Which tributaries disrupt downstream fining along gravel-bed rivers?

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Abstract

Tributaries and other lateral sediment sources can have a significant impact on river bed sediment texture and, in turn, on channel form. Sufficiently voluminous or distinct sediment inputs redefine the mainstem grain-size distribution, punctuating downstream maturation and isolating a sequence of discrete sedimentary links. Within these links fining processes usually dominate, such that models of sorting and abrasion, when applied to individual links, provide reasonable predictions of grain-size change. Links represent the fundamental natural unit within which fining models can be tested, developed and applied. Identification of significant lateral sources is therefore important, yet, beyond vague references to relative tributary size, sediment load, and sediment calibre, no criteria exist for the a priori discrimination of such sources. In this paper a procedure for identifying significant lateral (tributary) sources, without the benefit of grain-size information, is outlined. A high-resolution characterisation of bed material texture along two Canadian gravel-bed rivers facilitated classification of all their perennial tributaries as either significant or insignificant. Three absolute tributary basin parameters and their relative counterparts, chosen to reflect the likely controls on tributary significance, are then used to develop a discriminant function which isolates a large proportion of significant tributaries while minimising incorrect classifications. Examination of consistently misclassified (anomalous) tributaries reveals the importance of lateral source spacing and of inconsistencies in the geomorphic history of the contributing basins. In turn, a general tributary categorisation procedure is suggested which includes a logistic regression model for attaching probability statements to individual classifications. The generality of the discriminant and logistic functions cannot be assessed because of the lack of other suitable data sets. © 1998 Elsevier Science B.V.

Keywords: tributaries; grain-size discontinuities; lateral sediment sources; downstream fining; gravel-bed rivers

1. Introduction

Sediments supplied by tributaries and non-alluvial contacts are an important control on the pattern of grain-size change along gravelly alluvial systems and, in turn, on channel profile and form (Mackin, 1948). In particular, there is an association between some lateral sediment sources and discontinuities in downstream fining trends. Step changes are often observed at tributary confluences (Miller, 1958; Church and Kellerhals, 1978; Andrews, 1979; Knighton, 1980; Ichim and Radoane, 1990; Brewer and Lewin, 1993), at tributary fan contacts (Bradley et al., 1972; Dawson, 1988) adjacent to outcrops of non-alluvial materials such as glacial drift and
bedrock (Bradley et al., 1972; Werritty, 1992) and in association with mass movements that are coupled to the fluvial system (Brierley and Hickin, 1985). Along some channels, particularly low-order streams, the spatial density of lateral inputs may completely preclude systematic maturation (Krumbein, 1942; MacPherson, 1971; Rhoads, 1989; Rice and Church, 1996).

Such discontinuities reflect the adulteration of the mainstem bedload population by an influx of sediment which is sufficiently voluminous and/or sedimentologically distinct (relative to the mainstem population) to redefine bed material characteristics. Fluvial abrasion and sorting of the reconstituted population, in the absence of further inputs, often produces relatively systematic downstream fining trends. In turn, it has been demonstrated that a series of distinct size-distance relations best describe changes in bed texture along many fluvial systems. For example, a series of negative exponential models, each delimited by clear breaks at tributary junctions, significantly reduced unexplained variability along the Peace River in British Columbia (Church and Kellerhals, 1978), various upland streams in England (Knighton, 1984), part of the Sunwapta River in Alberta (Dawson, 1988), and the Pine and Sukunka rivers in British Columbia (Rice and Church, 1997).

Not all lateral sources have a persistent effect on bed material texture. Rice and Church (1997) define significant lateral sources as those associated with grain-size steps and the delimitation of fining sequences. They refer to the discrete channel reaches between significant lateral sources as sedimentary links. In contrast, insignificant lateral inputs are insufficiently voluminous and/or distinct to redefine the texture of the throughput population and simply augment residual variability within sedimentary links.

Sedimentary links are analogous, and sometimes equivalent, to hydrological network links but reflect the supply and transfer of sediment rather than water. Within these links fluvial fining processes are isolated from significant, lateral-source perturbations. Models of sorting and abrasion, when applied to individual links, therefore provide reasonable predictions of grain-size change. This is true of functional calibration models (e.g. Church and Kellerhals, 1978) and physically realistic mechanistic models (e.g. Parker, 1991; Hoey and Ferguson, 1994; Paola and Seal, 1995; Cui et al., 1996) because in both cases a single upstream sediment source is assumed. Indeed, until multiple source formulations are developed, the sedimentary link provides a fundamental natural unit within which fining models can be tested (see Hoey and Ferguson, 1994), developed, and applied. This is certainly the case at scales on the order of $10^0$ to $10^2$ km where lateral sediment inputs produce the familiar pattern of punctuated fining (cf. Rice and Church, 1997) although at scales of $10^3$ to $10^4$ km apparent simplicity may re-emerge in the form of a consistent fining gradient (cf. Paola et al., 1992; Robinson and Slingerland, 1997).

Identifying significant lateral sources and the associated sedimentary links (without the benefit of grain-size observations) is therefore important for the development and application of fining models. Potential sediment sources (tributaries and non-alluvial contacts) can be identified reliably using maps, aerial photographs and field reconnaissance. The problem is then to distinguish those particular sources which are likely to disrupt fining processes from those which are not. Beyond unspecified references to tributary size, sediment load, and sediment calibre there are no existing theoretical or empirical guidelines for making a-priori distinctions.

This paper seeks to fill that gap. The principal aims are to provide a predictive tool capable of identifying significant lateral sources, and also to examine the limits of predictive power that can be achieved in the light of contingent factors and simplifying assumptions.

2. Primary controls and methodology

Knighton (1980) and others have suggested that the relative volume and relative size characteristics of an input determine whether or not it redefines bed texture in the recipient channel. In particular, the larger the volume of an input and the greater the grain-size disparity between it and the mainstem material, the greater is the expectation that the mainstem texture is changed significantly. At confluences the situation is complicated by the concomitant influx of water which, if sufficiently large, modifies ambient stresses and, in turn, the bed material. A tributary which introduces a significant quantity of water but little sediment could, by increasing main-
stem competence, produce a significant change in texture. Therefore, the relative volume of a sediment input, its size characteristics relative to the recipient channel and, at tributaries, the relative contribution of water, are likely controls on the occurrence of grain-size discontinuities.

One approach to the problem of discriminating between significant and insignificant sources would be to simulate the mixing process at injection sites and, in turn, compare the resultant downstream texture with that upstream. This would necessitate characterising the flux rates and textural character of all potential sediment inputs. It would also require a model capable of incorporating the spatial and temporal complexities of the mixing process; for example, asynchronous arrival of material at the mixing site (Reid et al., 1989).

An alternative method is pursued here. It is based on identifying surrogate measures of the primary controls suggested above and, in turn, using independently classified significant and insignificant sources to define discriminant parameter values. It is most amenable to the assessment of potential tributary sources, because morphometric and hydrological basin parameters can serve as useful surrogate measures. Surrogate parameters are more difficult to define and ascertain in the case of non-alluvial contacts. The focus here, therefore, is on differentiating between significant and insignificant tributaries. Tributary fans are also considered since it may be possible to assess their significance using the same criteria.

Discriminatory criteria will be established using the tributaries of the Pine and Sukunka rivers in northeastern British Columbia (Fig. 1). Upstream of their confluence they have drainage areas of approximately 2500 and 2750 km$^2$, respectively. At hydrometric station 07FB003 (Water Survey of Canada), located near the mouth of Sukunka River, mean flow is 54 m$^3$ s$^{-1}$ and the mean annual flood is 480 m$^3$ s$^{-1}$. Within the study reaches, each of which is about 110 km long, average channel slope is approximately 0.0025 on Sukunka River and approximately 0.0014 on Pine River. Most of both study reaches lie within the Foothills Belt of the Rocky Mountains (Hart Ranges). Relief declines from about 900 m in the headwaters to about 600 m near the confluence and intensely folded and thrust-faulted Palaeozoic rocks are replaced by successively younger Mesozoic rocks. Shale, sandstone and quartzite lithologies dominate both basins. Late Pleistocene glaciation has left a legacy of morainal, glaciofluvial and glaciolacustrine deposits within both valleys. The present channels are intermittently coupled to non-alluvial sediment sources, migrate over alluvial accumulations several kilometres wide, and have wandering planforms. Active channel widths are approximately 40 m at the head of each reach and increase irregularly to about 120 m near their confluence.

A total of 139, 400-stone Wolman counts and 90 photographic samples provide a high-resolution characterisation of grain-size changes along both study reaches. Individual tributaries and other lateral sources have been classified as significant or insignificant depending on whether or not they are associated with a grain-size discontinuity and the initiation or termination of a fining trend (for details see Rice, 1996; Rice and Church, 1997). In all, 32 significant sources were identified, of which 23 are tributaries and 4 are tributary fan contacts (Fig. 2). In making these distinctions significant lateral sources were assumed to produce step increases in grain size. Step decreases in grain size have been observed (Andrews, 1979; Knighton, 1989; Sambrook Smith and Ferguson, 1995). However, they are relatively...
rare because a fine input must be sufficiently voluminous to affect main stem competence and capacity if it is to persist (Rhoads, 1989). Otherwise, the relative coarseness of the mainstem is indicative of a transport regime capable of removing the finer material.

3. Surrogate parameters and discriminatory criteria

The grain-size characteristics of the sediment supplied by a tributary stream ultimately depend on the origin of the clastic load and its subsequent modification within the tributary basin (Knighton, 1980). Lithology of source rocks and of alien unconsolidated materials, climatic and biotic controls on weathering processes, and the dimensions and structure of the drainage network are important in this regard. The volume of material carried by a tributary depends upon the amount of sediment supplied to the channel and the ability of the channel to transfer it downstream. Geomorphic history, climate, vegetation, basin area and hypsometry are important considerations. The volume of water leaving a basin is primarily dependent on its climate, vegetation and size.

Initially, one or more basin parameters which subsume the complexity of these three controls need to be identified. To simplify the problem, geomorphic history, lithology, vegetation characteristics, and climate are assumed to be homogeneous between the tributary basins of a given network. Fundamental consideration of scale then indicates that a measure of basin size is an appropriate starting point. Knighton (1980) suggests Shreve magnitude, and one might also consider basin area. Although Walling (1983) and Church and Slaymaker (1989) have exposed the unreliability of simple relations between basin area and sediment yield, it is reasonable to expect that both sediment and water yield are, to some degree, conditioned by tributary size.
In the field it was apparent that several large tributaries (for example, Chamberlain Creek) had no impact on mainstem sediments despite evidence of extensive sediment production and mobilisation within the tributary basin. Examination of the tributary fans reveals that aggradational, braided channels close to the mountain front give way to small, low-gradient, sandy distributaries in distal zones close to the mainstem. These cases indicate that Holocene fan storage is important in moderating tributary sediment yield and suggest that a measure of sediment delivery, rather than production, would be useful. Estimates of bedload yield are not feasible given the information requirements of mechanistic and morphological predictive methods. However, the nominal ability of a stream to transport sediment is reflected by the gross power \( \Omega = \gamma Q S \), which it possesses, where \( \gamma \) is the specific weight of water, \( Q \) is discharge, and \( S \) is the local energy gradient. A surrogate of this variable is the product of drainage basin area \( A \), and \( S \). This follows from the general observation that discharge is related to upstream basin area.

Canadian Water Survey gauging records were used to assess the regional relation between drainage area \( A \), and two-year discharge \( Q_2 \), (at which, in a majority of local gravel-bed rivers, bed material is mobilised; Bray, 1972). Ten stations within the Pine and Sukunka basins, and eleven stations in the Muskwa, Sikanni, Wapiti and Halfway drainages were used. The data and the regression are shown in Fig. 3. Four of the stations have short records of less than five years but do not appear to affect adversely the relation which is significant, has \( r^2 = 0.96 \) and a mean standard error of 0.17 (log units). In the original units, of \( \text{m}^3 \text{s}^{-1} \) and \( \text{km}^2 \), the relation is:

\[
Q_2 = 0.16 A^{0.96}
\]  

and, therefore, \( \Omega \propto AS \). When calculating stream power, \( S \) is usually approximated by the channel-bed slope \( s \). Tributaries like Chamberlain Creek suggest that transport capability in the distal reaches of a tributary is of primary importance. An appropriate surrogate of sediment delivery is then \( \Psi = A s_d \) where \( s_d \) is the channel-bed slope in the distal reaches of the basin being examined.

Based on these considerations, three variables were chosen for analysis; drainage basin area \( A \), network magnitude \( M \), and \( \Psi \) (which will be referred to as the basin area–slope product). In addition to absolute tributary values (denoted by a subscript \( t \)), these parameters were examined relative to those for the mainstem channel (denoted by a subscript \( m \)). It is expected that, where sediment and water yields are very small relative to the main channel, the tributary has little effect on texture because inputs are easily accommodated by the main stream, but that as the relative tributary inputs increase, an impact is more likely to occur.

3.1. Determination of parameter values and tributary classification

78 perennial tributaries enter the Sukunka study reach and 77 enter the Pine study reach. The Shreve magnitude of each basin \( M_t \), was determined from
the blue-line network on 1:50,000 N.T.S. (National Topographic Survey) maps, and tributary basin areas $A_t$, were measured using a digital planimeter. Distal channel slopes were determined from the maps and $\Psi_t = A_t s_d$ was then calculated for each tributary basin. For each parameter, relative values $M_t/M_m$, $A_t/A_m$, $\Psi_t/\Psi_m$ were calculated as the ratio of the tributary value to that for the mainstem basin upstream of the confluence.

Of 156 tributaries along the Pine and Sukunka Rivers (including the confluence of the two mainstem rivers), 23 are associated with grain-size discontinuities. The role of two of these tributaries in causing local discontinuities is unclear because of the presence of bedrock outcrops nearby and they were, therefore, excluded from the analysis. Four additional discontinuities are associated with tributary fan exposures some distance from the present confluence position. These were included as a separate group in this analysis, because production of fan deposits may be related to the characteristics of the tributary basin. The remaining 129 tributaries have no impact on texture.

3.2. Univariate analysis

For each parameter Fig. 4 shows the distribution of values for the 21 ‘significant’ and 129 ‘insignificant’ tributaries. Because of strong positive skewness, the original values have been logarithmically

![Fig. 4. Frequency distributions of logarithmically transformed parameter values for significant (shaded) and insignificant tributaries.](image-url)
transformed to facilitate examination. Two separate populations are apparent in each case, but none of the parameters unequivocally distinguishes between tributaries of the two types. A discriminatory criterion based on one of these parameters can correctly identify only a proportion $p$, of the significant tributaries and will incorrectly classify a proportion $q$, of the insignificant group. Optimal discrimination is achieved using a criterion which maximises $p$, while minimising $q$. The optimal discriminatory criterion for a given parameter can, therefore, be defined as that parameter value which is associated with the maximum difference between $p$ and $q$.

As expected, the mode of the significant group is greater than that of the insignificant group for each parameter. If $n_s$ is the number of significant tributaries which have a parameter value greater than a potential discriminatory value $v$, and $n_i$ is the corresponding number for the insignificant group, then:

$$p = \frac{n_s}{21}$$

and:

$$q = \frac{n_i}{129}$$

Fig. 5 shows the variations in $p$, $q$ and $(p-q)$ for each parameter, for values of $v$ from the observed
Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimal criterion, log (and original)</th>
<th>Proportion (p) (and count)</th>
<th>Proportion (q) (and count)</th>
<th>Proportion (u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
<td>&gt; 0.8 (6)</td>
<td>0.86 (18)</td>
<td>0.12 (16)</td>
<td>0.53</td>
</tr>
<tr>
<td>Area ((\text{km}^2))</td>
<td>&gt; 1.3 (20)</td>
<td>0.86 (18)</td>
<td>0.14 (18)</td>
<td>0.50</td>
</tr>
<tr>
<td>Basin area-slope product</td>
<td>&gt; −0.2 (0.63)</td>
<td>0.86 (18)</td>
<td>0.19 (24)</td>
<td>0.43</td>
</tr>
<tr>
<td>Relative magnitude</td>
<td>&gt; −1.5 (0.03)</td>
<td>0.81 (17)</td>
<td>0.08 (10)</td>
<td>0.63</td>
</tr>
<tr>
<td>Relative area</td>
<td>&gt; −2.0 (0.01)</td>
<td>0.95 (20)</td>
<td>0.22 (29)</td>
<td>0.41</td>
</tr>
<tr>
<td>Relative basin area-slope product</td>
<td>&gt; −0.4 (0.40)</td>
<td>0.81 (17)</td>
<td>0.13 (17)</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Criteria are based on the optimal differentiation between significant and insignificant tributaries. \(p\) is the proportion of the 21 significant tributaries which meet (exceed) the criterion. \(q\) is the proportion of the 129 insignificant tributaries which exceed the criterion. \(u\) is the proportion of values exceeding the criterion which are significant.

In all cases \(p\) exceeds 0.81, and is 0.95 for relative area. \(q\) varies between 0.08 for relative magnitude and 0.22 for relative area. That these single-parameter criteria isolate between 81 and 95% of significant tributaries is encouraging. However, the concomitant isolation of between 8 and 22% of the insignificant tributaries is problematic, since this represents between 10 and 29 incorrect classifications. Unfortunately, higher values of \(p\) are not associated with lower values of \(q\), and the proportion of isolated tributaries that are significant never exceeds 0.63 (relative magnitude). Inclusion in the significant group of the four tributaries whose fans are important sources does not markedly alter the performance of the criteria defined using the two major groups (Table 2). This indicates that discontinuities associated with fan exposures can be identified on the basis of their source basin characteristics about as reliably as significant contemporary channels.

Individually the six parameters distinguish a large proportion of the significant tributaries, but they also isolate an unhelpful proportion of those which have no influence on mainstem texture. It is possible, however, that an improvement in discriminatory power might be accomplished by using them in combination.

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proportion exceeding criterion, fan group (and count)</th>
<th>Revised proportion (p')</th>
<th>Revised proportion (u')</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
<td>0.50 (2)</td>
<td>0.80</td>
<td>0.56</td>
</tr>
<tr>
<td>Area</td>
<td>0.75 (3)</td>
<td>0.84</td>
<td>0.54</td>
</tr>
<tr>
<td>Basin area-slope product</td>
<td>1.00 (4)</td>
<td>0.88</td>
<td>0.47</td>
</tr>
<tr>
<td>Relative magnitude</td>
<td>0.25 (1)</td>
<td>0.72</td>
<td>0.64</td>
</tr>
<tr>
<td>Relative area</td>
<td>1.00 (4)</td>
<td>0.96</td>
<td>0.45</td>
</tr>
<tr>
<td>Relative basin area-slope product</td>
<td>0.25 (1)</td>
<td>0.72</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Discriminatory criteria are those given in Table 1 which are based on optimal differentiation of significant and insignificant groups. \(p'\) and \(u'\) are calculated following the inclusion in the significant group of the four tributaries with fans that are important sources.
3.3. Bivariate analysis

The two 'delivery' variables (basin area–slope product and the associated relative term) are plotted against the four 'production' parameters, in Fig. 6 (for area) and Fig. 7 (for magnitude). Significant and insignificant tributaries are differentiated, and the four tributaries with fans that are important lateral sediment sources are also indicated. In all cases the significant and insignificant tributaries plot in distinct, but never completely separate, areas of the bivariate space.

Lines which bisect the two main groups were added to the logarithmic scatter plots by eye. In most cases several lines were fitted before those which optimise $p$, $q$ and $u$ were identified (Figs. 6 and 7). Formal discriminant function analysis was not used because of the non-normality of the parameter values. Each line represents a discriminatory function, the equation of which is noted on the respective plot. Because there are fewer significant tributaries, the inclusion or exclusion of one such tributary in the region above a potential discriminatory line has a larger effect on $p$, $q$ and $u$, than including or excluding a member of the insignificant group. No account of this was taken when fitting the lines and it is reasonable to assume that these functions would be different if the group sizes were different.

The ability of these functions to differentiate between the two types of tributary can be gauged by the values of $p$, $q$ and $u$ associated with them (Table 3). Here, $p$ is the proportion of significant tributaries for which $y > f(x)$, where $y$ is the ordinate value for the tributary, $x$ is the abscissa value, and $f$ is the relevant discriminatory function. As before, $q$ is the corresponding proportion of (incorrectly identified) insignificant tributaries, and $u$ is the proportion of significant tributaries in the subset of all tributaries for which $y > f(x)$.

Compared to the univariate approach, values of $p$ are slightly lower and represent the omission of an additional one to three significant tributaries. How-
ever, the number of incorrectly classified insignificant tributaries, $q$, is drastically reduced (by at least 50%). The net result is a significant improvement in the proportion of tributaries which are selected that are significant sediment sources; values of $u$ range from 0.70 to 0.75 compared to 0.41 to 0.63 for the univariate criteria. However, using the performance of one of the better functions, for example that involving $A_t/A_m$ and $\Psi_t$, as a yardstick of general predictive capability, the identification of 80% of the

Table 3
Discriminatory power of bivariate functions

<table>
<thead>
<tr>
<th>Function</th>
<th>$p$ (and counts)</th>
<th>$q$ (and counts)</th>
<th>$u$</th>
<th>Revised, $p'$</th>
<th>Revised, $u'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_t = 422.67 A_t^{-1.79}$</td>
<td>0.81 (17)</td>
<td>0.05 (7)</td>
<td>0.71</td>
<td>0.80</td>
<td>0.74</td>
</tr>
<tr>
<td>$\Psi_t/\Psi_m = 2.92 A_t^{-0.55}$</td>
<td>0.76 (16)</td>
<td>0.05 (6)</td>
<td>0.70</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>$\Psi_t = 0.14 A_t/A_m^{-0.51}$</td>
<td>0.81 (17)</td>
<td>0.05 (6)</td>
<td>0.74</td>
<td>0.80</td>
<td>0.77</td>
</tr>
<tr>
<td>$\Psi_t/\Psi_m = 0.021 A_t/A_m^{-1.01}$</td>
<td>0.62 (13)</td>
<td>0.04 (5)</td>
<td>0.72</td>
<td>0.56</td>
<td>0.74</td>
</tr>
<tr>
<td>$\Psi_t = 18.03 M_t^{-1.11}$</td>
<td>0.67 (14)</td>
<td>0.04 (5)</td>
<td>0.74</td>
<td>0.64</td>
<td>0.76</td>
</tr>
<tr>
<td>$\Psi_t/\Psi_m = 7.83 M_t^{-0.99}$</td>
<td>0.71 (15)</td>
<td>0.04 (5)</td>
<td>0.75</td>
<td>0.64</td>
<td>0.76</td>
</tr>
<tr>
<td>$\Psi_t = 0.0017 M_t/M_m^{-1.94}$</td>
<td>0.76 (16)</td>
<td>0.05 (7)</td>
<td>0.70</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>$\Psi_t/\Psi_m = 10^{-6} M_t/M_m^{-3.91}$</td>
<td>0.81 (17)</td>
<td>0.05 (7)</td>
<td>0.71</td>
<td>0.72</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Discriminatory functions $y = f(x)$, fitted by eye. $p$ is the proportion of the 21 significant tributaries where $y > f(x)$. $q$ is the corresponding proportion of the 129 insignificant tributaries. $u$ is the proportion of significant tributaries in the subset for which $y > f(x)$. Revised values are for the same criteria following inclusion as significant the four tributaries whose fans are important sources. $\Psi$ is basin area–slope product, $A$ is area ($\text{km}^2$) and $M$ is Shreve magnitude. The subscript $t$ applies to tributary values and $m$ to mainstem values upstream from the confluence.
significant tributaries along a study channel is hardly superlative, especially if 23% of those isolated do not in fact have any impact.

4. Anomalous tributaries

To try and improve the performance of the discriminant functions, tributaries that were consistently misclassified were examined in detail. The relevant tributaries are listed in Table 4, with the number of bivariate relations for which they are anomalous.

4.1. Insignificant tributaries misclassified as significant

Of ten insignificant tributaries misclassified as significant, the anomalous nature of three of them is in doubt (Falling Creek, Fisher Creek, and Little Boulder Creek). Each case is characterised by relatively scarce or ambivalent local grain-size information, which leaves open the possibility that their original classification as insignificant is, in fact, incorrect.

In contrast, adequate grain-size information around the seven remaining tributaries suggests that these certainly are misclassified by the discriminant functions. There is no simple explanation for three of these anomalies (Bluff Creek, P14, and S25) and no general reason why they should be misclassified. For example, they do not exhibit unusual morphometry or lithological characteristics. Rather, they simply reflect the imperfection of the methodological assumptions. Examination of the four remaining anomalies (Sukunka River, Centurion Creek, Mountain Creek, and Wildmare Creek) provides more substantive insight.

First, in contrast to similarly sized significant basins, Wildmare’s fan does not fringe the Pine River in its present position. This suggests a lack of coarse material in the distal reaches of the tributary and might explain the lack of a grain-size discontinuity. Examination of fan positions might, therefore, be useful in distinguishing between tributaries which plot on or close to discriminant functions.

Centurion Creek flows within the trough which at one time carried Pine River in a northeasterly direction, toward Peace River. It is decidedly underfit (Dawson, 1881; Hughes, 1967) and flows across the former bed of a post-glacial lake. The stream is sluggish and sandy and, relative to similarly sized basins, carries little coarse bedload. This in part reflects the low gradient of the underlying lake-bed and the preponderance of fine lacustrine materials within the basin. In addition, because the valley floor is atypically wide and unrelated to the stream’s drainage area, lateral channel migration seldom accesses coarse tributary deposits stored close to the valley walls. It may be concluded that the misclassification of Centurion Creek is a consequence of its

Table 4

<table>
<thead>
<tr>
<th>Insignificant misclassified as significant</th>
<th>Significant misclassified as insignificant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sukunka River (8)</td>
<td>P54 (8)</td>
</tr>
<tr>
<td>Mountain Ck., P2 (8)</td>
<td>S19 (8)</td>
</tr>
<tr>
<td>Centurion Ck., P67 (8)</td>
<td>S48 (8)</td>
</tr>
<tr>
<td>Falling Ck., P20 (8)</td>
<td>P60 (8)</td>
</tr>
<tr>
<td>Fisher Ck., P19 (8)</td>
<td>Goodrich Ck., P49 (2)</td>
</tr>
<tr>
<td>Wildmare Ck., P65 (2)</td>
<td>S20 (2)</td>
</tr>
<tr>
<td>Bluff Ck., S56 (1)</td>
<td>Lean-to Ck., S22 (2)</td>
</tr>
<tr>
<td>P14 (2)</td>
<td>McLean Ck., S17 (1)</td>
</tr>
<tr>
<td>Little Boulder Ck., P8 (2)</td>
<td>Dickebusch Ck., S71 (1)</td>
</tr>
<tr>
<td>S25 (2)</td>
<td>Caron Ck., P56 (1)</td>
</tr>
<tr>
<td></td>
<td>Commotion Ck., P50 (1)</td>
</tr>
</tbody>
</table>

Tributaries are listed in general order of distance from the discriminant line, those further away appearing at the head of each list. Those misclassified by the preferred discriminatory function are underlined.
atypical history and unusual morphometry relative to other tributaries within the study area. In this sense Centurion Creek is truly an anomaly. Careful consideration of a tributary basin's history and relative character might indicate such anomalous tributaries a priori.

The categorisation of Mountain Creek as a significant source by the discriminant function highlights another important issue. A significant sediment source is defined (Rice and Church, 1997) as one which, in addition to injecting a sediment population capable of redefining mainstem texture, is associated

Fig. 8. Grain-size distributions and lithological composition of surface material upstream and downstream of the Burnt/Sukunka confluence.
with a fining pattern. Mountain Creek was classified as insignificant, even though it is associated with a large grain-size discontinuity, because it is not associated with any fining trends. The lack of fining at this particular site reflects an abundance of additional, local inputs, associated with a large glaciofluvial fan, which preclude systematic textural modification. The discriminant function correctly identifies this stream as one which is likely to be responsible for a grain-size discontinuity but, because it does not include any assessment of the proximity and abundance of other lateral sediment sources, it misclassifies the tributary. Clearly, this issue of source proximity and abundance should be incorporated in a tributary classification procedure.

Knighton (1980) suggests that, as tributaries approach the size of the mainstem the volume and texture of their input is likely to be similar to that in the main channel. This, in turn, suggests that the influence of tributaries diminishes as their relative size approaches unity. The lack of a significant step at the Sukunka/Pine confluence (\(A_r/A_m = 1.09\) or 0.92), supports this hypothesis, which, in turn, offers an explanation for the misclassification. Verification of this explanation would suggest that monotonically decreasing discriminant functions are inappropriate.

However, at the Burnt/Sukunka confluence, where \(A_r/A_m = 0.87\), the most striking grain-size discontinuity of all those observed provides contradictory evidence. There is no textural similarity between the two samples collected upstream of the confluence, the Burnt River material (BNT) being significantly coarser than its mainstem counterpart at SWB 8 (Fig. 8). Furthermore, the size distribution and lithological composition of the material downstream of the confluence at site BND is very similar to that of the Burnt River sample (Fig. 8). This suggests unequal mixing of the input populations and, in turn, the dominance of Burnt River's bedload input.

This is consistent with the contrasting nature of sediment supply and mobility upstream of the confluence. On Burnt River, approximately 2 km from the confluence, a glaciofluvial terrace scarp, approximately 500 m long and 30 to 50 m high, constitutes the left bank of the river. It supplies a large volume of coarse, unconsolidated material which instigates channel braiding. Lower terraces of fluvially re-worked, glaciofluvial material continue to supply material as the river approaches the confluence. In contrast, Sukunka River upstream of the confluence is confined within a bedrock canyon with several rock steps and waterfalls and an almost complete lack of mobile sediment. The bedrock control acts as a local base level, interrupting sediment transfers from the upper Sukunka valley, where there has been extensive Holocene aggradation. The large grain-size discontinuity at this confluence thus reflects the contrasting nature of sediment supply within the two contributing basins.

It is clear that basins of equal size do not necessarily have similar distal textures or similar bedload yields and that where two such basins meet a discontinuity may occur. There is no basis, therefore, to assume that discontinuities become less likely as relative size approaches unity. The importance of location and of geomorphic history, that is of contingent factors, is clear in these examples. Indeed, Rice (1996) argues that the contrasting geomorphic histories of the Pine and Sukunka basins, rather than their equal size, accounts for the lack of a discontinuity at their confluence.

4.2. Significant tributaries misclassified as insignificant

S19 and S48 were identified as significant sources, but in both cases a degree of doubt was involved and, in turn, their anomalous status, should be regarded as marginal. The remaining tributaries listed in Table 4 are certainly significant. There is no obvious reason for the incorrect classifications of McLean Creek, Lean-to Creek, S20, Dickebusch Creek, Goodrich Creek, Caron Creek and Commotion Creek. Rather, these anomalies simply reflect the imperfection of the discriminatory criteria.

In contrast, P54 and P60 are exceptional. These tributaries are relatively small and not very steep, yet they are associated with significant steps because they introduce some coarse material to reaches otherwise devoid of gravel. An input that would elsewhere be of limited significance is crucial in the lower Pine because the river transports very little coarse bedload in this section. As discussed in detail elsewhere (Rice, 1996) the lower Pine flows over the
bed of a post-glacial lake which once occupied the valley. Alluvial aggradation downstream of major tributaries like Commotion Creek has produced a series of alternating gravel and clay/sand reaches. P54 and P60 inject material into low gradient clay/sand reaches and, consequently, produce textural discontinuities. The discriminant functions are insufficiently sensitive to detect the relative difference in the transfer characteristics of tributary and mainstem and hence they misclassify the two tributaries. As with the exceptional cases discussed above, only detailed knowledge of local geomorphic history could aid in the correct a-priori categorisation of tributaries such as these.

5. Discussion

5.1. A-priori identification of significant tributary sources

Examination of anomalous tributaries has not revealed an additional general factor which could be parametrised and included in the discriminant functions to improve their performance. The bivariate criteria in Table 3 identify the majority of important tributaries while minimising the number of extraneous, incorrectly isolated, insignificant tributaries and are, therefore, more appropriate than the univariate criteria as the basis of a procedure for categorising tributaries. Choosing a function which is best able to isolate the fan group, as well as the significant tributary group, is desirable since it improves the overall proportion of significant lateral sediment sources that are identified. In assessing the relative performance and merits of the eight empirical functions it is, therefore, pertinent to consider the revised values (p' and u') in Table 3. These show that, in general, the functions vary little in their performance. Differences in p', q and u' reflect only small changes in the number of tributaries involved. In light of this, the effort needed to define the parameters involved becomes a relevant factor. In addition, to maximise the unknown generality of the chosen function, it is appropriate that it includes at least one relative measure.

On the basis of these considerations the discriminant function involving relative area and absolute basin area slope product:

$$\Psi_i = 0.14 \left( \frac{A_i}{A_m} \right)^{-0.51}$$

is most attractive (with high values of both p' (0.80) and u' (0.77), and q = 0.05) and is recommended for the preliminary classification of significant tributary sources.

While the underlying arguments regarding sediment production and yield are general, the transferability of this discriminant function is unclear. Regional geomorphic history is clearly important and it is unlikely that the Pine/Sukunka function is transferable to areas of markedly different physiography or climatic history. Lithology is also likely to be a limiting factor, restricting the use of the function defined here to areas of deranged sedimentary and low-grade metamorphic rocks. The generality of the function cannot be assessed because a suitable set of mainstem grain-size observations does not, to my knowledge, exist.

The majority of anomalies remain unexplained or are explained by singularities, rather than any common, identifiable attribute. Results should, therefore, be regarded as guidelines rather than definitive statements and, if at all possible, tributaries should be examined in detail to improve confidence in categorisations. Where field visits are impractical, mapping of surficial materials and geomorphic features from aerial photography will be useful. In marginal cases the position of a tributary’s fan relative to the main channel may indicate the likelihood of coarse bedload yield and, in turn, facilitate final classification. It is worth noting that, following careful examination of the sixteen surely anomalous confluences encountered on the Pine and Sukunka, only five could be explained by their particular circumstances. This indicates that, depending on the scale of the reach being examined, the improvement in overall classification gained by detailed examination of individual basins may not justify the additional effort required.

5.2. Tributary sources and sedimentary links

Not all significant grain-size steps are associated with the beginning or end of a fining sequence. Where lateral sources occur in close proximity to
one another, texture may be disrupted to such an extent that fining does not develop. Following the identification of tributaries that are likely to have an impact on texture, their spacing should be considered to aid identification of sedimentary links.

Using data from several catchments in the United Kingdom, Jarvis and Sham (1981) showed that the arrangement of tributaries along one side of a mainstem channel is not random. While small tributaries tend to be followed downstream by other small tributaries, large tributaries tend to be separated from each other by large distances and numerous, smaller tributaries. This is a simple corollary of the spatial requirements of tributary basin development. Large basins preempt the formation of other large basins in their vicinity, which implies that significant tributaries will not join the mainstem in close proximity to one another, at least from the same side of the basin.

In turn, non-fluvial sources and tributary fans, rather than other tributaries, are most likely to complicate the grain-size signal close to significant tributaries. The degree of coupling between channel and non-alluvial materials is, therefore, an important consideration. In small mountainous streams strong hillslope-channel coupling may be a general feature (Rice and Church, 1996) and mask the effect of tributary inputs (cf. Rhoads, 1989), but the spatial distribution of coupling in larger systems is more difficult to characterise (Rice, 1994).

5.3. Attaching probability statements to predicted classifications

Despite the relative success of the discriminant function it is clear that it is likely to misclassify some tributaries. In a predictive context it would be useful to ascertain the likelihood that a given set of tributary characteristics is associated with a significant grain-size discontinuity. The Pine and Sukunka data were, therefore, used to develop a relation between basin characteristics (relative area and absolute basin area-slope product) and the probability that a given tributary is significant.

An appropriate model utilises the logistic function, in which the dependent variable is constrained to range between zero and unity and which, therefore, facilitates description of a functional relation between a dichotomous dependent variable and one or more continuous independent variables. Here, tributary significance is the dependent variable \( P \) (with a value of 1 indicating significance and a value of 0 indicating insignificance) and the independent variables are \( X_1 = \log(A_r/A_m) \) and \( X_2 = \log(\Psi_r) \) (the logarithmic transformation introduced earlier is retained here in order to reduce non-normality of the data). Moreover, the dependent variable is treated as a probability, such that the fitted regression model yields the probability of obtaining \( P = 1 \) (the probability that a tributary is significant). The logistic model:

\[
P = \frac{e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2}}{1 + e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2}}
\]

is linearised by rearranging and taking natural logarithms to give the logit model:

\[
\ln \left( \frac{P}{1 - P} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2
\]

Relevant statistics for assessing model significance and overall fit are the likelihood ratio test and \( \rho^2 \) (Wrigley, 1985).

In the light of the examination of discriminant function anomalies the Pine and Sukunka data were modified prior to model fitting. First, the five tributaries which may have been misclassified were removed. Also, the classification of Mountain Creek was changed from insignificant to significant as it is associated with a significant grain-size step. Since singularities are, by definition, unpredictable and cannot be assumed to be of a similar nature and extent in other systems, it is appropriate to fit a model in the absence of those anomalous tributaries which have been explained (Sukunka River, Centurion Creek, Wildmare Creek, P54 and P60). Unexplained anomalies remain in the analysis. Predicted probabilities then reflect the likelihood of a tributary being significant, while assuming that it is not affected by peculiar historical conditions. The validity of this assumption must be determined for individual predictions by examination of the tributary basin. The four tributaries with fans that are important sediment sources were classified as significant such that the resulting relation describes the probability that either a tributary or the associated fan is a significant source.

The censored data are plotted in Fig. 9 along with
the discriminant function 5. All of the data points lie on the planes where $P = 1$ or $P = 0$. The significant logit model:

$$\ln\left(\frac{P}{1-P}\right) = 8.68 + 6.08X_1 + 10.04X_2$$

or:

$$P = \frac{e^{(8.68 + 6.08X_1 + 10.04X_2)}}{1 + e^{(8.68 + 6.08X_1 + 10.04X_2)}}$$

was fitted to the data using maximum likelihood estimation (Fig. 9) and has a $\rho^2$ value of 0.80. McFadden (1979) has suggested that $\rho^2$ values of between 0.2 and 0.4 represent a very good fit and an empirical graph presented by Domenich and McFadden (1975) indicates that values of $\rho^2$ close to 0.6 are equivalent to $r^2$ values close to unity. The slope of the fitted surface occupies that region where most of the misclassifications appear and characterises the uncertainty associated with categorising tributary basins which plot close to the discriminant function. For example, a basin with $\log(A_t/A_m) = -3$ and $\Psi_t = -1$ is unlikely to be significant ($P \approx 0$), whereas the categorisation of a basin with $\log(A_t/A_m) = -1.5$ and $\Psi_t = 0$ is less certain ($P = 0.39$), and may warrant further investigation. As with the discriminant function the generality of this model is unknown and is probably constrained by historical, climatic and lithological conditions.

6. Conclusion

It has been possible to develop operational guidelines for tributary classification based on relative basin area and the product of tributary basin area and the distal slope of the tributary channel. Consideration of local geomorphic history, of other sediment sources (particularly non-alluvial ones) and of tributary fan positions may help classify marginal cases and identify incorrect classifications. The generality of specified discriminant and logistic functions cannot be assessed because of the lack of other suitable data sets, but geomorphic history and lithology are likely to be primary constraints on the application of these functions elsewhere.

Beyond these practical guidelines an important implication of this investigation is that sedimentological networks and hydrologic networks do not necessarily correspond. Sedimentologically, Burnt River is more important than Sukunka despite their similar basin areas. A number of relatively small tributaries are highly significant sediment sources either because of internal circumstances or relative conditions on the mainstem that are often associated with local geomorphic history. These observations reflect the spatially discontinuous nature of sediment supply within fluvial landscapes, which contrasts with the more homogeneous distribution of water supply. This patchy, somewhat unpredictable, arrangement of important sediment sources in turn reflects local geomorphic history, lithologic heterogeneity and contingent factors. Models based solely on hydrological network order may be fundamentally inappropriate for understanding sediment fluxes and sediment characteristics within fluvial systems.

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