Research Article

Hydraulic geometry analysis of Ceyhan River, Turkey

Mehmet Ishak Yuce[1] · **Musa Esit**[2] · **Meltem Ciloglan Karatas**[1]

Abstract

Depth, width, velocity and suspended load are critical fluvial hydraulic characteristics, which mainly determine the shape of the cross-section of a river. The aim of this study is to determine at-a-station and the downstream hydraulic geometry parameters and obtain a relationship between sediment discharge and flow discharge of the Ceyhan River. Eleven hydrological stations were utilised in the analyses which are located on the river and its tributaries. Three of these stations have sediment, flow discharge and cross-sectional data, while four of them have only sediment and flow discharge and the other four have only flow discharge and cross-sectional data. The downstream hydraulic geometry parameters *b, f, m, a, c* and *k* were found to be 0.33, 0.38, 0.29, 14.82, 0.61 and 0.12, respectively. At-a-station hydraulic geometry parameters *b, f, m, a, c* and *k* were found to be 0.1676, 0.00654, 0.7669, 25.676, 1.8542 and 0.0901, respectively. A good power function correlation was noted between the sediment discharge and flow discharge with the average coefficient and exponent of 1.23 and 2.05, respectively. The results of the study are expected to be valuable for water resources planning and management projects in the basin.

Keywords Hydraulic geometry · Downstream hydraulic geometry · At-a-station hydraulic geometry · Ceyhan River · Sediment load

1 Introduction

Due to growing population, human activities especially in developing countries, water management is of great importance in watershed. To meet water resource demand, appropriate management of river basins is a necessity. For this purpose, comprehending the hydraulic geometry of river channels and their behaviours is important. The measurable hydraulic characteristics which constitute the form of rivers such as depth, width and velocity are achieved by expressing these values as a power function of flow discharge. These exponential relationships between the hydraulic geometry parameters and the flow discharge are called hydraulic geometry [1]. Hydraulic geometry can be applied either for at-a-station approach in which the changes in a particular cross-section is taken into consideration or downstream approach where changes all along the river channel and its branches are considered [2]. Both approaches were considered in this study. Hydraulic geometry is formulated by Leopold and Maddock [1] as a power function of flow discharge;

$$B = aQ^b \tag{1}$$

$$H = cQ^f \tag{2}$$

$$V = kQ^m \tag{3}$$

where Q is flow discharge, B is the water surface width, H is the average water depth, V is the average flow velocity; a, b, c, f, k and m are numerical constants. For rectangular channels width, depth and velocity satisfy the continuity equation which means summation of the exponents and multiplication of coefficients are equal to 1 (Eqs. 5, 6).

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Hydraulic geometry relation accepts that the flow is steady and uniform. A power function method is utilised to find the exponents and the coefficients.

$$Q = BHV \quad (4)$$

$$ack = 1 \quad (5)$$

$$b + f + m = 1 \quad (6)$$

Due to the importance and practical usage, many researchers have focused on hydraulic geometry content. Over the last decades, a lot of hydraulic geometry studies have been reported all over the world.

Leopold and Maddock [1] introduced hydraulic geometry theory by analysing the cross-sectional data of 20 rivers and found *b, f* and *m* values to be 0.26, 0.40 and 0.34, respectively, for at-a-station hydraulic geometry, while for downstream hydraulic geometry these values were noted to be 0.50, 0.40 and 0.10, respectively. Leopold et al. [3] stated that, in downstream hydraulic geometry, the width has tendency to increase more consistent than any other morphologic variable, as a square root of the discharge, while mean velocity tends to increase slightly at the downstream in most rivers. Chong [4] has realised that hydraulic geometry relations can be similar for different river environments. Richards [5] affirmed that the power relationships can be used for forecasting various types of channel cross-sections. Park [6] has studied 139 at-a-station sites and 72 downstream cases. The average values of *b, f* and *m* exponents were noted to be around 0.4–0.5, 0.3–0.4 and 0.1–0.2, respectively.

Huang and Warner [7] introduced that the coefficient of hydraulic geometry parameters is related to hydraulic roughness (Manning's n), slope and bank strength. Huang and Nanson [8] examined bank vegetation and found that dense bank vegetation causes narrower channels, while bed vegetation increases the flow resistance and causes wider channels, reduction in flow velocity and no significant change in depth. Singh [2] and Park [6] analysed the *b*, *f* and *m* values for different studies collected from literature for both at-a-station and downstream cases. Parker [9] realised that the *b*, *f* and *m* values show a similarity for different regions, while *a*, *c* and *k* values can be different from region to region. Kolberg and Howard [10] and Howard [11] stated that hydraulic geometry parameters show variations, depending on the bed material of alluvial channels. Rhoads [12] has explored variations of the hydraulic geometry and affirmed that generally the coefficients are more variable than the exponents. Since collecting real channel data is expensive and cumbersome, Allen et al. [13] recommended that hydraulic geometry relations are sufficient for planning-level models and with the combination of other analytical methods, it can be cost-effective and practical design method. Huang and Nanson [14] stated that the hydraulic geometry exponents show significant variation from one stream to another. Stewardson [15] has observed that change of hydraulic geometry parameter is connected to type of rivers, flow parameters, sediment load and bank material. For downstream studies of hydraulic geometry parameters of alluvial channels, a huge set of data is collected by Lee and Julien [16]. De Rose et al. [17] have studied downstream hydraulic geometry of the Victoria River and analysed 93 sites. For narrow and deep channels, Nanson and Huang [18] found that when flow velocity changes rapidly, water depth changes moderately and water surface width almost does not change.

Downstream hydraulic geometry of the Tigris River was determined by Muratoglu and Yuce [19]. The *b*, *f*, and *m* exponents for the Tigris River were found to be 0.469, 0.468 and 0.077, while *a, c* and *k* coefficients were observed to be 8.17, 0.18 and 0.66, respectively. Yuce et al. [20] determined the hydraulic geometry parameters of the Seyhan River and found *b, f* and *m* values of the downstream hydraulic geometry as 0.11, 0.56 and 0.33, respectively. Wilson [21] stated that the movements of sediment material in the rivers are in two different forms: bed load and suspended load. He described the bed load as part of the total load that passes right above the bed and affirmed this bearing load is being supported by intergranular collisions rather than liquid turbulence, while suspended load is a part of the load, especially supported by the turbulence of flow. The geological, topographical and climatic factors affecting sediment transport are numerous; the relationship to each other is too complex to analytically calculate the amount of sediment carried by any stream. Although there are many different estimation methods developed for this purpose, direct measurements results are always more reliable than calculations [22]. Due to the increase in rural population, sediment transport and erosion rate are increasing [23, 24]. For downstream studies of hydraulic geometry parameters of alluvial channels, a huge set of data is collected by Lee and Julien [16].

Eaton and Church [25] tested rational regime theory. They first tested the cases in which bank strength does not vary greatly and then tested the modified bank strength formula for vegetated gravel bed rivers in which bank strength changes with channel scale. The classical hydraulic geometry was found to show only an insignificant variation of channel form. Booker and Dunbar [26] established a method to predict hydraulic geometry of UK channels. Donald E. Reid et al. [27] investigated 61 cross-sections in British Columbia and noted that the mean velocity changes more rapidly with discharge. In 31 of 61 cross-sections, velocity exponent (*m*) was observed to be greater than the width and depth exponents combined. The average value of *m* was calculated to be

0.51, while average values of b and f were 0.20 and 0.29, respectively. Aisuebeogun et al. [28] noted that width-to-depth ratio is related to percentage of silt and clay in the channel perimeter. Julien [29] described downstream hydraulic geometry in three ways such as empirical concept, theoretical developments and equivalent channel width.

Ternary diagram of hydraulic geometry exponents apparently demonstrates differences and similarities among the basin system by showing simultaneously the value of all three exponents with time. Interpreted exponents give an idea about stream. While $b > f$ becomes a channel wider and shallower downstream, $f > b$, depth increases faster than width, shows a channel cross-section relatively deeper and narrower. $m = 0$ states that the channel velocity doesn't change with time. When $m = 0.5$, velocity increases rapidly in stream than area [31].

As lots of studies have been conducted about hydraulic geometry, including the ones mentioned above, hydraulic geometry is of great importance. First, hydraulic geometry relations are very practical to forecast fluvial processes of alluvial channel. Determining hydraulic geometry parameters of rivers is essential for design and management of hydraulic works, channel training works, flood control, hydropower generation, irrigation works, channel improvements, and so on. Under-sizing the river channel may cause severe flood problems, while oversizing the channel may start the degradation of biodiversity [30]. In order to develop sustainable and cost-effective river management strategies, hydraulic geometry parameters and sedimentations are of great importance, which helps to predict the physical characteristics of river systems for future works.

2 Study area and data

Ceyhan River Basin is situated in the eastern Mediterranean region, within the boundaries of Turkey. The catchment lies between 36° 33′ to 38° 44′ North latitudes and 35° 15′ to 37° 43′ East longitudes. It is bounded by the Seyhan River Basin in the west and northwest, the Asi River Basin in the south and the Euphrates River Basin in the east and northeast. Ceyhan River reaches the Mediterranean Sea, near the city of Adana (Fig. 1).

In this study, eleven flow and sediment stations were utilised. Three of these stations have sediment and discharge data, while four of them have only sediment and the other four have only discharge data (Fig. 1). The mean daily discharges, the channel cross-sectional data and sediment measurement data were collected from General Directorate of State Hydraulic Works of Turkey (DSI). In the analysis of every single station, the cross-sectional area data were utilised with the corresponding daily discharge values.

At-a-station and downstream hydraulic geometry parameters were calculated by employing power function analysis. A time period of 7 years ranging from 2004 to 2010 was considered in the investigation in order to

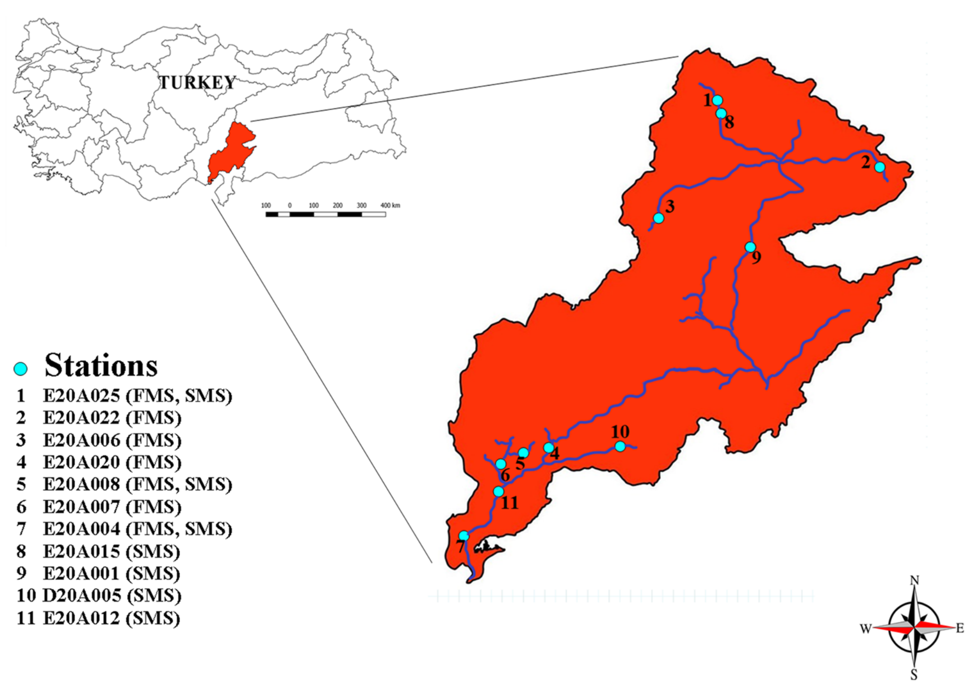

Fig. 1 Ceyhan River Basin and the flow and sediment measurement stations

Table 1 Flow measurement stations

Stations	Available flow measurements	Available cross-sections	Drainage area (km^2)	Latitude	Longitude	Altitude (m)	Sediment discharge (ton/day)
E20A004	1985–2014	2004–2010	20,466	36°57′28″	35°38′03″	15	7047.77
E20A006	1985–2014	2003–2010	739.2	38°01′55″	36°34′11″	1324	–
E20A007	1985–2014	2003–2010	623	37°20′29″	35°55′03″	35	–
E20A008	1985–2014	2003–2010	480	37°21′43″	36°05′05″	70	389.13
E20A020	1985–2011	2002–2010	14,705	37°16′01″	36°16′32″	83	–
E20A022	1986–2015	2004–2010	400	38°15′20″	37°32′01″	1347	–
E20A025	1996–2015	2004–2010	914.7	38°25′19″	36°55′12″	1222	82.97
E20A001	1968–1991	–	8484	37°37′15″	36°47′54″	18	3750.20
E20A012	1953–1965	–	19,778.8	37°01′57″	35°48′43″	30	42,881.80
E20A015	1956–1989	–	915.2	38°25′21″	36°55′14″	1180	65.80
D20A005	1961–2013	–	94	37°05′58″	36°20′12″	265	19.34

find a relationship between the flow discharge and the hydraulic geometry components of the river. The flow measuring stations utilised in the study are detailed in Table 1. The measured hydraulic characteristics of these seven flow measurement stations are presented in Table 2. Variations of hydraulic parameters are examined for two cases: (1) variations at a specific cross-section, which is known as at-a-station hydraulic geometry, and (2) variations along the channel, which is called downstream hydraulic geometry.

3 Materials and methods

3.1 At-a-station hydraulic geometry

At-a-station hydraulic geometry term is introduced by Leopold and Maddock [1] which is the relationship between the surface width, mean depth and mean flow velocity and water discharge. At-a-station hydraulic geometry brings out mean values over a certain period, such as a week, a month, a season or a year. In this approach, analyses are performed for a particular cross-section of the river, at a flow measurement station. A line fitted to the plot of daily discharge values versus the characteristics of the cross-sectional area of each station presents a power function which yields hydraulic geometry parameters. Graphics given in Fig. 2 represent at-a-station relationships between the flow discharge and hydraulic geometry parameters (width, depth, velocity) for seven flow measurement stations on the Ceyhan River. Empirical equations were derived by using a power function analysis. The average values of the exponents b, f and m were found to be 0.1676, 0.0654 and 0.7669, while the average values of the coefficients were noted to be 25.676, 1.8542 and 0.090, respectively, for at-a-station hydraulic geometry. For all stations apart from E20A020 and EA20A022 surface width, mean depth and mean flow velocity were observed to increase with increasing flow discharge. In E20A020 and EA20A022 measurement stations, the mean depth was noted to slightly decrease with increasing discharge which signifies shallow and wide cross-sections. At-a-station hydraulic geometry parameters are presented in Table 3. Ternary diagrams (the exponents b-f-m) for at-a-station are shown in Fig. 3.

3.2 Downstream hydraulic geometry

The concept of downstream hydraulic geometry includes longitudinal changes in channel width, mean depth and mean flow velocity for a given discharge of water over a period of time. In this method, investigations are performed for a number of cross-sections of a river for the same period of time. A line fitted to the log–log scale plot of mean daily discharge values versus the hydraulic geometry parameters of cross-sectional areas of seven stations for a period of 7 years exhibits a power function. Diagrams illustrated in Fig. 4 demonstrate the downstream hydraulic geometry relationships between the flow discharge and hydraulic geometry parameters (width, depth, velocity) for 7 years. The empirical equations were acquired by employing a power function analysis. The average values of the exponents b, f and m were found to be 0.1676, 0.0654 and 0.7669, while the average values of the coefficients were observed to be

Table 2 Daily discharge values and corresponding hydraulic characteristics

Flow measurement stations		Average daily discharge	Cross-sectional area	Water surface width	Average depth	Average velocity
No	Year	Q (m^3/s)	A (m^2)	B (m)	H (m)	V (m/s)
E20A004	2010	84.900	438.893	69.975	6.272	0.193
	2009	54.700	423.543	70.979	5.967	0.129
	2008	79.800	383.831	67.108	5.720	0.208
	2007	88.700	406.607	70.276	5.786	0.218
	2006	88.700	426.958	70.670	6.042	0.208
	2005	102.000	413.957	70.750	5.851	0.246
	2004	92.500	471.600	72.130	6.538	0.196
E20A006	2010	2.130	14.445	14.505	0.996	0.147
	2009	1.670	16.710	16.150	1.035	0.100
	2008	0.980	12.684	14.490	0.875	0.077
	2007	2.700	13.951	16.081	0.868	0.194
	2006	2.140	15.879	18.014	0.881	0.135
	2005	2.560	17.248	17.724	0.973	0.148
	2004	3.410	18.382	17.602	1.044	0.186
	2003	3.230	17.289	17.213	1.004	0.187
E20A007	2010	5.660	15.000	15.874	0.945	0.377
	2009	6.920	20.940	16.000	1.309	0.330
	2008	3.200	20.550	16.000	1.284	0.156
	2007	3.490	12.358	14.555	0.849	0.282
	2006	4.060	12.322	14.742	0.836	0.329
	2005	3.490	15.197	15.791	0.962	0.230
	2004	4.530	20.810	16.000	1.301	0.218
	2003	5.380	16.000	13.989	1.144	0.336
E20A008	2010	0.564	6.384	18.436	0.346	0.088
	2009	1.300	13.402	23.869	0.561	0.097
	2008	1.120	11.227	23.306	0.482	0.100
	2007	1.450	29.894	35.500	0.842	0.049
	2006	1.200	11.520	24.738	0.466	0.104
	2005	0.760	11.717	25.575	0.458	0.065
	2004	2.080	21.750	41.880	0.519	0.096
E20A020	2010	88.500	281.650	93.469	3.013	0.314
	2009	66.900	134.586	72.184	1.864	0.497
	2008	71.000	124.133	73.816	1.682	0.572
	2007	8.680	120.760	70.982	1.701	0.072
	2006	40.600	125.679	73.808	1.703	0.323
	2005	70.500	156.560	75.000	2.087	0.450
	2004	127.000	74.466	138.792	0.537	1.705
	2003	118.000	79.410	173.661	0.457	1.486
E20A022	2010	0.323	3.824	13.146	0.291	0.084
	2009	0.288	14.343	13.183	1.088	0.020
	2008	0.170	4.029	13.015	0.310	0.042
	2007	0.244	4.439	12.321	0.360	0.055
	2006	0.331	4.415	12.705	0.348	0.075
	2005	0.240	14.926	14.092	1.059	0.016
	2004	0.450	5.890	14.690	0.401	0.076
E20A025	2010	4.260	6.142	9.746	0.630	0.694
	2009	2.620	6.390	9.850	0.649	0.410
	2008	3.130	5.478	9.640	0.568	0.571
	2007	1.970	5.219	9.223	0.566	0.377
	2006	3.290	6.112	10.272	0.595	0.538
	2005	4.360	6.748	10.765	0.627	0.646
	2004	3.800	6.246	10.287	0.607	0.608

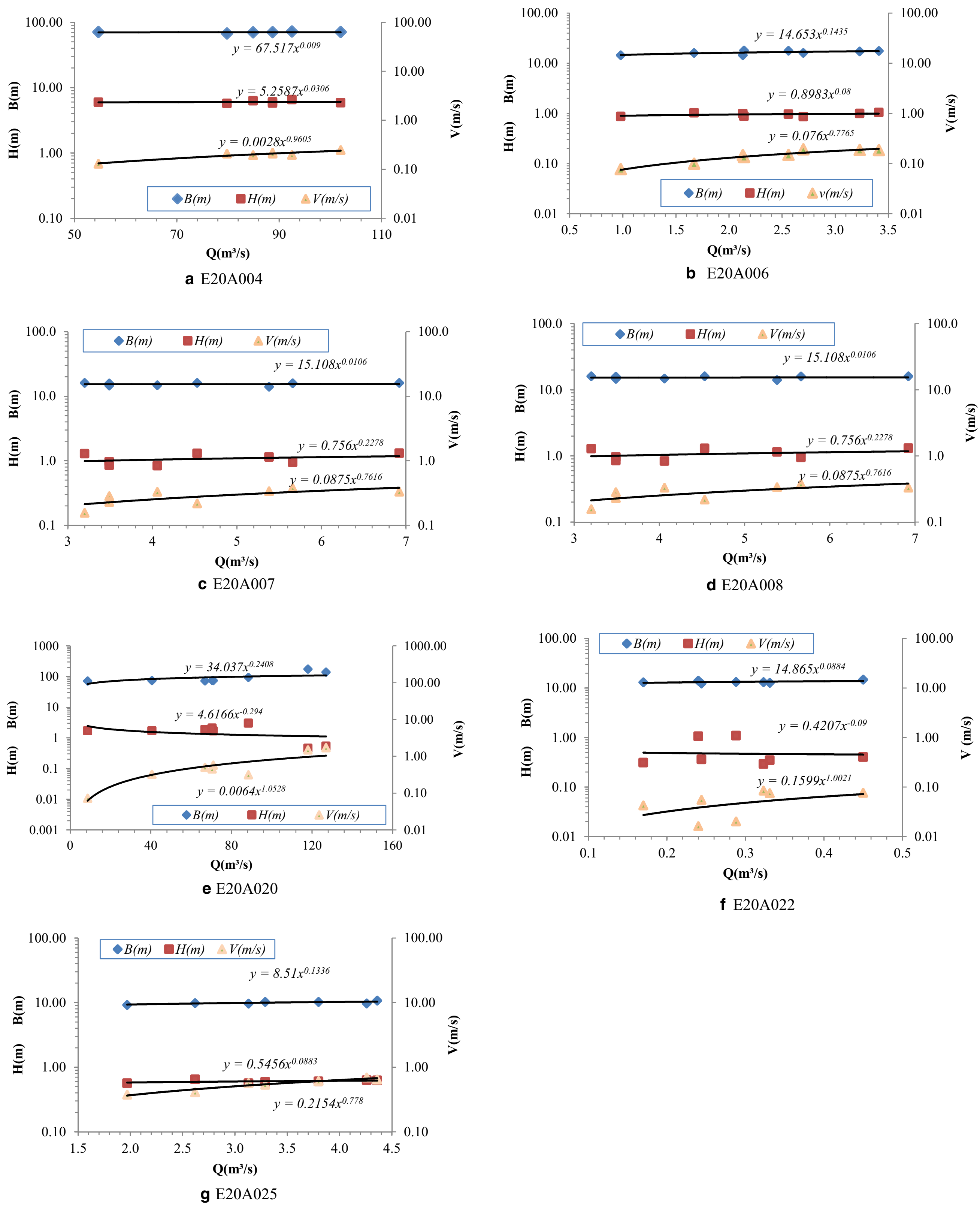

Fig. 2 Relationship between discharge and at-a-station hydraulic geometry parameters

Table 3 The exponents and coefficients of at-a-station hydraulic geometry parameters

Stations	Exponents			Coefficients			$b+f+m$	$a*c*k$
	b	*f*	*m*	*a*	*c*	*k*		
E20A004	0.0090	0.0306	0.9605	67.5170	5.2587	0.0028	1.0001	0.9941
E20A006	0.1435	0.0800	0.7765	14.6530	0.8983	0.0760	1.0000	1.0004
E20A007	0.0106	0.2278	0.7616	15.1080	0.7560	0.0875	1.0000	0.9994
E20A008	0.5475	0.4154	0.0371	25.0420	0.4841	0.0825	1.0000	1.0001
E20A020	0.2408	−0.2940	1.0528	34.0370	4.6166	0.0064	0.9996	1.0057
E20A022	0.0884	−0.0900	1.0021	14.8650	0.4207	0.1599	1.0005	0.9999
E20A025	0.1336	0.0883	0.7780	8.5100	0.5456	0.2154	0.9999	1.0001
Average	0.1676	0.0654	0.7669	25.676	1.8542	0.0901	1.00001	0.99997

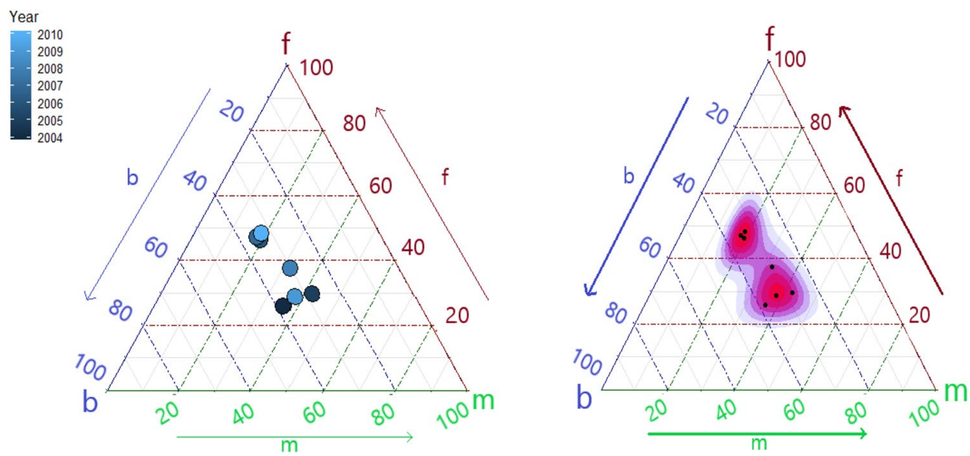

Fig. 3 Ternary diagram for *b-f-m* exponents (representing width, depth and velocity, respectively) for at-a-station hydraulic geometry equations

25.676, 1.8543 and 0.0901, respectively, for downstream hydraulic geometry. The width, mean depth and mean flow velocity were observed to increase with increasing flow discharge. The downstream hydraulic geometry parameters are given in Table 4.

3.3 Sediment discharge

Rivers have a capacity to transport large volume of sediment while conveying water [29]. Hence, the term sediment discharge becomes an important factor for water resources management. The sediment volume transported by streams is critical for all hydraulic engineering projects. Power function analysis was utilised to determine the relationship between the river stream discharge and the sediment discharge, as in Eq. 7.

$$Q_s = pQ^j \tag{7}$$

where Q_s (tons/day) is the river sediment discharge, Q (m^3/s) is the river flow discharge, p and j are the coefficient and the exponent of power function, respectively. For the selected seven flow measurement stations, the log–log scale sediment rating curves (Q–Q_s relation) are graphically presented in Fig. 5. In the analysis, it was observed that the sediment discharge is increasing with increasing flow discharge in all stations. The calculated coefficients and exponents of the power function are given in Table 5.

In addition to power function analysis, the relationship between the flow discharge and the sediment discharge was examined by performing the correlation analyses. Kendall, Pearson and Spearman correlations were utilised to determine the correlation coefficients. The correlation coefficients between the sediment discharge and river flow discharge for the seven flow and sediment measurement stations on Ceyhan River are given in Table 6. While D20A005 and E20A025 stations show the strongest relationship between these variables, especially with Spearman's coefficient, ρ, the other stations, in general, indicate a meaningful relationship between the flow discharge and the sediment discharge with Pearson coefficient, r. As the coefficients are examined, it is clearly seen that all correlation values are positive; then, one can say that there is a positive correlation between the flow discharge and the sediment discharge. The Kendall (*tau*) analysis results show

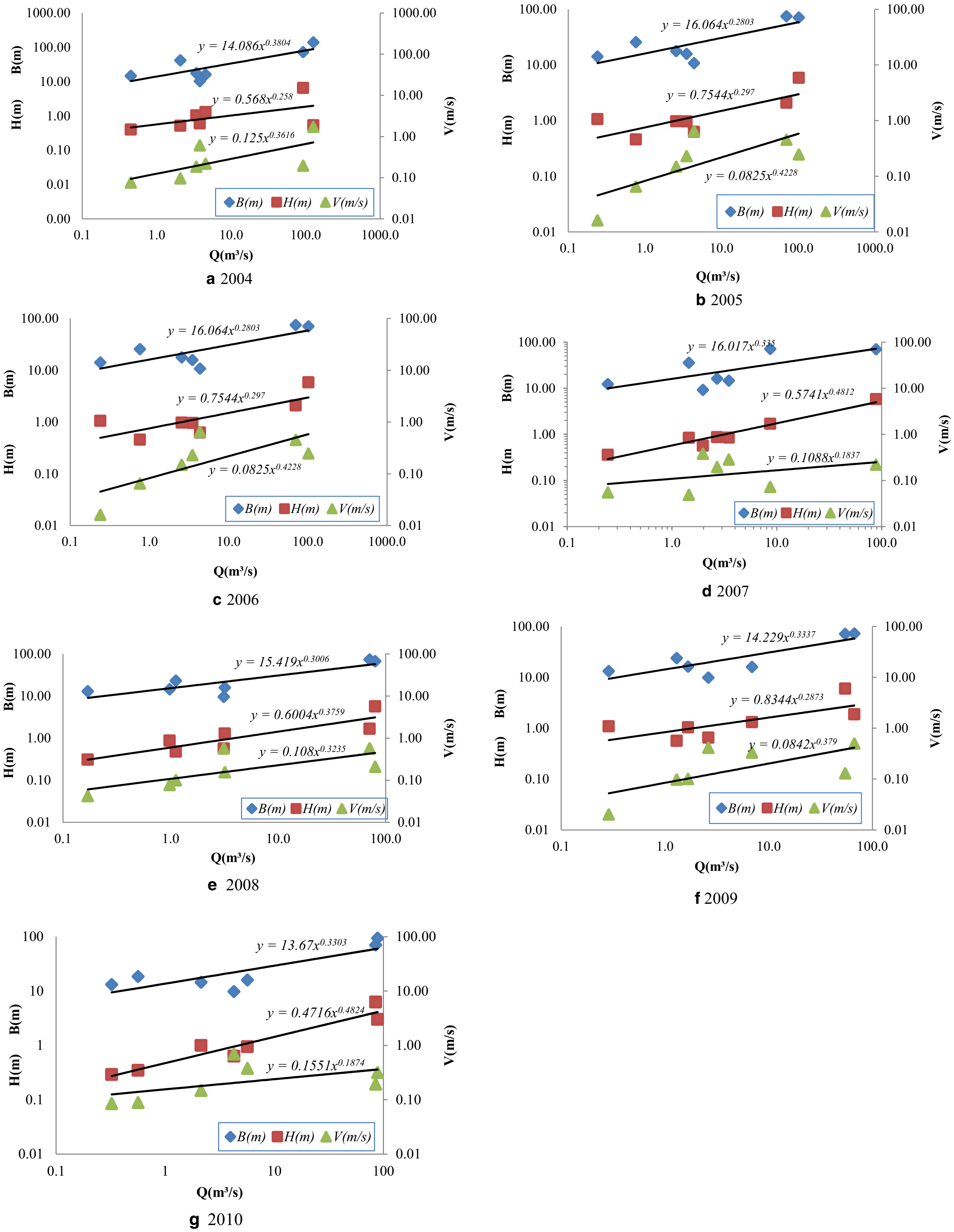

Fig. 4 Relationship between discharge and downstream hydraulic geometry parameters

Table 4 The exponents and coefficients of the downstream hydraulic geometry parameters

Year	Exponents			Coefficients			*b*+*f*+*m*	*a***c***k*
	b	*f*	*m*	*a*	*c*	*k*		
2004	0.3804	0.2580	0.3616	14.0860	0.5680	0.1250	1.0000	1.0001
2005	0.2803	0.2970	0.4228	16.0640	0.7544	0.0825	1.0001	0.9998
2006	0.3417	0.4611	0.1971	14.2400	0.4750	0.1478	0.9999	0.9997
2007	0.3550	0.4812	0.1837	16.0170	0.5741	0.1088	1.0199	1.0005
2008	0.3016	0.3759	0.3235	15.4190	0.6004	0.1080	1.0010	0.9998
2009	0.3337	0.2873	0.3790	14.2290	0.8344	0.0842	1.0000	0.9997
2010	0.3303	0.4824	0.1874	13.6700	0.4716	0.1551	1.0001	0.9999
Average	0.33186	0.377557	0.29359	14.81786	0.61113	0.11591	1.0030	0.99992

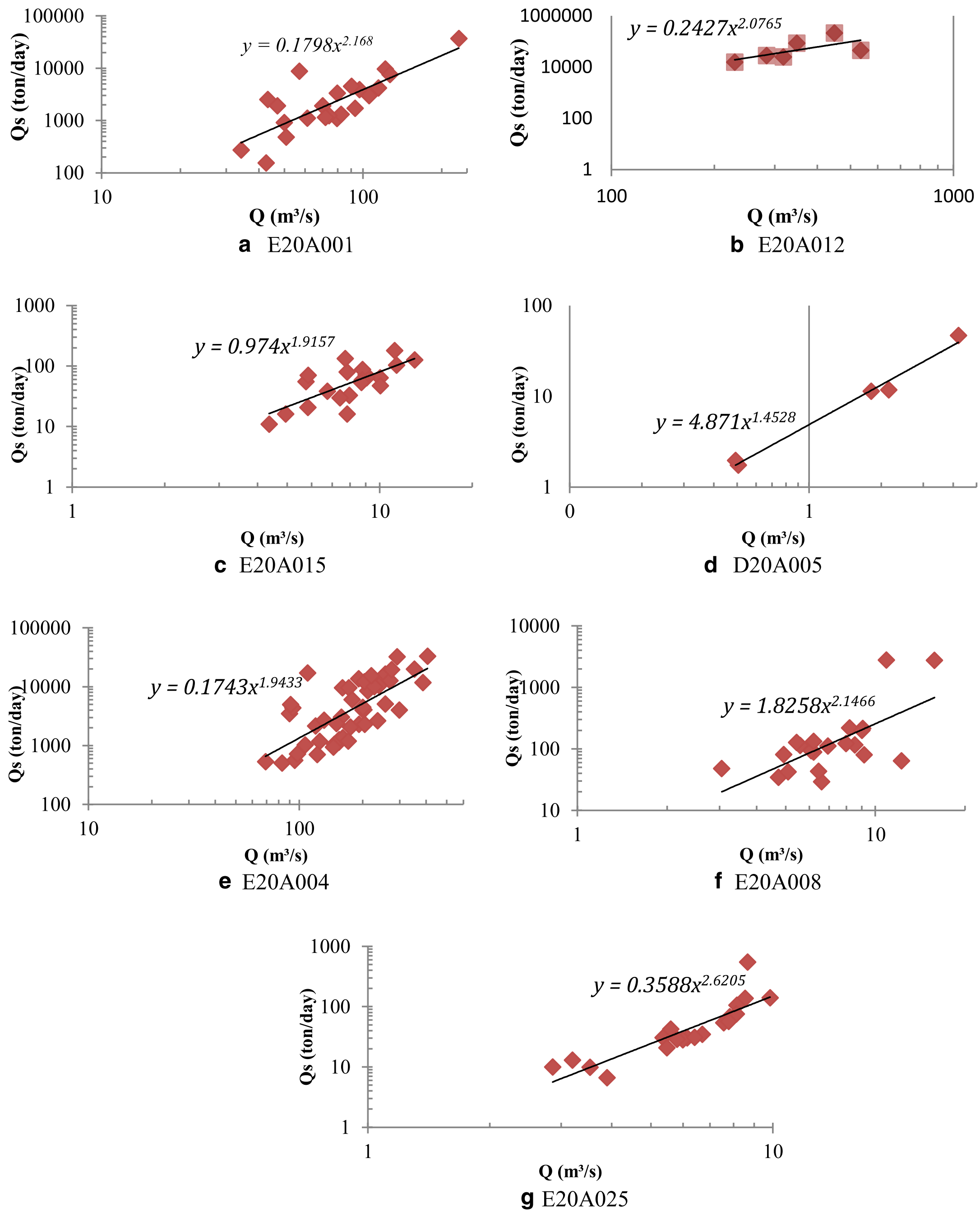

Fig. 5 Sediment rating curves (Q_s–Q) for seven stations

Table 5 Coefficients and exponents of the relationship between sediment and flow discharges

Stations	*p*	*j*
E20A001	0.1798	2.1680
E20A012	0.2427	2.0765
E20A015	0.9740	1.9157
D20A005	4.8710	1.4528
E20A004	0.1743	1.9433
E20A008	1.8258	2.1466
E20A025	0.3588	2.6205
Average	1.2323	2.0462

the highest correlation coefficients as 0.80 and 0.832 for D20A005 and E20A025 stations, respectively. The highest correlation coefficients, in Pearson test, were noted to be 0.968 and 0.865 for D20A005 and E20A001 stations, respectively, while in Spearman test the highest correlation coefficients were observed to be 0.9 and 0.941 for D20A005 and E20A025 stations, respectively. As a result of these analyses, significant changes can be observed in the geometry of D20A005 and E20A025 stations, in time. The results of this study could be used to predict the cross-sectional characteristics of the Ceyhan River at any point and might be useful for flood control, planning and management of hydropower generation.

4 Conclusion

Hydraulic geometry parameters and sediment transportation in a river are significant for water resources management, planning and controlling extreme hydrological events (flood and drought, etc.). In this study, at-a-station and downstream hydraulic geometry analyses were performed for seven flow measurement stations of Ceyhan River over a period of 7 years. The analyses were conducted in the form of a power function, in order to define the relationship between the flow discharge and the river flow characteristics.

Channels in the Ceyhan Basin may adjust a consistent pattern computed by the concept of hydraulic geometry. Exponents and coefficients given in Tables 3 and 4 for downstream and at-a-station adequately state the general hydraulic geometry relationships for Ceyhan Basin in Turkey, and these relationships can be inferred for other basins when they have similar characteristics. Hydraulic geometry parameters for Ceyhan Basin have been compared nicely with previous published theoretical values. However, a considerable range of exponents and coefficients in both at-a-station and downstream due to different geologic, climatic physiographic and morphologic environments applying the basic hydraulic geometry approach vary between streams. In summary at-a-station, for all stations apart from E20A020 and EA20A022 surface width, mean depth and mean flow velocity were observed to increase with increasing flow discharge. In E20A020 and EA20A022 measurement stations, the mean depth was noted to slightly decrease with increasing discharge which signifies shallow and wide cross-sections. For downstream, the width, mean depth and mean flow velocity were observed to increase with increasing flow discharge.

In addition to hydraulic geometry analysis, sediment discharge–flow discharge relationship has also been investigated. According to the results, the relationships at D20A005 and E20A025 stations were found to be more significant compared to other stations in terms of correlation coefficient. Depending on this relationship, the volume of the sediment transported in Ceyhan River can be estimated. This study is expected to shed light for hydraulic works in Ceyhan basin.

Table 6 Correlation coefficients between sediment discharge and flow discharge

Stations	Correlation coefficients					
	Kendall		Pearson		Spearman	
	tau	*p*	*r*	*p*	*ρ*	*p*
E20A001	0.558	0.000	0.865	0.000	0.706	0.000
E20A012	0.600	0.136	0.481	0.335	0.771	0.103
E20A015	0.486	0.002	0.670	0.001	0.647	0.002
D20A005	0.800	0.083	0.968	0.007	0.900	0.083
E20A004	0.554	0.000	0.692	0.000	0.699	0.000
E20A008	0.381	0.016	0.684	0.001	0.518	0.017
E20A025	0.832	0.000	0.538	0.015	0.941	0.000

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard This article does not contain any studies with human participants or animals performed by any of the authors. The manuscript does not contain clinical studies or patient data.

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