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Hydraulic Geometry and Channel Scour, Fraser River, British Columbia, Canada

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ABSTRACT

A simple model of at-a-station hydraulic geometry for a rectangular channel which scours above a threshold discharge is introduced to illustrate potential effects of scouring on the hydraulic geometry relations in rivers. Water Survey of Canada archival data are used to identify the threshold scour discharge (the transition from rigid to fully alluvial boundary conditions) for Fraser River at Marguerite, British Columbia. Data for channel width (w), water-surface elevation (E), flow depth (d) and mean velocity (v), are presented as conventional power-function relations and as untransformed linear relations, all dependent on discharge (Q). The latter reveal threshold scour-discharge-dependent discontinuities in E/Q, d/Q, v/Q and v/d/Q, consistent with model predictions but completely obscured by the corresponding conventional power-function relations. Thus, conventional data transformation is not recommended in studies of within-channel processes in rivers. Given that the threshold scour discharge appears to be identifiable from the hydraulic geometry of some river channels, several lines of further investigation are suggested.

INTRODUCTION

Principles of hydraulic geometry (Leopold and Maddock, 1953) recognize that, as discharge changes in a river, width, depth and velocity in the channel cross-section mutually adjust to accommodate the altered flow. These adjustments can be viewed as accommodations in time (at-a-station) or in space (downstream). “Downstream” hydraulic geometry refers these mutual adjustments to some formative discharge (usually bankfull flow) as it increases along a river as drainage area increases; it is interpreted as the dynamic and equilibrated response of a fully alluvial channel to the balance of flow forces and the resistance of boundary materials. “At-a-station” hydraulic geometry, on the other hand, refers these mutual adjustments in channel form to the changing stage at a given cross-section; it is interpreted as the largely

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passive accommodation of flows in an essentially rigid (non-alluvial) channel formed at some higher previous discharge (bankfull flow). Conventionally, hydraulic geometry relations are depicted as simple power functions of discharge although several researchers have noted that this convenient depiction is only approximate and may obscure physically meaningful departures from log-linearity (for example, see Knighton, 1975; Church, 1980). Nevertheless, the expedience of power-functions has focused thinking on the continuity of adjustments and has strongly influenced the theory of hydraulic geometry of river channels.

The purpose of this paper is to explore the nature of at-a-station hydraulic geometry in relation to a fundamental discontinuity in alluvial channels: the threshold transition from a fixed to mobile boundary. Physical reasoning dictates that at-a-station hydraulic geometry on an alluvial river must have at least two distinctly contrasting discharge domains. The first domain, ranging from zero discharge to that corresponding to the beginning of channel scour (threshold discharge), describes the hydraulic geometry of a fixed boundary. The second domain, ranging from threshold discharge to bankfull flow, describes a channel which is at least partly mobile.

Figure 8.1 illustrates schematically elements of a hydraulic geometry that one might expect in a rectangular channel with a well-defined threshold discharge ($Q_t$). As discharge increases to the point of scour at $Q_t$, flow velocity and flow depth increase over a fixed bed as relative roughness declines. Because the bed is fixed, water-surface elevation rises at the same rate as the depth of flow increases. Once discharge exceeds the threshold ($Q_s$) for bed scour, however, the elevation of the bed is progressively lowered (unless armouring develops or an obstruction such as bedrock is encountered). Since scour cannot instantaneously accommodate rapidly

![Figure 8.1](image-url)  

**FIGURE 8.1** Schematic hydraulic geometry for a rectangular channel in relation to the threshold scouring discharge ($Q_s$)
increasing storm discharge and thus fully absorb the change in flow, flow depth is now accommodated by both water-surface elevation increases and lowering of the bed. Thus the rate of increase in water-surface elevation with discharge declines, producing a single discontinuity in \( dQ/dE \) at \( Q_i \). In this example, the rate of change in flow depth also declines beyond \( Q_i \) along with flow velocity but the general case clearly depends on the relative rates of change in bed and water-surface elevations as discharge increases.

**THE FRASER RIVER: THE FIELD SITE AND DATA**

Ideal data to test for the presence of scour-induced discontinuities in hydraulic geometry are not as readily available as one might first suppose. A primary site requirement is that the channel boundary must begin to scour well before bankfull stage. Sand-bed rivers are likely candidates in this regard but they also are complicated by the effects of significantly changing bedforms. Gravel-bed rivers, on the other hand, often have regular planar beds but they also are often not mobile until discharges approach bankfull stage. Furthermore, most small rivers are not well suited to the purpose at hand because their typically flashy hydrology means that discharges greater than \( Q_i \) often are of such short duration that scouring of the bed is a distinctly disequilibrium phenomenon.

The site selected for this test is the Water Survey of Canada (WSC) gauging station at Marguerite on Fraser River in British Columbia (Figure 8.2). About half of the 232,000 km² Fraser catchment drains to this point on the river through a single and somewhat incised channel. Here the bed of Fraser River consists of sandy gravel, is seasonally mobile in response to snowmelt-induced sustained high flows, and is routinely monitored three to six times annually by WSC technicians in order to keep current the rating curve for the channel. Furthermore, Marguerite is the only gauging station on Fraser River which is not operated from a bridge with the attendant complication of structure-specific bridge-pier scour and fill; flow velocity and depth are measured from an aerial cableway.

Figure 8.3 shows a low-flow view of the Fraser River channel at Marguerite and several typical measured cross-sections for various discharges in 1986. At the mean annual flood \((Q_{33} = 4654 \text{ m}^3 \text{ s}^{-1})\) the river is about 220 m wide, averages 7.1 m in depth and flows at a mean velocity of almost 3 m s\(^{-1}\).

The principal data source for this study is the WSC technicians' field notes held in the WSC archives in North Vancouver, British Columbia. Eight years of records (1980–1987) for a period which included a wide range of discharges were selected for analysis, yielding 50 complete sets of channel and flow measurements. Velocity and flow depth were measured on the same line of section from a bank monument at verticals spaced at approximately 5% width or 10 m. In the few cases where the presence of ice caused this practice to be modified for near-bank measurements, cross-sections were adjusted by interpolation so that all measurements were based on the same reference verticals. A common gauge-height datum applies to the entire data set. Velocity was measured with a cable-suspended current meter (at 10 cm intervals in the vertical) and flow depths by line sounding. Total measurement error for depth and velocity averages for channel cross-sections probably does not exceed ±5%.
Figure 8.2 Location map of the Marguerite gauging station on Fraser River, British Columbia.
FIGURE 8.3 Fraser River at Marguerite gauging station. (A) A view of the channel at low flow. (B) Selected channel cross-sections for several discharges

Fieldwork at Marguerite was conducted to measure water-surface slope (by engineering transit) and to sample sediment from pits dug into exposed bars at low flow (February 1993).

Surface boundary materials at Marguerite station vary from year to year depending on the immediately preceding discharge history but generally consist of
sandy gravel with particle size ranging from 0.06 mm to >64 mm but averaging 20–30 mm \( D_{50} = 23 \) mm (Carson, 1988). A limited and rather inadequate sample of bedload collected and analysed by WSC suggests that the bedload \( D_{50} \) falls in the same range as the bed material itself. Carson (1988) estimates that, at high flows, about 14% of the bed material is entrained in suspension, the remainder moving as bedload. Pits dug in the channel bars exposed at low flow reveal that their surfaces are moderately armoured as a result of waning-flow winnowing of fines.

**DATA ANALYSIS**

**Hydraulic geometry**

The at-a-station hydraulic geometry for Fraser River at Marguerite is shown in the usual way in Figure 8.4. Relations between width, depth and velocity and the independent variable discharge, are well described by simple power-functions \( (R^2 > 0.94) \) and might be taken as yet another confirmation of the assumptions of conventional hydraulic geometry. Fraser River is rather canal-like here with little

![Figure 8.4 At-a-station hydraulic geometry for Fraser River at Marguerite (1980–1987), all scales are logarithmic](image-url)
variation in width and most (~95%) of the increase in discharge being more or less equally accommodated by changes in flow velocity and depth. It will be argued below, however, that the continuous logarithmic relations are more apparent than real and that the log-transformation of the data obscures important processes and their effects on the channel.

**Bed deformation**

Mean bed elevation is calculated as \( GH - d \) where \( GH \) is the gauge height (or water-surface elevation with respect to the gauging-station datum) and \( d \) is the average depth of flow over the bed (excluding bank zone). The measured record of mean bed elevation and mean daily discharge (Figure 8.5) for the eight-year test period is markedly periodic on the seasonal time-scale and out of phase. Annual peak (mean daily) freshet discharges in May–July varied from about 3000 m\(^3\) s\(^{-1}\) to a maximum of 5570 m\(^3\) s\(^{-1}\) (on 3 July 1986) while winter flows typically were less than 500 m\(^3\) s\(^{-1}\). As discharge increases to the seasonal peak flow during the freshet the river bed is scoured to a seasonal low while during declining autumn flows the bed fills and reaches its highest elevation during late winter. In high flow years (1985 and 1986, for example), the bed may be lowered from previous winter levels by as much as

![Graph showing variations in Fraser River bed elevation at Marguerite, 1980-1987](image-url)
1.75 m on average while deformation is much more modest for smaller freshets (about 30 cm in 1983, for example).

The successive cross-sections of the Fraser River channel at Marguerite shown in Figure 8.3b exhibit the typical pattern of boundary adjustment to the seasonal discharge hydrograph, in this case for the high-flood year 1986. Discharge on 2 April, recorded after the seasonally increasing flow had cleared ice from the station, was 1100 m$^3$ s$^{-1}$ and the average bed elevation stood at −1.03 m above datum. As discharge increased to 2020 m$^3$ s$^{-1}$ on 9 May, the bed filled and the mean bed elevation increased to −0.505 m above datum as sand was moved from deeper parts of the channel into storage in large longitudinal sand sheets. A further increase in discharge to 3510 m$^3$ s$^{-1}$ on 25 June, however, initiated general scour and the bar sediments were removed along with coarser basal sediments, lowering the average bed elevation to −2.12 m above datum; peak local scour during this period amounted to 3.4 m (almost 2 m of basal gravels below the surficial sand sheet). Discharge continued to increase until 2 June (5550 m$^3$ s$^{-1}$) although average bed elevation changed little with minor zones of cut in the area of the former bar balancing fill in the thalweg.

By 1 August discharge had declined to 1980 m$^3$ s$^{-1}$ and the bed had filled again to stand at −1.5 m average bed elevation, about 0.5 m above the lowest recorded average level for the year; locally the fill reached almost 2 m in this phase. A further decline in discharge to 678 m$^3$ s$^{-1}$ on 19 September was accompanied by continued filling of the bed to an average elevation of −1.24 m above datum, virtually back to its earlier 2 April position.

Measurements of winter bed elevations (and discharge) are complicated by the presence of ice on the river but it is clear from observation that sand accumulates in the channel during this period, causing some additional increase in mean bed elevation until the cycle of cut and fill is repeated in the following year.

**Threshold scour discharge**

Although the pattern of discharge and bed elevation depicted in Figure 8.5 clearly reveals seasonal alternations of bed scouring and filling, the precise discharge or gauge height at which scouring begins each year is not obvious because the bed-elevation series is not continuous.

Figure 8.6A shows a simple plot of bed elevation versus discharge but the relationship is poorly defined. There are several reasons for the scatter. First, the data include both scouring and filling events and hysteresis between discharge and bed elevation appears to be common. Second, the bed elevation measured on the day of the survey may well be partly a function of a preceding higher discharge. A further complication is that scouring may not start from precisely the same winter bed elevation in all seasons although the available measurements cannot resolve this question. Nevertheless, Figure 8.6A does suggest that bed elevations tend to decline at discharges higher than about 2500 m$^3$ s$^{-1}$.

If the data are generalized as a five-point moving average of bed elevation, the onset of scour is more clearly evident (Figure 8.6B). Once again, bed elevation clearly falls rapidly when discharge exceeds about 2500 m$^3$ s$^{-1}$.
If the minimum bed elevation reached by the seasonal scouring event (characterized by a continuous decline in bed elevation on the rising limb of the seasonal hydrograph) is correlated with the peak seasonal discharge, a strong inverse linear trend is evident (Figure 8.6C). This trend can be extrapolated to the winter bed level to provide a further indication of the threshold scouring discharge. Because
few winter measurements have been obtained it is not entirely clear where the average winter bed elevation occurs but the data suggest that it is within a few decametres (0–40 cm) of the gauge datum. These relations imply a threshold discharge for scour of about 2000 m³ s⁻¹.

Hydraulic relations and threshold scour discharge

The relations of various hydraulic and channel parameters to discharge for the Fraser River at Marguerite are shown as simple bivariate plots in Figure 8.7; the curves shown have been fitted by eye to highlight the behaviour of the river in the two flow domains (rigid boundary versus alluvial boundary).

Clearly, there are discontinuities evident in these plots, all but one of which correspond with the threshold scour discharge of about 2000 m³ s⁻¹. The exception is the plot of channel width versus discharge, which although displaying a discontinuity, is “kinked” at a much lower discharge (~1000 m³ s⁻¹) and maintains a linear trend across the threshold scour discharge. This observation is important to the discussion to follow because once the inset low-flow channel of the Fraser is filled (the cause of the width/discharge “kink” at about 1000 m³ s⁻¹), further increases in discharge are associated with a continuous change in channel width, consistent with the canal-like trapezoidal channel section at this station on Fraser River. That is, there is no discontinuity in channel width encountered at 2000 m³ s⁻¹ which could explain the discontinuities evident in the other trends shown in Figure 8.7.

The rating curve for the station (Figure 8.7A) can be described by two linear trends consistent with those postulated in Figure 8.1A. As discharge increases and fills the essentially rigid boundary of the channel, the water surface rises at a rate reflecting changes in the wetted channel shape and resistance to flow. At about the 2000 m³ s⁻¹ threshold discharge, further increases in discharge are associated with less rapid increases in water-surface elevation because, as discussed earlier, scour begins to lower the bed and the increases in flow depth dictated by continuity are now a function of changing bed elevation as well as changes in water-surface elevation.

Flow depth versus discharge (Figure 8.7C) displays a similar but far less pronounced change in gradient across the threshold discharge. This modest change reflects the accompanying and compensating changes in the gradients of water-surface elevation and bed elevation (see Figure 8.6) which have both shifted in the same direction as scouring increases.

The marked decline in the mean velocity/discharge gradient at the threshold scour discharge is quite clearly evident in Figure 8.7B, once again consistent in trend with that postulated earlier (see Figure 8.1B). The marked decline in the rate of increase in mean velocity with discharge when the threshold scour discharge is exceeded, suggests that increases in resistance to flow may be associated with scouring of the bed (unfortunately water-surface slope measurements over the relevant range of discharge are not available). Such a circumstance might be expected since scouring is spatially irregular and, in addition, scouring very likely leads to roughening of the boundary by exhuming large basal bed material.
The rapid decline in the velocity/discharge gradient \((v/Q)\) across the threshold scour gradient, accompanied by a much more modest decline in the flow depth/discharge gradient \((d/Q)\), has a net effect of reversing the discharge-dependent trend in the mean velocity gradient \((v/d)\) from positive to negative across the threshold scour discharge (Figure 8.7E).
CONCLUSIONS

These data indicate that the process discontinuity represented by the scour threshold on Fraser River at Marguerite is reflected in the hydraulic geometry of the channel. There is no reason to suppose that similar discontinuities are not a feature of all scouring (alluvial) channels although it will be most evident in larger rivers where discharge varies regularly on a seasonal basis, circumstances which ensure full equilibration of the channel with the controlling discharge. Certainly, elsewhere on Fraser River, a well-defined threshold scour discharge also appears to be evident in the seasonal changes in mean bed elevation (Sichingabula, 1993).

The scour-based discontinuities identified here are completely obscured by the conventional presentation of hydraulic geometry in which the data are logarithmically transformed (Figure 8.4). This observation suggests that, although power-function hydraulic geometry may be useful for some purposes, the data transformations on which it is based probably should be avoided if the within-channel processes are the subject of investigation.

Many interesting questions about hydraulics, sediment supply and transport in relation to scour thresholds in rivers are raised by this pilot study and invite further work, including among others:

(i) Is there a discontinuity in resistance to flow at the threshold scour discharge?
(ii) What is the relation of bankfull discharge to threshold scour discharge?
(iii) What is the relation of the threshold scour discharge to that causing incipient motion of bed material?
(iv) Since channel scouring releases locally stored sediment in the channel, is there a similar measurable discontinuity in suspended-sediment rating curves?
(v) Is there sedimentological evidence of this seasonal pattern of cut and fill recorded in the basal sediments of floodplains of rivers characterized by this behaviour?

The answers to these and other related questions are of considerable scientific interest but some of them may be of even greater engineering significance. For example, the prospect of predicting the flow conditions corresponding to incipient bed-material motion from hydraulic geometry relations is one which clearly demands further attention. This paper will have served its purpose if others are persuaded to consider these matters further.

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REFERENCES

Hydraulic Geometry and Channel Scour