Application of unit stream power theory to stable meandering and braided reaches of Sefidroud River

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Abstract

It is important to understand how channel geometry relates to discharge, and to be able to predict how the channel will adjust for a given discharge. This is significant both in a theoretical way, especially in relating channel geometry to given discharges in semi-arid and arid areas, and also in a practical way, for instance in river training and for a variety of instream and external uses. This needs to be able to predict channel geometry led to the development of the concept of regime, which was initially developed with respect to irrigation canals. This concept has since been applied to natural rivers, with the idea of "dominant discharge" being used to represent what discharge the channel is in regime for. Empirical regime equations for stable gravel-bed Sefidroud River were obtained based on data from 32 cross-sections. The stage discharge-rating curve for each cross-section was computed using one-dimensional ISIS hydraulic model. Morphological and sedimentological data were also obtained from field survey to determine stable width and depth from non-dimensional unit stream power theory for braided reaches of Sefidroud River.

1 Introduction

At-a-station or downstream methods may express determination of hydraulic geometry relations for rivers. These methods are evaluated by two different approaches mainly named as empirical and rational. In empirical approaches, water surface width (w), cross-section average depth (d) or flow velocity (V) are plotted on a log-log paper versus discharge (Q) as simple power functions. However, the variability in hydraulic geometry relationships among different

rivers, reaches of the same river, transects in a given reach, and different anabranches is so great as to be of little predictive value. This is due to the fact that discharge is not the only control of hydraulic geometry as it may not be linear on log-log paper any more [1]. Downstream hydraulic geometry may be expressed in terms of the entire river [2]. Although Ashmore's [2] results from a laboratory channel are broadly similar to those from single channel streams. However, it is difficult to make a strict comparison because in real rivers downstream increases in channel forming discharge are usually accompanied by decreases in slope and bed grain size while these parameters were held constant in Ashmore's experiments. Ferguson and Ashworth [3] show that mean channel width in braided rivers (with braiding index less than 2) varies with discharge, slope and median bed material size and that rational regime theories are generally better predictors of channel width than are empirical equations.

Alluvial river channels carry sediment load and erode their bed and banks locally in space and time. However, as they migrate across their valley surfaces, they may maintain stable or equilibrium, average forms unless during migration they encounter different bank materials or have a new discharge regime imposed on them [4]. Various types of equilibrium can be defined [5] of which two are particularly relevant, static and dynamic equilibrium. In static equilibrium, a balance between opposing forces brings about a static condition in certain system properties [6]. Although it is widely used in stable channel design, it has little apparent relevance to the fluctuating condition of natural rivers while, in dynamic equilibrium, in short term, river cross-section hydraulic parameters vary continually. This is reflected by bank collapse during and after peak flows causes temporary channel widening which may be balanced by slower depositional processes [7]. This condition of stable equilibrium, but not static form, may be termed steady state. As a matter of fact, regime is equivalent to the steady state equilibrium for which its relations are determined by applying dominant discharge which is the discharge just overtops the river banks known as bankfull discharge [8].

2 River classification

Leopold and Wolman [9] classified river channel patterns into three categories, namely, meandering, braided and straight. Each class being separated by threshold values of river discharge and channel slope. Bridge [10] found that Leopold and Wolman [9] classification system for river pattern was inappropriate. This was due to the fact that Leopold and Wolman [9] regarded a single channel division around a bar or island as a braid, and showed that hydraulic factors such as slope adjusted to the presence of braids. Meandering channels were defined as having a sinuosity (λ) greater than or equal to a value of 1.5, whereas channel multiplicity defined the braided pattern. Bridge [10] stated that this is unsatisfactory because the classes are not mutually exclusive and different parameters are used to define the different patterns, in that it may be a system with a sinuosity greater than 1.5, which also contains alluvial islands or bars [11]. Also, Leopold and Wolman's [9] scheme does not explicitly recognise the stability and instability of channel patterns. Rust [11] proposed a

system of alluvial channel classification based on two parameters: the braiding index and sinuosity. The braiding index was defined by the number of bars per mean meander wavelength, with single and multi-channel systems having a braiding index of less than and greater than one, respectively. The channels are then divided further into two categories of high and low sinuosity, with the distinction made at a sinuosity of 1.5. This classification lead to four channel types: (i) single-channel high-sinuosity (meandering); (ii) single-channel low-sinuosity (straight); (iii) multi-channel high-sinuosity (anastomosing); (iv) multi-channel low-sinuosity (braided).

Although streams adjust to water and sediment discharge, sinuosity (λ), river cross-section shape and bed material size are effective in river stability. Based on these parameters, rivers are classified in three categories stable, eroding and depositing in which sediment is transported as bedload, suspended load and mixed load (i.e. bed and suspended load) [12]. This classification is clearly shown in Table 1.

Table 1 River classification based on sediment load [12]

sediment transport	proportion of bedload to total load (%)	stable reach	
suspended sediment load	<3	(w/d)<7	$\lambda>2.1$
mixed load	3-11	7<(w/d)<25	$1.5<\lambda<2.1$
bedload	>3	(w/d)>25	$1<\lambda<1.5$

2.1 Classification of the braided pattern

A natural river will adjust its channel pattern spatially along its channel network and temporally at a given point to accommodate imposed flow and sediment regimes. The forms of a natural channel when viewed in plan fall within a continuum of channel patterns that is traditionally sub-divided into straight, meandering, braided and anastomosed. The term 'braided' has been given several definitions in academic literature over the past 40 years [10]. Leopold and Wolman [9] described the braided river as 'one which flows in two or more anastomosing channels around alluvial islands' while Lane [13] reported that a braided steam is characterised by having a number of alluvial channels with bars or islands between meeting and dividing again, and presenting from the air the intertwining effect of a braid'. Brice [14] recognised the importance of defining the difference between mid-channel bars or islands within braided rivers and portions of the floodplain excised by channel diversions and avulsions. Schumm [15] made the distinction between braided rivers that at low stages have islands of sediment or islands of semi-permanent vegetation, and multiple-thread rivers or anastomosing channels that have branches with individual channel patterns.

Based on alluvial rivers in China [16] and [17] further sub-divided the braided patterns into two types: the stable braided and the wandering (unstable) braided. The two types of braided patterns are quite different. In the former, the

river channel is relatively narrow and deep, the alluvial islands are well vegetated and therefore stablised with comparable height to the floodplain while in the latter, the channel is shallow and wide, the mid-channel bars are basically bare with very low erosional resistance, and thus they are very unstable. It is easy to see that this classification is similar to the distinction between braided and anastomosed rivers by some geomorphologists [18].

Bridge [10] concluded that these conflicting definitions of the braided pattern raise the issues concerning; (a) the difference between mid-channel bars and islands, (b) the precise nature of the interaction between flow stage and bars or islands and (c) the differences between the mechanisms of channel divergence that lead to river patterns termed as 'braided' and those defined as 'anastomosing'

3 Unit stream power application

In the analytical approach, the concept of minimum unit stream power is used to provide the condition of dynamic equilibrium. The concept states that for an alluvial channel, the necessary and sufficient condition of equilibrium occurs when the stream power per unit channel length, ρgQS, is a minimum subject to given constraints (where ρ=water density, g=gravity and S=channel bed slope) [19]. To differentiate meandering and braided reaches of the river, ρgQS=constant, is applied [20]. They concluded that river planform changes and consequently meander development is a function of (ρ, Q, S, ρ_s-ρ, D, g) where ρ_s= sediment particle density and D= sediment particle size. The Buckingham π theory was then applied to obtain non-dimensional form of unit stream power

$$P = \frac{QS}{\Delta\sqrt{gD^5}} \tag{1}$$

where P= non-dimensional unit stream power and $\Delta = (\rho_s-\rho)/\rho$= relative density

4 Dominant discharge

Dominant discharge refers to the steady flow, which produces the same regime channel dimensions over a period of years as the natural sequence of events [21] and [8]. Field observations [22] as well as model experiments [23] suggest that flows at or about bankfull stage may be the dominant ones for channel development because of the strong empirical relations between channel dimensions and bankfull flow.

In terms of erosion and deposition any change in the morphology of a river, other than by engineering works, must result from a local imbalance in the sediment budget. When in regime the river must have adjusted its bankfull morphology to transport the total sediment load supplied from upstream, such that, over a period of years, there is no net erosion or deposition. Analysis of records of sediment transported by rivers indicates that for stable channels the

bulk of the sediment is transported by intermediate flood events, which occur at or about bankfull flow [24] and [25]. Catastrophic floods, although individually transporting large loads, are too infrequent, while more minor frequent floods transport too small a sediment load.

4.1 Bankfull discharge

In recent years the term bankfull discharge has been in common use in fluvial geomorphology and has gained a considerable emphasis in literature. It may be defined as the discharge, which fills the channel without overtopping the banks. It is one of the most important characteristics of a channel location, and a quantity that reflects all the parameters of the basin.

In order to establish the overall bankfull morphology of the river and its associated discharge capacity, it is necessary to define the bankfull stage. A variety of definitions have been proposed many of which produce different values for channel dimensions and bankfull discharges [26]. It is important to identify a method that can be consistently applied, has general application and relates to the processes responsible for bankfull dimensions of the river. In this context, bankfull stage at a cross-section is identified morphologically by elevation at which the width-depth ratio is a minimum [25] and [27]. Once the bankfull stage is specified, its associated discharge is obtained from the discharge rating curve for the site.

5 Data evaluation

5.1 Sefidroud River characteristics

Sefidroud River is formed just upstream of Sefidroud Dam at the confluence of two main branches of Ghezel-Ozan and Shahroud River, the discharge gradually increases due to the inflow of tributaries along the river profile. It is located between 49° 15' and 50° 00' eastern longitude to 36° 45' to 37° 30' northern latitude with a catchment area of 2612 kilometre squares and 110 kilometres long which is discharged into Caspian Sea, [28]. Riverbed elevation immediately downstream of the dam is 190 metres above the sea level, which is the deepest reach of the river, while at the river mouth it falls dramatically to -26.5 metres, average slope of the river is about 1.97×10^{-3}. The longitudinal profile of the river is a characteristic feature, from the source of the river to the mouth, based on its planform, it is categorised into three classes: 1-Downstream of Sefidroud Dam to Tarik diversion Dam which is a mountainous area and flows over bedrocks. 2-Downstream of Tarik diversion Dam to Astaneh Bridge which is braided with stable vegetated islands. 3-Astaneh Bridge to Kian-Shahr Harbour that is meandering with bed and bank consist of alluvial material.

Construction of Sefidroud Dam started in 1963 and its actual operation was in 1969. Mean annual discharge of the river at Astaneh Bridge station is 140.6 cubic metres per second from 1969 to 1997 with a mean suspended sediment load of 28.399 million tonnes per year [28].

5.2 Data collection

As sefidroud River plays a major role in economy and agricultural products of Gilan Province in the north of Iran, it has always been regarded as a lifeline for that area. Hence there are reasonable data available such as, two sets of arial photographs for 1969 and 1989, in addition, cross-sections of the river were surveyed in 1969 and 1998, respectively. ISIS, one-dimensional hydraulic model, was also calibrated for the river and therefore enabled us to work out water discharge as well as water surface elevation associated with a particular width and depth. For the middle and end reaches of the study area, there were no noticeable changes to be observed from the arial photographs. In the middle reach, islands are composed of gravel and sand with perennial vegetation cover being well-established [28].

Bankfull discharge was selected as dominant channel forming discharge for the river. This was determined by the elevation at which width-depth ratio is a minimum which was also associated with 1.5 to 2 years flood return period on annual maximum series. Then discharge rating curves, obtained from ISIS analysis, were used to estimate the bankfull discharge for each cross-section.

6 Data analysis

The variables controlling stable river dimensions are the discharge, sediment load, calibre of bed and bank material and valley slope. Change in any one of these independent variables will eventually result in the development of new regime channel geometry, which is in equilibrium with the changed conditions. When stable, the channel morphology will be uniquely defined by the new values of the controlling variables.

The dependent variables describing alluvial channel morphology while the independent variables controlling it. These variables should be linked by governing equations, which define the adjustment mechanisms. If the relationship between the variables could be established, it would be possible to predict the multi-dimensional morphology of alluvial channels by the simultaneous solution of the governing equations.

According to Leopold and Wolman [9], river morphology dependent parameters (i.e. width, depth and velocity) can be correlated by discharge values as power functions. An attempt was first made to compute width and depth in terms of discharge values exponentially ($w=aQ^b$, where a and b=constants). For this purpose, the river was studied in two separate reaches braided and meandering, reach 2 and 3, respectively. In each reach, sixteen cross-sections were selected (i.e. eight pools and eight riffles in reach 3). After establishing bankfull discharge and its associated width and depth at each cross-section, correlations were made. The highest correlation coefficient (R) was for braided reach at 74% while it varied 40% to 60% for meandering reach. More importantly, b values varied 0.4 to 0.6.

Unit stream power theory was also applied to use bed slope and bed material size (D_{50}) to compute non-dimensional regime relations more accurately. (w/D_{50}) and (d/D_{50}) were also calculated at bankfull discharge for each cross-section to

establish non-dimensional relations between P and w as well as P and d. This was obtained for meandering and braided reaches separately while the entire river reach was also used for the same analysis Figures 1 and 2. However, the
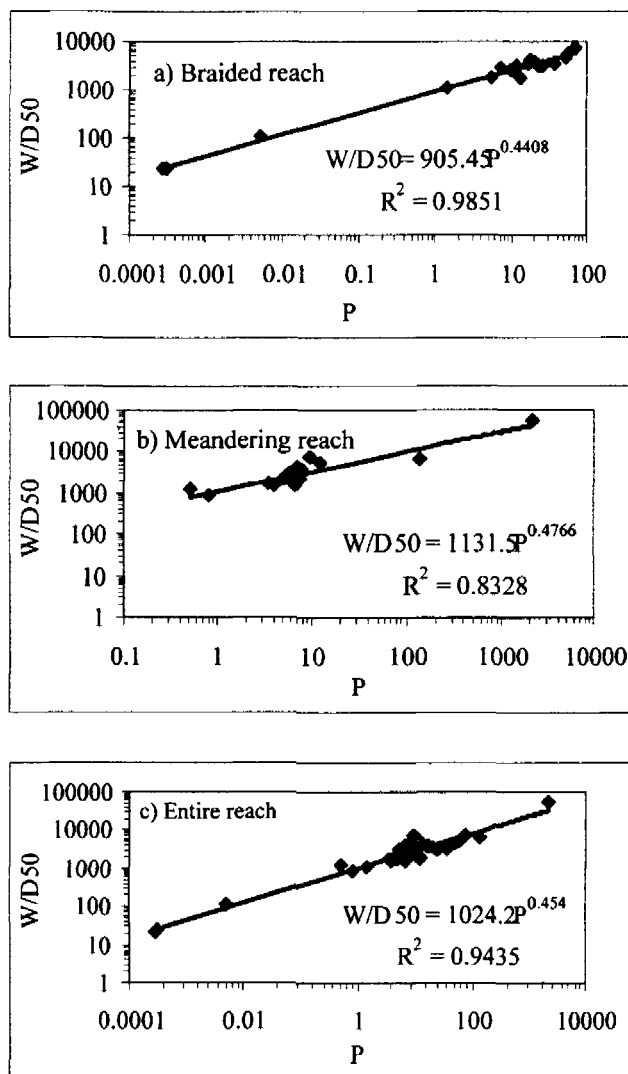

Figure 1: Plot of P against (w/D$_{50}$) for Sefidroud River.

correlation coefficients (R) are greater than 90% for all the cases. It is also noticed that exponents of discharge (Q) vary in the range 0.4-0.6. Table 2 and 3 show regime equations derived from unit stream power and best fit regression
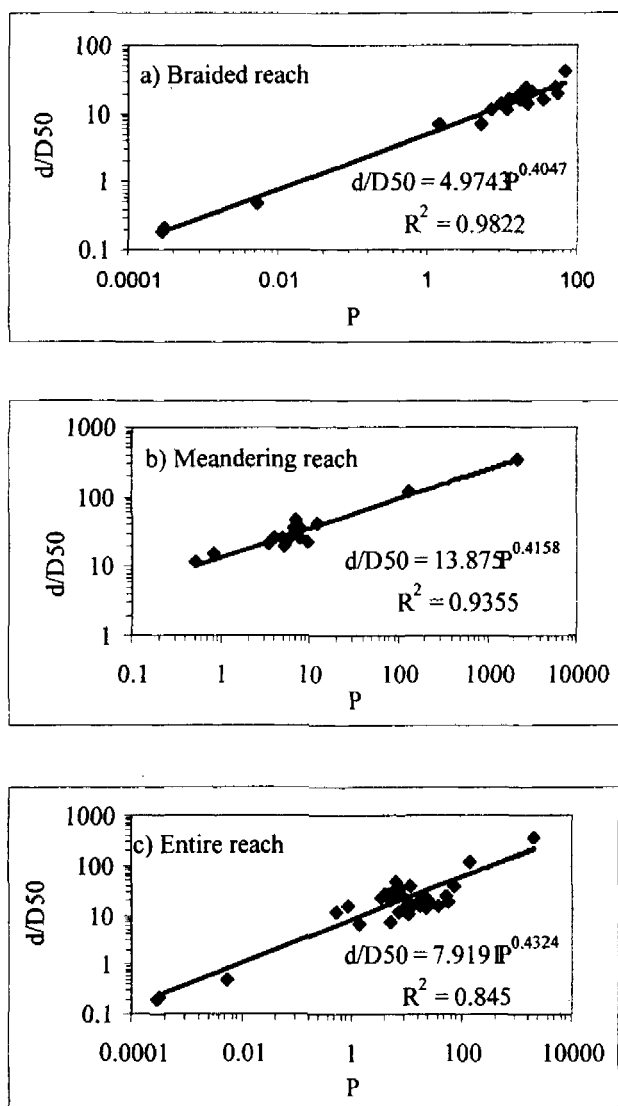
Figure 2: Plot of P against (d/D_{50}) for Sefidroud River.

line for Sefidroud River. These relations are comparable with those of Parker's [29].

7 Conclusions

It is observed that estimated width and depth, using Parker's [29], relations, are in discrepancy with those obtained from unit stream power theory for Sefidroud River. This may be due to the fact that Parker's [29] equations are not applicable

Table 2 Stable width for Sefidroud River, a, b, c and e are constants

	stable width (m)			
Sefidroud River	A	b	c	e
braided reach	445.3	0.44	-0.102	0.44
meandering reach	525.1	0.47	-0.192	0.47
entire reach	493.23	0.45	-0.135	0.45
best fit	3.83	0.528	-0.07	-
Parker [29]	4.4	0.5	1	-
equation	$w=a.Q^b.D_{50}{}^c.S^e$			

Table 3 Stable depth for Sefidroud River, f, g, h and i are constants

	stable depth (m)			
Sefidroud River	F	g	h	i
braided reach	2.59	0.405	-0.012	0.405
meandering reach	7.1	0.416	-0.04	0.416
entire reach	3.59	0.432	-0.08	0.432
best fit	-	-	-	-
Parker [29]	-	-	-	-
equation	$d=f.Q^g.D_{50}{}^h.S^i$			

to braided reaches or perhaps Parker's [29] equations were not derived non-dimensionally. Therefore, it is expected to obtain such relationships for stable braided reaches of rivers.

It is also worthwhile mentioning that these equations are probabilistic and the accuracy with which they can predict the hydraulic geometry will depend on the degree of correlation between the dependent and independent variables. In addition, the model will only apply within the limits of the observed field data.

Before the effect of river regulation can be established the bankfull dominant discharge must be related to some measurable characteristic of the flow regime. For the stable braided reaches of Sefidroud River, this has proved to vary in the range 1.5 to 2 years return period using annual maximum series.

Therefore to produce a more general model, it will be necessary to obtain data from a wider variety of river environments in order to reduce the covariance between the independent variables.

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