ANNUAL BED-ELEVATION REGIME IN THE ALLUVIAL CHANNEL OF SQUAMISH RIVER, SOUTHWESTERN BRITISH COLUMBIA, CANADA

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ABSTRACT

The aim of this study is to examine the annual regime of channel scour and fill by monitoring bed-elevation changes in a reach of Squamish River in southwestern British Columbia, Canada. Sonar surveys of 13 river cross-sections in a sandy gravel-bed single-channel study reach were repeated biweekly over a full hydrologic year (1995/6).

The survey results show that bedload movement occurs as waves or pulses forming bedwaves that appear to maintain an overall coherence with movement downstream. These bedwaves propagate downstream by a mode here termed pulse scour and pulse fill, a process distinguished from the conventional mode of scour and fill commonly associated with flood events (here termed local scour and local fill). Bedwave celerity was estimated to be about 15.5 m d−1 corresponding to a bedwave residence time in the study reach of almost one hydrologic year.

The total amount of local bed-elevation change ranged between 0.22 m and 2.41 m during the period of study. Analysis of the bed-elevation and flow data reveals that, because of the bedwave phenomenon, there is no simple relation between the mean bed-elevation and discharge nor any strong linear correlation among cross-sectional behaviour. The bed-elevation data also suggest that complex changes to the bed within a cross-section are masked when the bed is viewed in one dimension, although no definitive trends in bed behaviour were found in the two-dimensional analysis.

Although a weak seasonal effect is evident in this study, the bed-elevation regime is dominated by sediment supply-driven fluctuations in bedload transport occurring at timescales shorter than the seasonal fluctuation in discharge. The study also indicates that bed-elevation monitoring on Squamish River, and others like it, for purposes of detecting and measuring aggradation/degradation must take into account very considerable and normal channel-bed variability operating at timescales from hours to months. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: channel scour; sediment wave; bedwave celerity; sediment supply; bedload transport

INTRODUCTION

Change in the bed elevation of alluvial rivers is a response to a sediment-supply deficit or surplus at the bed and is a normal part of the hydraulic adjustments a river makes to variations in discharge and sediment load. Such changes occur on a range of timescales and it is conventional to distinguish long-term change (years–decades), termed aggradation or degradation, from short-term responses (hours–days), termed scour or fill, such as those associated with the passage of a single flood.

Many cases of channel aggradation or degradation are documented for rivers (e.g. Galay, 1983; Knox, 1977, 1995; Simon, 1989) and usually these represent a response to system-wide environmental change that shifts the channel from one state of equilibrium to another. Similarly, many cases of short-term changes in bed elevation have been reported in the literature. Some relate to the cycle of rising-limb scour and falling-limb fill associated with single flood events (e.g. Leopold et al., 1964; Culbertson and Dawdy, 1964; Andrews, 1979; Chang, 1986). Others have been attributed to pulses in bedload-transport rate related to the
downstream passage of bedforms and, more recently, to the translation of barforms (e.g. Mosley, 1978; Meade, 1985; Hoey, 1992; Hoey and Sutherland, 1991; Gomez et al., 1989; Whiting et al., 1988; review in Knighton, 1998). Over time, by definition, these short-term effects represent self-cancelling excursions from the longer-term trend in mean bed-elevation behaviour.

Bed-elevation changes on an intermediate timescale of months are not well documented in the literature. One of the more orderly responses of bed-elevation change at this timescale may be the seasonal pattern observed on large rivers with pronounced nival flow regimes. Hickin (1995) describes a strongly periodic pattern of bed-elevation change on Fraser River at Marguerite in western Canada which is driven by the seasonal hydrograph. This is the seasonal timescale equivalent of the short-term cut and fill accompanying the passage of a flood. The relative orderliness of the seasonal regime of bed elevation here reflects the facts that, unlike a flash flood, the cycle of seasonal high to low flow is a regular annual event and the flow durations are long enough to allow the channel bed to fully equilibrate to the changing discharge. Furthermore, on large rivers such as the Fraser (drainage area at Marguerite is 114 000 km²), this seasonal pattern is not obscured by the effects of storm-related floods that can dominate the hydrology of smaller rivers.

Hickin (1995) speculated that, on a smaller-scale channel, we might expect to see the seasonal regime of bed elevation on which is superimposed a second order of bed-elevation fluctuations related to storm events, mimicking the annual hydrograph. By extension, we might expect that, on smaller rivers still, the storm-related bed responses probably obscure completely those bed-elevation changes related to seasonal snowmelt (the freshet).

Although Sichingabula (1993) reports that similar seasonal bed-elevation changes are apparent at several other Fraser River locations, Hickin’s (1995) study is based on just one cross-section of the channel and the relation of the bed behaviour here to elsewhere in the channel remains unknown. Certainly it has been shown elsewhere (e.g. Andrews, 1979) that section-to-section variation in scour and fill within a single channel reach can be distinctly non-synchronous.

It is the purpose of this paper to report the results of a reach-based, year-long, bed-elevation monitoring programme on Squamish River, British Columbia, designed to explore further the character of the seasonal bed-elevation regime, in this case on a much smaller (and more manageable) system than the Fraser, but one large enough to be a prospective candidate for exhibiting the mixed bed-elevation regime behaviour noted above.

STUDY SITE

Squamish River, located approximately 40 km north of Vancouver in southwestern British Columbia (Figure 1), is over 150 km long and drains an area of approximately 3600 km². It is located in the Coast Mountain Range within a fault oriented, glacially scoured valley. Much of the headwaters rise to more than 3000 m a.s.l. and the catchment is approximately 20 per cent glacier covered.

The climate is characterized by relatively warm, dry summers and cool, wet winters. Precipitation is the result of orographic uplift of moist air masses that travel up the steep-walled valley of Howe Sound into Squamish valley. Winter storms occurring as rain-on-snow events generate large flows in Squamish River during October–December while late winter snow accumulates to melt later in the following spring as the seasonal snowmelt peak (freshet).

The fluvial regime of Squamish River is typical of rivers in glaciated basins: low water during the winter months is followed by increased flow as summer approaches. The freshet begins in mid-to late April and a maximum is often reached by mid-June. The peak freshet discharge is 500 m³s⁻¹ and extends until late July, after which discharge declines until the end of the year to a minimum discharge of 80 m³s⁻¹ in January (Figure 2). The mean annual discharge for Squamish River, based on 43 years of record, is 250 m³s⁻¹. The maximum instantaneous discharge, which occurs in the fall to early winter and is associated with rain-on-snow events, can exceed eight times the mean annual discharge.

The hydrograph for the study period (Figure 3) follows this general pattern, with two noteworthy exceptions: a large increase in discharge occurred during late July, and a second storm period in mid-October

produced discharges of greater magnitude than the summer hydrograph crest, but less than those associated with the November storm period. In all other respects, however, the study period hydrograph is representative of Squamish River long-term behaviour.

The 4.5 km long study reach begins approximately 19.0 km upstream from the mouth of Squamish River and ends 1 km upstream of the Cheakamus River confluence (Figure 4). The study site is a moderately low-gradient (0.0005) reach located near the downstream end of a meandering segment of the river. The gentle slope is the result of the Cheekye fan, which exerts a local base-level control and results in the study reach being a zone of sediment storage (Figure 5). Examination of historic air photos indicates that there have been no discernible changes in the planform of the study reach for at least the last 45 years.

Thirteen cross-sections were positioned within the reach (Figure 4), located so as to capture all the bend effects of the meander planform: a cross-section positioned at a river-bend axis was followed by one positioned in a straight inflection segment, and so on.

Bed material throughout the reach is composed primarily of sand and gravel with larger material associated with localized tributary inputs. River banks consist primarily of sands and silts. The larger bed and bank material (cobble and boulders) is derived from debris flows and fans that originate from tributaries flowing into Squamish River from the west, and possibly Cheekye River to the east. This debris flow material appears to be quite stable as the rocks have established vegetation growing on them. Flow from tributaries entering the study reach is estimated to be less than 5 per cent of the total flow and sediment input is negligible.
METHODOLOGY

Sampling scheme
Channel cross-sections were surveyed on routine field-site visits which began on 5 June 1995 and continued until 24 June 1996. Visits were weekly during the freshet period (June to August 1995, and May to June 1996) and biweekly during lower flows. There were 30 full field monitoring visits throughout the study period involving approximately 15 surveys per station, except for cross-sections 6 and 7, which were sampled on every visit.

Every other cross-section was sampled during a site visit and the remaining sections were sampled on the subsequent field visit (Table I). Cross-sections 6 and 7 were sampled every field visit so that there was an overlap between the two groups of cross-sectional data and a basis for cross-correlation of the two survey series.

Field survey procedures
Flow depth was measured with a Lowrance X-16 chart-recorder from a 3 m long inflatable boat and an engineering level was used to measure water-surface elevation (measurement error was less than 0.5 cm). A graduated survey line was extended across the river and attached to anchor pins on each bank to provide horizontal position control.

The vertical position was controlled by the average water level in the channel and by the water-surface slope over the cross-section. Both were determined by surveying the water surface on both banks of the river at a cross-section using an engineering level and were referenced to a local datum. It was found that the water-surface slope across the channel did not contribute significantly to variations in the mean bed-elevation.
measurements (for example, the greatest adjustment to the mean bed-elevation due to a sloping water surface was 2.9 cm when a maximum superelevation of 16 cm was measured).

Once the graduated survey line was in place at a station, the boat was run across the channel using the survey line for horizontal position. The sonar chart was electronically marked at the beginning and end of each run and at each intervening 10 m graduation on the survey line, thereby horizontally fixing the survey position along the cross-section. At various times survey repetitions were performed to facilitate the assessment of data precision and accuracy.

Data processing

Sonar charts were digitized using a scaling calibration for each marked 10 m interval. At least 15 points (often 20 or more), stored as x,y coordinates matching the bed profile, were digitized for each 10 m spacing on the chart. This cross-section data file was imported into a spreadsheet and the bed elevation at each whole metre calculated and adjusted to account for the water-surface slope. The adjusted values were tabulated and mean bed-elevations determined.

For analysis purposes, calculation of the mean bed-elevation excluded the near bank as these areas exhibit the greatest distortion/variability on the chart paper. The bed width was also limited by the lowest flow. These truncated mean bed-elevations were tabulated and graphed, as were the profiles of the cross-section through time. To examine two-dimensional changes within a cross-section, the bed was divided into quarters for independent analysis.

All charts for each cross-section were digitized with the single exception of cross-section A (Figure 4); here, accumulations of large woody debris on the stream bed made accurate identification of the river bed position unreliable.
Figure 4. Survey locations in the study site on Squamish River
Discharge

Daily discharge and water-level data were obtained from the Water Survey of Canada station 08GA022 at Brackendale and from rating curves based on water-level measurements made at each cross-section for this study.

Accuracy

There are four major sources of potential error in determining the mean bed-elevation: depth-sounder measurement errors; diurnal bed-elevation fluctuations; bedform (mainly dunes) movement through a cross-section (possibly accounting for observed changes in the mean bed-elevation as suggested by Colby (1964) and Foley (1978)); and operator error in digitizing sonar charts.

In order to evaluate these potential errors, two sets of tests were conducted: monitoring of a single cross-section for an extended period of time revealed the nature of the first three potential sources of error, while multiple digitizing of a single chart addressed the fourth.
Sonar repetitions

Cross-sections 12 and 13 were monitored continuously for 9.5 and 5.0 h respectively, to test reproducibility of the surveys. Thirteen surveys for cross-section 12 and nine for cross-section 13 were digitized and analysed; the test results are shown in Table II.

The small amount of variation in the mean bed-elevation throughout the day and between samples during the day justifies the procedure of obtaining a single sonar survey at a given station per visit. There was no observed trend in the mean bed-elevation during the day, implying that the time at which a sample is taken during the day is not important. Both monitoring days had discharges well above the mean annual discharge of 250 m$^3$ s$^{-1}$ implying that the consistent results in the mean bed-elevation are not due to lack of bed-material movement. The results also show that, although the sonar charts reveal minor variations on the bed through time—presumably from the migration of bed forms (dunes)—they do not significantly affect the overall mean bed-elevation.

Digitizing accuracy

A single chart was digitized ten times in order to test for operator variability in the digitizing process. The test yielded a standard deviation for the entire width of the channel of 0.002 m and for the test segment of the bed it was 0.003 m. When the test chart was subdivided into quarters (near right bank, mid-right bank, mid-left bank and near left bank) the standard deviation for a given quarter bed segment was 0.004 m. We conclude that the error associated with the digitizing process is negligible.

RESULTS: WITHIN-SECTION BED-ELEVATION CHANGES

November storm period

The November storm period, consisting of four to five contiguous individual storms over approximately 3.5 weeks, is associated with pronounced changes in the mean bed-elevation (Figure 6). Of the 13 cross-sections analysed, ten display a drop in the mean bed-elevation in response to increased storm flows and three an increase (cross-sections 1, 6 and 12). The change at cross-section 12, however, is not unequivocal since there may have been a short period of time after the November storm period when the bed dropped but quickly recovered (Figure 6); sampling may not have been sufficiently dense to detect such rapid changes in mean bed-elevation. Although the November storm period produced a large change in bed elevation in a relatively short period of time, it was not solely, nor even mainly, responsible for observed changes in the bed over the year. Indeed, as much bed-elevation change was seen during the non-storm period, although these changes generally took place at a slower rate.

Yearly period

When viewed in the full year time frame, overall trends in mean bed-elevation include a general drop in the bed with the passing of the freshet in most of the cross-sections. Nevertheless, some cross-sections show a contrary increase in mean bed-elevation while others remain relatively unchanged. The limited duration of study makes it difficult to identify any further patterns within the cross-sections in a yearly time frame.

Table II. Bed-elevation statistics from continuous-monitoring test in cross-sections 12 and 13

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Number of runs</th>
<th>Date</th>
<th>Hours of monitoring</th>
<th>Discharge (m$^3$ s$^{-1}$)</th>
<th>Mean bed-elevation (m)*</th>
<th>Standard deviation (m)*</th>
<th>Standard error (m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>13</td>
<td>21 July 1996</td>
<td>9.5</td>
<td>275</td>
<td>3.169</td>
<td>0.022</td>
<td>0.006</td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>10 August 1996</td>
<td>5.0</td>
<td>399</td>
<td>2.393</td>
<td>0.035</td>
<td>0.012</td>
</tr>
</tbody>
</table>

* values are for the test segments of the channel bed
Figure 6. Mean bed-elevation changes for all cross-sections, 1995/6
although cross-section 12, and to a lesser extent cross-section 13, do seem to exhibit a cyclical pattern from the 1995 to the 1996 freshet.

Three smaller-scale patterns in the behaviour of the bed are evident in Figure 6: a phase of bed stability where little change was observed in mean bed-elevation; a periodic phase in bed elevation; and a pattern characterized by a build-up of material which markedly increased the mean bed-elevation, followed by a rapid drop. Individual cross-sections were not restricted to just one of these behaviours. Indeed, most exhibited two of these patterns and none is exclusive to a single cross-section.

A phase of bed stability (unchanging bed elevation across three or four sequential surveys), primarily during the post-November storm period, is evident in many cross-sections (1, 5, 7, 8, 9, 10 and, to a lesser extent, 4 and 6). Outside this period, cross-section 5 was the only one that demonstrated stability over most of the study period, although the pre-November storm period is associated with a weak periodic pattern in bed-elevation change. The stability in cross-sections 8, 9 and 10 may be linked to events at cross-section 7. Cross-section 7 is located at a point of channel confinement by a tributary fan (see Figure 4) and high flows will induce scouring at this site. Here, after scouring in response to the November storm period and displaying a short period of bed stability, the bed accumulated sediment and returned to a near pre-storm bed level, effectively erasing the large flow-induced impacts to the bed at this location. This hoarding of sediment at cross-section 7 may have reduced downstream sediment supply. This trapping of sediment dampened local fluctuations and accumulation of sediment in the bed downstream at cross-sections 8, 9 and 10 and possibly still further downstream, thus causing these cross-sections to exhibit little change during the same period.

The second of these observed patterns is periodic in nature, in that the bed fluctuates up and down between upper and lower limiting bands of bed elevation which may be stationary or non-stationary. Many of the cross-sections (2, 3, 4, 6, 7, 8, 10, 11 and 13) show this periodic behaviour in mean bed-elevation prior to the November storm period, but only cross-sections 2, 3, 6 and 11 maintain this pattern after the event. Unfortunately, data point density is not sufficiently high in some cross-sections to confirm whether the observed changes are more gradual, such as the trend seen in cross-section 3, or more erratic, as seen in cross-section 11.

The third pattern, consistent across many of the cross-sections, involves a general increase in the mean bed-elevation followed by a rapid flushing of bed material, resulting in an abrupt drop in the bed-elevation. This pattern is evident in nine of the 13 cross-sections (1, 3, 4, 7, 8, 10, 11, 12 and 13). In some cross-sections, the dramatic bed changes can be attributed to the November storm period, but in seven others (cross-sections 1, 4, 8, 10, 11, 12 and 13), these observed changes occur outside the storm period.

Correlation and regression analyses of bed-elevation and discharge

It was our initial expectation, based on an earlier study of Fraser River behaviour (Hickin, 1995), that for Squamish River, there might be relatively simple linear relations among bed elevation in the various cross-sections, and between discharge and bed elevation. However, simple correlation and regression analyses failed to confirm these assumptions. While changes in bed elevation in a given cross-section are directly related to those elsewhere in some cases, in others the relation is inverse, and in still others it is characterized by statistical independence. Similarly, for some cross-sections bed elevation is a direct function of discharge, in others the relation is inverse, and in still others there is no statistical dependence between discharge and bed elevation.

The absence of a simple relation between discharge and bed-elevation is quite significant because it suggests that movement of sediment into the reach is to some extent independent of discharge. This fact, together with the occurrence of the direct and inverse relations among bed elevation between cross-sections, led us to consider the alternative and more complex bedwave behaviour discussed later in the paper.

Mean bed-elevation by quartiles

Characterizing boundary adjustments in terms of mean bed-elevation for the entire cross-section is a limited basis for analysis because it may hide significant but self-cancelling within-channel variation in bed elevation (Skolds and Sturm, 1986). In this study, changes within an individual cross-section are examined by
Figure 7. Mean bed-elevation changes for quartered sections at all survey stations, 1995/6
dividing the stream bed into four quartile channel segments. Results of this quartile-based analysis are presented in Figure 7.

The bed quarters of nine of the 13 cross-sections (2, 3, 5, 6, 7, 8, 11, 12, 13) tend to exhibit an in-phase variation in elevation over time. In some cases the bed-elevation change is greater in particular sections, but the overall trend is the same in all quarters. Greater variability is seen in the remaining four cross-sections. Cross-section 4 exhibits a clear example of simultaneous scour and fill but it is also less clearly evident in cross-sections 1 and 10. Cross-section 9 exhibits changes in the bed elevation on one side of the channel while the other side remains essentially unchanged.

In the case of cross-section 4, the left bank (LB) and near LB portions of the channel responded quite strongly to the November storm period, compared to the right side of the channel. The result was a shift in the position of the thalweg from the left to the right side of the channel. Then, during the winter low flows and the following rise into the 1996 freshet, the channel began to return to its previous pre-storm configuration. This thalweg migration was not apparent in the other cross-sections.

The partitioned bed sections of cross-sections 3 and 13 have similar trends and mimic the change in mean bed-elevation, but contrast distinctly with other cross-sections. There was an across-the-channel build-up of bed material prior to the November storm period, followed by a pronounced drop in all sections of the bed. To a lesser degree, cross-section 8 exhibits the same pattern, but the build-up prior to the November storm period does not occur across the entire channel, nor is there a pronounced drop in the bed after the storm period. These three cross-sections are located at an inflection point of the meandering channel.

With respect to position within the channel, seven of the 13 cross-sections (3, 4, 5, 7, 10, 12, 13) show the greatest bed-elevation change in one of the central portions of the channel and six show the greatest change nearest the banks (cross-sections 1, 2, 6, 8, 9, 11). There also appears to be no simple association between the pattern of within-channel bed-elevation change and the shape of the channel cross-section. This surprising result suggests that the downstream locus of highest boundary shear stress (and therefore maximum scour) was not completely in phase with these low-amplitude meanders during all boundary-deforming flows observed during the study period.

Table III shows the total amount of change in bed elevation for the quarter sections and for the bed as a whole during the study period. Compared to the amount of change in the bed as a whole, five of the 13 cross-sections (1, 2, 6, 8, 11), have a greater amount of absolute change in all of the bed quarters, six cross-sections (3, 5, 7, 10, 12, 13) show greater change in three of the four bed quarters, and the remaining two cross-sections (4, 9) show greater change in two of the four quarters. Two of the cross-sections (1 and 11) have more than three times as much bed-elevation change in one quarter, compared to the bed as a whole.

When the degree of change observed in all quarters is greater than that of the bed as a whole, it is the result of self-cancelling changes occurring at the same time in different portions of the bed. Those quarters

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Change in MBE</th>
<th>Bed quarters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RB</td>
<td>near RB</td>
</tr>
<tr>
<td>1</td>
<td>0.444</td>
<td>0.729</td>
</tr>
<tr>
<td>2</td>
<td>0.606</td>
<td>0.702</td>
</tr>
<tr>
<td>3</td>
<td>1.722</td>
<td>1.962</td>
</tr>
<tr>
<td>4</td>
<td>0.453</td>
<td>0.354</td>
</tr>
<tr>
<td>5</td>
<td>1.086</td>
<td>0.325</td>
</tr>
<tr>
<td>6</td>
<td>0.483</td>
<td>0.582</td>
</tr>
<tr>
<td>7</td>
<td>2.410</td>
<td>2.485</td>
</tr>
<tr>
<td>8</td>
<td>0.832</td>
<td>1.150</td>
</tr>
<tr>
<td>9</td>
<td>0.614</td>
<td>0.315</td>
</tr>
<tr>
<td>10</td>
<td>0.589</td>
<td>1.031</td>
</tr>
<tr>
<td>11</td>
<td>0.220</td>
<td>0.526</td>
</tr>
<tr>
<td>12</td>
<td>0.613</td>
<td>0.391</td>
</tr>
<tr>
<td>13</td>
<td>2.169</td>
<td>1.507</td>
</tr>
</tbody>
</table>
exhibiting less change than the bed as a whole are still areas of significant activity, as the smallest amount of change observed in any one quarter is more than 30 cm.

Analysis of the partitioned bed shows that generally there are larger internal fluctuations occurring in almost all portions of the bed relative to the mean changes in the bed as a whole. The large amount of change observed within a section supports Skolds and Sturm’s (1986) concern about the limitations of a one-dimensional analysis of the bed and confirms observations made by others (Hey, 1978; Galay, 1983). However, the exploratory two-dimensional examination of the bed in this study failed to identify any definitive trends.

RESULTS: WHOLE CHANNEL

Downstream sediment movement

The patterns of bed-elevation change over space and time evident in the complete data set for Squamish River include channel adjustments that appear to propagate downstream (Figure 6). For example, the bed-elevation peak labelled 8a in Figure 6 appears to move downstream through cross-sections 10 to 13 as a coherent wave. This wave-like behaviour implies that sediment movement through the reach must also occur as pulses or waves rather than as a continuous supply or influx to the reach. Although the present analysis of bed-wave translation through the sequential cross-sections is inevitably subjective in detail, the general pattern is clearly evident and dictates that the bed-elevation change at a given cross-section is not only the result of the changing discharge but that it is also dependent on fluctuating upstream sediment supply.

Squamish River is not unique in this regard. As we note earlier, the wave- or pulse-like behaviour of bedload movement in river channels has been reported in several other studies (Meade, 1985; Mosley, 1978; Griffiths, 1979; Lekach and Schick, 1983; Madej and Ozaki, 1996; Wathen and Hoey, 1998) and attempts to model sediment-wave movement have been made by Pickup et al. (1983), Hoey and Sutherland (1991), and Lisle et al. (1997). Church (1983) notes that in Bella Coola River, in western Canada, sediment also moves in waves. He suggests that dispersion of the wave with downstream movement is minimized as a result of sediment storage areas that permit the reconcentration of sediment in the wave. Unlike these cases, however, the present study documents the translation of multiple bedwaves (or a bedwave system) through a natural channel.

Because movement of sediment in the study reach appears in the form of pulses or waves it is useful to distinguish between scour and fill that is induced by the passage of a pulse or wave of sediment on the one hand, and scour and fill that is related to local erosion and deposition commonly associated with the passage of a flood, on the other. The former process is here termed pulse scour and pulse fill and the latter is local scour and local fill. Pulse scour and fill involves sediment-wave translation with little or no other external supply or storage of sediment while local scour and fill involves only local sediment exchanges (see Colby, 1964).

Defined in this manner, it is possible for a channel section to simultaneously undergo any combination of these independent processes. For example, a cross-section may exhibit pulse scour that may be enhanced by local scour or dampened by local fill. The term ‘peak’ is used here to describe the apex of a sediment pulse moving through a cross-section brought about by pulse fill and the term ‘trough’ for the nadir between two sediment pulses brought about by pulse scour.

Mean bed-elevation changes interpreted from this pulse or wave perspective place each cross-section in the context of the bed-elevation changes in the surrounding cross-sections. Only peaks and troughs of sediment pulses that could be clearly isolated and tracked across many cross-sections through time are identified in Figure 6. Although there are other peaks and troughs present, because of the coarseness of the sampling density or the small amount of change observed in the mean bed-elevation at a particular cross-section, these minor peaks are difficult to isolate and therefore not identified. Furthermore, those peaks and troughs that are tracked do not persist through the entire reach. The apparent downstream movement of peaks and troughs suggests that sediment movement past cross-section 1 may have reached as far downstream as cross-section 11 during the study period. Back-tracking of the peaks and troughs from the cross-section furthest
Figure 8. The TDE matrix showing zones of elevation change with respect to survey dates and cross-section location in the study reach.
downstream (13) suggests two general peaks (3 and 8 in Figure 6) which persist up to cross-section 10 but do not clearly appear in cross-section 9; they possibly reappear at cross-section 7 and even further upstream.

In order to examine the bed-elevation changes in relation to both time and to distance downstream, a three-dimensional matrix was developed (Figure 8). This matrix has the relative position of the cross-sections and the survey date as the respective x and y axes. The values within the matrix are determined by the change in the mean bed-elevation from the previous time period, a positive or negative sign being assigned depending on whether the bed rose or fell from the previous sample date. The value associated with the position in the matrix is either 0, 0-5 or 1 where zero represents a change of less than 5 cm in the mean bed elevation, 0-5 represents a change between 5 cm and 10 cm, and 1 indicates a change of 10 cm or greater. Thus, a value of ‘−0.5’ would indicate a drop in the bed from the previous date of more than 5 cm but less than 10 cm. This time/distance/elevation-change matrix is hereafter referred to as the TDE matrix.

The spacing for the cross-sections along the x-axis of the TDE matrix reflects the distance from cross-section 1 in the downstream direction following the centre of the channel. The date is on the y-axis, with 6 June 1995 as the starting point in time as all cross-sections were sampled on either 5, 6 or 7 June. Isolines have been drawn to generalize the elevation-change zones in the time–distance domain that correspond to the change in mean bed-elevation leading to the troughs or peaks identified in Figures 6 and 8.

**TDE matrix observations**

The TDE matrix integrates changes in the mean bed-elevation through time and in the downstream direction and facilitates the tracking of peaks and troughs. Specifying the bed-wave migration pattern through time, however, is complicated by the varying rates at which the peaks and troughs move downstream during different parts of the year. Physical reasoning suggests that a larger discharge will not only move more sediment, but will also move it faster than in lower flows. During periods of lower flows, the slope of the peak and trough trajectories will be steeper in the time–distance domain because it takes longer for the ‘unit’ to move a given distance downstream. Peak and trough migration rates can also be affected by bed armouring, a process which commonly occurs on Squamish River bars during periods of low flow. Bed armour may minimize or eliminate trough movement through a cross-section because the flow may be inadequate to disrupt the armour, and consequently little change occurs in the mean bed-elevation. A further complication is that a large proportion of suspended sediment may settle out during lower flows, obscuring the peaks and troughs in the gravel by smoothing out the bed, although there was no direct evidence of this occurring.

Periods of relative inactivity in the mean bed-elevation are also evident in the TDE matrix although the bed-elevation data alone are not sufficient to ascribe a cause. A stable bed-elevation may simply mean that there is no bedload movement but it could also imply bedload movement with a locally balanced sediment budget. A more complex cause involves the blending of a peak with a trough resulting in no net bed-elevation change. In this case, sediment forming a faster-moving peak converges on, and fills, the downstream trough, consequently smoothing out the bed. Similarly, a faster-moving trough converging on, and blending with, a downstream peak can have the same self-cancelling effect on bed elevation. In these circumstances, the original peak and trough are difficult or impossible to identify.

Several bed features, labelled troughs A and B and peaks 3/3a, 4 and 8/8a in Figures 6 and 8, have relatively easily trackable migration patterns and are described below.

Trough A is clearly evident in all locations except cross-sections 5 and 10 and appears to travel through the entire study reach during the survey period. At cross-section 5 the trough might have been missed as a result of the sampling scheme. Although trough A is absent at cross-section 10, downstream extrapolation of its position is consistent with the decline in mean bed-elevation at cross-sections 12 and 13.

Peak 4 passed through cross-section 1 near the end of the freshet, following the passage of trough A, and reached cross-section 11 by the end of the study. Its trajectory in the TDE matrix is not as clearly defined as that for trough A, although it is evident throughout most of the reach. As with trough A, however, there are certain cross-sections where peak 4 apparently is absent, such as in cross-section 5 as noted above. Peak 4 seems to reappear in cross-section 6 and is obscured again as it reaches cross-section 7, after the November storm period. This storm may have caused the sediment in the peak to disperse and partially blend with trough A, resulting in an overall smoothing out of the bed. This smoothing, as well as the large amount of local scour
that appears to have occurred at cross-section 7, has resulted in the dampening of peak 4 as well as of trough A. The effect of this dampening is manifested downstream at cross-section 8, where the peak is barely discernible.

Peak 4 is also absent in cross-sections 9 and 10, but reappears and passes through cross-section 11 near the end of the study. Its absence here is likely the result of the peak material converging on and blending with trough B, thereby destroying firm evidence of either of them. Extrapolation of the peak 4 position based on its celerity to cross-section 8 puts it at cross-section 11 as shown in Figure 8. It is not apparent why peak 4 is missing in cross-sections 9 and 10.

Trough B is the second trough appearing in cross-section 1 at the beginning of the November storm period, and is clearly visible at cross-sections 2 and 3. Although the lowest point of the trough appears to occur at both cross-sections simultaneously, the actual time separation here cannot be resolved because of the low sampling density during that time period. Once trough B reached cross-section 2 the mean bed-elevation may have remained almost unchanged because the bed behaviour at cross-section 1 suggests that very little sediment was being introduced from upstream at this time.

By the time it reached cross-section 4, trough B is no longer as well defined as it was upstream although it becomes quite distinct again at cross-sections 5 and 6 before attenuating once again through cross-sections 7 and 8, quite possibly because of interaction with the converging peak 4. It also seems likely, however, that cross-section 7, with its extremely low post-storm mean bed-elevation, acted as a local sediment sink, preventing propagation of any bedwave forms through the reach. Much of the incoming sediment from upstream appears to accumulate in cross-section 7, rebuilding the bed back to its pre-November storm level.

A peak/trough unit, possibly representing peak 4 and trough B, is evident in cross-section 11 by the end of the study period. Based on this assumption, wave celerity calculations for this unit are consistent with those of other peaks and troughs migrating through the lower reach at this time.

Peak 8/8a is most easily followed through the study reach by back-tracking from cross-section 13, where it is most apparent (see Figures 6 and 8); its trajectory can be traced in the TDE matrix back to cross-section 3. Like other peaks and troughs in the bedwave system, there are some cross-sections where peak 8 is either obscured or absent. It is easily tracked back to cross-section 10, is absent at cross-section 9, but evident in cross-sections 8 to 3.

Peak 8 is visible at cross-section 7, just before the November storm period, but thereafter appears to be split into two subpeaks. This may be the result of local scour and fill or to trough A converging on peak 8; however, the latter does appear to be cleanly separated from trough A throughout the study reach from cross-sections 3 to 13. Although trough A and peak 4 are absent at cross-section 5, peak 8 is visible, albeit if somewhat obscured.

Peak 3/3a is also best defined at cross-section 13 and its trajectory in the TDE matrix most easily followed by back-tracking upstream to cross-section 7, where it first appears at the beginning of the study. Peak 3 appears to have a complex origin, perhaps forming from the combination of two smaller peaks. Downstream of cross-section 7 to cross-section 8, both peak 3 and a slightly smaller and earlier one (peak 3a) are visible. Although the peaks are not evident in cross-section 9 (which exhibits only a modest and gradual rise in the bed), they are clearly evident in cross-section 10. The two peaks are seen clearly in cross-section 11, but by the time they reach cross-section 12 and move into cross-section 13, they seem to have become one single peak. This combination of peaks may be more apparent than real, however, since the caveat with respect to the low sampling rate in this phase of the survey obliges us to recognize that the second peak may simply have been missed.

### Sediment wave velocity

The slope of the bedwave trajectories in the TDE matrix data provide a basis for calculating the downstream migration velocity of the peaks and troughs (Table IV).

The ‘velocities’ have been calculated in two ways. In the first and conventional approximation, the total migration distance of a trough/peak is divided by the total travel time. In the second method bedwave migration rate is equal to the total distance travelled divided by the number of days that a threshold discharge is exceeded. This method accounts for periods when there is no significant sediment transport and it may

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mean bed-elevation, within sections and in the downstream direction, reported in this study. Bedload movement through this reach of Squamish River during the study period is in the form of waves or pulses that appear to maintain an overall coherence with movement downstream. These waves propagate downstream by a mode here termed pulse scour and pulse fill, a process distinguished from the conventional mode of scour and fill commonly associated with flood events (here termed local scour and local fill). Analysis of the bed elevation and flow data reveals no simple relation between the mean bed-elevation and discharge or any strong correlation among cross-sectional behaviour. Bedwave celerity was estimated to be 15·5 m d\(^{-1}\) corresponding to a bedwave residence time in the 4·5 km long study reach of almost one hydrologic year. The bed-elevation data also suggest that complex changes to the bed within a cross-section are masked when the bed is viewed in one dimension, although no definitive trends in bed behaviour were found in the two-dimensional analysis.

**SUMMARY AND CONCLUSIONS**

Monitoring of 13 channel cross-sections for a complete hydrologic year forms the basis for the changes in mean bed-elevation, within sections and in the downstream direction, reported in this study. Bedload movement through this reach of Squamish River during the study period is in the form of waves or pulses that appear to maintain an overall coherence with movement downstream. These waves propagate downstream by a mode here termed pulse scour and pulse fill, a process distinguished from the conventional mode of scour and fill commonly associated with flood events (here termed local scour and local fill). Analysis of the bed elevation and flow data reveals no simple relation between the mean bed-elevation and discharge or any strong correlation among cross-sectional behaviour. Bedwave celerity was estimated to be 15·5 m d\(^{-1}\) corresponding to a bedwave residence time in the 4·5 km long study reach of almost one hydrologic year. The bed-elevation data also suggest that complex changes to the bed within a cross-section are masked when the bed is viewed in one dimension, although no definitive trends in bed behaviour were found in the two-dimensional analysis.

This study suggests that the strong seasonal signal in the bed-elevation regime reported by Hickin (1995) for the much larger Fraser River does not persist down to the scale of Squamish River. Here the bed-elevation regime is dominated by supply-driven fluctuations in bedload transport occurring at timescales shorter than the seasonal fluctuation in discharge. Unlike previous investigations, the present study also shows that migrating peaks and troughs form an undulating bed morphology which moves through the study reach as a sensibly coherent bedwave system.

In order to detect and measure aggradation/degradation in the long term, this study indicates that bed-elevation monitoring on Squamish River must take into account very considerable channel-bed variability operating at timescales from hours to months. There is no reason to suppose that Squamish River is unique in this regard.

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