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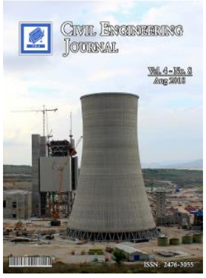

Field Study of Morphological Parameters in Step-Pool Streams

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Abstract

Nowadays, step-pool formations have attracted a lot of attention, which are distinguished by the successive arrangements of the bed, suitable geometry, and the tumbling flow pattern, which can highly disperse water energy. Field study of a step–pool channel, along with one of the upper reaches of Kamandan River indicated a strong correlation between several morphological parameters of the river such as reach slope, step length, step height, pool depth, local slope, and the like. The length of the reach under the study is 145 meters and has an intermediate morphology based on Montgomery and Buffington's classification. Therefore, twelve distinct step units were identified for 145 meters upstream while the rest was formed by steep morphology. In the present study, different definitions of wave length were applied to establish the relationships among the above parameters. For instance, the difference between apexes of every two successive step elevation was found to have a considerable relationship with the wavelength with a determination coefficient of 0.9. In addition, bankfull width and depth, along the profile for different cross-sections, were determined to establish a relationship between these parameters and pool spacing. Further, the parameters were applied to create a relationship with step heights.

Keywords: Step-Pool; Kamandan River; Morphology; Mountain River.

1. Introduction

Step-pool channels are considered as a series of stream morphological kinds which change downstream within watersheds. Channel types in mountain watersheds typically progress downstream from disorganized cascade reaches to fluvially organized step-pools, plane beds, pool-riffles, and dune ripple channels. Step-pool morphology is defined by a series of steps, similar to a staircase in the river bed [1]. Step-pool bed forms were identified at low discharges following the morphological classification of Montgomery and Buffington (1997). In their classification, step-pool streams are identified by longitudinal steps formed by large clasts which separate the pools including finer material. Cascades are typically longitudinal and they are laterally regarded as disordered bed materials including individual boulders separated by small pools [1]. In the classification of Grant et al. (1990), step-pools and cascades operate differently while the step-pools of Chin (1999) include both cascades and step-pools. The step-pool bed results in alternating critical to supercritical flow over steps and subcritical flow in pools. Step-pools are a typical bed morphology in streams exceeding ~2–3% gradient [1-3]. Generally, step-pool morphology is associated with steep gradients, and small width to depth ratios. Although step-forming clast sizes are typically comparable to annual high flow depths, a stepped longitudinal profile may be developed in steep sand-bedded streams [4]. Chin (1989) suggested that step-pools can be recognized by their staircase-like longitudinal profile resulting from accumulating cobbles and boulders which are located transversely across the channel, alternating with pools including finer material. In addition, step-pools change the path of water and sediments from uplands to lowland basins [5], which received a great deal of support by many researchers to maintain upland aquatic ecosystems [6-8]. Chin et al. (2009) concluded that reproducing the physical

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properties of step-pool reach may ensure maximum stability for a restored stream profile [9]. In addition, artificial step-pools can be used to present soft restoration procedures where concrete is used. In this context, Nikseresht et al. (2013) utilized the structures of step- pool to study two-phase flow in spillways numerically [10].

Morphological and hydraulic approaches were adopted to model step-pool properties [11]. Based on the hydraulic approach, the equations governing flow and sediment transport are studied through step-pools [12, 13]. However, step-pools have created some challenges for the researchers in different aspects, due to consistent interaction between step-pool hydraulics and bed form variations, which may question the validity of available flow resistance equations for gravelling and cobbling bed rivers [14-16]. These problems explain the reasons why morphological approaches have been widely used in relation to hydraulics in stream restoration [8]. Based on this approach, several relationships are available in the step-pool dimensions, both in length and height, compared to other geometric factors [17]. Most geometric equations have focused on slope and boulder diameter while other parameters such as the active width [18] and woody debris density [19-22] may play a significant role in step-pool morphology.

In order to understand step-pool formation processes and hydraulic controls, a large number of researchers considered step-pool geometry by establishing some relationships between step length (L), step height (Hs), grain size diameter (D), channel gradient (S), and stream width (w) [6, 23]. Step-pool channels are characterized by their range of slopes between 0.03 and 0.07 m/m [1] and step elevations to control energy dissipation [24].

The ratio of step height to length to bed gradient, Hs/L/S, is an often-cited measure of step geometry which indicates the amount of elevation change created by step-pool sequences and the presence of reverse slopes between the steps [25]. Abrahams et al. (1995) suggested that step-pool channels are ideally organized in such a way that flow resistance can be maximized, which is only achieved if $1< ((H/L) /S) <2$ [26]. Maximum flow resistance is associated with an optimal distance between the bedforms and their height. The considerations of the Kennedy region of antidune formation and the analysis of planform step types depending on stream power both suggest that steep channels have a potential for self-stabilization by modifying the step–pool structure toward a geometry which provides maximum flow resistance and maximum bed stability [27].

D'Agostino and Michelini (2015) used his own database to verify the estimation of velocity relationships developed by other researchers in step-pool reach of mountain streams. Further, flow regime and structure have been studied by a number of researchers [28]. According to Sindelar and Smart (2016), flow regime is related to the mean value of the Froude Number in a step-pool reach while Maddahi et al. (2016) studied the effect of bed form variations on flow structure [29, 30]. Johnson (2017) reported that the stability of river beds largely depends on how clustered (i.e., close together) the largest sediment grains are (typically boulders). The clustering statistics predict hydraulic roughness better than D84 does (the diameter at which 84% of grains are smaller), suggesting that the spatial the organization of the bed can be a stronger control than grain size on flow hydraulics. Initial conditions affect the degree of clustering at stability, indicating sensitivity to history [31].

Torabizadeh et al. (2018) concluded that flow resistance is considered as a function of geometric, bed material size, longitudinal slope and hydraulic radius in addition dimensional analysis was conducted to derive a non-dimensional relationship for Chezy coefficient in step-pool reaches. Then, it was calibrated for the measured data set of Dizin, Ammameh and Rio Cordon. Comparable results of calibration with a river located in a different environment suggested that flow resistance features in semiarid and humid streams may have similar effects on non-dimensional Chezy coefficient [32].

Regarding morphology of step-pool streams, many field and experimental studies could establish various empirical relationships. However, the present study aimed to evaluate mountain streams in a semi-arid environment, which is conducted by field surveys in Kamandan River, Iran. In this respect, bankfull width and depth, along with the profile for different cross-sections, were determined to establish a relationship between these parameters and pool spacing. In addition, these parameters were utilized to create a relationship with step heights.

2. Methods

2.1. Study Area

In order to follow the objective of the study, Kamandan River was selected as the case study. It is one of the main branches of Joob River, derived from the north flank of Zagros Mountain in 20 km south of Azna from OshtoranKuh Watershed (Figures 1 and 2). Snowmelt is generated by late spring-early summer peak flows. Water discharge and bed material sampling were measured in Kamandan River. Elevation of the study area is approximately 3881 m above the sea level, with a drainage area of 110 km^2.

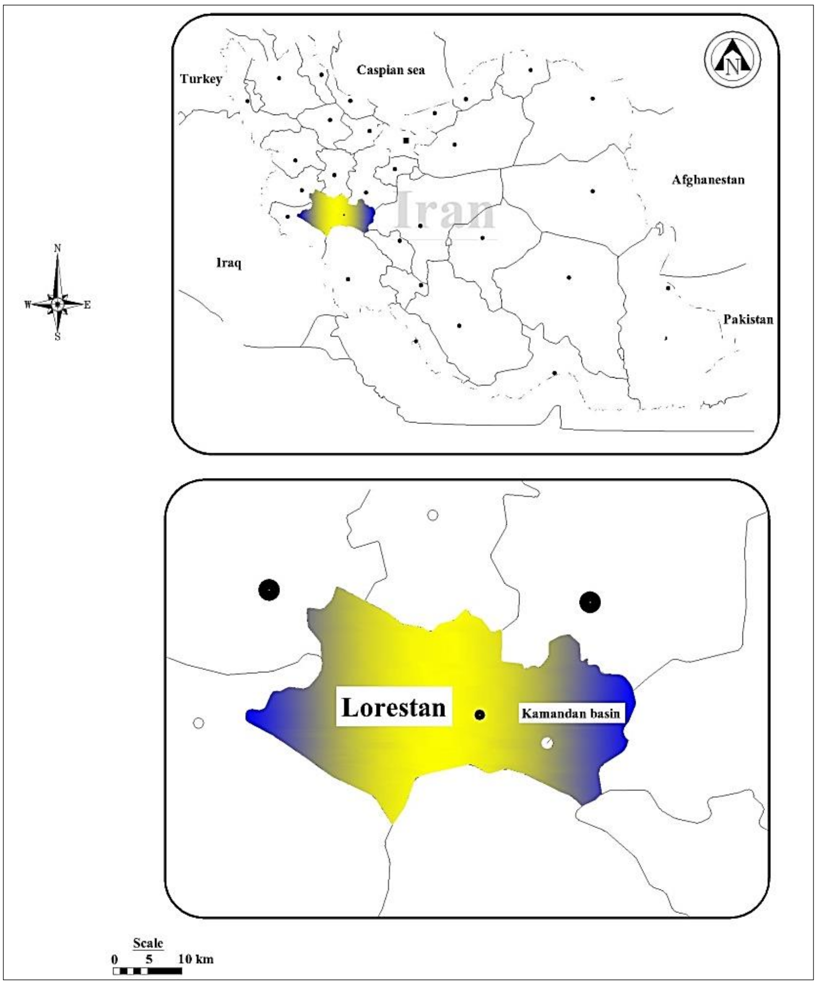

Figure 1. Study area of Kamandan step-pool

Figure 2. An overall view of Kamandan Reach and mapping stations

The study reach is sinuous with the length of 12 times higher than the average bankfull width 5.28 to 7.8, along which 12 steps were clearly observed and divided into four subreaches with 3 steps in each reach. Gradient variations ranged 2%-4%. Typically, bed sediments are poorly imbricated, weakly rounded and steps are formed by irregular accumulation of boulders across the channel. In addition, no woody debris was observed in the reach under study. Discharges have been recorded since 1967 at a gauging station maintained by the Iran Water Resources Management Company that is located approximately 300 m downstream from the study reach. Based on discharge data, Kamandan River has a snowmelt-driven hydrologic regime, with average peak discharges occurring in mid-June (3.32 m^3/s) and 80% of total flows occurred between April and October (1.47 m^3/s).

2.2. Field Measurements

River survey was made along 145 m of the study reach. Total station was used to survey the area with 2256 topographic points (Figure 3).

Figure 3. Topography measurements

Topographic points were selected by considering several characteristics such as crest and bottom of the steps, breaks in the slope, reach uniformity, isolated boulders in bed. The distance between points varied from 30 cm to 2 m. Analogous maps were established to extract 13 cross sections from the topographic survey. Since no significant change was observed in the river bed during field surveys, one representative longitudinal profile of the river bed was drawn. The data were collected in four different dates to monitor river discharge in different conditions of low, medium and high flows. In the first field survey, bed topographic and water surface profile were simultaneously measured while water surface profiles were regarded as the only measurements in other occasions.

As illustrated in Figure 4, the survey data were processed to work out step-pool geometry and water surface profile, based on the definitions. The principal quantities measured by several investigators were defined in the section diagram. L= step–pool unit wavelength (crest-to-crest or pool-to-pool length), H=total drop (of the bed) between pools, H_{crest}=total drop (of the bed) between steps, H_{max}=total drop (of the bed) between step and pool and Li=pool length. Superscripts identify those studies used for the indicated quantity [e.g., 2, 6, 23, 26, 33].

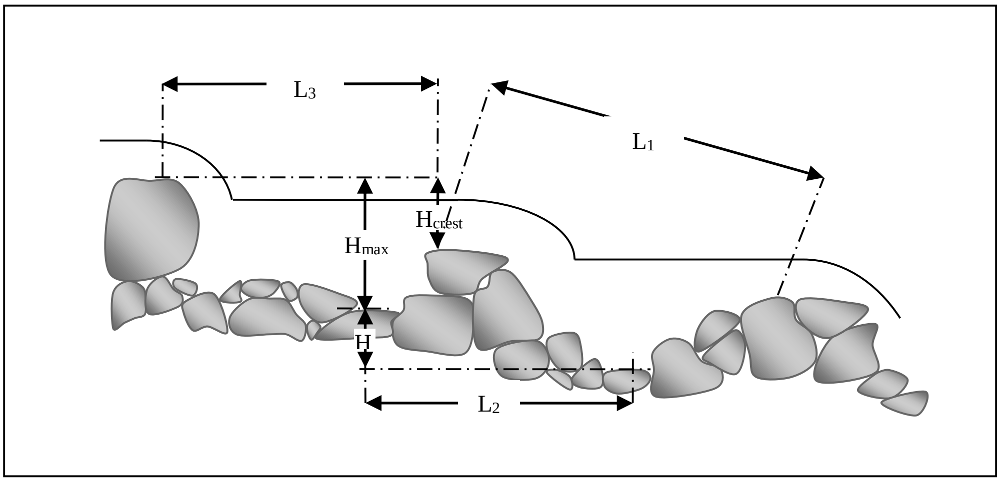

Figure 4. A schematic longitudinal section of a step–pool channel unit

Reach slope was obtained by averaging the local slope values from the survey data, along the thalweg.

3. Results

Step wavelengths and height characteristics were measured based on the topographic map of the study reach for each of the step units. Table 1 reflects different definitions of the wavelength applied to establish the relationships among the morphological parameters such as step height, bankfull width, local slope, and the like. Figure 3 illustrates the definitions. As shown, in the reach samples, the average wavelengths for L_1, L_2, and L_3 are 12.51, 11.81, and 11.68 m, respectively, while a dominant step height (H_{max}) ~ 0.5 m characterizes step–pools in this stream. These values of H_{Crest} yield a characteristic wavelength to height ratio of approximately 10:1 for the 12 step–pool sequences in the reach.

Based on distance downstream, the variation can be observed in the morphology of step–pool streams [3]. A large number of researchers emphasized that the steps are more distinctly described and appeared more regularly at the steep headwaters, which change into longer and smaller downstream gradually [17]. A breakdown of step–pool characteristics in a separate reach indicates that this is generally the case for stream in the Kamandan River basin (Table 1). The variations of step wavelength, as well as all of the drop elevations along thalweg direction (H_{Crest}, H_{max}, and H) are not possible. Figure 5 displays the positive correlation between H_{Crest} and wavelength (L_3) with a determination coefficient of 0.82. The ratio of H_{Crest} to L_3 for every step unit yields local slope. The slopes are relatively superposed with global slope of the study reach. In other words, the gradient of regression line is equal to reach slope. Figure 6 indicates another positive correlation and local slope (H/L_2) for step units, which is related to general slope.

Table 1. Step-pool morphological characteristics

Step No.	Wavelength (m)			H_{Crest}	H_{max}	H	Bankfull width*
	L_1	L_2	L_3	(m)	(m)	(m)	(m)
1	11.69	25.77	11.63	0.33	0.31	0.67	6.31
2	17.22	2.99	16.59	0.46	0.55	0.24	6.06
3	4.38	4.09	2.88	2.10	0.34	0.09	7.59
4	5.53	10.01	5.46	0.18	0.10	0.37	7.57
5	11.04	10.97	9.14	0.32	0.49	0.43	7.07
6	14.46	6.82	12.94	0.49	0.70	0.16	6.86
7	6.96	4.15	6.70	0.19	0.22	0.23	7.80
8	19.83	23.21	19.45	0.49	0.76	0.71	6.37
9	13.54	12.72	12.85	0.43	0.59	0.34	6.98
10	6.97	6.17	6.45	0.11	0.20	0.28	7.11
11	17.43	27.41	16.76	0.52	0.77	0.76	6.36
12	21.19	7.47	19.27	0.58	0.92	0.16	5.76

* Bankfull widths are measured in steps.

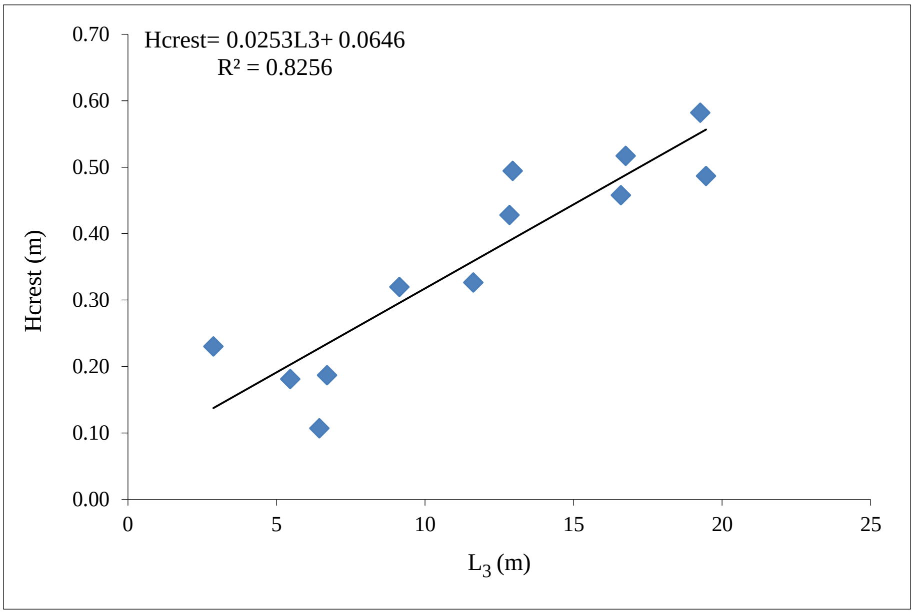

Figure 5. Relationship between L_3 and HCrest along the study reach

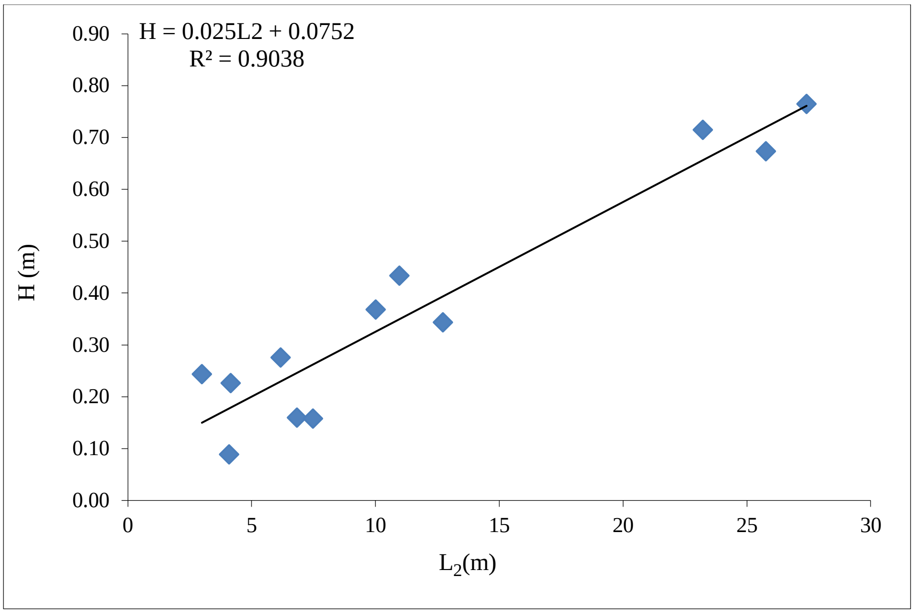

Figure 6. Relationship between L_2 and H along the study reach

In addition, a considerable configurtion of steps and pools was observed in steep reaches. In fact, the changes in step characteristics can influence the pool configurations and vice-versa. In general, the contribution of flow resistance for running region (The region between two step regions is called run region) increases when an increase occurs in the difference between apexes of every two successive steps, compared to the step region. In this case, the main amount of energy of stream flow dissipates in run region. Therefore, the role of step region as an energy dissipater decreases, leading to a reduction in the step height. Instead, as shown in Figure 7, step spacing should be adapted with the flow properties such as flow turbulence and water surface osculation. An increase in the crest spacing leads to an increase in H_{max}. Consequently, pool depth is deepened under these circumstances and streamlines in deep pool can be easily rolled and make some eddies to damp the turbulent behind the step crest. In spite of scattering in bankfull width data, a considerable trend is observed in the study reach (Figure 8). In Figures 7 and 8 as L_3 increase, H_{max} increases and W_{bf} decreases.

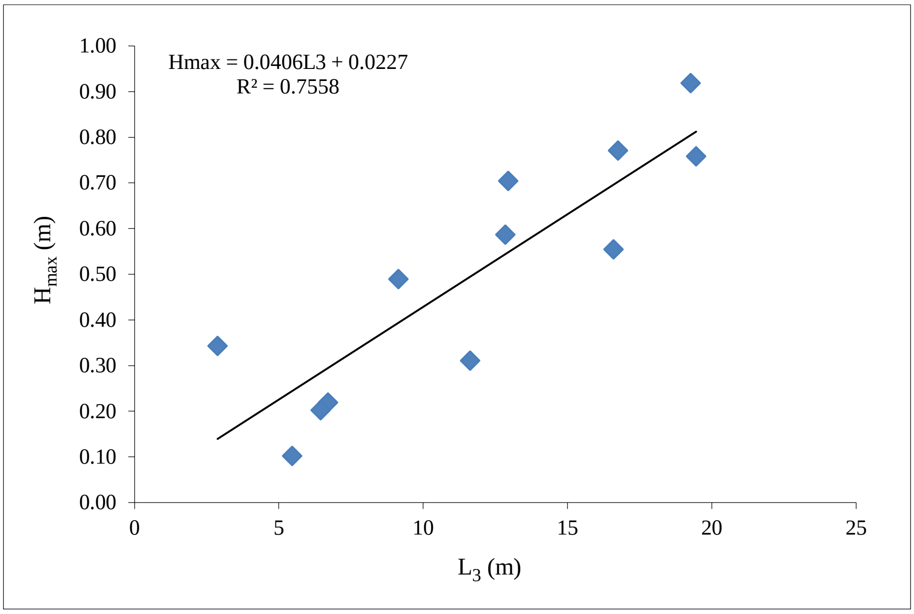

Figure 7. Relationship between L_3 and H_{max} along the study reach

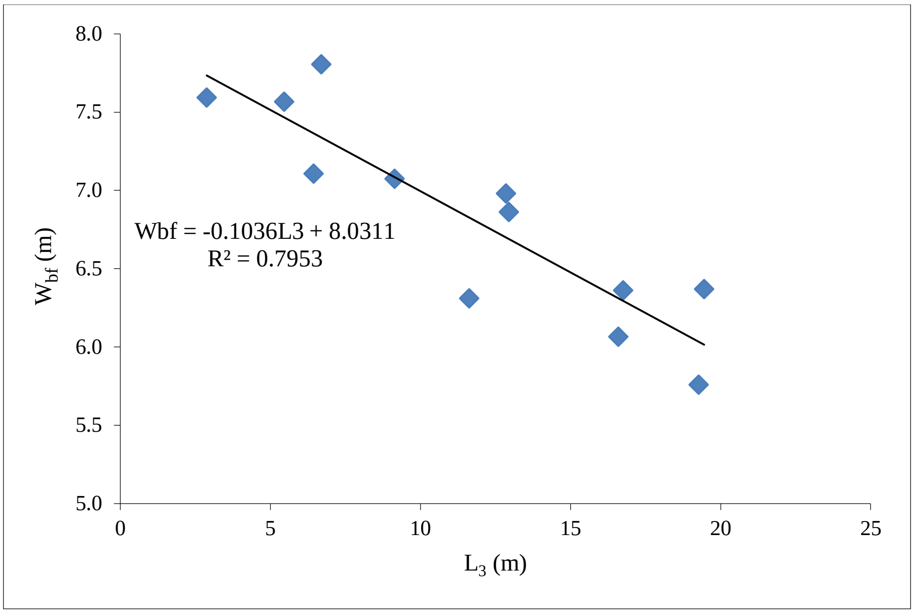

Figure 8. Relationship between L_3 and W_{bf} along the study reach

Analysis of 12 step pools in Kamandan River yields provisional answers to the two stated research questions for this paper, and insights into the causal relationship of the step–pool form. First, step–pools in the Kamandan River are characterized by an average wavelength to height ratio of approximately 10:1, with a morphologic structure that varies with channel gradient. Second, despite the strong association with a gradient that suggests a direct process control, analysis reveals the relationship to reflect correlation, but not necessarily causality. Step height is controlled by the size of the rocks comprising the step, whereas wavelength is likely related to a larger system operation driven by the formative discharge at high flow. Because discharge and material size are the probable direct controls, step wavelength and height can be expected to associate with any parameter that correlates with these variables, including distance downstream and channel slope. The expository roles of discharge and material size provide the foundation for a conceptual model of proposed process-form linkages for step–pools in a spatial context.

Specific process that controls wavelength the horizontal dimension, on the other hand, remains tentative and has important implications for the source of step–pool sequences. An accurate formulation has yet to be achieved, but significant potential lies in understanding the relative roles of width, depth, and velocity variables that determine discharge on wavelength variations. Partitioning the relative roles of these variables could provide the foundation for a more complete description for the step–pool morphology, individually as it relates to variations downstream.

4. Conclusion

In the past, the morphology of step-pools has been studied with regard to their hydraulics because their morphologic features are too irregular to be precisely associated with a sequence of artificial structures (e.g., a series of drop, check dams) and too orderly to conclude that the composition of the overall hydraulic behavior is not predictable. The increase of our science is necessary because river restoration suggestions for steep streams in environmentally sensitive areas should report as much as possible for the step-pool kinematics.

The results of data analysis in some morphological parameters of the step–pool reach in the Kamandan River basin yielded empirical answered some questions for the present study, and the existence of the relationships among the step–pool parameters in mountain streams. Steps and pools in the study reach were characterized by an average wavelength to height ratio of approximately 10:1, with a morphological structure and parameters such as particle size which varied with the distance from the beginning of the reach. The present study aimed to set the ground for more empirical work toward a holistic approach of the step–pool morphology.

Although no precise formulation has been obtained, considerable potential lies in understanding the relative roles of width, depth, and velocity on wavelength variations, which are responsible for determining discharge. However, partitioning the relative roles of these variables may be difficult, although it may prepare the basis for a more comprehensive explanation for the step–pool morphology, especially as it is related to variations in downstream.

Regarding step–pools in the larger context of the fluvial system, consistent spacing is considered as the result of an orderly pattern of scour and deposition. Regular form in spatial structure indicates a groundwork reciprocal adjustment among flow, sediments, and geometry. In this context, step–pools may also be considered as a kind of meandering, the difference as the scale and the dimension in which the meander operates.

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