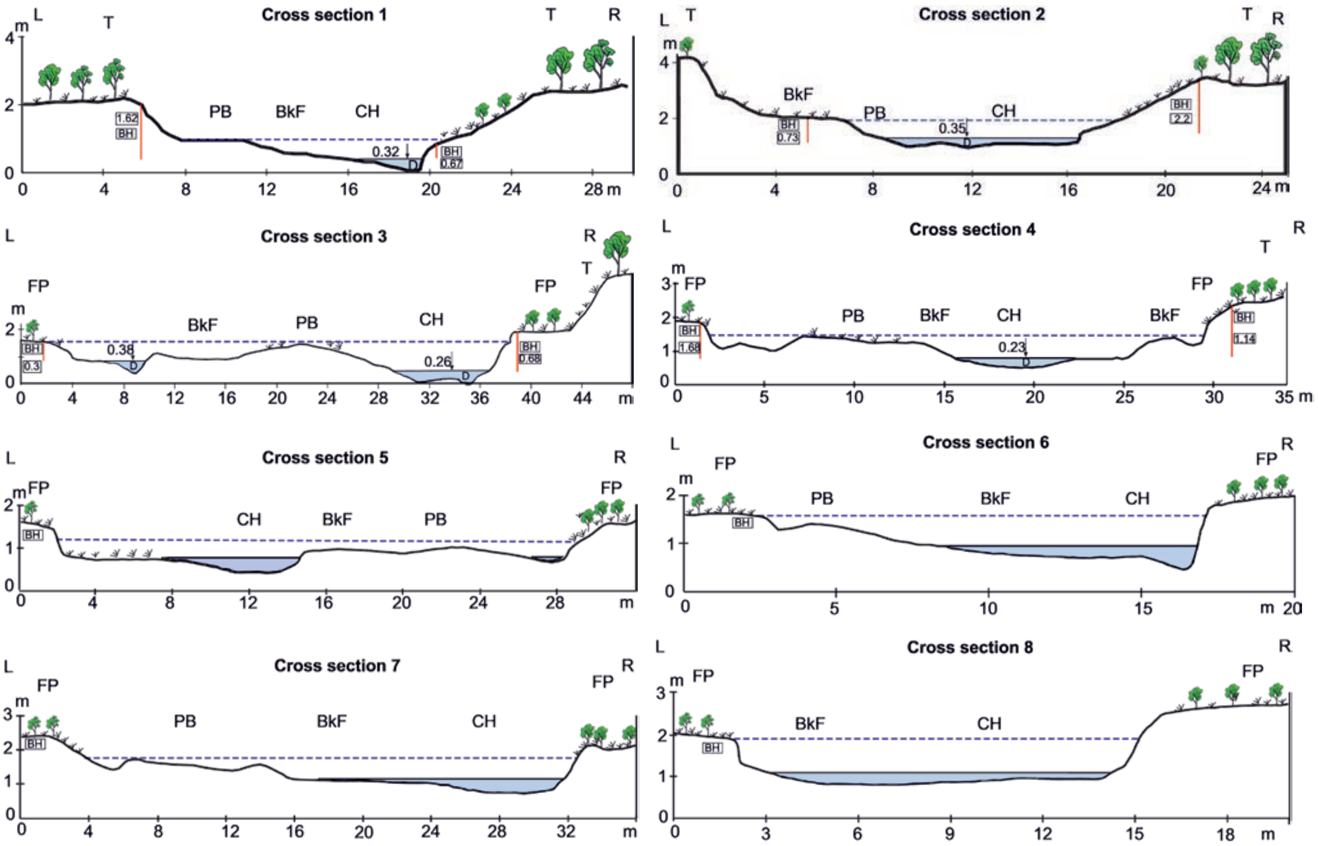

Fig. 2. Transverse profile of cross-sections 1 to 8.

of Yerjan village. The third cross-section is located at a distance of 3.95 km from the second cross-section at the beginning of Rostam Abad village. The fourth cross-section (an multi-thread channel with braided pattern) is located about 2.8 km below the second cross-section. The fifth cross-section is located in the lower part of the river and is about one kilometer away from the center of Rudak village (Fig. 2 and Table 1).

Hydrological analysis of Haji Arab River: The data of the gauging station in the Haji Arab basin above Rostam-Abad village over a period of 1979–2018 were used for the hydrological analysis (Fig. 3). The mean annual discharge was 0.62 m^3/s. According to Fig. 3, river flow starts from April and the maximum flow occurs in April and May, and the discharge decreases in March and February. The peak discharge is occurred in spring; so the stream regime in this basin has been the type of snowy and rainy river. Therefore, the maximum discharge and floods in the Haji Arab River occur in spring.

The discharges of the Haji Arab River were divided into four classes based on the characteristics and frequency of discharge, which includes discharge class less than 1, discharge class 1–3, discharge class 3–5 and discharge class 5–7 m^3/s. The occurrence frequency of each of the discharges in the classes has been determined based on the data of the Haji Arab hydrometric station. Based on flow data, 87.15% frequency is in class less than 1, 10.93% frequency is in class 1–3, 1.1% frequency is in class 3–5, and 0.81% frequency is in class 5–7. The stream hydrological condition for the studied cross-sections has been calculated in different discharge classes. For this purpose, chan-

Table 1. Morphometric characteristics and bank conditions of the cross sections 1 to 5.

Cross section	Pattern	Width channel (m)	Bed slope (%)	Base flow (m^3/s)	Bankfull discharge (m^3/s)	Bank protection	Bed material	Riparian vegetation cover
1	sinuosy (shallow curve)	31.34	0.15	0.2	13.62	none protected	gravel, sand, silt	unvegetated
2	meandering	31.29	0.58	0.43	19.42	none protected	gravel, sand, silt	unvegetated
3	meandering	35.25	1.52	0.23	22.66	none protected	gravel, sand, silt	unvegetated
4	braided	35.56	1.05	0.32	11.87	none protected	gravel, sand, silt	scrub/shrubs
5	sinuosy (shallow curve)	10	0.096	0.32	0.99	none protected	gravel, sand, silt	short/creeping herbs or grasses

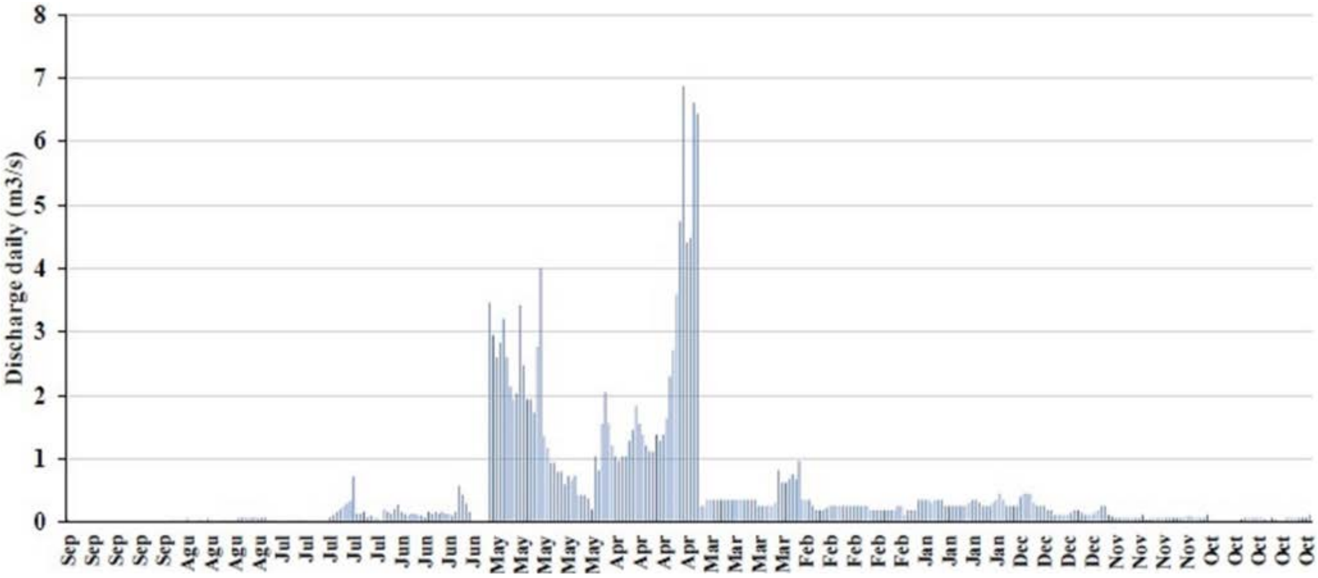

Fig. 3. The monthly discharge of the Haji Arab River (1979–2018).

nel morphometry and hydrological characteristics have been calculated for different classes in each cross-section (Table 2).

Sedimentological characteristics of cross-sections: Particle size of bed sediment has been measured by pebble counts and shovel samples methods. Also, the amount and percentage of soil texture and its classification were obtained using the statistical program Gradistat v.8. Based on the results, in the cross-section 1, 2 and 4, the particle size was smaller and the d50 of sediments was 10 mm on average. Meanwhile, cross- section 3 has d50 less than 2 mm due to the braided pattern, and about 55% of the sediments are almost fine pebbles (2 mm). In the cross-sections of 5 the highest amount of particles frequency was related to cobble and then large pebble; also, the d50 of these cross-sections was larger than 20 mm (Table 3).

AGE in the studied cross sections

Based on the amounts of stream power in different discharges and particles, the annual geomorphic power was calculated for different discharge classes, that is 6, 4, 2 m^3/s; and also, the AGE was obtained for different discharges. Finally, the total AGE in different discharges was calculated as the AGE of that cross-section based on kilowatt hours per length. This amount of energy is the reference to detect the change of the total power compared to the previous and subsequent cross-sections which are in

Table 2. Hydrological parameters of the cross-section 1 to 5.

Cross section	Discharge class 2 (m^3/s)			Discharge class 4 (m^3/s)			Discharge class 6 (m^3/s)			Discharge class of bankfull		
	Current (m/s)	Width channel (m)	Max depth (m)	Current (m/s)	Width channel (m)	Max depth (m)	Current (m/s)	Width channel (m)	Max depth (m)	Current (m/s)	Width channel (m)	Max depth (m)
1	1.06	11	0.26	1.37	11.6	0.35	1.58	12.1	0.42	3.17	13.1	1.07
2	0.61	14.8	0.3	0.81	19.1	0.8	1.2	22.1	0.96	1.5	55	1.1
3	1.01	9.9	0.33	1.31	10.5	0.43	1.52	11.1	0.51	1.73	16.9	0.74
4	0.89	10.6	0.35	0.91	18	0.46	0.96	23.3	0.53	1.63	41.9	0.95
5	1.08	7	0.6	1.3	8.1	0.76	1.45	9.8	0.88	1.54	12.2	0.99

Table 3. Granulomeres data of cross sections 1 to 5.

Cross section	Sand (1 mm) %	Very coarse sand (2 mm) %	Fine gravel (4.7 mm) %	Medium gravel (9.5 mm) %	Coarse gravel (19 mm) %	Very coarse gravel (38 mm) %	Cobble (64 mm) %	D50 (mm)
1	0.66	2.76	6.92	21.86	34.26	21.66	11.88	13.63
2	2	1.32	2.84	11.27	32.45	51.64	0	19.42
3	0.44	0.7	3.2	12.7	27.01	23.42	32.53	22.66
4	6.94	55.7	11.19	19.96	6.15	0	0	1.7
5	1.57	2.37	4.16	10.52	17.34	21.8	42	32

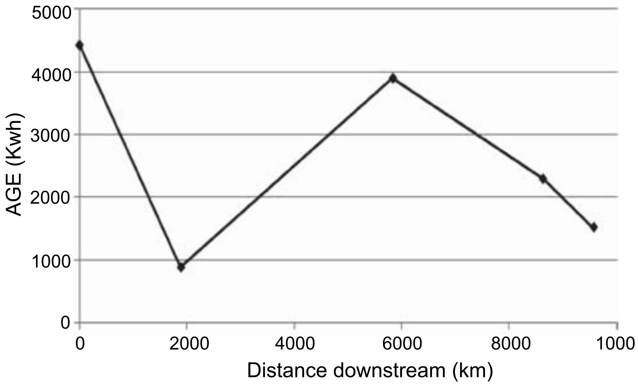

Fig. 4. The AGE in the study reaches (upstream to downstream).

the state of erosional or depositional; and this situation can be observed from the AGE of each cross-section. Based on the previous information, the critical specific stream power was calculated for each of the cross-sections at different discharges for 7, 2, 5, 19, 9, 64, 38.4 particle size. Also, the amount of stream power in different discharge classes for different particle sizes has been calculated.

The AGE in the reach 1 is 4419.85 kilowatt hours per length. Therefore, cross-section 1 with the maximum AGE has the most energy in compared to other cross-sections, due to the narrowing of the channel width (13.1 meters), increased discharge (40.48 m^3/s), flow velocity (3.17 m/s) and more slope of the riverbed (0.15 m/m). In fact, one of the important factors in the energy difference is the continuity in the bed slope. The river has local slope changes by passing from cross-section 1 to cross-section 2 (Table 1 and Fig. 4).

The AGE of the second cross-section is 887.51 kilowatt hours. This cross-section has less geomorphic energy than the first and even the next cross-sections, because the channel pattern has changed in this cross-section and the width of the channel has increased, the flow velocity and the bed slope has decreased compared to other cross-sections (Table 1 and Fig. 4).

The AGE of the third cross-section is 3895.52 kilowatt hours. This cross-section has more AGE than the previous and subsequent cross-sections due to the decreasing of channel width and increasing of the bed slope and flow velocity. In fact, the presence of steep cross-sections can indicate the maximum AGE (Table 1 and Fig. 4).

The AGE of the fourth cross-section is 2288.35 kilowatt hours. The AGE of this cross-section, has decreased in compared to the previous cross-section, because the river pattern of this cross-section is braided and the channel width has increased, and the flow velocity has also decreased (Table 1 and Fig. 4).

The AGE of the fifth cross-section is 1514.39 kilowatt hours. The AGE of this cross-section, has decreased in compared to the previous cross-section. which is caused by the morphometric characteristics of the channel, especially the slope and flow velocity. Also, the riparian vegetation of the channel is more than the other cross-sections, which has reduced the velocity of the flow (Table 1 and Fig. 4).

AGE balance

Fig. 4 shows the changes of AGE in the downstream of the river, especially for each cross-section along the river channel. Some interesting information can be observed in the results; geomorphic energy peaks are generally related to the pattern, slope and morphometry of the cross-section. In fact, the above cases cause a cross-section to act as a cross-section with sedimentation or erosion conditions. In this method, the energy balance of each cross-section is compared to the previous cross-section, and from the second cross-section onwards, the energy balance is calculated because it is necessary to obtain the difference of each cross-section compared to its previous cross-section.

Based on the calculation of the energy balance of each cross-section compared to the next cross-section, the results showed that the amount of the energy balance in cross-section 2, 4 and 5 are positive and the river is in a depositional state, and the energy balance in sections 3 is negative. As a result, erosional conditions dominate in this cross-sections and the energy of this cross-sections is more than the energy of their upstream (Table 4, Fig. 5).

The positive geomorphic energy balance of section 2 shows that this section is in a depositional state and has the potential to deposit sediment and accumulate on the bed. The geomorphic energy of this reach decreased compared to the previous reach because of the increase in channel width, decrease in slope, change in the channel cross-section and position, and placement in the meandering channel. The type of bed composition in this reach is gravel which is coarser than the previous reach (Table 4).

The morphometric characteristics of the river in the 3rd cross-section caused an increase in the geomorphic

Table 4. Annual geomorphic energy balance in Haji Arab River.

Cross section	$AGE_{(R)}$	$AGE_{(R-1)}$	$\Delta AGE_{(R)}$
1	4419.85	–	–
2	887.51	4419.85	3532.34
3	3895.52	887.51	-3008.01
4	2288.35	3895.52	1607.17
5	1514.39	2288.35	773.96

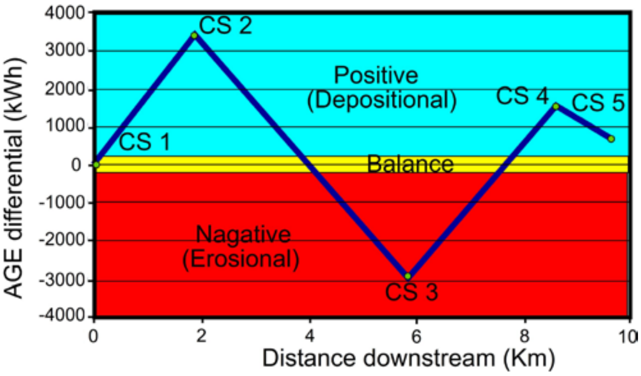

Fig. 5. AGE balance in the reaches of Haji Arab River.

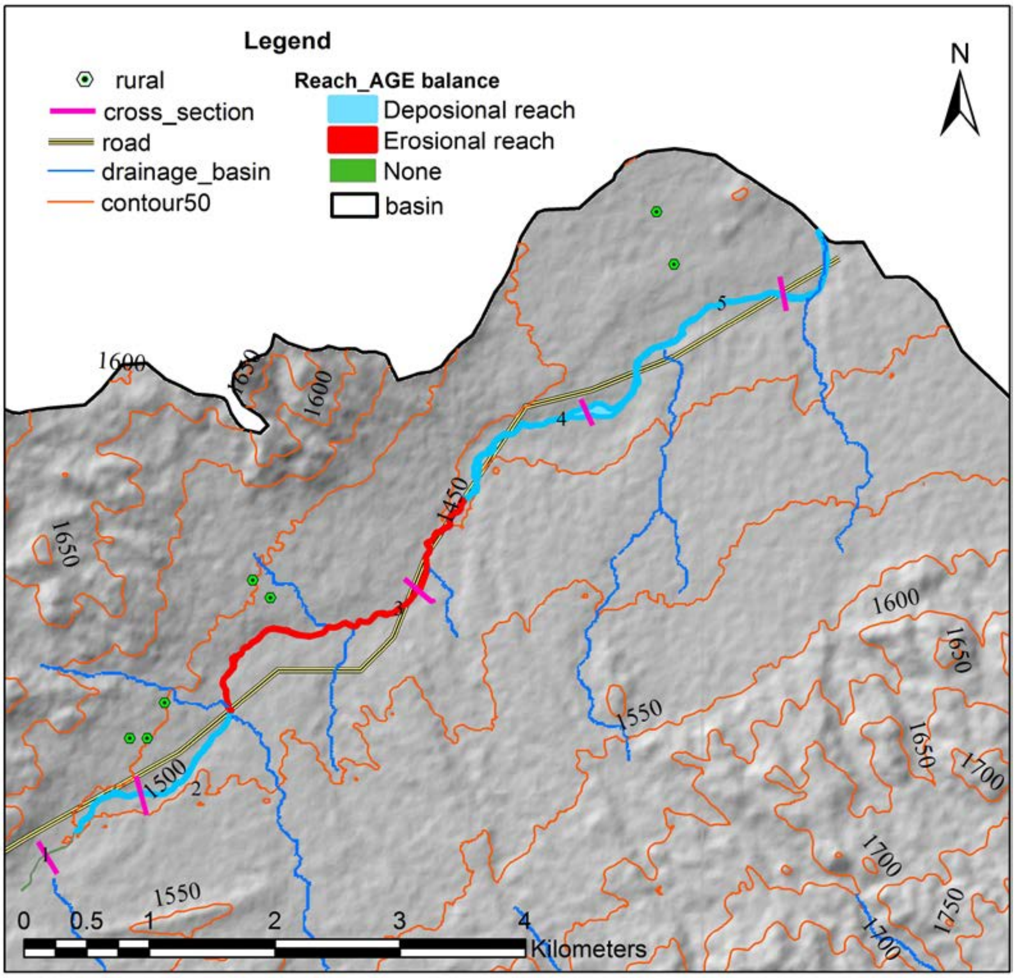

Fig. 6. Erosional and depositional situation for cross-sections of Haji Arab River.

energy and as a result the geomorphic energy balance was also negative and the river was in an erosional state. Therefore, depositional forms have decreased, and the size of bed sediments has increased, and the gravel and coarse-grained sediments has dominated compared to the previous cross-section. Also, the erosional situation in these sections can be seen in the lack of riparian vegetation and the instability of the channel bank (Table 4).

The geomorphic energy of the river has decreased in the cross-sections 4. As a result, the geomorphic energy balance is positive, so the river is in a depositional state, and there is a potential for sediment deposition and accumulation on the bed (Fig. 6). Increasing the channel width, changing the channel morphometry, decreasing the slope, changing the channel position (partly confined) and placement in the bend of meandering channel have decreased the geomorphic energy of this cross-section compared to the previous cross-sections. The bed sediments texture in this cross- section is coarse pebbles and on the left bank of the channel, sedimentation dominated and point bar was formed. Also, the tree and shrub vegetation have growth due to the presence of bars on the side of the channel, and with the increase of the roughness coefficient, the flow velocity and the stream power have decreased (Table 4).

The geomorphic energy balance is negative in cross-section 5, as a result, this reach is in an erosional state and has excess energy for sediment transport. The increasing of the energy at this cross-section was due to the decrease of the channel width and the increase of the slope and the flow velocity. Also, at this section, human interventions can be observed in the form of sand and gravel mining, destruction of vegetation, land use changes and the Inflow of wastewater from agricultural lands, which has caused the erosion of the bank (Table 4). Comparing the results of the AGE, the rapid geomorphic assessment techniques, and field survey in the Haji Arab River showed that the AGE has good performance.

DISCUSSION AND CONCLUSION

This research has investigated the effect of stream power in the instability and morphological changes of the channel in the Haji Arab River. For this purpose, the difference between the energy budget and the stability of the river channel has been studied using the AGE in a reach (10 km) of Haji Arab River. The parameters affecting the erosion and deposition of sediments on the bed and river

Table 5. Comparison of the results of the AGE, rapid geomorphic assessment techniques and field evidences in Haji Arab River.

Cross section	AGE	Rapid geomorphic assessment		Geomorphic evidence
		CSI index	OSEPI index	
1	–	highly unstable	unstable	Bank erosion, no formation of sedimentary bars.
2	depositional	highly unstable	moderately stable	Existence of sedimentary forms on the banks such as point bars, sedimentary and gravel bars.
3	erosional	moderately unstable	moderately stable	Reducing Depositional forms, increasing the size of bed sediments (gravelly and coarse-grained sediments), Lack of vegetation on the bank and bank instability, armoring bed.
4	depositional	moderately unstable	highly stable	Fine-grained bed sediments (Fine gravel), prevailing sedimentation and point bar formation, existence of lateral and sid bar, tree and shrub vegetation growth.
5	erosional	moderately unstable	unstable	Absence of sedimentary midchannel bar and point bar within channel, undercut the river bank, absence of fine sediments, armoring bed.

bank have been evaluated to calculate the AGE. These parameters include stream velocity, effective discharge, total stream power along the channel, specific stream power, channel width, channel slope and flow regime.

This study estimates the AGE and bank instability and prepare a map of sensitive reaches. The results showed that the first reach has the highest AGE and the second reach has the lowest AGE. In terms of the AGE balance, cross-sections 2, 4 and 5 are positive and the river is in a depositional state, and cross-section 3 have a negative energy balance and the river is in an erosional state.

According to the available findings, the most important factor in reducing the AGE in the second cross-section was the decrease in the slope of the bed and the flow speed in the state of bankfull discharge. The field survey showed that in the end part of this reach, the slope advance and bedrock outcropping has created a local base level. This protrusion has reduced the energy gradient in the upstream reach, while the downstream part of the river has been eroded and incises into the alluvial sediments. Under the above conditions, the channel is confined and single-channel. Therefore, the sedimentation process in the upstream reach of the outcrop was much faster than the erosion in the downstream reach (Meshkova and Carling, 2012).

As mentioned, the third cross-section has more AGE than its previous and subsequent cross-sections due to its steeper slope and higher speed, and is in a state of erosion. Field investigations showed that this cross-section is located at the end of a part of the channel with a length of one kilometer, which has a confined condition with a high slope. In this section, the presence of andesitic crystalline tuffs on the left bank of the channel and the alternation of ticked coarse-grained calcareous sandstone and marl on the right bank have caused the channel to be confined and the slope increased. The above conditions have increased the geomorphic energy of this part of the river and the river is in the erosion stage. The investigation of river bed sediments also shows that the mold sediments in this part are coarse-grained sediments and the D50 of the sediments in this part is 22.6 mm (Table 3).

In the fourth cross-section, the AGE has decreased. After the third cross-section, the river flows for 2 kilometers in a partly confined position on the of the river channel deposits, and on the left bank of the channel, the gravel plain and cultivated lands dominate, and on the right bank, there are older terraces and gravel fans. In this reach, the pattern of the river is braided and the width of the river has increased and the slope and speed of the flow have decreased and sediment tends to accumulate in where the channel locally widens. The braided reach exhibits a gradual flattening of bed slope towards the gravel trap. In this part, the river is multi-channeled and there are many gravel barriers between the channels. These conditions indicate the reduction of flow energy and the creation of sedimentation conditions in this part of the river. In the fifth cross-section, in terms of geological and morphological conditions, it is similar to the previous period reach, with the difference that the amount of slope and also the speed of the flow is lower than the previous reach. As a result, the geomorphic energy in this cross-section is less than the previous cross-section and the depositional state continues.

The comparison of the results from the energy balance at different cross-sections showed that due to the Constant discharge in the study reaches, the most important factors affecting the difference in energy balance and changing the erosional or depositional status of the river are the channel morphometry (width and depth of the stream, the slope of the reach and the channel pattern) which has an effect on the hydrological conditions of the stream, including velocity, shear stress and stream power.

It should be noted that the texture of bed sediments and the riparian vegetation are other effective factors that affect the roughness coefficient, stream velocity and stream power. Therefore, despite the similarity of some cross-sections in terms of pattern, the amounts of geomorphic energy and their stability conditions have been different. This condition was due to the effect of woody vegetation on the stream bank and the protection of the river bank (cross-section 5) and the presence of coarse-grained sediments (cross-section 3).

Interesting features is the existence of the main AGE peak in the reach affected by the geological features, which are characteristically steeper than neighboring reaches and, therefore, act as sediment transfer reaches with little potential for either progressive erosion of deposition. Examination of the differentials calculated for individual cross-sections reveals considerable variability over short distances in the available energy for performing geomorphological work, reflecting the characteristic local variability in bed slope, cross-sectional geometry and bed-sediment composition.

The results of the CSI model show that bank instability in the Haji Arab River is mainly affected by stream bank erosion, the riparian vegetation and bed material., respectively. Also, the instability of the channel has a significant relationship with the channel pattern, vegetation covers and type of channel materials (Table 5).

According to the results of the OSEPI, the most effective factors in determining the stability of the left bank are the woody vegetation of the bank and bend of the river. Also, the woody vegetation of the river bank, and the percentage of bank height with a bank angle greater than 80 degrees, unconsolidated material and the stream curvature are equally effective in the stability of the right bank, respectively (Table 5).

Comparing the results of the AGE with rapid geomorphic assessment indices, shows that the results of the OSEPI are more consistent with the erosional and depositional status of the reaches based on the AGE which means depositional reaches had stable conditions and erosional reaches were unstable. AGE can be used in the management of the river channel and flood risk. Characterizing sediment transport conditions in terms of energy balance is an innovative technique that conceptually focuses on fluvial drivers. In this case, the energy of the river can play a role in the geomorphic activities more than the prediction of river morphology. In fact, the practical value of this method is the accurate interpretation of the results and provide an index for the comparison of river reaches. On the other hand, the results of this method can determine potential geomorphic responses, although this method cannot replace methods based on geomorphic field studies (Soar *et al*., 2017).

The limitations of this method are that the sediment transport controllers were not used in the stream power calculations. Other limitations are the very high sensitivity of the channel banks to changes, especially the relative sensitivity between the bed and the bank, the limitation of sediment supply, the structures that control the persistence of sediment beyond the local scale, the evolution and restoration of the channel or the lack of restoration of the channel after a flood event (Soar *et al*., 2017).

REFERENCES

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material. Geological Society of America Bulletin 94, 1225–1231.

Bagnold, R.A., 1977. Bed Load Transport in Natural Rivers. Water Resources Research 13, 303–312.

Belletti, B., Rinaldi, M., Buijse, A.D., Gurnell, A.M., Mosselman, E., 2014. A review of assessment methods for river hydromorphology. Environmental Earth Sciences 73, 2079–2100.

Bizzi, S., Lerner, D., 2015. The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. River Research Applications 31, 16–27.

Bull, W.B., 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90, 453–464.

Buraas, E., Renshaw, C., Magilligan, F., Dade, W., 2014. Impact of reach geometry on stream channel sensitivity to extreme floods. Earth Surface Processes and Landforms 39 (13), 1778–1789.

Chorley, R., Standly, A., David, S., 1984. Geomorphologhy (1st ed). Mehuen and Co, London, 316–341.

Darby, S.E., Rinaldi, M., Dapporto, S., 2007. Coupled simulations of fluvial erosion and mass wasting for cohesive river banks. Journal of Geophysical Research 112, F03022, doi:10.1029/2006JF000722.

Downs, P.W., Dusterhoff, S., Leverich, G., Soar, P.J., Napolitano, M., 2018. Fluvial system dynamics derived from distributed sediment budgets: perspectives from an uncertainty-bounded application. Earth Surface Processes and Landforms 43 (6), 1335–1354.

Eaton, B., Church, M., 2011. A rational sediment transport scaling relation based on dimensionless stream power. Earth Surface Processes and Landforms 36, 901–910.

Ferguson, R.I., 2005. Estimating critical stream power for bedload transport calculations in gravel-bed rivers. Geomorphology 70, 33–41.

Hafez, Y., 2000. Response theory for alluvial river adjustment to environmental and man-made changes. Journal of Environmental Hydrology 8, 1–19.

Heeren, D.M., Mittelstet, A. R., Fox, G.A., Storm, D.E., Al-Madhhachi, A.T., Midgley, T.L., Stringer, A.F., Stunkel, K.B., Tejral., R.D., 2012. Using rapid geomorphic assessments to assess streambank stability in Oklahoma Ozark streams, American Society of Agricultural and Biological Engineers 55(3), 957–968.

Hooke, J., 2003. Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. Geomorphology 56, 79–94.

Hosseinzadeh, M.M., Esmaili, R., Matesh Byranvand, S., 2020. Analysis of channel bank erosion rate using exposed roots of trees: a case study of lavij stream, northern Alborz Mountains, Iran. Journal of Mountain Science 17(5), 1096–1105.

Jain, V., Preston, N., Fryirs, K., Brierley, G., 2006. Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. Geomorphology 74, 297–317.

Kale, V., 2007. Geomorphic effectiveness of extraordinary floods on three large rivers of the Indian Peninsula, Geomorphology 85(3), 306–316.

Kondolf, G.M., Piégay, H., 2003. Tools in Fluvial Geomorphology, 2nd Edition, Wiley-Blackwell, ISBN: 978-0-470-68405-4, 560 pp.

Lane, E.M., 1955. The importance of fluvial morphology in hydraulic engineering. American Society of Civil Engineers 81, 1–17.

Leopold, L.B., Bull, W.B., 1979. Base level, aggradation, and grade. Proceedings of the American Philosophical Society 123, 168–202.

Mackin, J.H., 1948. Concept of the graded river. Geological Society of America Bulletin 59, 463–512.

Meshkova, L.V., Carling, P.A., 2012. The geomorphological characteristics of the Mekong River in northern Cambodia: A mixed bedrock–alluvial multi-channel network. Geomorphology 147–148, 2–17.

Minghui, Y., Hongyan, W., Yanjie, L., Chunyan, H., 2010. Study on the Stability of Noncohesive River Bank. International Journal of Sediment Research 25(4), 391–398.

Newson, M.D., 1992. Geomorphic thresholds in gravel-bed rivers. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds), Dynamics of Gravel-Bed Rivers. John Wiley & Sons: Chichester, UK, 3–15.

Nupur, B., Vikrant, J., Shashank, S., Niraj, K., Vikas, J., 2014. Controls on Morphological Variability and Role of Stream Power Distribution Pattern, Yamuna River, western India. Geomorphology 227, 60–72.

Parker, C., Thorne, C.R., Clifford, N.J., 2015. Development of ST:REAM: A reach-based stream power balance approach for predicting alluvial river channel adjustment. Earth Surface Processes and Landforms 40, 403–413.

Reinfelds, I., Cohen, T., Batten, P., Brierley, G., 2004. Assessment of downstream trends in channel gradient, total and specific stream power: A GIS approach. Geomorphology 60, 403–416.

Sear, D.A., Newson, M.D., Brookes, A., 1995. Sediment-related river maintenance: The role of fluvial geomorphology. Earth Surface Processes and Landforms 20, 629–647.

Soar, P.J., Wallerstein, N.P., Thorne, C.R., 2017. Quantifying River Channel Stability at the Basin Scale. Water 9, 133–164.

Thorne, C.R., Soar, P.J., Skinner, K.S., Sear, D.A., Newson, M.D., 2010. Driving processes II. Investigating, characterising and managing river sediment dynamics. In: Sear, D.A., Newson, M.D., Thorne, C.R. (Eds), Guidebook of Applied Fluvial Geomorphology. Thomas Telford: London, UK, 120–195.

Tokaldany, E., Darby, S., Tosswell, P., 2007. Coupling Bank Stability and Bed Deformation Models to Predict Equilibrium Bed Topography in River Bends. Journal of Hydraulic Engineering 133, 1167–1170.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37, 130–137.

Wallerstein, N.P., Soar, P.J., Thorne, C.R., 2006. River Energy Auditing Scheme (REAS) for catchment flood management planning. In: Proceedings of the IAHR River Flow, Lisbon, Portugal., 6–8 September.