GRAVEL MANAGEMENT IN LOWER FRASER RIVER

prepared for

The City of Chilliwack

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by

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Executive Summary

This report makes recommendations for the extraction of gravel from the gravel-bed reach of Fraser River between Laidlaw and Sumas Mountain for the purpose of maintaining or increasing flood security along the reach by lowering flood water levels. Almost all previous experience of gravel extraction from gravel-bed rivers has been for volumes removed to greatly exceed the rate of recruitment. This leads to dramatic degradation and simplification of the channel morphology. In Fraser River, the rich riverine ecosystem depends essentially upon the complex channel morphology that is maintained by the transport of bed material -- mainly gravel -- along the channel; significant simplification of the channel would put the riverine ecosystem at risk. Therefore, a rational basis for assessing gravel volumes to be removed requires the sediment budget for the reach to be established. Then, extraction volumes may be compared with gravel recruitment rates.

Accordingly, the bed material budget of the gravel-bed reach is established. This is a complex, ongoing task. Our latest analysis incorporates new analyses and establishes a best estimate of the bed material influx rate over 47 years at 285 000 m^3 bulk volume. On the basis of this figure, a review of experience of gravel extraction in rivers elsewhere, and consideration of the Fraser River ecosystem, the following recommendations are made for Fraser River:

1. *The rate of bed material removal for the next several years should not exceed 285 000 m^3a^{-1}, on average, although individual operations might exceed that figure when best engineering judgement indicates that larger extractions must be made to improve water levels locally to assure flood security.*

This represents a proposal to increase by 4x the long-term annual extraction rate, and to approximately treble recent extraction rates.

2. *The bed material extraction ratio should not exceed 1.5 in comparison with the best estimate of gravel recruitment over the most recent 5 year period.*

The foregoing recommendation represents the best current estimate that can be made of a prudent limiting extraction rate to avoid significant changes to the river morphology and riverine ecosystem. The ratio is different than that given in recommendation 1 in view of the more limited integral time for estimating sediment recruitment.

3. *Recommendations 1 and 2 should be implemented in a precautionary and adaptive manner. Each extraction should be regarded as an experiment, with physical and biological surveys conducted at each extraction site before and after removal, and follow-up monitoring to determine the net impact over several succeeding years. In addition, monitoring of riverwide morphological conditions should be undertaken. As soon as the results from several sites are consistently interpretable and trends in mean channel condition are discernible, recommendations 1 and 2, and all others in this report should be reviewed and revised.*

This recommendation stems from the uncertainty that still attends many of the conditions and processes that will be associated with extraction at an accelerated rate.

4. *The rate of gravel removal in any short sub-reach along the river should not exceed one-half the estimated local bed material transport rate in a sequence of three consecutive years, except near the downstream limit of gravel deposition (downstream of km 110).*

This proposal is to ensure that the downstream process of sediment transfer is not short-circuited by concentrating extraction in the upstream part of the reach.

In the following recommendations, a "type 1 situation" is a sudden narrowing of the channel zone. "Type 2" is a situation where high resistance to flow is encountered, and "type 3" is where the river crosses a high riffle.

5. *In situations of types 1 and 2, gravel should be removed from the bar surface and riverward flank within the downstream two-thirds of the bar area in order to increase high flow conveyance of the channel and reduce local and upstream water levels.*

6. *In situations of type 3, a major bar-crossing channel should be developed by removing gravel from the wetted channel on a favourable alignment. These cases will be related to navigation requirements on the river. Choice of alignment should consider the likelihood that the river will maintain the selected alignment for some time; the practical needs for navigation; and the likely effects downstream of the resulting alignment of the current. Likely alignments are apt to be already present in the form of chutes across the bar.*

Material should not be removed from the headmost portion of the bar, an area of high flow attack which customarily is relatively heavily armoured. Removal of this surface might destabilize the bar in unforeseen and undesirable ways. Nor should the highest points on the bar be systematically removed.

7. *The technique of 'bar-edge scalping' should be investigated as a relatively effective gravel extraction method for improving channel conveyance whilst maintaining characteristic river morphology. Trial excavations should incorporate monitoring programs to investigate silt release, effects on subsequent gravel quality for spawning, and impacts on benthic invertebrates.*

8. *Extractions should be designed to mimic sedimentary features that create irregular bar edges in order to maintain physical microhabitat features.*

These are novel proposals that deserve critical scrutiny. These and the following proposals are designed for minimum local disturbance to the riverine ecosystem.

9. *Gravel should not be extracted in consecutive years at any site. Repeat extraction should not be considered at any site where there is evidence for ecological stress in the form of significantly changed occurrence of benthic organisms or fishes except in the case of chronic aggradation that presents a significant risk of breaching flood security.*

The last two proposals are to ensure orderly integration of gravel extraction with other developments that might affect the river in the future.

10. *A proposal to increase the draft for navigation in the gravel-bed reach or to provide a more extensively engineered navigation route than has been the past custom should be*

subject to environmental impact assessment with respect to possible effects on the riverine ecosystem.

11. *A plan should be developed to assure adequate sand and gravel supplies for the Lower Mainland region over the next 30 years. The plan should not rely on industrial-scale gravel extraction from Fraser River.*

Report history

This is the final report on a project to determine the sediment budget of Fraser River, initiated in 1998. Reports of progress were previously made as follows:

Sedimentation and flood hazard in the gravel reach of Fraser River: progress report; 15 April, 1999

Sedimentation and flood hazard in the gravel reach of Fraser River: progress report; 31 March, 2000

Sedimentation and flood hazard in the gravel reach of Fraser River: progress report; 25 September, 2000 (superceding the report of 31 March)

Gravel management in lower Fraser River (draft report); 1 March, 2000

This report supercedes all of these reports. The sediment budget figures given in this report replace earlier estimates, and contain some significant changes. The recommendations for gravel management are similar to those of the report of 1 March, 2001, but discussion of them has been expanded in this report.

The revision of 12 December is to correct some figures in the sand budget which are incorrectly reported in the original issue of 18 October. The errors originated in an error in the GIS and from some undetected spreadsheet errors. They do not affect the gravel budget and have no effect whatsoever on the recommendations of the report, which are entirely unchanged. However, the appendix has been expanded so that it is now possible for the reader to completely reconstruct any of the results in the sediment budget.

Acknowledgments

The study of the sediment budget of the gravel-bed reach of lower Fraser River has been supported by funding from the British Columbia Emergency Flood Protection Program, administered by the former British Columbia Ministry of Environment, Lands and Parks, and delivered through the City of Chilliwack. Mr. Terry Keenhan, P.Eng., formerly of the Ministry of Environment, Lands and Parks, mobilized the program. Mr. Ron Henry, Senior Hydraulic Engineer in the Lower Mainland Regional Office, British Columbia Ministry of Water, Air and Land Protection (MWLAP) provided able technical supervision in the second two years. Mr. Gary Wickham, P.Eng., Supervisor of Works and Operations, City of Chilliwack, and his staff administered project funding. Dr. Marvin Rosenau, Senior Habitat Biologist for MWLAP provided important discussion and review of the project at several stages. Contributions to this report concerning the ecology of the river were made by Ms. Laura Rempel, who is conducting a parallel study of the ecology of the gravel-bed reach. The authors are grateful for all of this help and cooperation.

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1 INTRODUCTION

1.1 CONTRACT OBLIGATION

This report represents the fulfillment of task 2.1 (Geomorphic criteria for channel management) under the Year 3 studies of the gravel budget in Lower Fraser River conducted at the Department of Geography, The University of British Columbia, under an agreement with the City of Chilliwack. That task is to present geomorphic criteria to guide decision-making on proposed gravel removals from Fraser River in the Lower Mainland. Because gravel removals from Fraser River have, to date, remained modest, the task also entails summarizing experience from rivers elsewhere with a broadly similar geomorphic history. This project corresponds with task 6.6 as outlined in a 1998 memorandum of the British Columbia Ministry of Environment, Lands and Parks describing planning studies for management of flood security in the gravel-bed reach of Lower Fraser River. The reach of primary interest extends from Laidlaw (river km 155) to Matsqui Bend (km 90), immediately upstream of Mission (Figure 1).

The project incorporates ongoing analysis of a sediment budget exercise conducted in years 1 and 2 of the study.

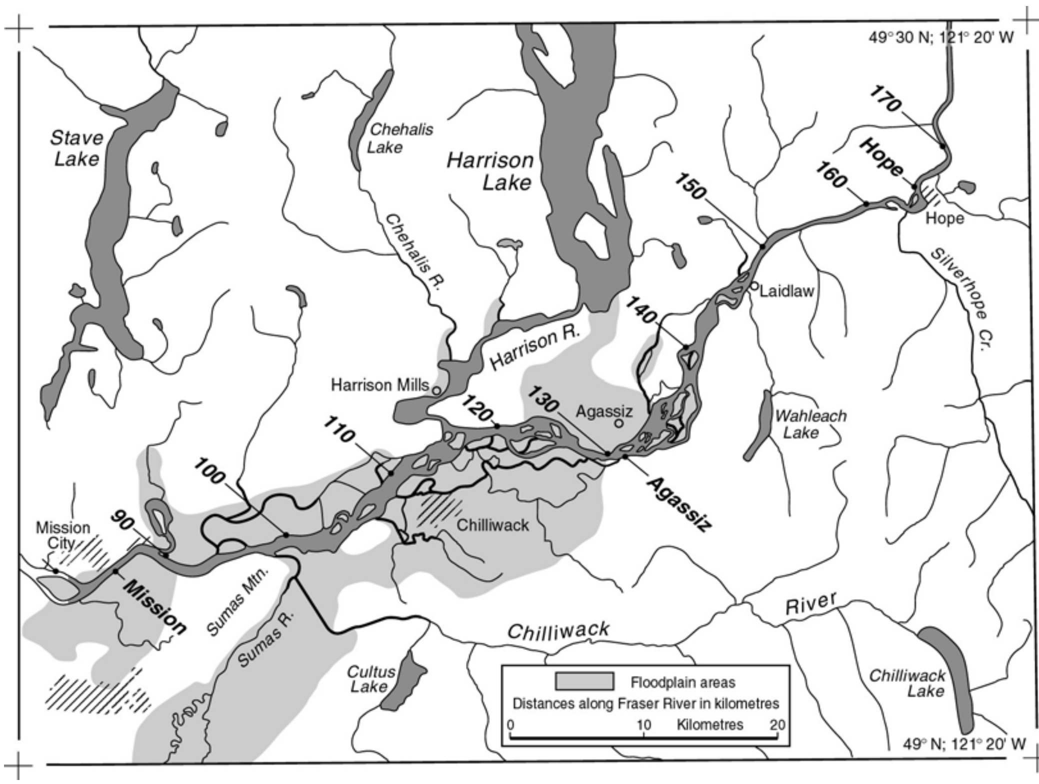


Figure 1. Map of the study reach showing river kilometres upstream from Sand Heads. The study reach lies between km 85 (Mission gauge) and km 155 (Laidlaw).

This study presents the context and technical recommendations for gravel removal from the river, should it be decided that gravel removal represents a viable strategy for managing water levels in the river. Gravel removal is only one of several strategies that might be pursued to manage water levels. The report is not intended to advocate the strategy of gravel removal.

1.2 STATEMENT OF THE PROBLEM

Fraser River poses a significant potential flood hazard to human settlement within the Lower Mainland of British Columbia. With annual minimum flows of order 1000 m^3s^{-1} and flood flows of order 10 000 m^3s^{-1}, the annual range of flow is about 10x. This is normal for a large river. In the natural state, this range of flows was sufficient to flood extensive areas of the restricted floodplain of the river within the Lower Mainland. After the great flood of 1894, efforts commenced to protect developing settlements from the river, efforts that have now continued for a century.

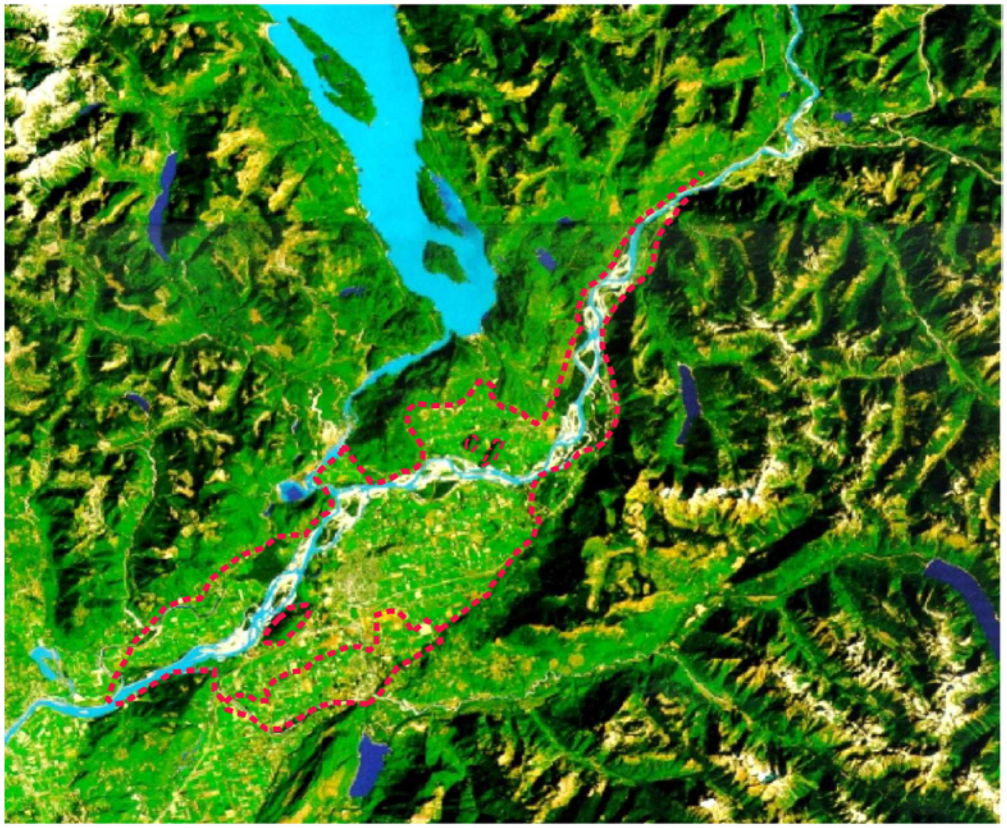
The river follows a steep, confined course through the mountains where it picks up rocks, gravel, sand, silt and clay from the banks and from tributaries. Within the Lower Mainland, the gradient of the river declines quickly as it approaches the sea. It cannot continue to move the larger material on the reduced gradient. The largest material is abandoned first, so that the river between Hope and Sumas Mountain flows over its own gravel deposits. These deposits form a confined alluvial fan -- a wedge of sediment restricted within the confines of the relatively narrow valley northeast of Sumas Mountain (Figure 2).

An alluvial fan is a deposit of river-transported sediment dumped where the river encounters a sharply reduced gradient. Such fans are common at mountain fronts. Alluvial fans continue to accumulate sediment so long as the river delivers material that cannot be transported across the fan and beyond. This is the situation on Fraser River, so the river in the eastern Lower Mainland is aggrading -- raising its bed -- as additional gravel and sand are deposited there year by year. This process slowly raises water levels, hence flood levels.

Because of the aggradation, rivers on alluvial fans are laterally unstable. They shift course relatively quickly because the deposited sediment fills the current channel bed, creating an obstruction to the conveyance of water downstream and raising the bed above the adjacent fan surface. The water then finds a new course around the deposits. How unstable a river is depends upon the sediment volume deposited annually in comparison with the size of the channel. On Fraser River, the deposits are modest and the river is not highly unstable.

Throughout the twentieth century a program of river dyking and bank protection has been pursued in order to protect adjacent land from flooding, and to reduce or eliminate erosion of those increasingly valuable lands. As a result the river has been held within a channel zone that is more narrowly confined than it originally was. The confinement is not extreme; the chief effects have been the cutoff of sidechannels and elimination of floodwater storage areas. Confinement of a river raises flood water levels beyond those they otherwise would reach and increases the rate of rise of the riverbed because sediment deposition occurs only within the restricted channel zone.

A



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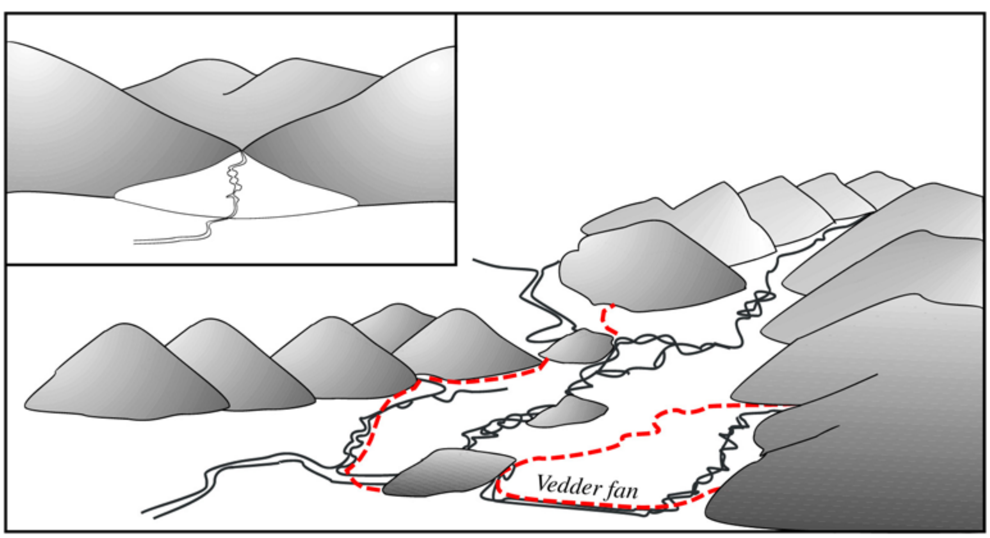


Figure 2. Situation of the gravel-bed reach of Lower Fraser River: (a) satellite photograph of a part of the Lower Mainland, showing the area of the confined fan of Fraser River (dashed red line). The Chilliwack (Vedder) River fan is also shown; (b) sketch to define an alluvial fan, and the confined gravel fan of Fraser River.

There is an additional dimension to the problem. The consequence of gravel deposition and modest instability in the river is the complex pattern of bars, islands and secondary channels in the river between Laidlaw and Sumas Mountain. These features create aquatic and riparian habitat of exceptionally high quality. The modest instability renews the habitat at a rate to which the river fauna can easily adapt. Habitat renewal is an essential process for the maintenance of habitat quality. Hence, the ecological wealth of Fraser River in the gravel reach -- which contributes substantial economic value through various fisheries -- is the product of the modest rate of gravel deposition. There is, furthermore, increasing public appreciation of the recreational and aesthetic qualities of the river which stem in significant degree from the morphological complexity and habitat values, hence from processes associated with the aggradation. Therefore, actions taken to mitigate flood hazard and river instability must reckon with possible consequences for the habitat quality.

As the bed of Fraser River rises (aggrades) in the gravel-bed reach, the water surface level also rises for a given flow. If no action is taken to offset this process, the level of flood protection afforded by the dykes along the river is progressively reduced. It is known that, in some places along the river, the dykes are today not sufficiently high to assure protection against the water level for which the dyke system was designed; that is, the 1894 flood of record (UMA, 2001). There are a number of means by which this developing hazard might be mitigated, including

- raising the dykes;
- reconstructing the dykes with more generous setbacks (which would have the effect of increasing flood conveyance within the expanded floodway);
- maintaining or lowering high water levels locally by gravel removal to lower the bed level;
- maintaining or lowering high water levels locally by channel training works;
- relying on institutional and social actions to maintain social protection (such actions would include some mix of restrictive land use zoning; insurance; emergency measure planning).

One means to offset the rise of the river bed is to remove material from the river so the bed is prevented from rising. However, such an action might have significant effects upon the rich and diverse riverine ecosystem that is such a valued element of the river. In order to determine how much gravel might be removed from the river and how it might best be recovered, it is necessary to answer a set of linked questions:

- how quickly is the river bed aggrading? (i.e., what is the sediment budget of the river?)
- where is sediment being deposited?
- how does sediment deposition influence the morphology and ecology of the river?
- how much gravel needs to be removed in order to mitigate the flood hazard?
- from where should gravel be removed in order to mitigate the flood hazard?
- how much gravel could be removed before the river morphology and ecosystem are significantly changed?
- how might the river morphology and ecosystem be affected by gravel removal from the channel?
- in light of ecosystem needs, what would be the best manner in which to remove gravel from the river?

In the light of the history of settlement and river management, some additional questions become important to answer as well.

- how does channel confinement influence the transport and deposition of sand and gravel in the channel?
- how wide should the channel zone of the river be in order to ensure that significant physical and ecological functions will be sustained?
- how do gravel removal and channel confinement affect each other?

Environmental change must also be factored into the problem. The river is large and changes only slowly in response to changes in the environment. Management decisions about the river taken now may eventually be reinforced or confounded by environmental change, so it is important to foresee, so far as we can, what trends in flow and sediment supply might occur in the future, and to consider these in developing long-term plans for river management. Specific questions include the following:

- what trends might appear in future floods?
- what are the sources of sediment supply to the river?
- how might these sediment sources change in the future?

It is the purpose of this report to answer these questions so far as possible with the information in hand about the river, to indicate what are the implications of the imperfect state of knowledge about the river and its ecosystem, to propose actions that may be taken now to manage gravel deposition in the river, and to suggest means to improve knowledge.

1.3 OBJECTIVES

It is the objective of this report to contribute toward the development of a management plan for the Laidlaw-Mission reach of the river by answering the questions posed above. The most important specific objectives are:

1) to establish the sediment budget for the river;
2) to appraise the implications of establishing a program of removals of gravel from the river in order to maintain security against flood hazards;
3) to determine where, how, and how much gravel could be removed;
4) to forecast the consequences for the river morphology and ecology of gravel removals.

The following sections of this report address these objectives.

2 THE SEDIMENT BUDGET AND THE MORPHOLOGY OF FRASER RIVER

The principal factors that control the morphology (form) of a river channel are the water and the sediment supplied to the river, and the gradient down which the river flows. Both the quantity and the calibre (size) of the sediment matter. The morphology of the river channel is simply the result of the transport and deposition of the sediment. In the long run, sediment erosion and deposition lead to adjustment of the slope, so water and sediment are the true governing factors. These factors are related in an expression presented many years ago by the American engineer, E. Lane (1955):

$$Q_s/Q \sim S/D$$

wherein Q_s is sediment discharge and Q is water flow, so the quotient is sediment concentration, S is channel slope and D is sediment grain size. The symbol ~ indicates that the statement represents a proportional relation, rather than an exact equation. Slight rearrangement yields

$$Q_s \sim QS/D$$

QS represents the power of the river (equivalent to the rate of loss of potential energy as the water flows downslope), so the relation indicates that the transport of sediment is directly proportional to stream power and inversely proportional to the size of the grains. Flow in the gravel-bed reach of Fraser River does not vary greatly (except for the step change at the Harrison confluence) so, as slope declines, this relation says that either the size of the transported material must decline, or the quantity of sediment transported must decline, or both. This relation shows, then, why the larger material in the sediment load entering the gravel-bed reach of Fraser River is deposited as the river slope declines downstream.

In order to determine how much material is deposited, hence how quickly the bed is aggrading in the gravel-bed reach, we need to know the sediment budget of the reach. For the purpose of appraising changes in bed elevation along the reach, we require knowledge of the variation of the sediment budget along the channel. The only practical way to obtain this information is to obtain sequential surveys of the channel and to derive the changes in channel by survey comparisons (see Ashmore and Church, 1998). For this study, we have compared surveys made in 1952, 1984 and 1999. These are the only detailed, full reach-length surveys available. We have made the comparisons within 1-km "cells" along the channel (Figure 3). This is achieved within a Geographic Information System into which the survey data are entered. To obtain an absolute reference we have assumed that the transport of gravel past Mission is zero. Since sediment transport measurements have been made there by the Water Survey of Canada (see McLean et al., 1999) we know that this assumption is practically correct. Sediment transport measurements were also made at the Agassiz-Rosedale Bridge during the period 1966-1986, and these observations are available to check results.

Another important assumption of the method is that, between two successive surveys, scour or fill are essentially continuous at any one position in the channel; that is, there is no compensating scour and fill (which would be undetected).

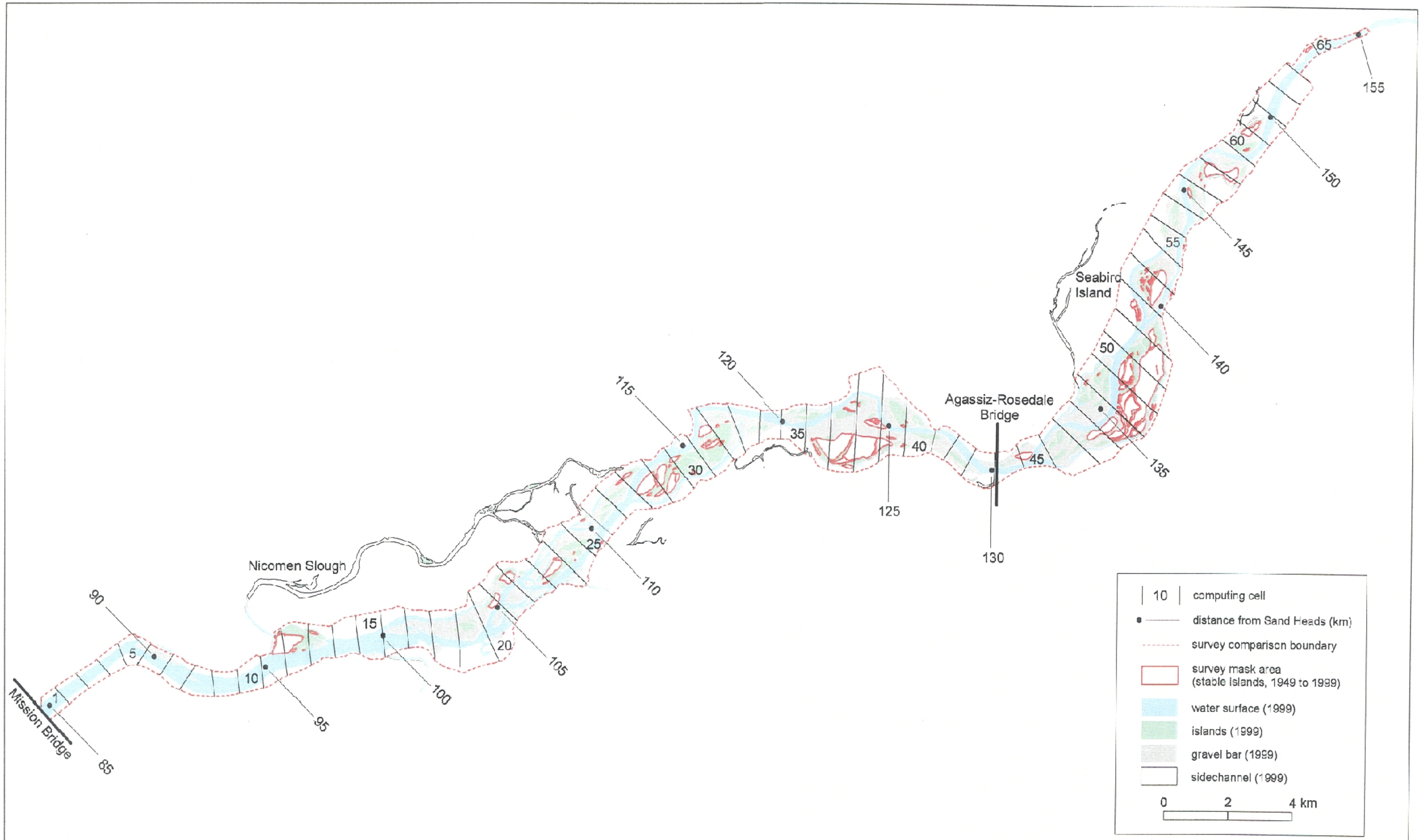


Figure 3: Map of Fraser River showing the computing cells used to determine the sediment budget

Given the relatively modest transport of bed material in Fraser River, in comparison with the size of the river, and the "style" of instability, which consists of persistent lateral movements of the channel over a period of years as the result of bank erosion and bar deposition, this assumption appears to be reasonably fulfilled, at least for a number of years. However, our surveys are separated by many years, so it is necessary to investigate this assumption. Our tests are detailed below. General tests of the method of survey comparisons on Fraser River are reported by McLean and Church (1999) and a detailed description of the survey comparisons is given in Appendix 1.

2.1 THE SEDIMENT BUDGET CALCULATIONS

In this section we give a summary description of the sediment budget calculations. A detailed description is given in the Appendix to this report. The method of successive survey comparisons yields information on the transport of bed material along the channel. *Bed material* is the sediment that makes up the bed and lower banks of the river channel -- the material that determines the morphology of the channel. In contrast to bed material, *wash material* is sediment that passes through a reach suspended in the water and is not deposited on the bed and lower banks. Such material may, however, be deposited in quiet backwaters, where it is no longer retained in suspension, and overbank during floods on channel islands and on the floodplain within the dykes. Figure 4 shows the division between bed and overbank material exposed in a river bank. In Fraser River, overbank material is medium sand and finer material. We consider only the portion of this material of size similar to that of bed material, that is, material coarser than 0.177 mm. We have determined from sampling that this is about 30% of the overbank material.

Figure 4. Photograph to illustrate bed material and overbank material.

Sand moving on or near the bed of Fraser River may be deposited with bed material in the interstices of gravel, or it may form pure sand deposits on the tops and in the lee of bars. Once vegetation becomes established on high bar tops, sand accumulates rapidly there and forms a new island. We have kept track of these developments in our sediment budget and we treat island sands as overbank material.

The sediment budget calculations are given in summary form in Table 1 and detailed breakdowns for the 65 computing cells between Mission bridge and Laidlaw (Figure 3) are given in table A3. Since the 1984 survey did not extend beyond the Agassiz-Rosedale Bridge, we can not subdivide the total period for this upper reach. Subperiod budget calculations are given for the Mission-Agassiz reach (cells 1-43) in tables A1 and A2 and the sum for the two periods is in table A4.

The sediment budget calculations include estimates for both gravel and for medium to coarse sand (i.e., sand > 0.177 mm that forms part of the bed material). This introduces a significant computational problem. Gravel transport into the reach is on the order of 350 000 tonnes/yr, whereas the transport of medium and coarse sand through the reach is on the order of 3 000 000 tonnes/yr. A modest error in the sand budget might overwhelm the gravel budget. The following paragraphs detail the computations that underlie our current sediment budget calculations.

Net change in sediment deposited in the channel zone is calculated directly from the survey comparisons. The division between sand (meaning medium and coarse sand) and gravel is based on an estimate of the proportion of the deposit that is sand. This result was previously estimated as a summary figure from a review of sediment texture analyses along the channel. We have now examined the sand fraction in all available bed material samples and determined the trend in sand fraction along the channel (Figure 5). The data upon which the relation is based consist of gravel samples taken and analyzed in 1983 by D.G. McLean (reported in McLean, 1990), and samples taken in 2000 and analyzed by our group. McLean's samples consisted of bulk samples shoveled from individual sites on bar heads or bar flanks along the river between Laidlaw and Matsqui Bend. Our samples each consist of portions gathered from nine sites on a bar and pooled for analysis. Separate sample collections were made for the upper, middle and lower one-third of each bar (Figure 6), so there are three data for each sampled bar. We compared separate sand fraction analyses for upper, middle and lower bars and found no systematic difference. We also compared separate analyses for the 1983 and 2000 samples, and found no significant difference. Hence, we made a single estimate of the trend using all data. The trend has guided our estimate of a 30% sand fraction along most of the reach. This is actually higher than the trend indicates because coversand deposits on bar tops -- typically of order 30 cm to 1 m in thickness -- are not well sampled. Near the downstream end of the reach, where we do not have extensive samples, we have adopted McLean's original estimates, based on channel bed samples. The sand fraction adopted for each cell is reported in tables A1 through A4.

We made separate analyses for the channel proper and for changes in island and bank areas during the inter-survey periods. This is because the upper part of islands and banks consists of finer sands. We have excluded these finer deposits ("overbank sediments") from the sediment budget by estimating the overbank thickness from profiles of old floodplain surface, old bartop surface, and recently established vegetated surfaces (see Figure 7).

Table 1. Summary of sediment budget calculations

Period	Net change in channel			Net change islands/banks			Mining			Total deposition in the reach		
(units of account)	gravel	sand	total	gravel	sand	total	gravel	sand	total	gravel	sand	total
Agassiz-Mission												
1952-1984 (10^6 m^3)	4.717	2.390	7.107	-0.531	-3.407	-3.938	1.364	0.585	1.950	5.550	-0.431	5.119
annual (10^3 t a^{-1})	258.0	130.7	388.7	-29.0	-186.3	-215.4	74.6	32.0	106.6	303.5	-23.6	279.9
1984-1999 (10^6 m^3)	2.678	0.651	3.329	-0.334	-0.245	-0.579	0.936	0.416	1.352	3.279	0.823	4.102
annual (10^3 t a^{-1})	312.4	76.0	388.4	-39.0	-28.6	-67.6	109.2	48.5	157.7	382.6	96.0	478.6
1952-1999 by summation												
(10^6 m^3)	7.395	3.041	10.436	-0.866	-3.652	-4.577	2.300	1.002	3.302	8.829	0.392	9.221
annual (10^3 t a^{-1})	275.3	113.2	388.6	-32.2	-136.0	-168.2	85.6	37.3	122.9	328.7	14.6	343.3
1952-1999 by direct survey difference												
(10^6 m^3)	*1.899*	*1.254*	*3.154*	*2.612*	*-1.155*	*1.457*	*2.300*	*1.002*	*3.302*	*6.811*	*1.101*	*7.912*
annual (10^3 t a^{-1})	*70.7*	*46.7*	*117.4*	*97.2*	*-43.0*	*54.3*	*85.6*	*37.3*	*122.9*	*253.6*	*41.0*	*294.6*
Laidlaw-Mission (by direct survey difference)												
1952-1999 (10^6 m^3)	-1.446	-0.180	-1.626	3.955	-0.978	2.977	2.825	1.227	4.053	5.334	0.070	5.404
annual (10^3 t a^{-1})	-53.8	-6.7	-60.5	147.3	-36.4	110.8	105.2	45.7	150.9	198.6	2.6	201.2

Notes: All volumes are bulk volumes (not mineral volumes). Mined quantities from Weatherly and Church (1999). See text for further discussion.

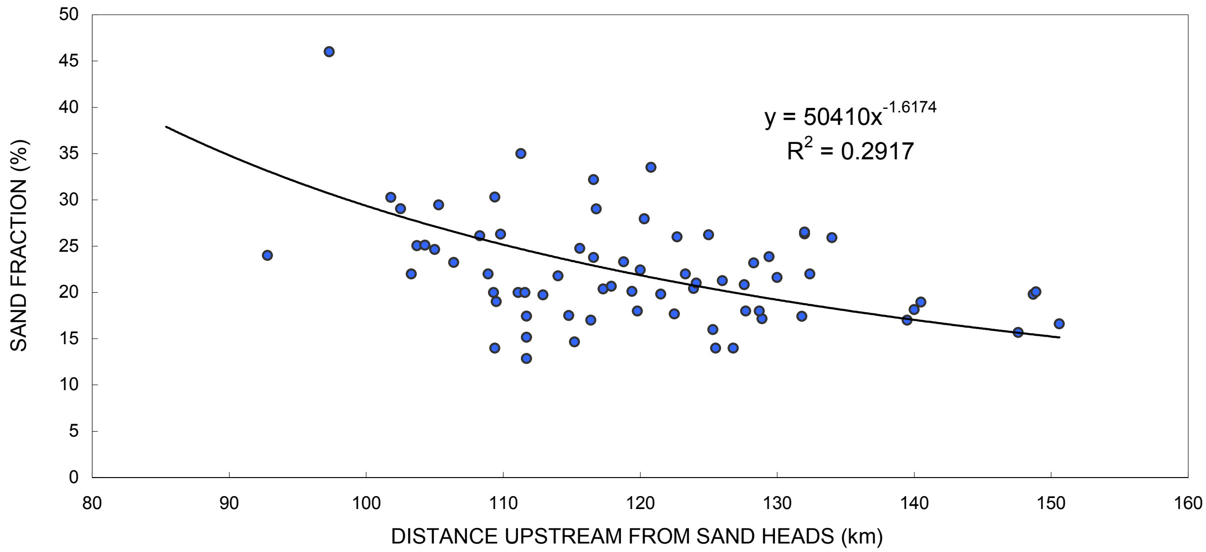


Figure 5. Variation of the sand fraction in Fraser River bed material in the gravel bed reach, based on 1983 and 2000 samples

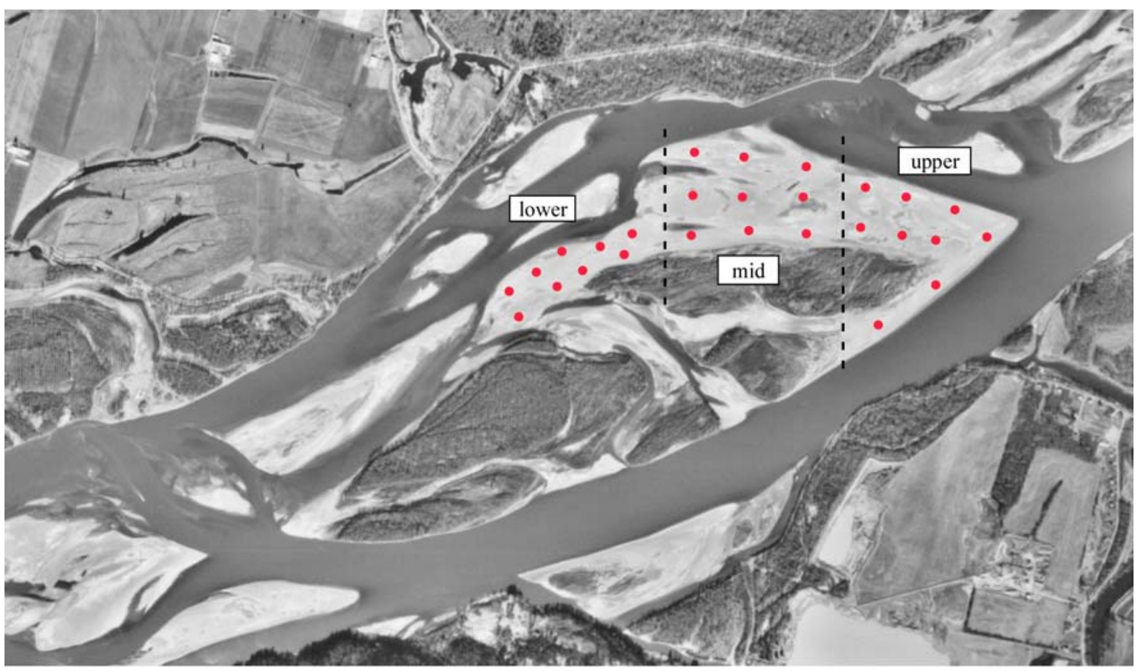


Figure 6. Sampling scheme over a single bar for the determination of bed material texture. Each spot represents the location where a sample of bed material (about 20 kg) was recovered. The nine samples in each sector of the bar were combined to constitute one sample representing the area. Typically, there were three analyzed samples per bar. The illustration is Wellington Bar.

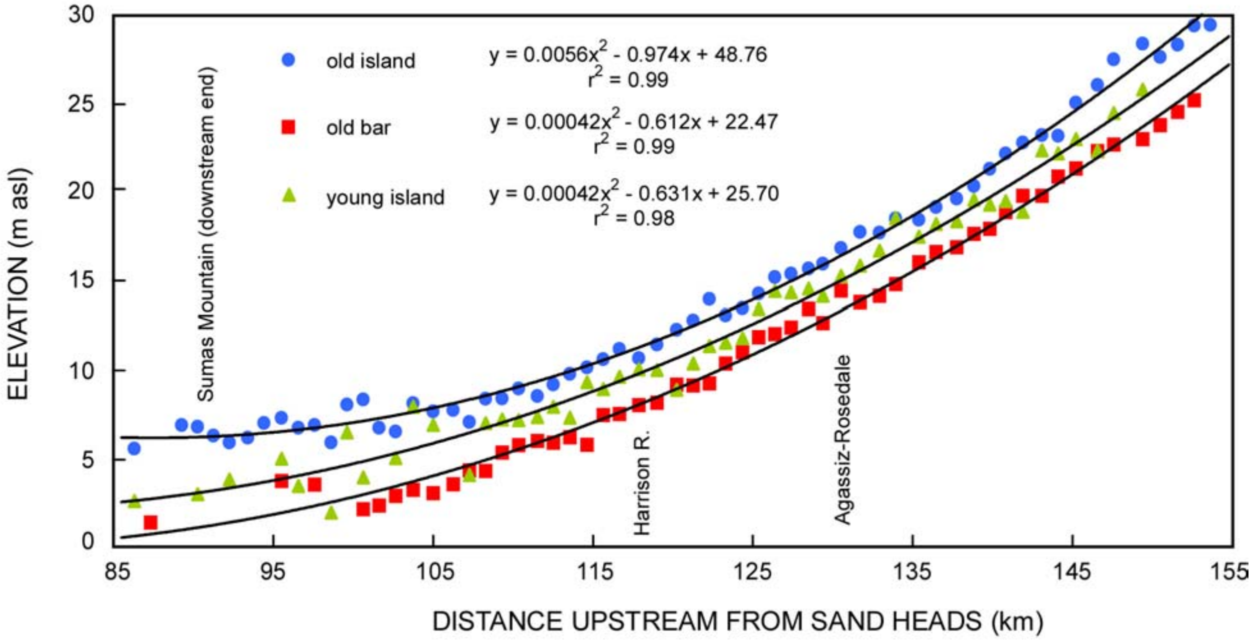


Figure 7. Variation in sand member thickness along Fraser River gravel bed reach (constructed from survey elevations on old floodplain surfaces and recently vegetated bar tops).

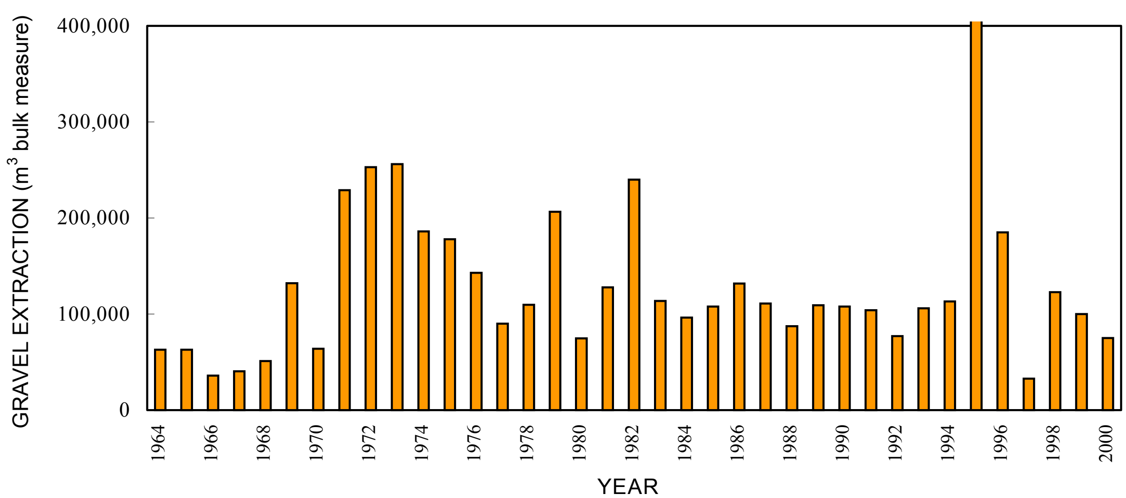


Figure 8. Historical variation in volume of gravel mined between Hope and Sumas (1964-2000).

On the basis of the profiles, we estimated 3 m for old surfaces and 0.84 m for recently constructed flood surfaces. This latter figure is one-half of the top level thickness of recent deposits, since recent deposits will be found in various stages of construction at the time of the survey. We estimate 30% of the sand in these deposits is >0.177 mm. Material eroded or deposited below the specified overbank thicknesses are assumed to be gravel bar material with the composition of channel gravels.

The record of material mined from the channel was determined by Weatherly and Church (1999) for the period 1964-1998 and is given in updated form as Figure 8. The records are known to be incomplete for the period prior to 1974 (when the industry became regulated) and no systematic data are available prior to 1964. Amounts removed in the early period were probably small. However, during 1949-1952, immediately before the first survey in our set, significant volumes of river gravel were used to repair and upgrade dykes following the 1948 flood. The incomplete records introduce a negative bias into our sediment budget estimates. The magnitude of this bias is unknown but probably is small. The totals are divided between sand and gravel on the basis of a constant 30% sand fraction, which is consistent with operators' reports and with our assumption about the constitution of channel and bar gravels. The results are added to the estimates of deposition in each cell from which material was mined. It is supposed that the material would have remained there if it had not been removed.

To convert sediment bulk volumes to sediment weights, a bulk density of 1750 kg m^{-3} is adopted, based on a small number of measurements conducted on Fraser River sediments that yielded the result 1770 ± 110 kg m^{-3} (n =6; 2 standard deviation range).

The sediment budget calculations present a remarkable aspect. The annual apparent gravel deposition in the reach declines systematically as the observing period (the time between successive surveys) becomes longer. This outcome occurs despite the fact that the shorter observing periods (15 and 32 years) are subperiods of the longest period available (47 years). In this comparison, reference is made to the 47 year period calculated directly from the 1952 and 1999 surveys. The outcome could only arise as the consequence of some systematic, time-dependent bias in the data. We take up this consideration in the next section.

2.2 ERRORS IN THE SEDIMENT BUDGET

The sediment budget calculations detailed above are subject to a number of errors. The surveys are subject to measurement errors and the analysis of the data may introduce further errors due to interpolation between measurement points and errors introduced by imperfect GIS models. Errors may also occur if any of the assumptions inherent in the approach are violated. The first two sources of error should limit the precision of the results, but should not introduce systematic biases. However, the last two sources (GIS model error and violation of assumptions) may bias the results. We first consider precision, and then turn to questions of bias.

McLean and Church (1999: see also McLean, 1990) studied the errors introduced by the sonar surveys and by DEM interpolations of surfaces amongst the survey points. Test computations were made in several 1000 m (long) x 500 m (wide) reaches along the river using various interpolated data grids. They found that no further gain in precision occurred after the grid was reduced to 40 m x 20 m, representing an 800 m^2 area of the bed. This is actually denser than the primary sounding density in 1952 (approximately 1 point in 2000 m^2). In the present study, the 1999 survey was deliberately thinned to be similar to the 1952 survey density. However, the

1984 survey covered a more restricted area than the other two surveys and additional points were added by photogrammetry for the present analyses. Grid densities for DEM comparisons in this study were 25 x 25 m.

We found that rms errors in elevations interpolated by the ARCINFO DEM typically averaged ±0.96 m in the 25 x 25 m spaced test grids over the three surveys, and varied between ±0.66 m (1984) and ±1.12 m (1952) in the individual surveys. These results seem to be very high. They arise because the actually surveyed points remain densely distributed along separate survey lines so that DEM models actually interpolate bed elevations within a generally sparse but locally dense set of surveyed points. The surveyed points exhibit real local depth variation, not all of which can be accommodated by the model. An estimate of the precision of elevation changes between surveys would, then, be $E_{dif} = (E_1^2 + E_2^2)^{1/2}$, where E_1 and E_2 are the interpolation errors of successive surveys. E_{dif} varies between ±1.22 m (1952-1984) and ±1.56 m (1952-1999). These results would apply to individual pixel comparisons. The rms error of the *mean* bed elevation difference in a specified reach would be $E_{av} = E_{dif}/n^{1/2}$, where n is the number of independently determined points in the comparison. Adjacent points are not independent of each other: both the continuity of topography and the mathematics of the grid interpolation algorithm create spatial dependence (hence duplication of information). Interpolation algorithms typically use arrays of 9 adjacent points to estimate the central point in the model. If we accept this array as representing the limit of spatial correlation, then the number of independent points in a computing reach is n' = n/9. The typical number of cells in a reach is of order 10^3. These data yield rms errors of mean bed elevation change of order ±0.10 m in a computing reach (varying between ±0.11 m for 1952-1984 and ±0.14 m for 1952-1999. These limits apply directly to comparisons of mean bed elevation changes between successive surveys in individual 1-km computing cells. The bed elevation changes are not subject to the further errors discussed below.
The corresponding limits of volumetric precision are typically of order $\pm 10^5$ m^3 because the area of a typical cell is about 10^6 m^2. The pooled error for an entire survey is 575 x 10^3 m^3 for the period 1952-84, 623 x 10^3 m^3 for 1984-99, and 882 x 10^3 m^3 for the direct survey comparison between 1952 and 1999 over the entire Laidlaw-Mission reach. For the sum of period budgets in the Agassiz-Mission reach it is 848 x 10^3 m^3. These numbers are of order 10% of a typical sediment budget term and apply strictly to the gross budget (that is, we have no error measure for the gravel removed from the channel).

We are able to make a further empirical test of our results. Within our computing cells there is a limited area of floodplain that is known to have been stable throughout the period 1952-1999. Data for these areas were derived by different methods for each survey. The 1952 contour maps were interpolated. Photogrammetric elevations were established in 1984. The 1999 survey included laser altimetry of the floodplain, yielding a dense network of points. Again, the 1952 survey essentially limits the data resolution. Distributions of estimated differences in elevation on the floodplain are shown in Figure 9 for the three intersurvey periods.

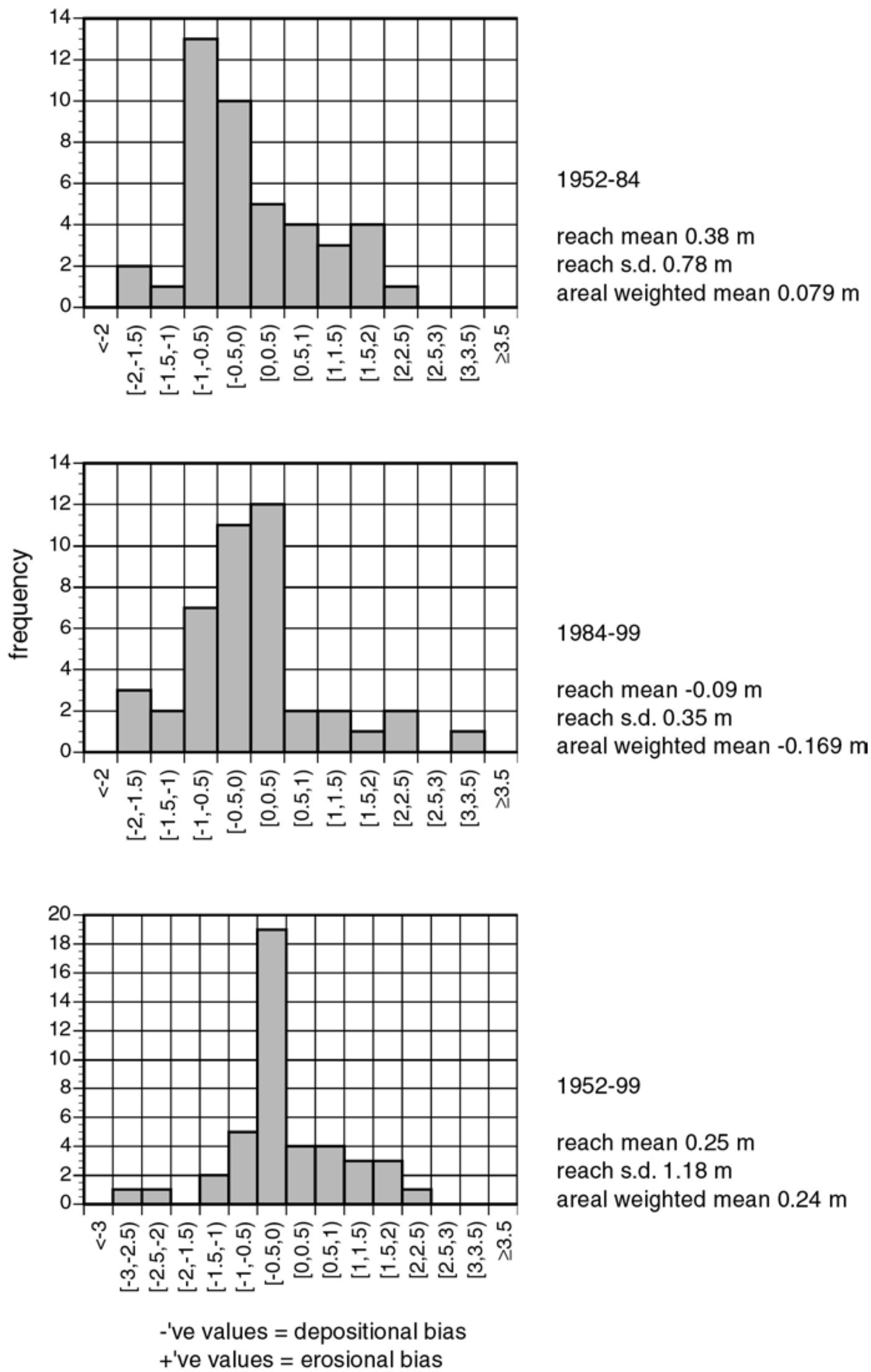


Figure 9. Histograms of intersurvey apparent changes in elevation on “stable” overbank surfaces.

Raw differences (equivalent to the E_{dif} values discussed above) are of order 10 to 40 cm, but the area-weighted summary effect is of order 10 cm. The largest mean weighted difference is +24 cm between 1952 and 1999. The construction of the data makes this apparent erosion. Over 47 years, there may easily have been as much as 20 cm of apparent settling on these heavily occupied, former flood surfaces, so the result appears to be not at all unusual. Of course, real changes may have occurred at some sites, as well. These numbers are much smaller than the estimated errors of sonar comparisons and may be expected to hold over exposed surfaces, such as bars and islands (where, however, vegetation may impair elevation estimates). The implication is that the volumetric precision is probably better than estimated in the last paragraph.

To estimate grid points from original data, GIS programs employ modelled surfaces fit to the data. In data-sparse areas toward the edge of the model, the surface fits can become quite biased. Successive estimates of volumetric changes in ARCVIEW showed that this is a problem in the river data. We overcame this problem in the river (between cross-sections spaced at up to 250 m) by hand adjustments of contours, and we avoided the problem toward the edge of the data field by restricting the final computing area as close to the active channel zone as possible; that is, well within the limits of the data field. However, we have no quantitative estimate of whether model bias was entirely avoided.

The major assumption of the sediment budget method from successive surveys is that there is no compensating scour and fill between surveys. The size of Fraser River means that channel changes occur relatively slowly, and trends of scour or fill at individual sites tend to persist for some years. Nonetheless, the longer is the period between successive surveys, the more likely it is that compensating scour and fill will occur. When it does occur, the successive surveys do not detect the full change and the sediment budget is, accordingly, underestimated. Even for Fraser River, 47 years is a long time between surveys and several lines of evidence suggest that, within this period, compensating scour and fill have occurred. Most straightforwardly, channel maps for dates close to the survey dates reveal serial erosion and refilling of some sites within the period. More specifically, our sediment budget calculations enabled us to code individual computing units (pixels) according to transitions from survey to survey. Specific transitions imply either fill (aggradation) or scour (degradation) as follows:

channel → bar surface:	fill
channel → island or floodplain surface:	fill
bar surface → island or floodplain surface:	fill
bar surface → channel:	*scour*
island or floodplain surface → bar surface:	*scour*
island or floodplain surface → channel:	*scour*

Any sequence of three states (over three surveys) indicating persistent scour, or fill, or no change should yield unbiased results for total change in sediment storage. But any sequence in which scour and fill succeed each other will indicate the presence of bias in the estimate of change over the entire period. One expects that, as the intersurvey period becomes longer, the incidence of such problematic changes will increase. We examined the occurrence of such sequences in our data. Within the period 1952-1999, 23.2% of the 90,700 individual DEM pixels in the Agassiz-Mission reach exhibited problematic sequences of transition. Of these, 89% exhibited the transition sequence island or bar → water → bar, indicating erosion in the period to 1984, followed by deposition at the same site.

The effect of compensating scour and fill is to introduce a negative bias into estimates of the sediment budget. The bias increases in proportion as the total volume of compensating scour and fill increases. The outcome is evident in Figure 10, which plots the sediment budget in the form of estimates of mean annual sediment influx (that is, the total budget divided by the number of years in the observing period), against the length of the intersurvey period. This shows a systematic decline -- which we interpret as increasing negative bias -- with increasing length of the intersurvey period. A means to obtain an estimate of the true mean annual sediment budget is to extrapolate the results back to a time interval within which little bias (i.e., little compensating scour and fill) is expected to occur. We do not know what that time is, but it probably is less than 10 years and possibly less than 5 years. This range of periods gives, for the gravel budget, estimates between 400 000 tonnes/yr and 420 000 tonnes/yr. If we adopt the adjustment equation directly, the average annual gravel influx is 440 000 tonnes. The bias appears to increase at about 0.9% per year between surveys. Sands do not show such consistent behavior, since much of the sand deposition is associated with the development and disappearance of the bartop and overbank deposits.

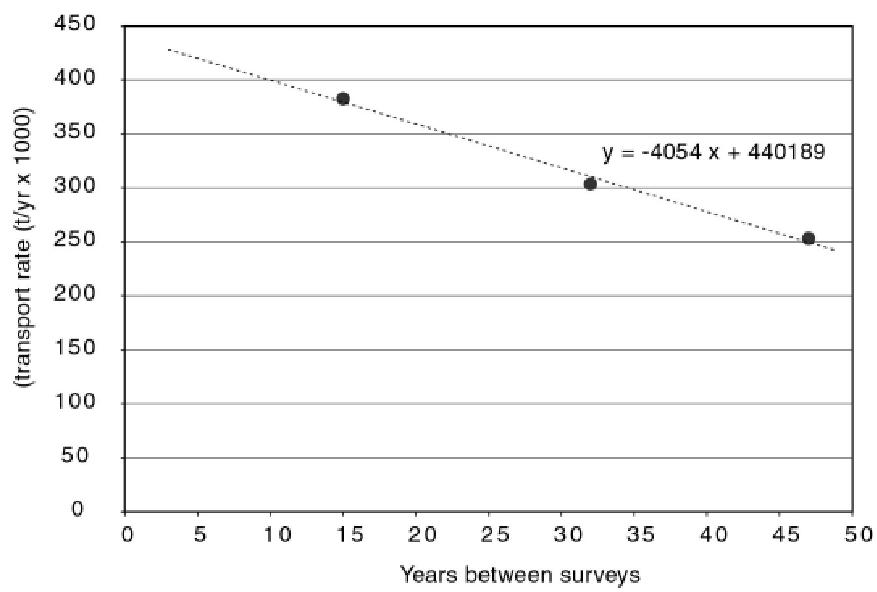


Figure 10. Net apparent influx of gravel as a function of intersurvey period for the reach between Agassiz and Mission.

There remains an additional complication in this analysis. Since virtually all of the gravel that enters the study reach remains within it (or is borrowed from it), it ought to be found regardless of whether it has been displaced within the reach between surveys. That is, there should not be a gravel bias, the cut and fill problem notwithstanding. (In contrast, sand leaves the reach and so may genuinely go missing.) It is possible -- indeed, probable, that gravel is displacing sand at some sites, particularly toward the lower end of the reach. That phenomenon would result in a negative bias of the gravel estimates, and the bias may be complicated since our estimates of the gravel fraction would then become involved. We cannot, at present, resolve this matter, and we are left with the appearance that the gravel estimates do become biased over time.

2.3 THE WSC PROGRAM OF SEDIMENT TRANSPORT MEASUREMENTS

For a period of 20 years between 1967 and 1986, the Water Survey of Canada conducted bedload transport measurements at the Agassiz gauge, immediately downstream from the Agassiz-Rosedale Bridge. The data of this measurement program constitute information upon which to base an estimate of annual recruitment of bed material independent of the sediment budget. Hence, to the extent that the sediment transport estimates are reliable, they permit a check on sediment budget estimates. At Agassiz, it is assumed that gravel moves on the bed and all sand moves in suspension. Hence bedload is assumed to represent the gravel influx.

The Agassiz measurements have been analyzed by McLean et al. (1999). Briefly, a rating curve was constructed by plotting the available measurements against the discharge at which the measurement was taken. The data, reproduced in Figure 11, exhibit great scatter about the rating curve. There are three plausible sources for the scatter:

1. Relatively few actual bedload samples were taken in each measurement -- typically two or three samples in each of 5 or 6 verticals across the channel. On the other hand, bedload movement is known to be highly variable, both temporally and spatially, so substantial sampling variance is possible (McLean and Tassone, 1987, analyzed the measurements in this light);

2. The bedload samplers used in Fraser River are subject to catch biases (as are all such samplers). Corrections have been made to the observed sampler catches based on calibration tests conducted for the various samplers. The calibrations and corrections are discussed in McLean et al (1999). Nevertheless, these manipulations remain a potential source of error. A recent analysis by Sterling and Church (in review) suggests that catches in samplers similar to those used in Fraser River typically are negatively biased in the gravel range.

3. Bedload transport remains relatively low at all discharges in Fraser River. At low rates, the transport remains highly variable, being controlled as much by available supply as by the theoretical hydraulic capacity of the flow to transport material. Again, high sampling variance is the expected result.

To estimate annual bedload transport, McLean et al. (1999) estimated the expected load from the regression for 1000 m^3s^{-1} steps in discharge. Using the flow duration curve, the fraction of the load falling within each flow class was determined. The pooled weighted error was also determined for an annual transport estimate, and indicated that the load is specified to within ±40%. Further details of these calculations are given in McLean and Church (1986).

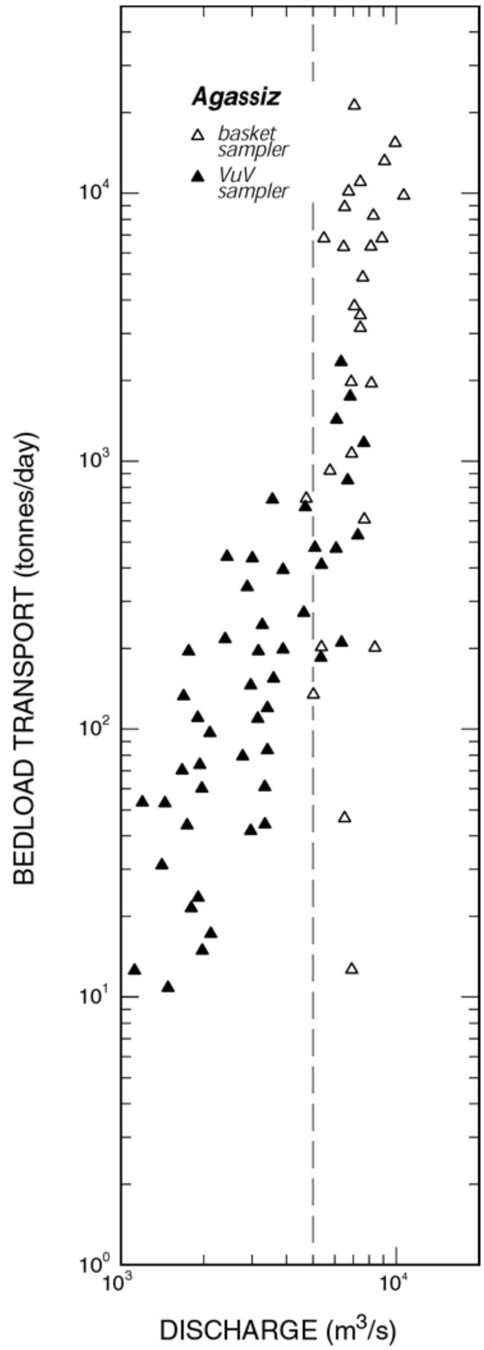


Figure 11. The rating curve for gravel transport at the Agassiz-Rosedale Bridge, derived from measurements made by the Water Survey of Canada between 1967 and 1986.

To estimate the annual influx of gravel to lower Fraser River, a more direct calculation is to regress the estimated annual loads against a relevant flow index. Possible flow indices include annual water volume (equivalent, from an information perspective, to mean annual flow); volume exceeding 5000 m^3s^{-1}, and annual maximum daily flow. Since the transport is highly nonlinear (increasing at more than the 5th power of flow according to the rating curve), the maximum flow -- which achieves most of the transport -- appears to be the most relevant criterion of the three. Accordingly, estimated annual gravel loads at Agassiz (McLean et al., 1999; table 4) were regressed against annual maximum daily flow for all years (1967-1986) for which estimates of the transport exist. The result is

$$G_a = 2.231\text{x}10^{-19} Q_{max}^{6.037}$$

(r^2 = 0.873), wherein G_a is the annual gravel influx in tonnes and Q_{max} is the annual maximum daily flow, in m^3s^{-1}, measured at Hope. The standard error of estimate of this relation translates into a 95% range in probability (confidence interval) of between 0.43 and 2.3x the nominal result, which is larger than the estimated 40% variance range of an individual annual estimate. Hence, real variability in the year-to-year sediment delivery for a given peak flow introduces moderate additional variability. At the nominal threshold for gravel transport of 5000 m^3s^{-1}, the equation predicts 4600 tonnes. The analysis of variance is given in Table 2 (showing the relation to be highly significant) and the equation is illustrated in Figure 12. The residuals from regression are shown in Figure 12 (inset): they show no structure at all, so the selected equation certainly is appropriate.

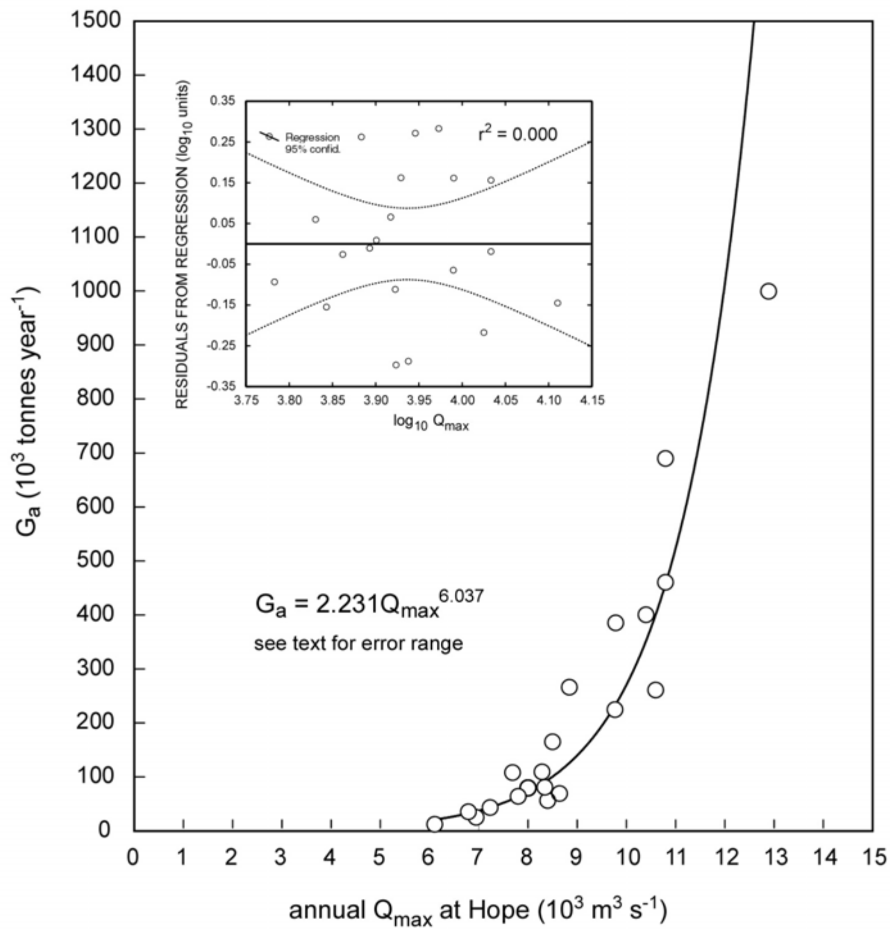


Figure 12. Rating curve for annual gravel load at the Agassiz-Rosedale Bridge based on WSC measurements; (inset) the correlation between residuals from the rating curve and Q_{max}, expressed in the logarithmic units of the original regression calculation.

Table 2. Analysis of variance for the regression of annual gravel influx to lower Fraser River

	Sum of squares	df	Mean square	F	p
Regression	4.307	1	4.367	131.7	$< 10^{-6}$
Residual	4.964	18	0.033		

Figure 13 displays estimated or observed annual bedload (assumed equal to gravel load) influx at Agassiz for the entire period 1952 through 1999. The running sum of the annual influx indicates a cumulative addition to the reach of 4 334 000 m^3 in the period 1952-1984, and 6 002 000 m^3 during 1952-1999. These figures are subject to errors, which arise from the error range of the individual annual estimates from regression. Over the 47 year period, the pooled error estimate is $+1.765 \times 10^6 m^3$ or $-0.774 \times 10^6 m^3$.

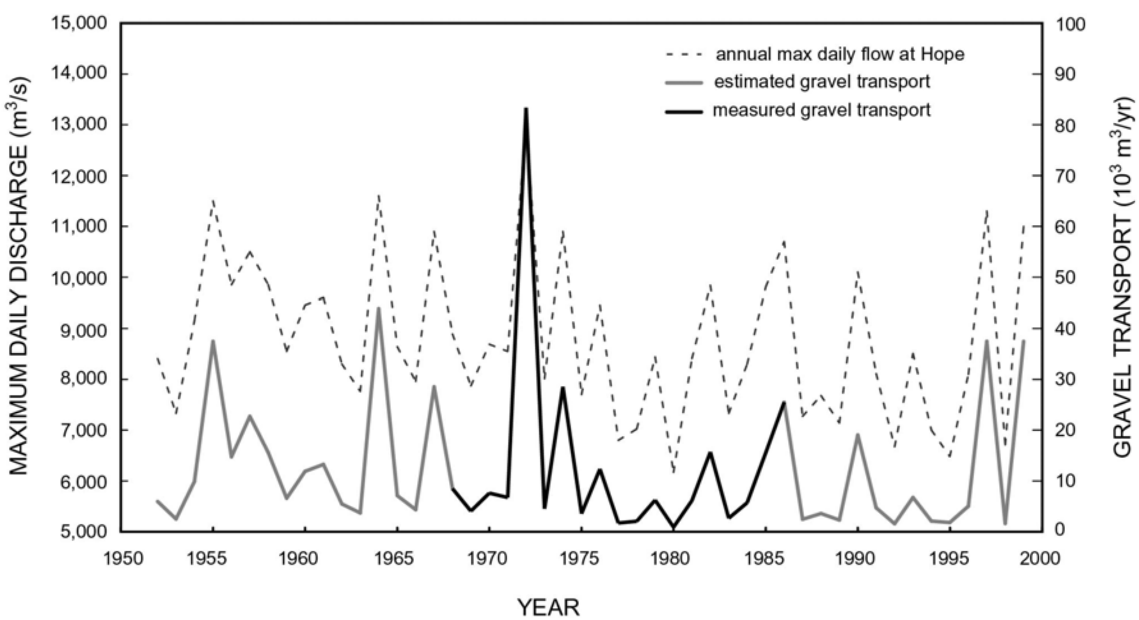


Figure 13. Temporal variability of gravel transport: the record of WSC observations at Agassiz (data from McLean et al., 1999; table 4) and computed results for years with no observations.

2.4 APPRAISAL OF THE SEDIMENT BUDGET

To appraise the results reported above, it is necessary to recall that there are reasons to suppose that both the sediment budget as determined from surveys and the influx estimates from the sediment transport equation might be negatively biased. In the case of the transport estimates this circumstance arises from the possibility that the sediment trap might undersample the load carried by the river. Estimates of the sediment budget derived from the sediment transport calculations (which are considered to include gravel only) are compared in Table 3 with the gravel budget observed and estimated from survey. The sediment budget indicates larger totals than the integration of sediment transport estimates. Within error bounds, the period 1952-1984 is self-consistent, but the 1984-99 period and the 47 year totals from the sediment budget have error bounds that just fail to overlap. The lowest error bound of the bias-corrected gravel budget estimates also just fails to meet the upper bound of the raw (sum of periods) sediment budget estimate. The bias-corrected estimate from the sediment budget, up to 11 200 000 m^3 in 47 years, or 420 000 tonnes a^{-1} influx of gravel, must be regarded at present as a maximum estimate.

Table 3. Comparison between sediment budget and sediment transport estimates: gravel influx at Agassiz (10^3 m^3 bulk measure)[1]

	1952-1984	**1984-1999**	**1952-1999**
Sediment budget			
by survey	5 550	3 279	8 829[2]
upper bound[3]	6 084	3 777	9 641
lower bound[3]	5 016	2 781	8 016
bias-corrected estimate[4]			10 740 – 11 280[3]
upper bound[3]			11 620 – 12 160
lower bound[3]			9 860 – 10 400
Sediment transport	4 334	1 668	6 002
upper bound[5]	5 885	2 510	7 767
lower bound[5]	3 654	1 299	5 228

1 The corresponding table for total bed material influx (i.e., including sand) is Table A 5.

2 sum of constituent periods

3 Based on the sediment budget precision analysis adjusted to the gravel fraction. See text, p.14.

4 Based on the range 400 000 to 420 000 tonnes/yr. See text, p.17. The error range is estimated by adopting the sediment budget precision error for the full period.

5 Error bound obtained by pooling individual annual error estimates for all years in the sum. The annual estimates are derived from the 95% confidence band for regression estimates.

One further circumstance of the gravel budget points toward this total. In the lowermost portion of the reach (cells 1-17), the 47-year summed budget indicates a *deficit* of -2.434 x $10^6 m^3$ of gravel; that is net erosion of gravel of about 50 000 $m^3 a^{-1}$ but there is nowhere for this gravel to have gone, the downstream limit of gravel occurring within this reach. If this deficit is false, it would add about 2 million cubic metres to the gravel budget; that is, just about the difference between the raw and bias corrected estimates. It is possible that most of the bias arises from budget problems in these cells.

Why should there be problems at the lower end of the reach? In this reach there are no islands and few emergent bars, so we know relatively little about the gravel/sand fraction of the sediments here. There is the distinct possibility that the sand/gravel fractions have been misassigned (the sand budget in the reach is modestly positive at 0.688 x $10^6 m^3$). Furthermore, this is the reach in which substitution of gravel for sand is most likely to occur, which might directly give rise to bias.

However, given the drift of the gravel budget estimates outside the error range of the sediment transport estimates in the 1984-1999 period, it must also be regarded as a possibility that the overall survey results for the latter period have estimated too much gravel and too little sand. Inasmuch as most floods in this period were modest, this is a distinct possibility. Hence, the most prudent estimates of the long-term gravel budget at present appear to lie near or somewhat above 8 x 10^6 m^3 influx over 47 years; that is an influx of about 300 000 tonnes a^{-1}. There is very little likelihood that figures below the actual sediment transport estimate of 6 000 000 m^3 in 47 years, or 225 000 tonnes a^{-1}, are credible. This figure should be regarded as a lower bound of credible estimates.

Our best estimate of the annual gravel recruitment to lower Fraser River downstream from the Agassiz-Rosedale Bridge at present falls in the range between 300 000 tonnes a^{-1} (170 000 m^3a^{-1}) and 400 000 tonnes a^{-1} (230 000 m^3a^{-1}). For sand deposited in the reach, our best estimate is about 15 000 tonnes a^{-1}, but this includes a substantial net loss of sand from island and floodplain sites. The observed deposition of sand in the channel is 113 000 tonnes a^{-1}, based on the sum of periods budget. But, over a long period, the estimate derived from the sand fraction of gravel deposits -- estimated to be 30% -- probably furnishes the best estimate of net sand recruitment to the channel bed. In comparison with the figures for gravel given above, the estimates probably fall between 130 000 tonnes a^{-1} and 170 000 tonnes a^{-1}, slightly higher than the observed amount. These amounts could not be detected from the sand budget based on Agassiz and Mission transport measurements. The preferred range of gravel estimates bracket the best long term estimate from the sediment budget, but the sand estimates are higher than that derived directly from the sediment budget. (It should also be recalled that some uncertainty still attends the division between sand and gravel in the deposits of the reach.)

The sediment budget for the Laidlaw-Agassiz reach can be assessed only by direct survey difference between 1952 and 1999, yielding estimates that we expect to be biased. Table 1 gives those estimates. If we suppose that the bias of the gravel budget has increased at 0.9% per annum, then the mean annual influx at Laidlaw would be about 300 000 tonnes a^{-1}. This produces a gravel deficit between Laidlaw and Agassiz of 50 000 tonnes a^{-1} (adopting 350 000 tonnes a^{-1} – the middle of the preferred range of estimates at Agassiz), or -2.350 x 10^6 tonnes over 47 years. This is -1.345 x 10^6 m^3, which is close to the estimate from survey of -1.477 x 10^6m^3 for the reach. The sand budget in the reach determined from survey is -1.031 x 10^6m^3 (-38 380 tonnes a^{-1}), which is about 45% of the total sediment loss, hence a credible figure, considering the sum of channel sands and overbank sands. These numbers imply that the bias created by compensating scour/fill is not large within this reach. That appearance is consistent with persistent degradation, when there is a reduced probability for compensating deposition to occur. Nonetheless, it is clear from the sedimentology of the bars and from the survey that depositional sites do occur within the reach. It appears that the gravel influx to the study reach from upstream is about 300 000 tonnes a^{-1}.

2.5 WHY DO SUCCESSIVE ESTIMATES OF THE SEDIMENT BUDGET VARY?

During the period of our study, we have steadily refined the budget. Successive budget estimates are summarized in Table 4. Our initial sediment budget was based on the 1952-1984 data for the Mission-Agassiz reach and is identical to the budget reported by McLean and Church (1999). That budget focused on gravel and excluded sand by making an assumption about the fraction of sand contained in the bed material of the river. The assumption was based on sediment samples taken at many places along the river. We later realized that it is not practical to exclude the medium and coarse sand that forms a part of the bed on bar tops and bar tails. Hence, our

September 2000, budget estimates (Church et al., 2000) include an estimate of sand deposits in the channel only. The most recent estimates attempt to incorporate the bed material size sands included in the overbank sand member of the sediment deposits.

Table 4 shows that, apart from the aberrant March, 2000 estimates, the estimates of the gravel budget in the Agassiz-Mission reach for the 1952-1984 period have varied within a range of less than ±25% about the current estimate. However, the 1984-1999 estimates in this reach have varied widely. Inspection of all the figures for this period and reach reveals that this outcome is due to changes in the apparent sand budget, the consequence of decisions about the area included in the budget and the means to estimate the sand budget. The sensitivity to the sand budget in the second period reflects the relatively increased importance of erosion/deposition from the channel banks. The 1952-1999 budget then reveals swings of nearly ±50% over the successive budgets.

In comparison, the sand budget exhibits large relative swings, going even from positive to negative -- in part the consequence of changing conventions about how to account for it. These derive from our developing but still imperfect knowledge of the fractions of sand and gravel in the sediment deposits within the reach. However, the absolute changes - again, excepting the March 2000 report – are not large. The net sand budget is, on balance, not far from zero. Sediment transport measurements indicate that there is a loss of sand from the Agassiz-Mission reach. McLean and Church (1986; see also McLean et al., 1999) determined that sand transport past Mission was greater than sand transport past Agassiz in most years during the WSC observing program. Silt and clay, in comparison, are transported in similar quantities past both stations, within the margin of observing precision.

The average annual difference in transport of coarse and medium sand between Mission and Agassiz is apparently about 550 thousand tonnes (McLean et al., 1999). Over 47 years, this would amount to 26 million tonnes evacuated from the reach. All estimates of the sand budget in the reach are starkly at variance with this figure. No plausible adjustment of the sediment budget can explain this discrepancy.

The remaining potential source of bias is the sand transport rating at Agassiz. The conditions in the channel make it very possible that the measurement program there failed to detect a significant amount of sand moving over the bed. The bias would need to be -28%, which is considerably larger than the estimated precision of the measurements, to cover the discrepancy.

Table 4. Successive sediment budget estimates in the gravel-bed reach (10^6 m^3 bulk measure)

Report	Gravel	Sand	Total	Remarks
(a) Agassiz-Mission: 1952-1984				
1999 Progress	4.069			Based on McLean and Church (1999): gravel only
2000 Progress (March)	2.715	-2.945	-0.230	First attempt to incorporate sand: in-channel sand only
2000 Progress (Sept)	4.879	2.051	6.930	Revised survey analysis: survey coverage extended
2001 Draft (March)	5.729	0.300	6.029	Revised computations; sand fraction and overbank volumes revised
This report	5.550	-0.431	5.119	*Revised GIS model; sand fractions further revised*
(b) Agassiz-Mission: 1984-1999				
2000 Progress (March)	2.347	-5.588	-3.241	As above.
2000 Progress (Sept)	6.483	-1.319	5.164	As above.
2001 Draft (March)	7.150	-1.524	5.626	As above.
This report	*3.279*	*0.823*	*4.102*	*As above.*
(c) Agassiz-Mission: 1952-1999				
2000 Progress (March)	4.852	-9.590	-4.738	As above. Results by direct survey difference.
2000 Progress (Sept)	10.996	0.950	11.946	As above. Direct difference.
2001 Draft (March)	12.589	0.192	12.781	As above. Direct difference.
This report	*8.829*	*0.392*	*9.221*	*As above. Sum of periods.*
(d) Laidlaw-Mission: 1952-1999				
2000 Progress (March)	2.763	-10.455	-7.692	As above. Results by direct survey difference.
2000 Progress (Sept)	11.161	1.020	12.181	As above.
2001 Draft (March)	13.566	0.143	13.709	As above.
This report	*5.334*	*0.070*	*5.404*	*As above.*

Nor do the locations of significant sediment accumulation vary between successive sediment budgets. As an indication of this, the pattern of sedimentation as estimated from the March 2001 budget estimates are compared in Figure 14 with the current estimates. The patterns diverge significantly only for the gravel/sand division in computing cells 1-17, probably as the result of the unknown status of the gravel and sand fractions of the total sediment load and sediment deposits in this gravel/sand transition reach, and from assumptions made about the disposition of gravel, as discussed above.

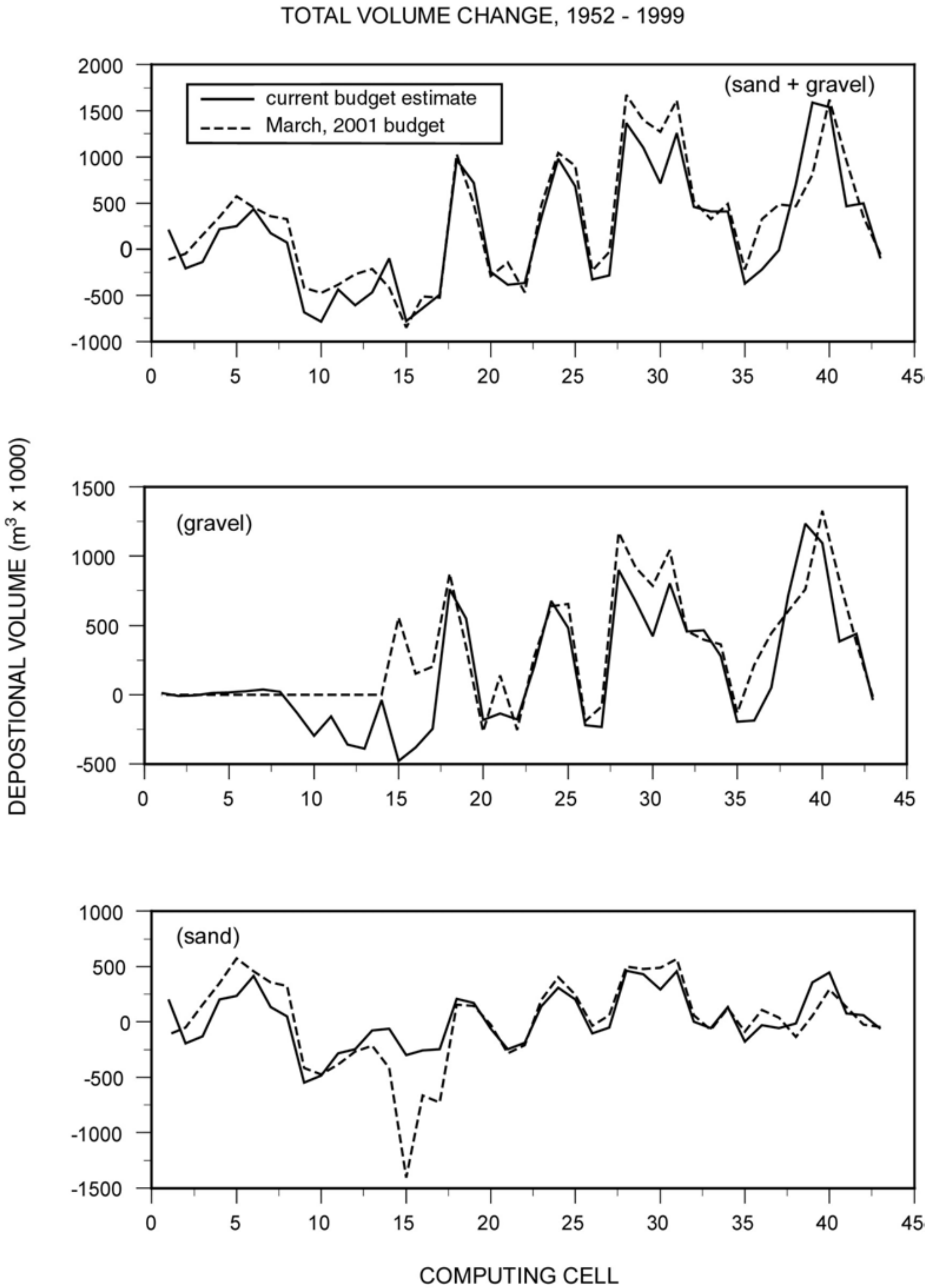


Figure 14. Distributed sediment budgets in two successive determinations: Agassiz-Mission.

It is important to emphasize that the differences amongst our successive estimates of the sediment budget are (except for the March 2000 results, the first exercise using the 1999 survey data) comparable with the probable precision of the estimates in any case. Fluvial sediment transport and sedimentation estimates made by any means are subject to errors of up to 2x (except, perhaps, estimates derived from dense surveys in geometrically simple areas, such as a reservoir bottom). The differences amongst our successive estimates do not change the conclusion of our study: gravel influx to the study reach is modest. Furthermore, the changes in the overall budget have not significantly altered the distribution of aggradation along the channel (see Figure 15).

A significant feature of the bed material budget of Fraser River, not emphasized in the multi-year sediment budgets discussed above, is the high inter-annual variability of sediment influx into the reach. Gravel transport is a highly sensitive function of flow so that, in years with high freshets, sediment influx is much greater than in years with modest flows. This is revealed from record of bedload transport measurements and estimates displayed in Figure 13. This feature is of major significance for the management of gravel accumulation in the river.

2.6 SEDIMENTATION IN THE GRAVEL-BED REACH

Sedimentation and erosion of the channel leads to changes in bed elevation. The straightforward assessment of bed level changes entails obtaining a topographic model of the actual channel bed and floodplain surface for each survey date, registering the two models together, and obtaining the volumetric difference (ΔV) between the two model surfaces. Bed level change is then

$$\Delta h = \Delta V/A$$

where A is the area over which the volume change has been calculated. Computed in this way, values of Δh should average properly (when appropriately area-weighted), and should sum properly over successive inter-survey determinations because no adjustments have been made to the computed volume changes. However, to determine bed level change within the channel only, it is necessary to restrict A to the area of the channel. This introduces an initial complication since bank erosion and deposition mean that the channel area is not precisely the same between the two surveys. In order to obtain results based on the bed material budget, further adjustments must be made. The adjustments are taken up in the detailed description of the procedures to obtain bed level changes given in the Appendix of this report.

Two sets of bed level changes are reported in Table A 6, unadjusted changes, and the changes based on the sediment budget. Inasmuch as the latter figures are restricted to changes within the channel zone associated with the erosion or deposition of bed material (whereas the former include the effects of changes in island and floodplain surfaces as well), the latter figures -- those based on the sediment budget -- are preferred in this report as the basis for estimating changes in channel bed elevation. (The reader is cautioned that, because of the sand budget adjustments entailed in arriving at the bed material budget of the river, these bed elevation changes do not sum between surveys; the unadjusted figures also given in table A6 do sum straightforwardly.) The estimated bed level changes between 1952 and 1999, based on the sediment budget figures, are shown by computing cell in Figure 15. This figure represents the net (actual) estimated bed level changes after gravel removals have been considered and serves to identify areas where significant net accumulation has occurred. Since these figures incorporate sediment budget calculations, they are subject to the possible biases associated with the sediment budget (in comparison, the unadjusted figures are not).

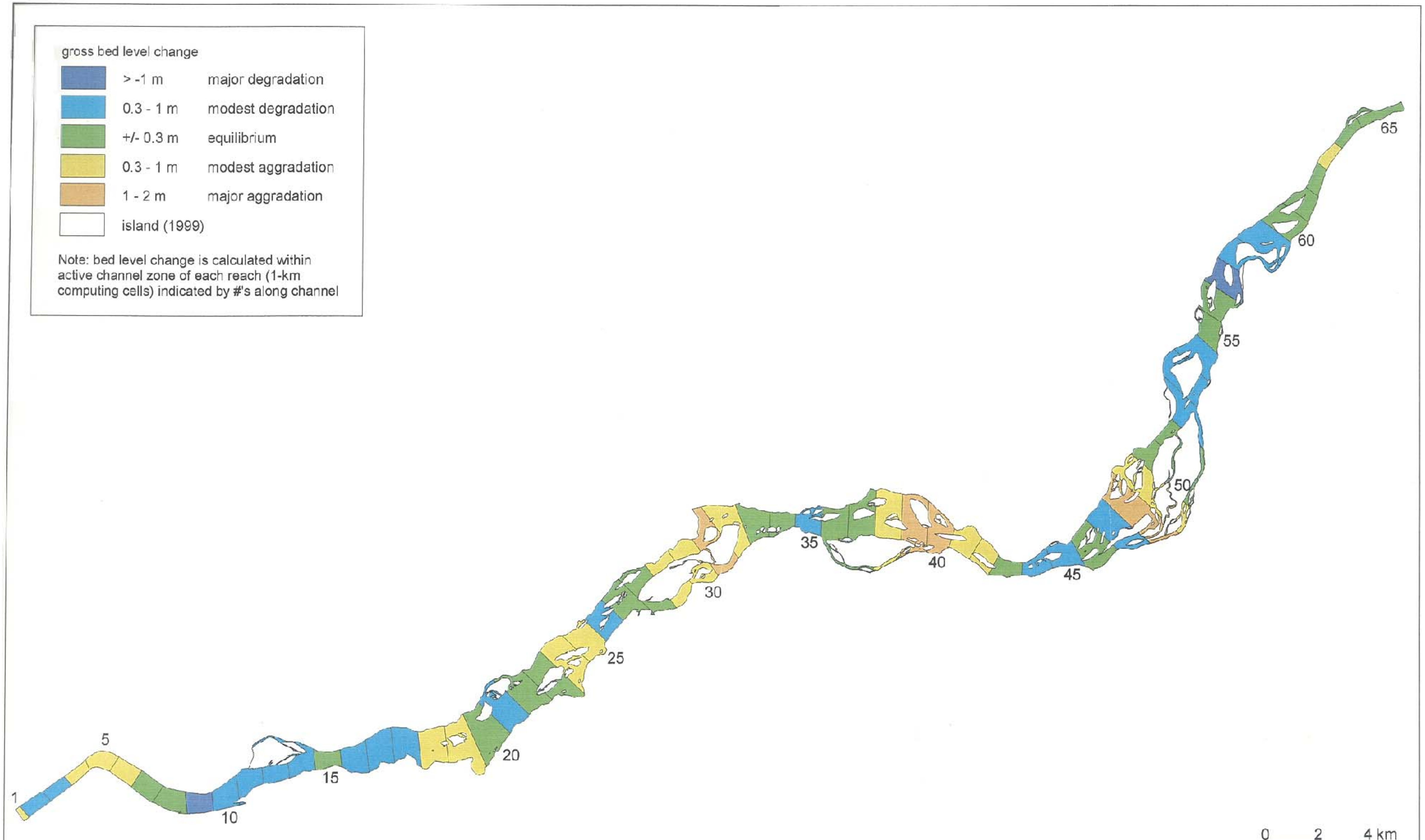


Figure 15: Net bed-level change between Laidlaw and Mission, 1952-1999 (based on the adjusted sediment budget data)

Figure 16: Gross elevation changes in the gravel-bed reach of Fraser River, 1952 - 1999 (based on modelled surfaces for each date)

Aggradation averaged over the entire reach is 2.1 ± 1.3 cm over 47 years (in comparison, 8.6 cm for the gross change before gravel removal is factored in). This result amounts to about 0.5 mm a^{-1}. In the reach downstream of the Agassiz-Rosedale bridge, the average figure is 10.9 ± 2.1 cm., for a rate of just under 2.5 mm a^{-1}. However, actual aggradation is strongly localized, with reaches experiencing up to 1.5 m of net fill. In comparison, maximum net degradation is about -1.1 m. The pattern of actual scour and fill is even more complex (Figure 16).

It is commonly supposed that sediment is transported through a reach of a river, once flows exceed the threshold to mobilize material, in a more or less continuous carpet on the bed of the stream, and in suspension in the water. If the reach is aggradational (there is a net deposition of sediment), it is supposed that the deposition is relatively continuous. Whilst the fine sediment that moves in suspension is transported more or less continuously over considerable distances, the bed material does not move in this way at all. Once entrained from an eroding bank or bar, the bed material is moved downstream on the bottom ("bedload") or as intermittently suspended material until it encounters the next bar (Figure 17). Here, much of the entrained load is deposited onto the bar surface. This reduces the channel cross-section area. To compensate, the river is forced to erode a nearby bank or bar, and the process repeats itself. Sediment transfer is a discontinuous process, and there is a continual exchange occurring between mobile material and deposits. In Fraser River, characteristic transfer distances for bed material are a few hundred metres to 2 or 3 kilometres.

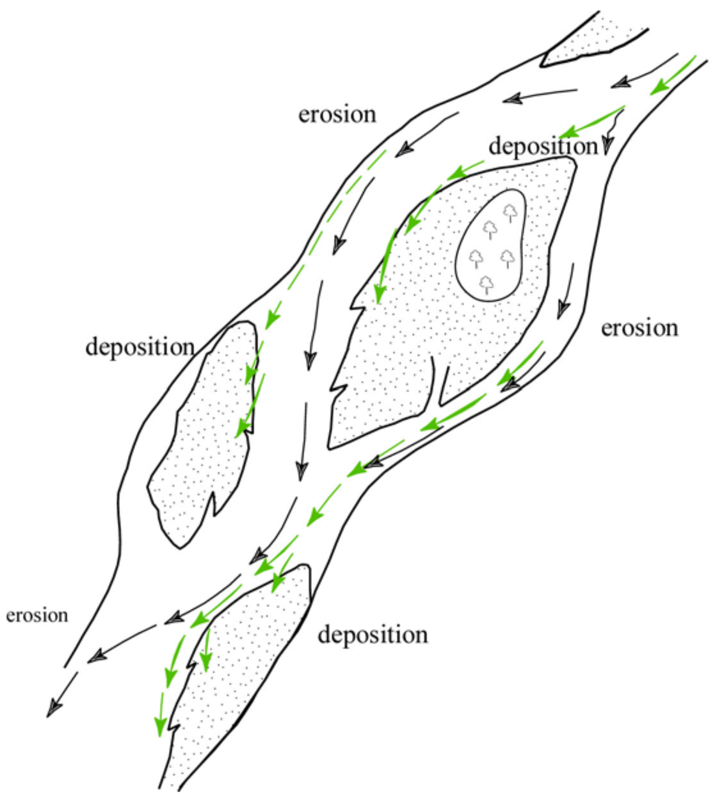


Figure 17. Pattern of gravel movement in Fraser River (green arrows: black arrows represent the main river current).

Aggradation occurs where the quantity deposited characteristically is larger than the quantity entrained from nearby. Bars develop to some maximum height that is the highest to which gravels can be pushed by the river currents. This level is near normal flood water levels (i.e., water levels at 7000 to 8000 m^3s^{-1} flow). Sands can be transported to higher levels and deposited on bar tops (cf., Figure 7, which shows the regularity of bartop elevations and the superposition of sand deposits). Once vegetation (almost always willow and cottonwood) becomes established in the sands or bartop gravels, sand is trapped rapidly and an island develops with a top surface that approaches the elevation of the adjacent floodplain, which may be 2 or 3 metres higher than the bar surfaces.

At some places along the river, the overall configuration of the channel influences flow velocities and sediment deposition. For example, at the mouth of Harrison River today, Fraser River is forced to execute a very sharp left turn where it runs into Harrison Knob (Figure 18). The energy necessary to make this turn is gained by water "piling up" upstream. This raises the water surface, reduces velocities, and induces major sediment deposition on Harrison Bar. In technical terms, the resistance to flow is high at Harrison River mouth, so flow slackens upstream and sedimentation occurs. This example indicates that aggradation is concentrated in certain places along the channel -- places that are determined by the overall configuration of the river. After some years (of order 10 years or so in the case of Fraser River), the net result of persistent sediment aggradation changes the configuration of the channel. Eventually, the conditions that created the unusual aggradation are relieved and aggradation becomes concentrated somewhere else.

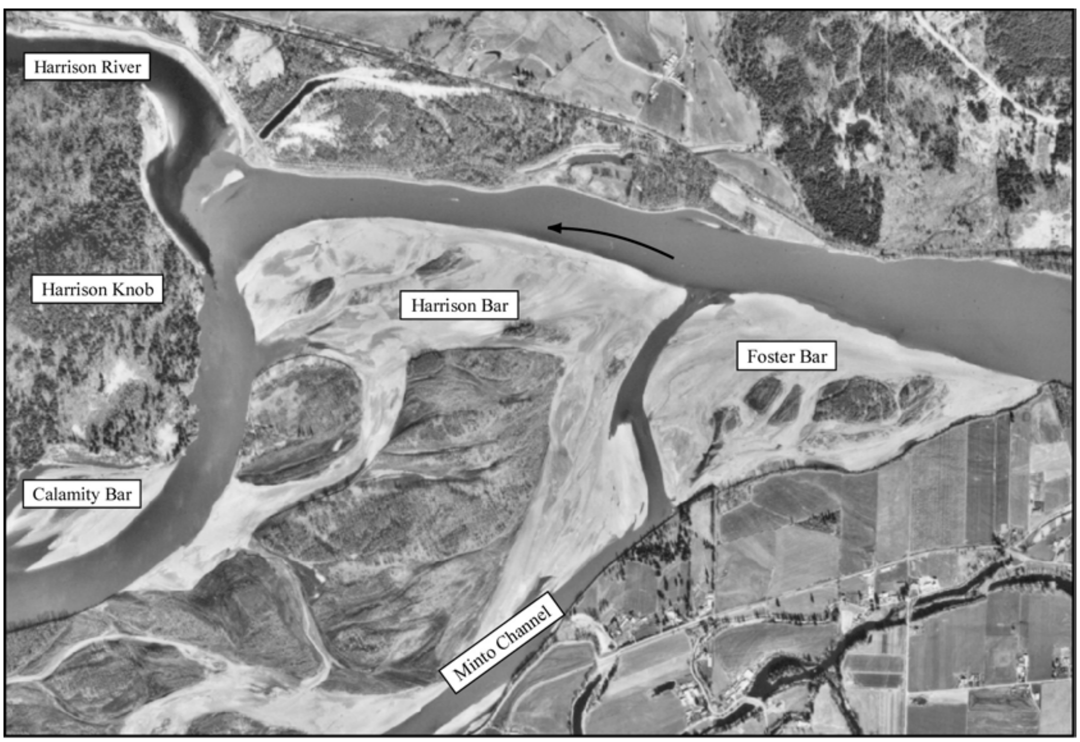


Figure 18. Fraser River at the mouth of Harrison River (1999 alignment), showing the sharp bend.

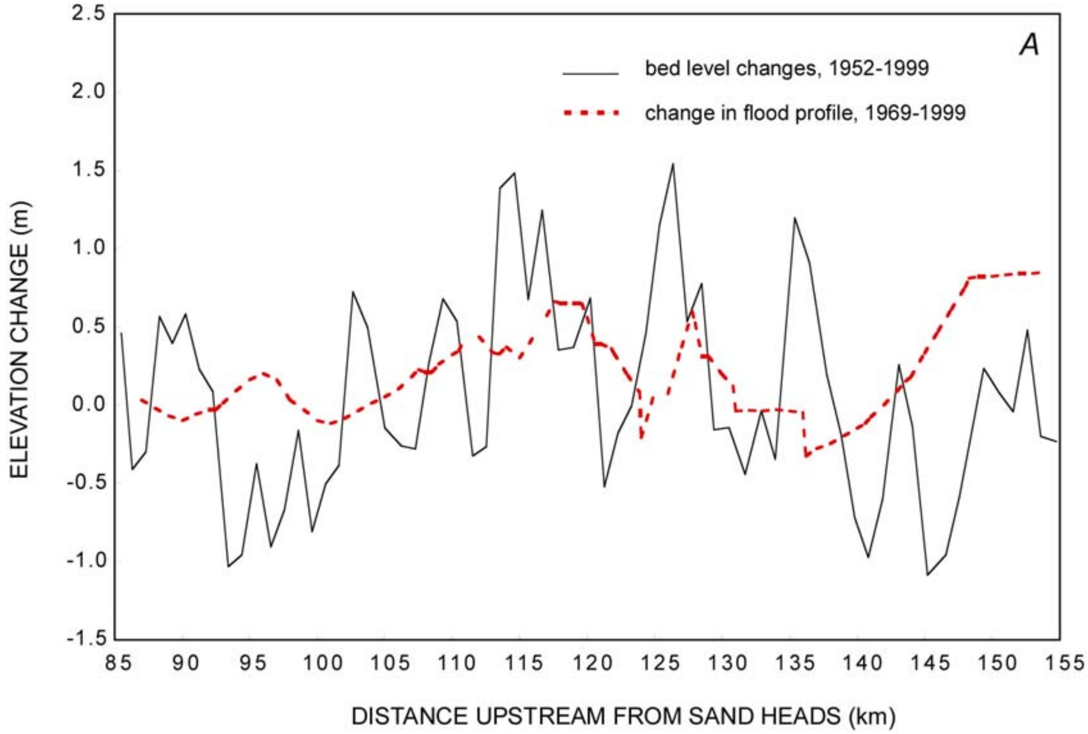
In summary, aggradation is concentrated at certain places along the channel where the current channel configuration slows the river flow and induces persistent bed material sediment deposition. Twenty years ago, such an area was the area immediately in front of Mt.Woodside, extending to the mouth of Greyell (Jesperson) Slough. Today, such areas include lower Herrling Island, Harrison River mouth, and the Webster Bar (Chilliwack Rock) area (see Figure 19). The details of the sedimentation process in each of these reaches is different, but they all lead to localized aggradation and compensating erosion nearly. The summary pattern of channel changes that has resulted over a period of 47 years is illustrated in Figure 16. There is a pronounced tendency for erosion and deposition both to occur in most sections, and for the downstream pattern of erosion and deposition to follow present and former lines of the main channel.

Further details of the sedimentation process are important. During an individual flood, sediment may be mobilized from an eroding bank relatively continuously for some weeks and moved onto a downstream bar relatively continuously. On the bar this creates a sheet of fresh sediment, one or a few grains thick, that advances over the bar surface. The sheet has a sharp front and may have sediment grains of a distinctive size (in comparison with the material already on the bar). Successive sheets may overrun each other and eventually create a step-front that may be one or more metres high (Figure 20a). When such fronts are draped across the side of a bar, extending into the deepwater channel, they create scalloped topography along the edge of the Figure 20b). On the declining stage of freshet flows, water washing over the bar may collect and drain through the bar front in small eroded channels called "chutes" (Figure 20c). Often water collects from successive sheets on the streambank side of the bar and scours a deeper channel against the bank. These details create varied topography around bars that become important elements of fish habitat as waters rise and fall over the bar.

2.7 THE MORPHOLOGY OF THE GRAVEL-BED REACH

The gravel-bed reach of Fraser River is classified as a "wandering channel" (Desloges and Church, 1989) (Figure 21). Such channels are characterized by discontinuous low-order braiding, the presence of channel islands, usually non-overlapping, and an identifiable principal channel that exhibits irregular sinuosity. Braiding refers to the division of deepwater channels around bars. "Discontinuous, low-order" braiding refers to the fact that the channel is not everywhere divided around bars and, when it is, there are only two or a few deepwater channels in the cross-section. "Irregular sinuosity" refers to the fact that the main channel moves from side to side of the channel zone, but is not regularly meandered.

Channels of this kind develop as the result of low intensity and temporally irregular movement of bed material. They are common in mountain valleys of the Canadian Cordillera in the present day and are presumably part of the legacy of the last ice age (which ended about 10 000 years ago). At that time there was a large volume of glacial sediment available for transport by the major rivers. Progressive restabilization of the landscape has occurred since, as those sediments have been moved to positions that are more stable in the contemporary landscape.



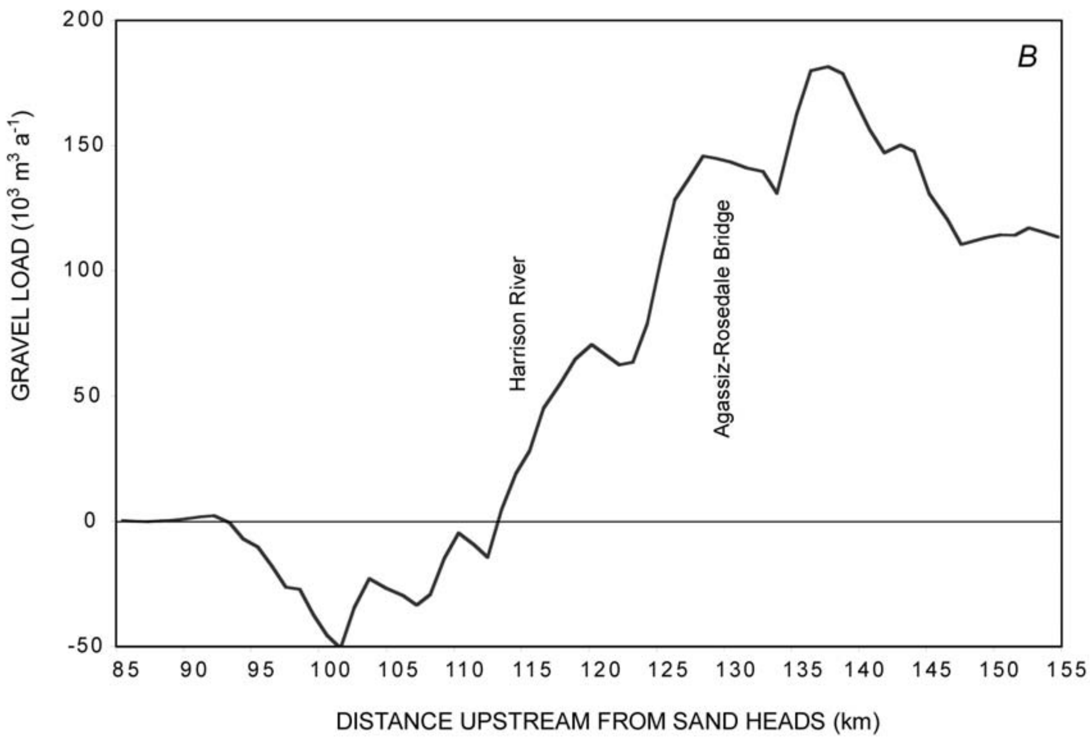


Figure 19. Distribution of sedimentation along Fraser River in the gravel-bed reach, 1952-1999; (a) bed level changes (as averages for 1-kilometre cells). The change in flood profile between 1969 and 1999 (from UMA 2000; 2001) is shown for comparison; (b) the downstream trend of gravel transport over the same period.

A

B

C

Figure 20. Details of the sedimentation process in the gravel-bed reach. (a) gravel "wave" front on Queens Bar, August 2000; (b) successive gravel sheets wrapped around a bar head: upper Harrison Bar, August, 2001; (c) chutes cut through an advancing wave front: Lower Herrling Island, March, 1998.

Figure 21. View of the wandering channel of Fraser River: view upstream toward Herrling Island from km 130.

If bed material transport increases significantly in such a channel, it becomes more continuously braided as the result of the increased volume of sediment temporarily stored in the channel. If the bed material transport declines, or if sedimentation is inhibited by some means, the channel adopts a single-thread, more or less sinuous course along the line of the principal channel. In the former case, the aggrading sediment steepens the channel until a gradient is reached that allows the increased volume of sediment to be transported farther downstream. In the latter case, gradient is reduced as bars are eroded away. The most effective way to reduce the gradient quickly is for the channel to become more sinuous (hence to increase the length of the flow path). The semi-mathematical relation discussed at the introduction to this section can be rearranged to describe these differences. In a diagram of Q versus S, rivers with different bed material loads, hence with different morphological patterns group systematically. Figure 22 shows such a plot, with points for many rivers that were used to define the relation. Lines are drawn in the plot to define the limits (in S and Q) of occurrence of braided channels, wandering channels, and single-thread channels. An interesting feature of the plot is that the upper limit of single-thread channels occurs, for a given Q, on a steeper gradient than the lower limit of multi-thread channels. So there is a zone of overlap between the two channel "styles". This is a consequence of bank condition. A braided, laterally unstable channel maintains banks that are weak because firmly rooted vegetation has no opportunity to develop. Conversely, a relatively stable, single-thread channel concentrates bank attack on the outside of alternating bends, so much of the bank has the opportunity to develop stabilizing vegetation cover that resists general attack up to some considerably higher stream gradient and hydraulic force.

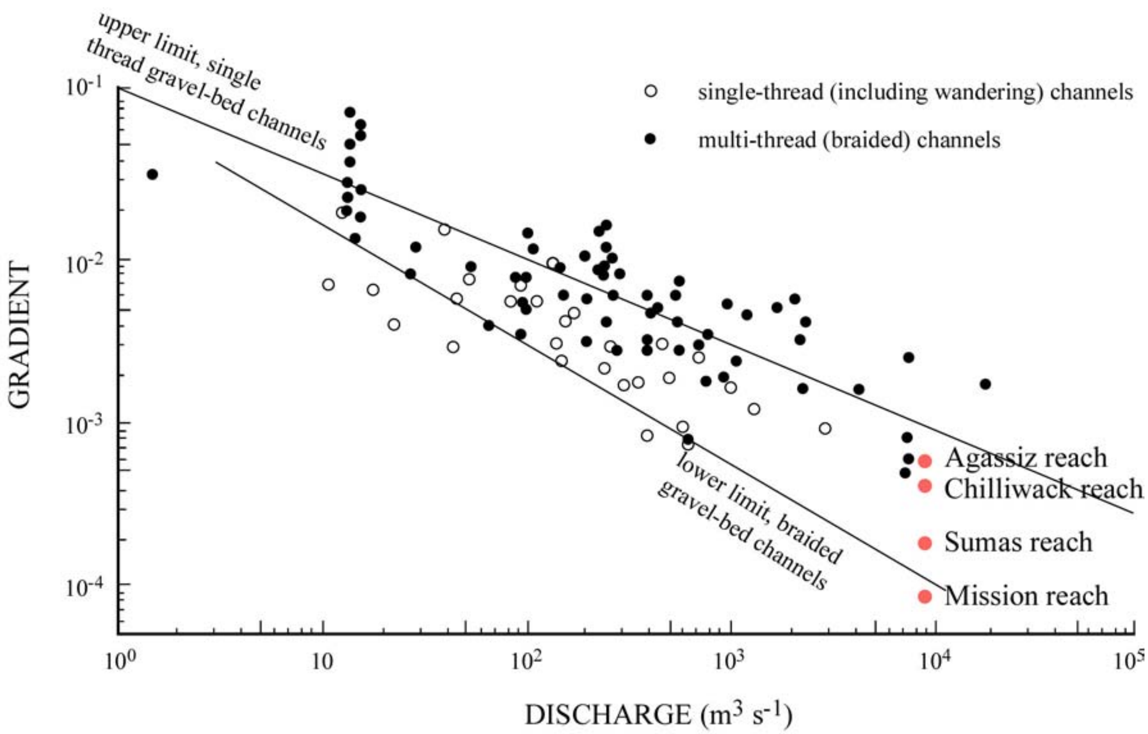


Figure 22. Slope-discharge graph to discriminate single-thread and multi-thread channels. Four major sub-reaches of Fraser River gravel-bed reach are shown in the diagram. See text for discussion.

The four major sub-reaches of the Fraser River gravel-bed reach are plotted on this diagram. *They all fall in the zone of overlap between multi-thread and single-thread channels*. The distal reach (Sumas reach) falls at the lower limit of this zone and, indeed, is the reach within which the transition from multi-thread to single-thread characteristic of the lowermost part of Fraser River occurs. Fraser River in the gravel-bed reach retains its wandering, multi-thread habit only conditionally. If the channel is once forced into a single thread, it could retain it.

Through the past century, the morphology of the gravel-bed reach has been substantially modified by engineering action. Riverfront landowners, of course, do not wish to see their land eroded. So, wherever the river has threatened to erode laterally into improved land, or threatened to erode facilities such as the railways, or approached the flood-protection dykes, the channel banks have been strengthened to resist erosion. Bank protection almost always consists of stone revetment. In this way, a substantial portion of the entire channel has been constrained from lateral movement by bank strengthening. Table 5 gives the data of the current extent of bank hardening and Figure 23 shows the location of hardened banks along the river.

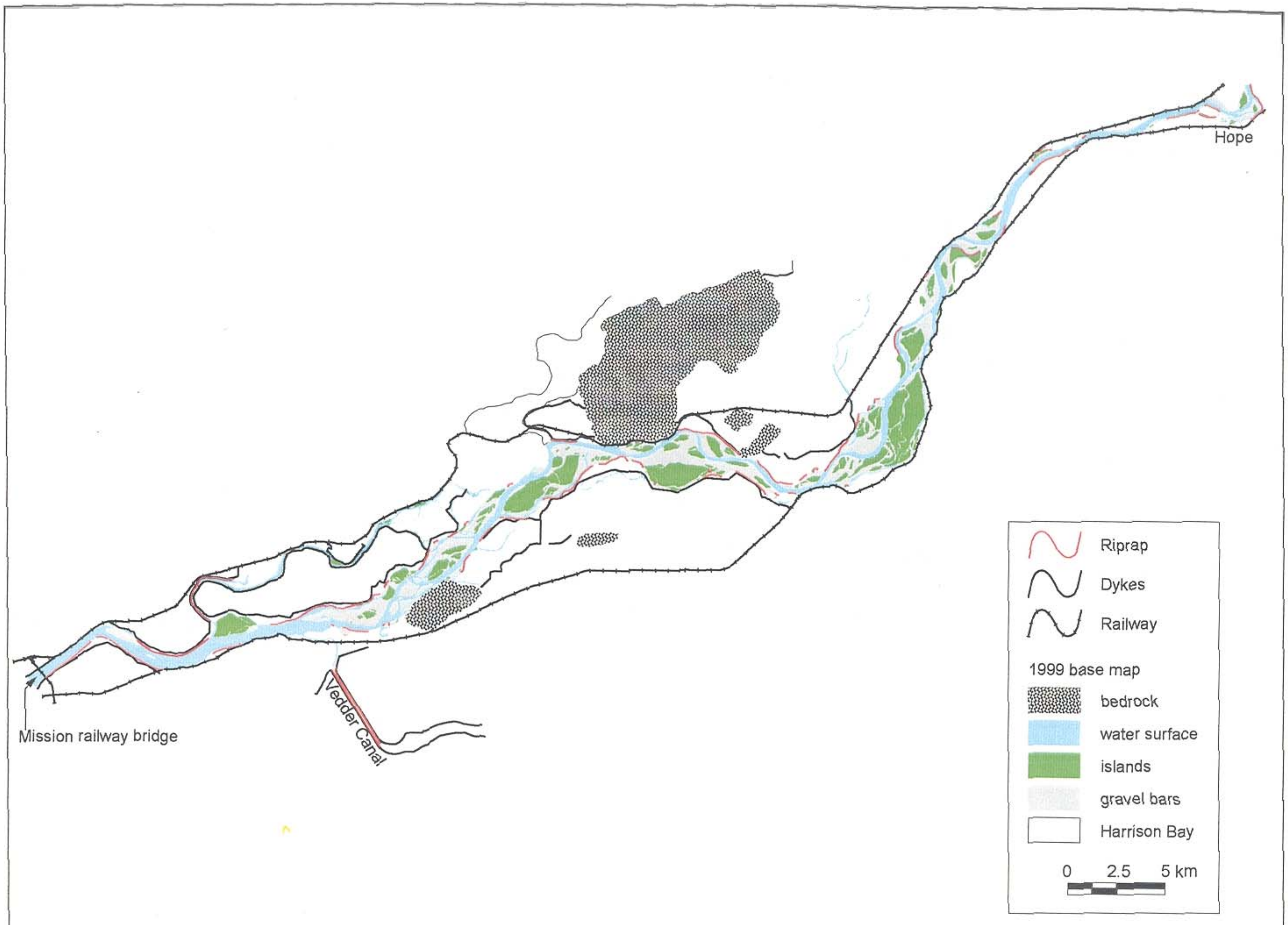


Figure 23: Location of hardened banks and dykes along Fraser River between Hope and Mission

Table 5. Summary of bankline hardening on Fraser River between Mission and Hope bridges

Reach	Total bank[1] length (m)	Railway[2]	Dykes	Riprap[3]	Bedrock[4]	Total protected[5]	% protected
Sumas	31 925	4 715		13 760	4 873	23 348	73.1
Chilliwack	35 739		173	14 898	6 525	21 596	60.4
Rosedale	26 346	4 091		14 202	833	19 126	72.6
Cheam	42 501	18 358		11 739		30 097	69.2
Hope	32 202	6 207		8 692	2314	17 213	53.5

1 Outer banks of the channel only; does not include island shoreline.
2 Railway includes many banks that otherwise would be classified as bedrock.
3 Riprap includes rock berms 2907 m, mainly in Cheam Reach.
4 Bedrock includes non-fluvial, non-erodible banklines, such as along Mission Bend.
5 All categories are exclusive (i.e., any length of bankline is included in one category only).

Channel zone width has decreased over the century as well. Figure 24 shows the active channel zone width (water + exposed bar surfaces) at various dates since 1913.

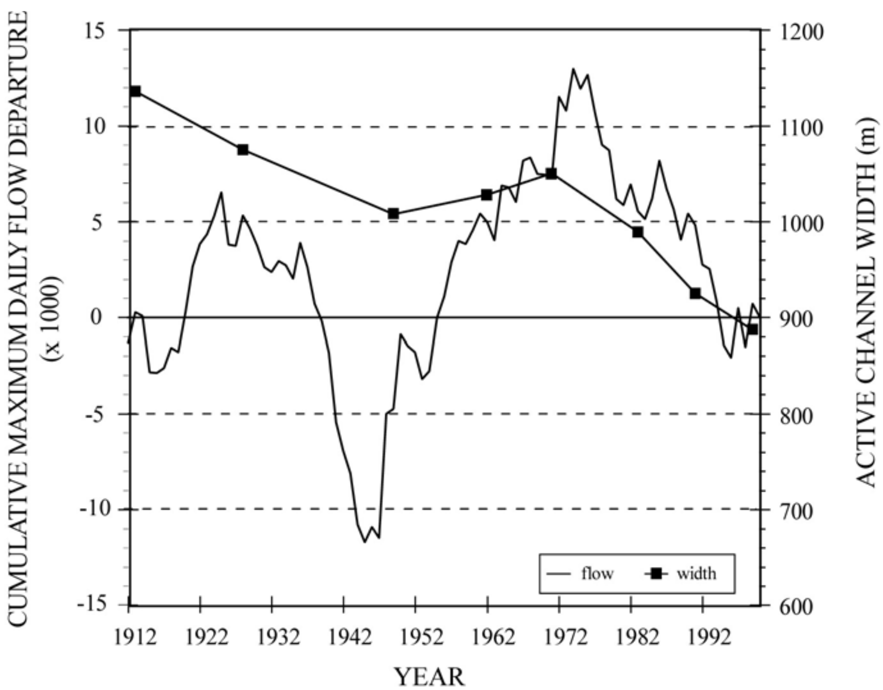


Figure 24. Variation of active channel zone width with the trends of annual maximum daily flow. The flow trend is indicated by the cumulative departure from the long-term mean (in this case, mean annual flood). Accumulated departures $x_i = \sum (Q_i - \langle Q \rangle)$, where $\langle Q \rangle$ indicates the long-term mean, identify principal trends: a descending plot signifies persistently below-average flows, a horizontal plot signifies flows persistently near average, and an ascending plot signifies flows persistently above average.

The changing width has followed the trends of flow through time. The part that bank hardening and channel constraint have played in this evolution is not easily separable from natural effects. Nevertheless, the channel zone is today, on average, only 80% as wide as it was early in the 20th century even though there has been no definitive long-term trend in flow.

Narrowing of the channel encourages the eventual transition from wandering to single-thread. But the sediment influx has not obviously decreased. Confinement of flow to a narrower, deeper and faster flowing channel forces the bed material influx to be transported farther downstream more quickly, ultimately creating problems of lateral instability and aggradation downstream, nearer the limit of the gravel-bed reach. The pattern of aggradation illustrated in Figure 19 is consistent with the possibility that sediment is being forced through the reach more rapidly today than in the past, leading to significant sedimentation problems downstream of Agassiz (today, from Harrison River mouth downstream).

3 RIVER MORPHOLOGY AND THE RIVERINE ECOSYSTEM

Although there have been many studies of biota in gravel-bed streams, work in large rivers is mainly restricted to fishery studies. Ecosystem characterizations are limited to small gravel-bed streams. So far as we know, there is no extant study of the whole ecosystem in a large, coldwater gravel-bed river. Similarly, there is very little information on the response of cold gravel-bed river ecosystems to gravel extraction. As a consequence, a study has been initiated in Fraser River that is designed to provide information on the long-term effects of gravel management on the riverine ecosystem. Most of the discussion in this section is derived from progress in that study.

Some studies have been made in warmer water streams in the southern United States. In addition, a certain amount can be inferred from studies of effects downstream from dams. Dams create some effects analogous to those of gravel extraction inasmuch as they intercept bed material moving through a stream system. However, they also impose a degree of flow regulation, the effect of which may be confounded with the sedimentary effects.

The physical environment of a river forms the foundation upon which the ecosystem is constructed. Hence, we may make progress toward understanding the potential effects on the ecosystem of gravel extraction by considering interactions between stream biota and the physical environment. This section of the report summarizes information on that topic.

3.1 RIVERINE HABITAT

Fraser River is a steep, cobble-gravel mountain river with major lakes in its headwaters, fed primarily by the soft waters of melting seasonal snow. Such rivers are characteristic of the glaciated mountains of the northern hemisphere. The Fraser is one of the most productive of such systems. The riverine ecosystem depends in an essential way on the characteristics just enumerated. It is a cold, fast-water ecosystem (Northcote and Larkin, 1989).

Fraser River is steep and runs fast because it drains high mountains with a recent history of uplift. It is a cobble-gravel system in virtue of this and the proximity of glaciation. The major water source is seasonal snow, again in virtue of the relatively great elevation of much of the basin and the northern position. The headwater lakes are a legacy of the glaciation. Fast, cold water is the habitat of salmonine fishes. There are 10 such species in Fraser River and, today, it has the greatest abundance of salmonine fishes of any river in the world (Northcote and Larkin, 1989).

The cobble-gravel reach of lower Fraser River provides conditions conducive to spawning of some species and rearing of several others. These conditions include:

- fast, cool, soft waters of moderate turbidity, sufficient to provide protection from predators, but not to significantly impede activities;
- a range of gravel sizes to provide suitable spawning conditions and high production of benthic organisms;
- moderate gravel transport, so that gravels are cleaned and renewed regularly;
- strongly seasonal flows, so that the gravel substrate is stable during egg incubation;
- side and back-channels and complex sediment deposits around bars, providing a range of rearing habitats, including “escape” areas during flood;

- a range of depths at all flows, providing habitat for all activities in all seasons; and
- abundance of shoreline (because of the multiple channels), providing edge habitat and high volumes of drop-in food.

These conditions are the direct consequence of the wandering habit of the river, in turn the consequence of the relatively steep gradient and modest but persistent influx of gravel.

3.2 RESPONSE OF AQUATIC ECOSYSTEMS TO GRAVEL EXTRACTION

We have located only one research study describing the impact of gravel mining on stream biota, though that paper makes reference to a number of reports from fisheries and conservation agencies, primarily in southern American states. All of the work has appeared within the last 10 years, implying that concern has been raised relatively recently.

Brown et al. (1998) established a formal experimental design to study channel morphology, incidence of benthic organisms, and fishes in pools and riffles in three relatively small rivers in Arkansas. They studied three sites with "intensive" mining (one assumes that this means pit excavations) and 10 sites with "extensive mining" (bar scalping). They made measurements upstream ("control"), onsite and downstream. No details are given of stream hydrology or of the gravel extractions. It is possible to infer that the streams were 20 to 50 m in width and that gravel supply is relatively limited. Extraction was ongoing during the measurements. Significant findings included the following:

- channel morphology was changed downstream and riffle area was reduced in the study streams;
- fine organic matter transfer from riffles to pools was reduced;
- density of invertebrates was reduced at the extensively mined sites;
- total density of fish in pools and of sportfish (*Micropterus* sp. -- bass) in pools and riffles was reduced downstream from the intensively mined sites;
- silt-sensitive species became less numerous downstream.

Brown et al. conclude, following Kanehl and Lyons (1992), that recovery time in small rivers may require decades. This is because the primary changes are physical ones based on the gross imbalance between rates of gravel extraction and rates of replenishment, which would require many years after the cessation of mining to overcome. Total ecological restoration may then become impossible since certain species may be extirpated in the meantime, or definitive succession or replacement processes may exclude former elements of the system (cf. Amoros et al., 1987).

Large rivers possess much greater inertia, both physically and ecologically, than the smaller streams investigated by Brown et al. The disturbance imposed by mining a small channel is relatively catastrophic in comparison with the disturbance imposed on a large channel, except in the case that a very large extraction operation is established in the large channel. Hence, the acute systemic effects observed by Brown et al. would mostly be difficult to detect in a large river. But the stresses identified by them would nevertheless be locally present in a large river; they could create acute effects at individual sites and could exert cumulatively significant systemic effects over many years. To the extent that they permit relatively easy detection of certain effects, the small stream studies provide useful guidance.

An example given by Ligon et al. (1995) of downstream changes after tributaries were dammed illustrates the potential subtlety of effects in large rivers. McKenzie River in the Oregon Cascades is a largely unmodified cobble-gravel river with a wandering alluvial reach very similar in character to that of Fraser

River. Flows in McKenzie River are about 15% of those in Fraser River. Flood control dams have been built on two tributaries, regulating flow from 27% of the basin. This has reduced the magnitude of peak flows by about 55% for the last 30 years. Contemporary peak flows, in the range 500 m^3s^{-1} to 800 m^3s^{-1} just reach bankfull. This appears not to constitute a significant modification of the in-channel process regime of the river. However, it has significantly reduced the mobility of the coarsest bed material in the reach, so that bar reconstruction and bank erosion have been greatly reduced.

The net result is a significant reduction in the availability of medium cobble gravel (ca. 100 mm), growth of vegetation on bar tops, abandonment of side channels and consequent elimination of islands. Numbers of islands, island area, island perimeter, and streambottom wetted area have all declined by about 50 per cent. The cobble gravels constitute spawning gravel for chinook salmon, which cannot move the larger material with which the bed has become armoured. The other changes represent loss of important rearing habitat. In the same period, the chinook salmon run in this river has declined by about 50%. It would be superficially difficult to establish the cause of this decline, but the common observation of female salmon superimposition over the same redd (on average 8.5 fish per redd) strongly suggests that limitation of spawning area and consequent density-dependent mortality are important causes of the decline.

3.3 THE PHYSICAL BASIS FOR THE ECOSYSTEM IN FRASER RIVER

Significant ecological effects in large rivers may be even more subtle than indicated by the last example. Initial results of our ecological studies (Church et al., 2000) indicate that distinctive groupings of fishes segregate themselves into different microenvironments in the river. We have classified the river at three levels:

- by morphologically distinct subreaches within the overall gravel-bed reach;
- by bar-riffle units within each subreach;
- by habitat types within each bar-riffle unit.

We have identified 13 habitat types (Table 6; Figure 25) on the basis of 9 physical characteristics (Table 7). Typical units are of order tens of meters in shore-normal width, and hundreds of metres alongshore. A characteristic area would be of order 1000 m^2. Repeated sampling for juvenile fishes has demonstrated the ecological distinctiveness of these units (Figure 26, Figure 27). Two important attributes of these habitat types indicate that their occurrence and persistence are sensitive to changing physical conditions in the river channel.

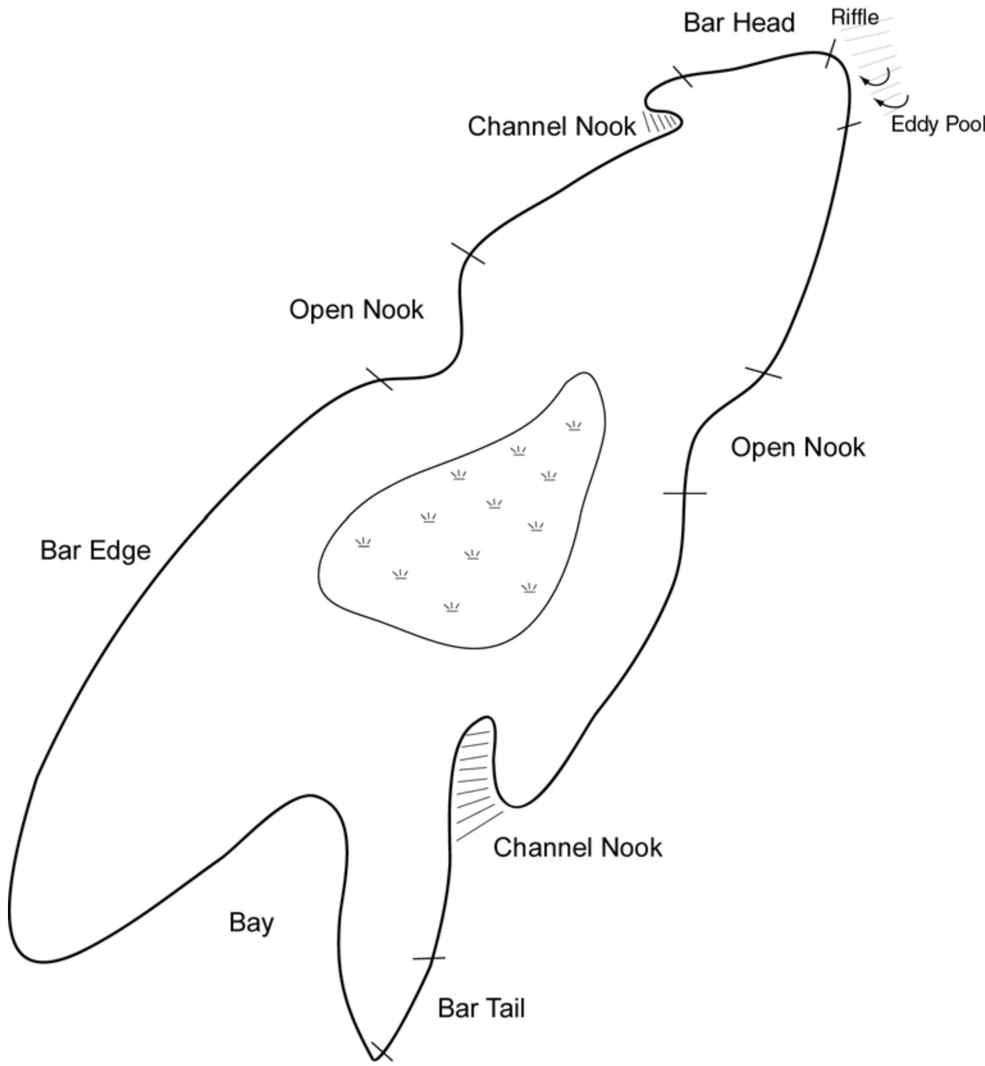


Figure 25. Sketch to illustrate the typical occurrence of microhabitat units around a bar.

First, these habitat units are created directly by the physical processes of sedimentation and erosion that build and modify the bars. Nooks and bays are defined by the edges of gravel sheets that move onto the bars and add sediment to them, or by the ends of bar-top channels. Bar head, bar tail, and bar edge units are characterized by particular hydraulic conditions typically found in these environments, whilst riffle and eddy units are defined by the disposition of sediment deposits that steer water currents around the bar. As bars are modified, the occurrence and frequency of these units are changed.

Table 6. Physical and ecological attributes for 12 habitat types in the gravel reach of Fraser River.

HABITAT TYPE	*BANK SHAPE*	*BANK SLOPE*	*FLOW TYPE*	*VELOCITY RANGE (cm/s)*	*RIPARIAN VEGETATION*	*POSITION ON BAR*	*CHANNEL TYPE*	*DOMINANT SUBSTRATE CLASS*	*SUBSTRATE TYPE*	*FISH SPECIES DIVERSITY*	*MEAN CPUE ± SE (ALL SPECIES)*
Bar Head	flat	< 5^o	tranquil	26 – 80	none	upper	main side	cobble	clean	low	s: 0.11 ± .02
Bar Tail	flat	< 5^o	tranquil	26 – 50	none willow	lower	main side	gravel	clean or sandy	moderate	s: 0.17 ± .02
Bar Edge – Steep	steep	> 5^o	tranquil	6 - 80	none	mid lower	main side	gravel	clean or sandy	moderate	s: 0.27 ± .1
Bar Edge – Flat	flat	< 5^o	tranquil	26 – 50	none willow	upper mid lower	main side summer	cobble gravel	clean or sandy	low	s: 0.10 ± .01
Riffle	flat	< 5^o	rough	50 - >80	none	upper mid lower	side summer	cobble gravel	clean	moderate	s: 0.15 ± .06
Eddy Pool	steep	> 2.5^o	back eddy	0 – 25	none	upper mid	main side summer	gravel sand	sandy	high	s: 0.25 ± .05
Open Nook	flat	< 2.5^o	tranquil standing	0 – 25	none willow	upper mid lower	main side	cobble gravel sand	clean or sandy	high	s: 0.75 ± .19
Channel Nook	shallow or deep	variable	standing	0 – 5	none willow	upper mid lower	main side summer	gravel sand	sandy or blanket	high	s: 0.38 ± .09
Bay	shallow or deep	variable	standing	0 – 5	variable	mid lower	side main	sand	blanket	moderate	s: 0.33 ± .09 g: 0.05± .02
Cut Bank	steep	> 15^o	tranquil standing back eddy	0 – 25 26 - >80*	variable	upper mid lower	side main	gravel sand	sandy or blanket	moderate	g: 0.03 ± .02
Rock Bank	steep	>15^o	tranquil standing back eddy	0 – 5 6 - >80*	variable	upper mid lower	side main	cobble sand	insufficient data	no data	no data
Rip Rap	steep	> 5^o	standing tranquil	0 – 25 26 - >80*	none willow	upper mid lower	side main	rubble sand	insufficient data	low	g: 0.04 ± .04
Open Water	flat	n/a	standing tranquil	0 – 50 51 - >80*	none	upper mid lower	side summer main	cobble gravel sand	variable	low	g: 0.003 ±0.001

Table 7. Definitions of attributes for habitat types in the gravel reach of Fraser River

1.	**Bank Shape:**	*Steep*: linear profile, steep angle *Deep*: concave profile, steep angle *Flat*: linear profile, low angle *Shallow*: concave profile, low angle
2.	**Flow Type:**	*Tranquil*: little vertical mixing, smooth surface *Rough (turbulent)*: irregular flow path, vertical mixing *Back Eddy*: reverse orientation of flow in the upstream direction *Standing*: no velocity
3.	**Velocity Range (cm/s):**	the average of 9 measurements in a beach seine area classified according to the following flow classes: 0 – 5 cm/s, 6 – 25 cm/s, 26 – 50 cm/s, 51 - 80 cm/s, and > 80 cm/s
4.	**Riparian Vegetation:**	*None*: no vegetation within 25 m of sample site *Willow*: most advanced stage is willow *Alder*: most advanced stage is alder *Forest*: thick vegetation of mixed stages present
5.	**Position on Bar:**	*Upper*: upper 1/3 portion of bar *Mid*: middle 1/3 portion of bar *Lower*: lower 1/3 portion of bar
6.	**Dominant Substrate:**	*Silt*: < 63 µm *Sand*: 63 µm – 2 mm *Gravel*: 2 mm – 64 mm *Cobble*: > 64 mm
7.	**Substrate Type:**	*Clean*: gravels have little or no fine material present *Sandy:* gravels partially obscured by a thin, discontinuous veneer of sand *Blanket:* gravels buried beneath a sequence of sandy deposits
8.	**Fish Species Diversity:**	*Low*: < 0.02 fish/m^2 (seine), < 0.006 fish/m^2/hour (gillnet) *Moderate*: 0.02 – 0.03 fish/m^2 (s), 0.006 – 0.008 fish/m^2/hr (g) *High*: > 0.03 fish /m^2 (s), > 0.008 fish/m^2/hr (g)
9.	**Fish Size Range (g):**	fish size expressed as weight (g) because body morphometry varies for each species
10.	**CPUE:**	"Catch Per Unit Effort", defined as the number of fish/m^2 (seine) or fish/m^2/hr (gillnet). CPUE is given for all species (n=24), for salmonids only (n=10) and for 3 species separately (i.e., juvenile chinook, mountain sucker, largescale sucker) to demonstrate species-specific differences in habitat associations.
11.	**Aquatic Insect Production**:	*Low*: qualitative estimate based on experience *Moderate*: qualitative estimate based on experience *High*: qualitative estimate based on experience
12.	**Terrestrial Insect Input:**	*Low*: qualitative estimate based on experience *Moderate*: qualitative estimate based on experience *High*: qualitative estimate based on experience

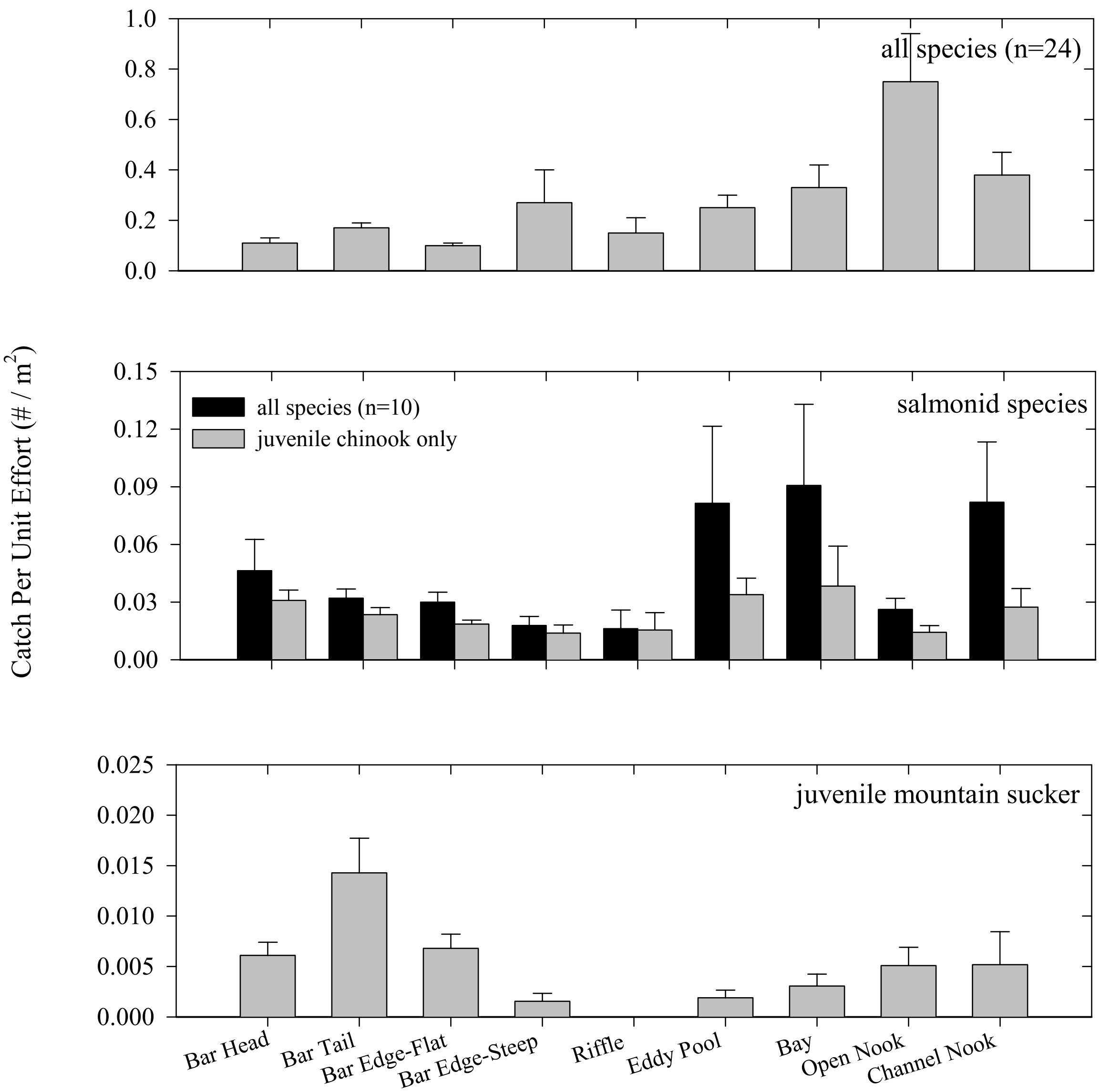


Figure 26. Variation in occurrence of fishes in bar-edge microhabitats (from Church et al., 2000: figure 17).

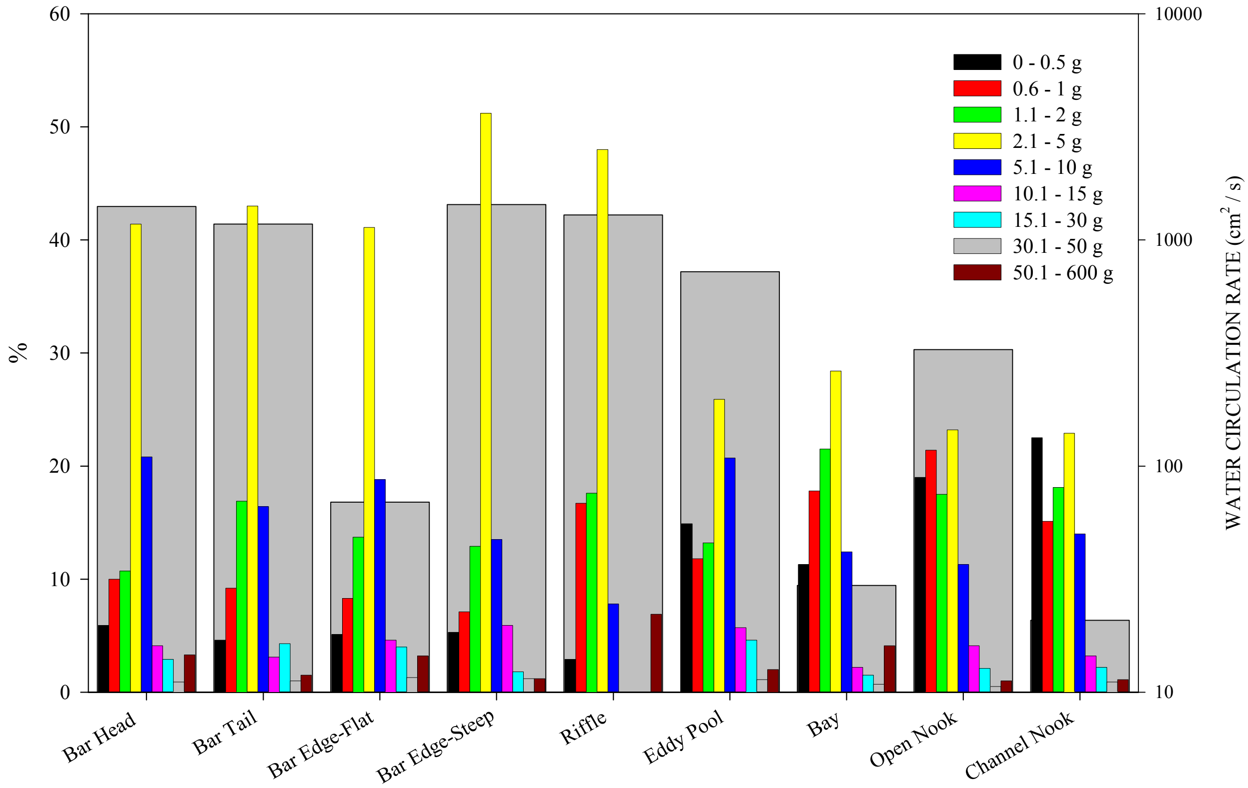


Figure 27. Variation in occurrence of fishes by weight classes over bar-edge microhabitats. Fish were collected by four methods (beach seine, gill net, minnow trap, electroshocking) in each of 9 habitat types in the gravel reach of Fraser River. Sampling took place in summer 1999 and 2000, and in the intervening winter and spring. Water circulation (calculated as mean water depth*mean velocity) is shown by the solid grey columns behind (from Church et al., 2000: figure 18).

Second, the units are stage-sensitive (see Figure 28 and Figure 29). As stage changes through the year, the incidence and location of each habitat type around the bar changes.

Events that modify the shape and elevation of channel bars have a definitive effect on the occurrence of these habitat units. To the extent that benthic organisms and fishes are differentiated in these units, modifications of the bars will visit differential effects on various groups of animals. Of course the bars are changing continually with the normal processes of erosion and sedimentation along the river. However, a systematic change in those processes, or in the characteristic morphology of the bars, such as could arise from a change in the hydrological or sedimentary regime of the river, or from systematic human manipulation of the bar sediments, may effect a systematic change in the ecosystem (cf. the example of McKenzie River, Oregon, quoted above).

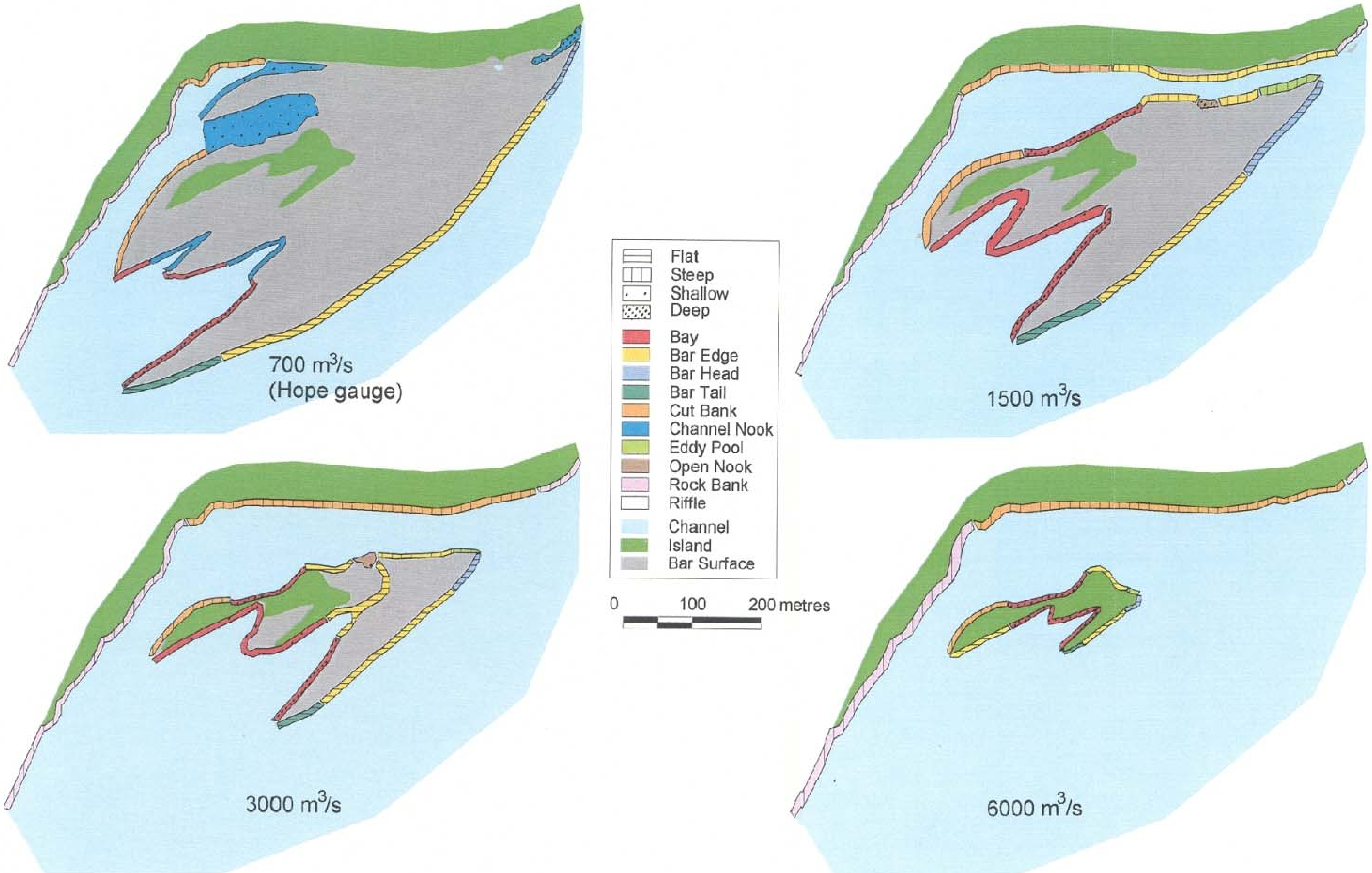


Figure 28: Habitat variation with stage over Calamity Bar (1999 bar configuration)

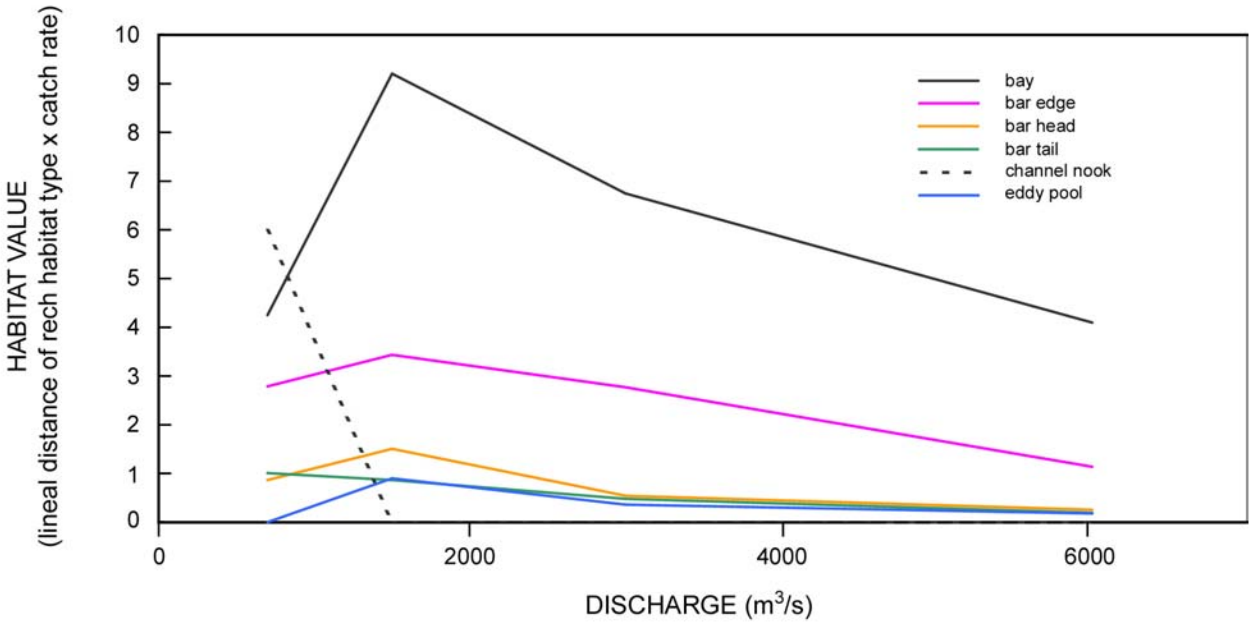


Figure 29. Relative area of habitat available at various stages on Calamity Bar, as illustrated in Figure 27 (analysis by M. Rosenau).

What is perhaps surprising about this outcome is the relatively small spatial scale at which the fundamental connection is made between the ecosystem and the physical system that supports it. *The scale is set by the very local scale at which the animals differentiate their environment and adapt their behaviour.* It lies well within the site scales on which humans customarily engineer changes in river morphology and processes.

Another critical feature of habitat units is their limited occurrence at very high flows. At flows above about 7000 m^3s^{-1}, most open bar tops in Fraser River become submerged and large numbers of fish occupy the relatively slack water there (M. Rosenau, personal communication, 2001). Above about 9000 m^3s^{-1} (i.e., flows approximating mean annual flood), there are significant currents over most bar tops. Bar-edge habitats disappear. Fishes that normally occupy these units must seek refuge elsewhere. It is also known that benthic invertebrates that normally reside in shallow water move with changing stage (Rempel et al., 1999). Actions that would systematically change the riverbed topography (including certain gravel borrowing methods) so that the spatial extent or temporal duration of deep water is systematically increased would prolong the period of high flow stress on both benthic organisms and fishes. Whilst some species may be able to tolerate this change, others likely would be lost from affected sites.

3.4 LESSONS FOR GRAVEL MANAGEMENT

It is apparent that changes along rivers that alter the gross morphology or the sedimentary morphology of the channel may have a systematic impact on the riverine ecosystem. Such changes occur naturally. To the extent that they do, the occurrence or relative abundance of various organisms may be expected to change. In a large river like Fraser River, the morphological response to even a quite abrupt and major environmental change would take years or decades to be worked out. Consequently, changes in the riverine ecosystem are unlikely to be noticed except through systematic, continuous observations. There have been few programs of systematic observation of ecosystem properties in the past.

A factor that buffers the effect of natural changes in large environmental systems is the considerable year-to-year variability of the environment. In a river, seasonal and annual flows vary significantly about the mean condition. Correspondingly, sediment influx, erosion and sedimentation also vary. The latter processes vary spatially within the channel on time scales of years to decades as bars and islands are constructed and eroded. The riverine ecosystem is adapted to tolerate change at this scale. Moderate instability created mainly by sediment replenishment has conditioned the development of an ecosystem that is resilient to environmental variability. In comparison, changes in the mean condition of the system are usually modest (Figure 30) and they can be tolerated so long as the range of requisite habitats remains present.

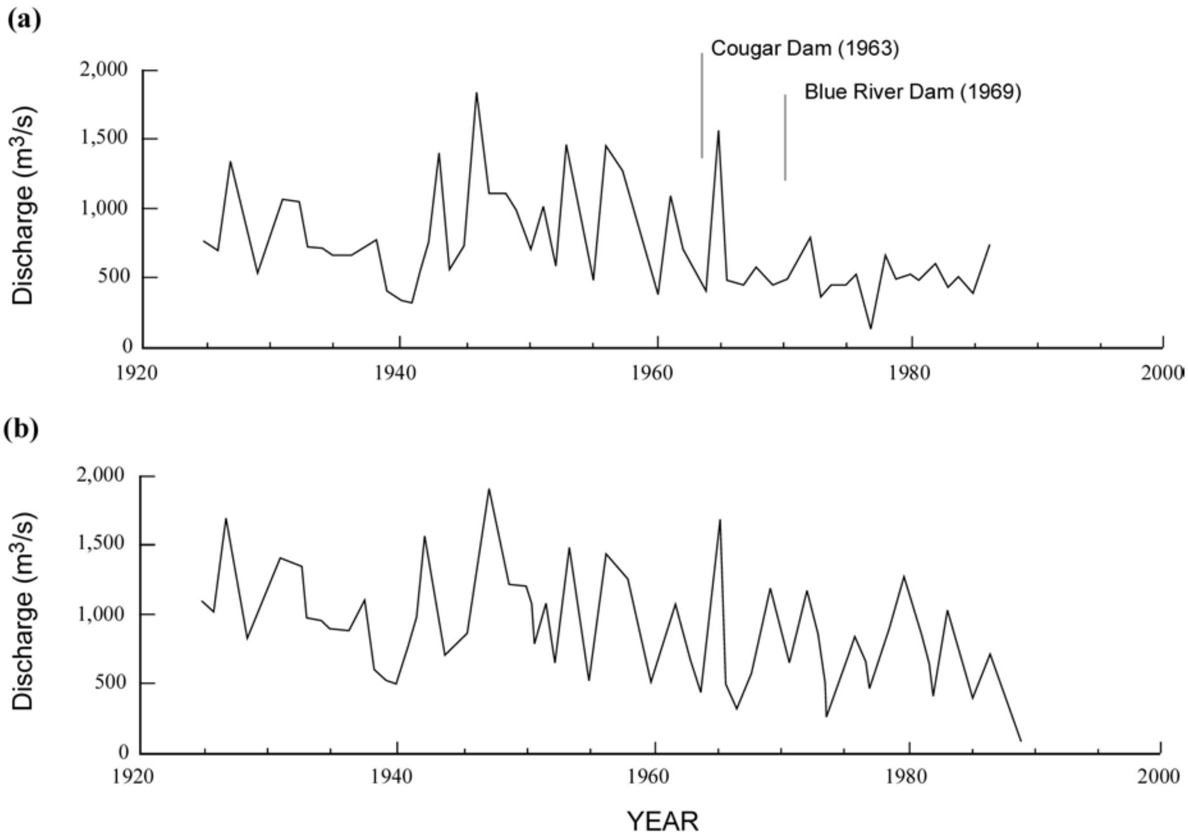


Figure 30. Variation in flow regime: (a) annual maximum flow in McKenzie River, Oregon, the result of flow regulation (from Lignon et al., 1994: fig 1); (b) hypothetical change in flow due to climate change. A linear trend is superimposed on a pattern of annual variability similar to that of pre-regulation McKenzie River. In (a) short term variability is reduced and the change in flow is abrupt; in (b) variability is not reduced and the change is gradual.

A problem introduced by human management of a river, well illustrated by the McKenzie River example, is that changes imposed by humans are abrupt and may be large, persistent, and have low variability (e.g., Figure 30a). Such changes introduce sudden or large progressive shifts in the mean condition of the system to which the riverine biota may not be able to adapt. An example might be a decision to lower all bar tops over some length of channel to increase flood conveyance. The result would be the elimination of certain habitat units at certain times of year over a distance that may be greater than the ability of some organisms to move.

Accordingly, sound management practices with respect to gravel management are ones that:

- seek to preserve the topographic variability of the channel over all spatial scales;
- seek to maintain the entire normal range of topographies in the channel;
- seek to maintain naturalistic sedimentary features at all spatial scales, but particularly at local scales in the channel;
- seek to avoid dramatic changes in the duration or severity of ecologically stressful flow conditions in the channel as a whole and at specific sites.

Such practices will maintain the range of habitats and physical conditions necessary to support the diverse riverine ecosystem.

4 ALLUVIAL GRAVEL EXPLOITATION AND MANAGEMENT

Alluvial gravels in active stream channels have been exploited and manipulated for a long time. The principal reasons for disturbing riverbed gravels include, in general order of historical precedence, channel management to increase flood security or to reduce bank erosion, channel maintenance for navigation, placer mining, and borrowing gravel for industrial aggregate. Placer mining may or may not entail removal of gravel from the river, but the other three purposes almost always do. Amongst them, the extraction of gravel from riverbeds for industrial aggregate has been the overwhelmingly dominant reason for riverbed disturbance since the middle of the twentieth century. This activity may, of course, fulfill one or more of the other purposes at the same time.

Very rarely has planning of gravel manipulation extended beyond the immediate purpose for the activity. In particular, the consequences for the sediment budget of the river, for river morphology and consequent fluvial processes, and for the riverine ecosystem are almost never considered. In most cases, the sediment budget of the river is not even known before gravel manipulations are undertaken. In this circumstance, there is no possibility to consider the morphological and ecological consequences in more than a speculative way.

This section of the report reviews documented prior experiences of gravel extraction from stream channels, giving particular attention to some cases that contain useful lessons for planning gravel management on Fraser River. After the review of experience, some general conclusions are drawn that will guide the recommendations for Fraser River.

4.1 EXPERIENCE OF GRAVEL EXTRACTION FROM RIVER CHANNELS

Possibly the longest documented history of manipulation of a gravel-bed channel is that of the Arno River of Tuscany, Italy (Rinaldi and Simon, 1998). It is described as originally being, in the alluvial parts of its course, a wandering channel like that of Fraser River. The river has been manipulated since Roman times, both to gain gravel supplies for works, and to arrange protection against floods. Major engineered modifications of the channel date from the 18th century, when land use began to increase sediment yield to the river so that it became less stable. Since the late 19th century, the river has been almost completely confined within embankments in its alluvial reaches, and further land use changes have substantially reduced sediment supply to the river. Since the early 20th century gravel mining from the channel has been a major activity, peaking in the period 1945-1980. In addition two dams were constructed on the river in the 1950s. Neither the sediment budget nor the volumes of gravel extracted are well known. The river has experienced massive degradation since the mid-19th century -- between 2 and 8 metres in various reaches.

There have been multiple external influences on the river, so it is difficult to draw clear conclusions about cause and effect. There is, however, a remarkable sequence of channel surveys, commencing in the mid-19th century, so the documentation of modern degradation is of exceptionally high quality. Two phases of degradation are recorded, one extending from the turn of the 20th century until about 1950, and a second, more severe phase since. The first phase of degradation coincided with the completion of modern projects of channel straightening and confinement within flood embankments, which increased the sediment transporting capacity of the river at the same time that the establishment of modern land use laws were effecting a reduction in sediment yield to the river. The river training, of course, substantially reduced bank erosion along the river. The later, more severe, phase of degradation was the evident result of massive gravel extraction combined with the establishment of the upstream dams, which dramatically reduced sediment supply to the river.

A similar history has occurred on the Piave River, in northeastern Italy (Veneto) (Surian, 1999). Again, confinement, land use change, dams, and massive gravel extraction have produced a 65% reduction in channel width and a reduction in braid index from 3 to 1.5 (the braid index is the ratio of length of channels to length of valley, and is an index of number of channels comprising the river). They also caused 2 to 7 m of degradation within the last 100 years. The river has been degrading throughout the Holocene Epoch (the last 10 000 years of geological time), but the rate has been accelerated by 10x as the result of human interference with the river. The obvious lesson to draw from these cases is that gravel extraction grossly in excess of gravel supply causes dramatic riverbed degradation; the less obvious one, perhaps, is that channel training and confinement, and trends in sediment supply have significant effects on aggradation/degradation along the river too.

Since the 18th century, most significant rivers in central and western Europe have been similarly confined in order to facilitate land development, to establish flood protection, or to facilitate navigation. Some interesting experience has been gained on the Rhone River upstream of Lyon, France, another wandering gravel-bed channel. Roux et al. (1989) report that agrarian clearances in the middle ages enhanced the lateral instability of the river by weakening the streambanks. An 18th century response to the instability was the construction of submerged (i.e., low) embankments, the purposes of which were to stabilize the channel and to facilitate navigation. The embankments constrained the main channel zone to 1 km width and created backwaters with limited circulation that functioned as spawning and nursery areas. This development is reported to have enhanced diversity in the aquatic system but, amongst fishes, it encouraged the proliferation of cyprinid species at the expense of salmonids.

Since the mid-19th century, the river has been channelized to facilitate navigation, to provide flood protection, and to produce hydroelectric power. These activities, along with gravel borrowing, have produced up to 3 m of degradation along the river and cut off back channels. The contemporary ecosystem is substantially simplified.

Petit et al. (1996) provide details of the Miribel channel of the Rhone River, near Lyon, established in the period 1848-57 to improve navigation. The channel simplification (Figure 31) reduced flow resistance and increased the mean gradient so that flow velocities and sediment transport capacity were increased. The result after 130 years was 4 m of degradation in the upper 9 km of the channel, and 4 to 6 m of aggradation in the lower 17 km. Concern for the aggradation near Lyon led to a decision, in 1957, to mine gravel from the river.

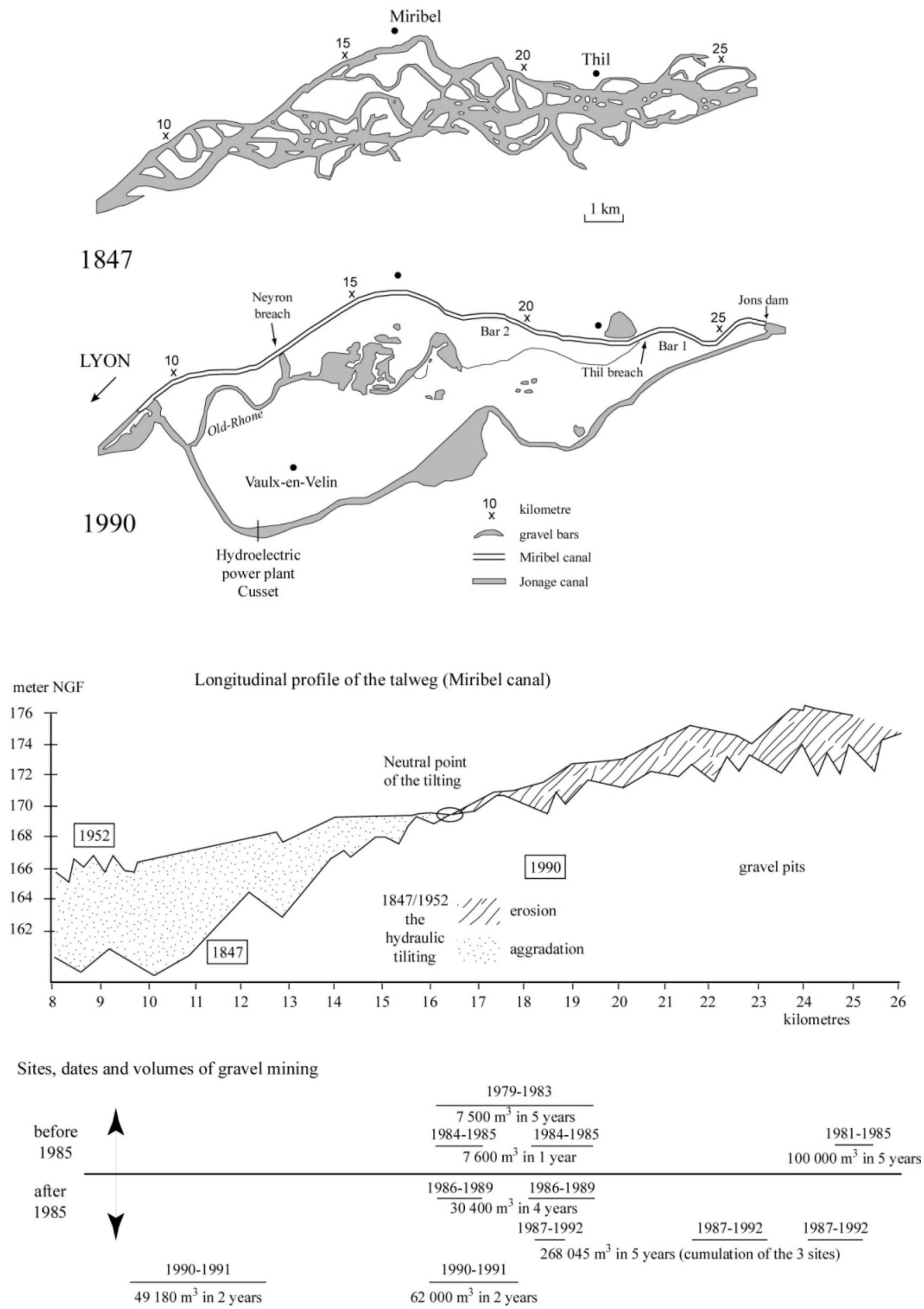


Figure 31. The simplification of the Miribel channel, Rhone River near Lyon, France (from Petit et al., 1996: figs 22 to 24). The graph illustrates the pattern of recent aggradation and degradation. Gravel extraction periods and volumes are shown below the graph.

Gravel extraction in the order of 5 million tonnes has since created up to 4 m of erosion throughout the channel and initiated significant bank collapse as the river attempted to establish a meandering habit in the channel. As the result, gravel mining was stopped after 1990. A significant lesson from this history is that channel training may have some effects similar to those associated with gravel extraction, and may create a need for gravel supply management.

Two additional comments of Roux et al. (1989) are of interest. They report, on the basis of palaeoenvironmental analyses of the river deposits, that the greatest ecological complexity in the Rhone River was associated with the wandering reaches. They also speculate that the channel braiding present in the 18th century may have been a response to transient increased sediment yields during the Little Ice Age -- the cold period of the 17th to 19th centuries. This appearance suggests that river morphology may respond sensitively to changes in sediment influx, and the preceding point suggests that the ecosystem may be similarly sensitive to such changes.

Sear and Archer (1998) review the history of gravel extraction from streams in northeast England during the last 50 years. These rivers have quite limited gravel influx and storage, so gravel extraction led to rapid reduction in the quantity of gravel stored along the channels and to degradation. A significant concern was the loss of gravel suitable for salmon and trout spawning. Once this was realized, further extraction was prohibited. Sear and Archer observe that most of the worked channels were originally relatively stable with more or less heavily armoured beds, but that breakup of the armour led to lateral instability, particularly during large floods. This phenomenon is likely the consequence of increased bed material entrainment and transport following the breakup of the armour (cf. Lagasse et al., 1980). They also noted that channels with a natural sediment balance poised between aggradation and degradation are very sensitive to disturbance. Many wandering channels fit this description. They speculate that gravel extraction in areas of aggradation, so long as it remains less than the supply, should not lead to dramatic changes in channel processes or morphology, but they observe that maintaining 'safe' extraction rates is difficult because of large inter-annual fluctuations in sediment influx.

Documented experience of gravel extraction from rivers in North America derives mainly from the United States, where regional geological history has in many places produced only limited terrestrial aggregate resources. The history of gravel removal from California streams has been extensively reviewed by Kondolf (1993, 1994a, 1998a, 1998b). Rivers draining the mountains of California provide by far the most abundant and accessible source of high quality aggregate available in the state. The state mines 120 million tonnes per annum (Kondolf, 1998b), almost all of it from rivers, in comparison with a generous estimate of 13 million tonnes per annum of gravel recruitment to California streams (Kondolf, 1998b). The order-of-magnitude difference between these two numbers is interesting. Many of the extraction projects were originally justified on the basis that the streambed gravel is a renewable resource because of sediment influx, hence that it can be mined in perpetuity without significant net effect on the river channel. The sediment budget of the river, which must be known in order to apply such a concept rationally, in fact is almost never known. Estimates, even by experienced engineers, of gravel influx rates to river reaches have commonly been a similar order of magnitude larger than actual sediment recruitment rates. The discrepancy probably arises from the common misperception that large volumes of gravel observed to be stored in streambeds must correspond with large rates of gravel influx.

In California, many streambeds dry up, or nearly dry up, in summer. It has therefore been easy to extract large volumes of gravel directly from the streambed, and from deep pits in floodplains immediately adjacent to the channel. The result, absent effective regulations (Kondolf, 1994b), has been dramatic degradation of stream beds over distances of many kilometres. Noteworthy cases are summarized by Harvey and Schumm (1987), Sandecki (1989), Kondolf and Swanson (1993), and Florsheim et al. (1998), while Collins and Dunne (1990) give a review of experience in California. Riverbed degradation of order 1 to 5 m in just a few decades is common. Collateral damage has included bank collapse, threatened and collapsed engineering structures (especially bridges), lowering of groundwater tables, and complete reorganization of river morphology.

Cases from Washington state documented by Collins and Dunne (1989, 1990) perhaps provide more indicative experience for British Columbia. Like British Columbia, Washington has extensive deposits of glacial sands and gravels, and so recourse to riverbed borrowing has been much less frequent and less extreme than in California. Three rivers draining the southern flank of the Olympic Mountains in Grays Harbour County present a situation that has some affinities with Fraser River (Table 8).

Table 8. Comparison of Olympic Mountains rivers with Fraser River

Criterion	Humptulips[1]	Wynoochie[1]	Satsop[1]	Fraser[2]
mean flow (m^3s^{-1})	36	37	57	3410
mean annual flood	558	449	766	9790
river gradient	0.0023 – 0.0004	0.0017 – 0.0005	0.0015	0.0006 – 0.00005
bed material influx (m^3a^- 1 bulk volume)[3]	5 000	4 000	8 000	245 000 – 325 000
bed material extraction (m^3a^-1 bulk volume)[3]	30 000	25 000	13 000	91 725
duration of extraction record (a)	25	19	20	36
extraction ratio[4]	6:1	6:1	1.6:1	0.4:1 – 0.3:1

1 measured at the most downstream gauge. Gradient range shown for the reach of interest.
2 Mission gauge
3 Bulk volume; that is tonnes a^{-1}/1.75 tonnes m^{-3}. Includes sand and gravel. Estimates are minima for the Washington streams due to incomplete records. Actual extracted totals may be as much as 2x higher. Gravel extraction for Fraser River is averaged over 36 years of reported data, hence does not correspond with the result averaged over 47 years reported in table 1.
4 Gravel extraction/bed material transport

Scaled by flood flows, Fraser River is about 20x the size of the Grays Harbour rivers, but bedload transport is at least 30-60x larger. Bed material transport in the Grays Harbour rivers has not been measured directly, but has been estimated by several methods, yielding results that vary by a range of about 4x. Median values are reported in table 8. Gravel extraction over extended periods on Fraser River has, however, been only 5 to 10x larger than on the smaller rivers. The smaller rivers are being mined at rates that exceed gravel influx by 1.6 to 6x on average. In some individual years, the difference has been 10x (Collins and Dunne, 1989).

There are some similarities as well between the history of development of these rivers and that of Fraser River. After 1880, woody debris was removed from the channels and side-channels were blocked to enhance navigation and facilitate log drives. Flood protection measures have been put in place throughout the 20th century. Like Fraser River, these are significant salmon spawning streams. There is no other source of serious disturbance along these rivers (a dam in the headwaters of Wynoochie River is discounted as having an insignificant effect.)

The rate of gravel removal in the Grays Harbour rivers has remained relatively more modest than in most cases reviewed thus far. Removals have been limited to amounts scalped off exposed bar surfaces. Nonetheless, significant bed degradation has occurred (Figure 32).

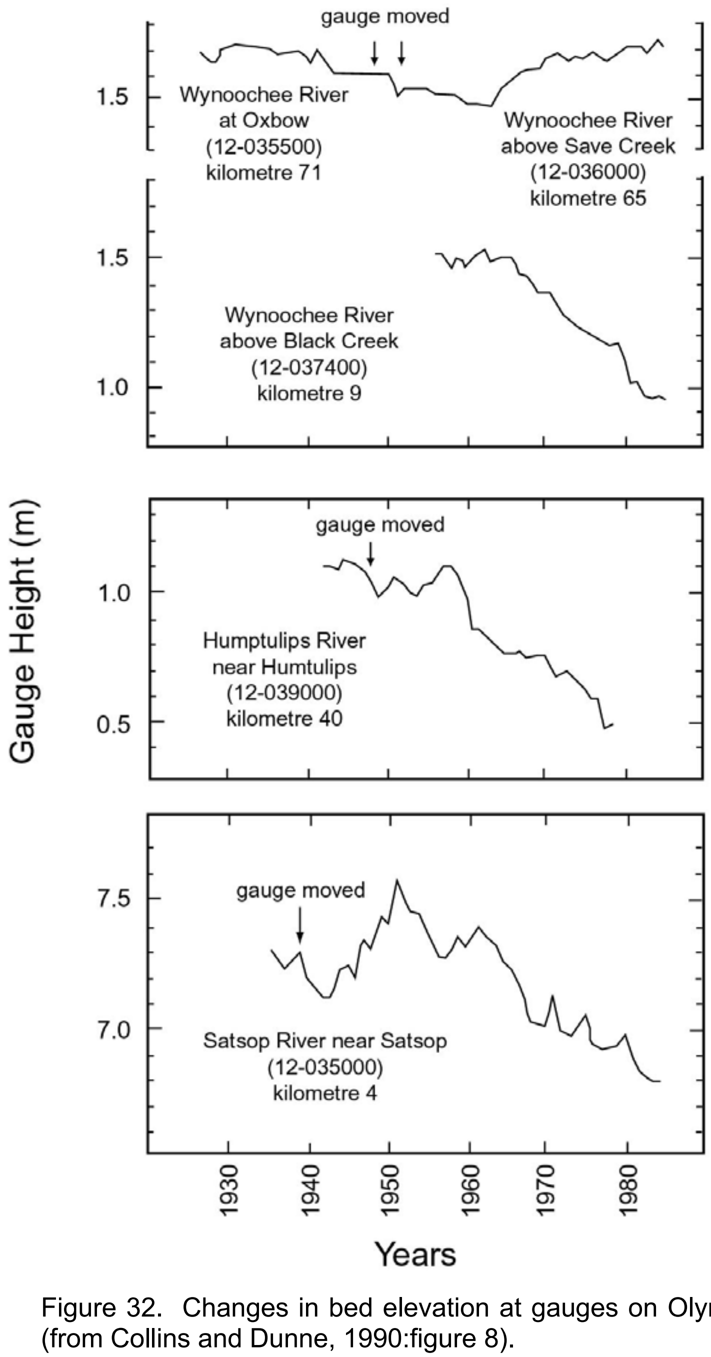


Figure 32. Changes in bed elevation at gauges on Olympic Mountains river, Washington (from Collins and Dunne, 1990:figure 8).

The rate of degradation has been 0.03 m a^{-1} in recent decades in the lower reaches of the Humptulips and Wynoochie rivers, and 0.02 m a^{-1} in Satsop River, with some indications of aggradation upstream of the disturbed reaches. Runoff has remained stable during the period of degradation. Rivers of this type, which are in the same general regime class as Fraser River, are sensitive to persistent removal of gravel at rates that exceed gravel recruitment.

Another instructive example quoted by Collins and Dunne (1990) concerns gravel extraction from a bar on Skykomish River, near Everett, Washington. Measurements from air photographs taken in 1948 and 1961 revealed that a bar near Monroe was accreting gravel at a rate of about 2300 m^3a^{-1}. Gravel extraction began in 1961 at an average rate of 38 000 m^3a^{-1}. By 1969, not only was the worked bar diminished, but so were neighbouring bars upstream and downstream. From 1969, extraction was reduced to 11 500 m^3a^{-1} and the bar grew slightly, but neighbouring bars did not. From 1976, extraction was reduced to about 10 000 m^3a^{-1}, and the reach stabilized. A bend immediately downstream from the worked bar had been eroding at a rate of 4.6 m a^{-1} between 1933 and 1961, but it stabilized after gravel extraction began. The reduction in gravel transfer along the channel stabilized the downstream bank, probably because bar development there ceased.

4.2 BRITISH COLUMBIA CASE HISTORIES

To the writers' knowledge, there has been only one deliberately monitored program of gravel removal on a British Columbia river. That case is Vedder River, near Chilliwack. Three cases in which histories of gravel removal have been reconstructed in much the same manner as in those described above are reported by Sutek and Kellerhals (1989) and are briefly reviewed below.

In the lower Cowichan River near Duncan, gravel removals have been authorized by the Water Management Branch for the purpose of flood control. Cowichan River drains Cowichan Lake, which intercepts effectively all the sediment yielded from the upper drainage basin. The gravel accumulation in the lower river derives from erosion of high banks composed of glaciofluvial outwash downstream from the lake. Minimum estimates of the gravel recruitment rate and an estimate of the amount of gravel removed are given in Table 9. The record of gravel removed and the effect on river bed level at the Duncan gauge, which is 800 m upstream of the most upstream removal, are shown in Figure 33. The gravel was removed by bar scalping, the effect of which was to create a more rectangular channel, with a wider, shallower section, and virtual disappearance of the bars from the scalped reach.

Mamquam River enters Squamish Valley immediately north of the town of Squamish and flows across a large gravel fan to Squamish River. The fan aggrades as the gravel brought down by the river is deposited. Dykes have been constructed to protect the community and Highway 99, and to hold the channel in its current course. Gravel is removed to maintain the level of flood protection afforded by the dykes. Gravel supply is estimated by repeated long profile surveys during a period with no gravel extraction. Gravel extraction records are fragmentary, and only a 4-year period between 1982 and 1986 is reported. The approximate sediment budget is given in Table 9. Local degradation in the channel near the extraction site was as much as 2 m and the pool-riffle sequence was essentially eliminated. The effect at the gauge, located at the head of the fan, is shown in Figure 34. Again, upstream propagating degradation is shown.

Table 9. Documented gravel removals from British Columbia rivers

Criterion	Cowichan	Mamquam	Lillooet	Fraser[1]
mean flow (m^3s^{-1})	52.0	25.5	125	3410
mean annual flood	265	155	538	9790
river gradient	0.0035	0.005	0.002	0.0006 – 0.00005
bed material influx (m^3a^{-1} bulk volume)	2200[2]	25 000	40 000	245 000 – 325 000
gravel extraction[3]	18 000	140 000	30 000	91 725
duration of extraction record (a)	14	4	7	35
extraction ratio	8:1	6:1	0.75:1	0.4:1 – 0.3:1

1 Mission gauge. Data for Fraser River as in Table 8.

2 *Minimum estimate based on surveys in the affected reach and known extraction. Gravel throughput is not considered.*

3 Bulk volume; that is tonnes a^{-1}/1.75 tonnes m^{-3}. Includes sand and gravel. Gravel extraction for Fraser River is averaged over 36 years of reported data, hence does not correspond with the result averaged over 47 years reported in table 1.

Lillooet River at Pemberton is an aggradational reach upstream of Lillooet Lake. The history of channel management here is complex. Around 1950, the channel was straightened to facilitate land development and passage of high flows. Furthermore, the level of Lillooet Lake was lowered (by dredging the outlet) by about 2 m. Both of these actions should have had significant effect in lowering the streambed. However, gravel deposition apparently has offset these effects. Lillooet River has glacial headwaters and drains a significant area of incompetent volcanic rocks in the Mt. Meager area, so its sediment load is substantial. After 1980, gravel was removed from the channel. In Table 9, only gravel removed from Lillooet River is reported: an equivalent amount has been taken from tributaries in the vicinity of Pemberton. Figure 35 shows the specific gauge record for the river. A very slight degradational trend is observed, but there is no detectable change associated with the onset of gravel removal. Gravel supply was estimated by several indirect methods and yielded consistent results. Gravel removal is less than the estimated supply, so the lack of an obvious response is not surprising.

In the last 10 years, a program of systematic gravel extractions has been conducted on Vedder River, the distal reach of Chilliwack River. The reach is on an alluvial fan and the channel is confined within setback dykes, hence the case appears superficially much like that of Fraser River.

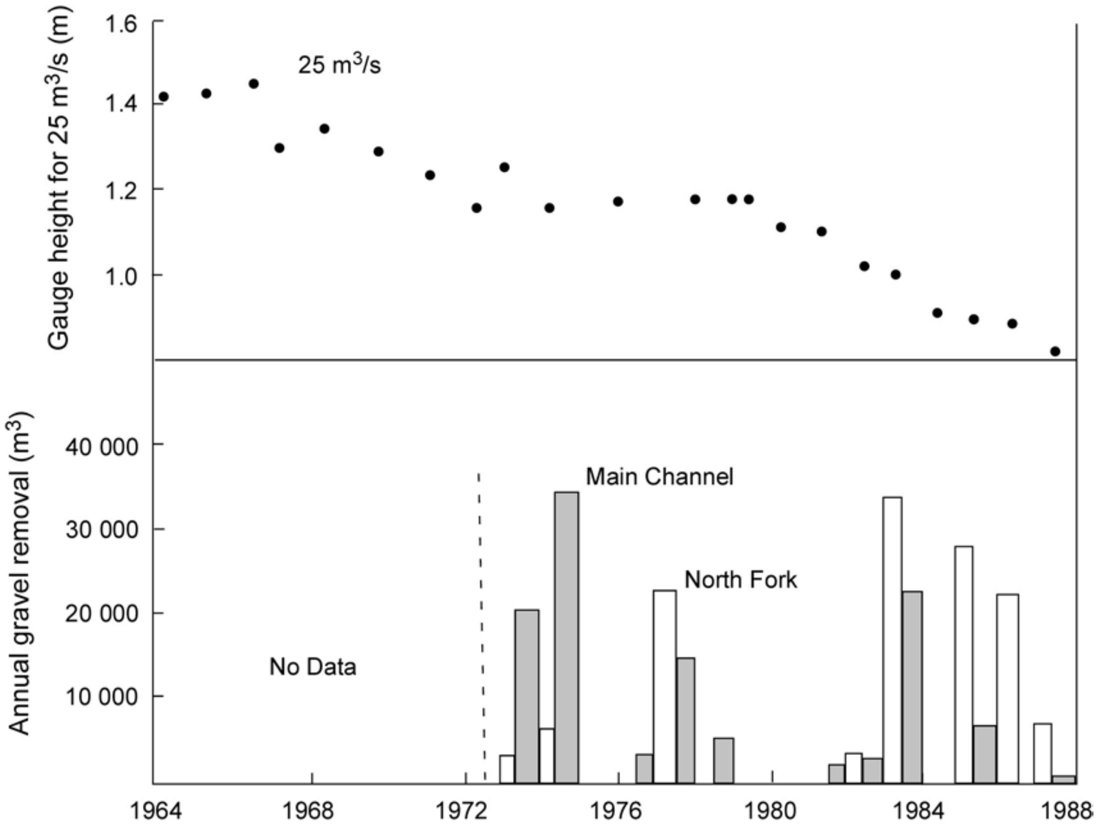


Figure 33. Change in bed elevation at Duncan gauge of Cowichan River and the record of gravel removed downstream.

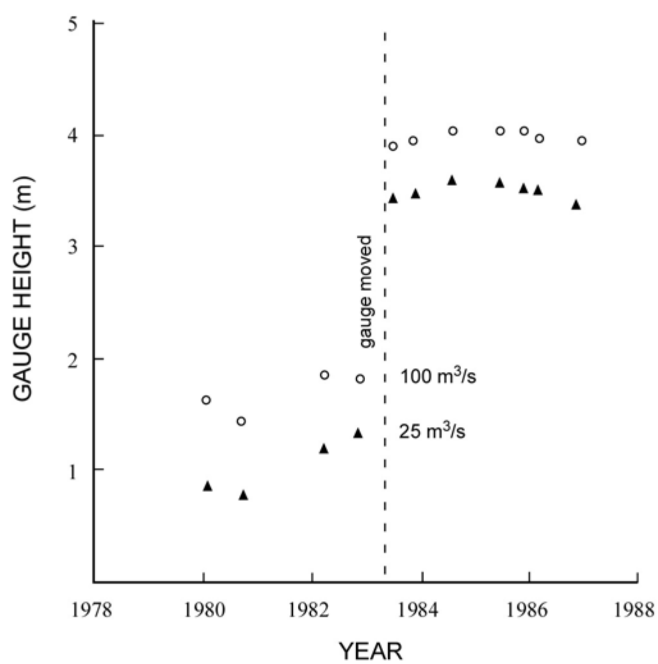


Figure 34. Change in bed elevation at Mamquam River gauge.

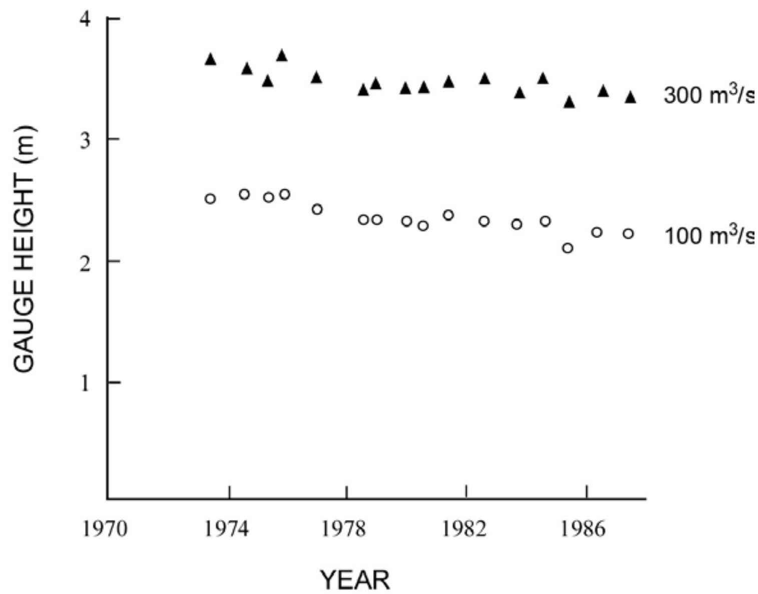


Figure 35. Change in bed elevation at Pemberton gauge on Lillooet River.

The river has a mixed snowmelt/autumn rain flood sequence. Mean annual flood in the dominant autumn flood sequence is 335 m^3s^{-1} and the estimated mean annual influx of bed material to the Vedder reach is 50 000 m^3 (Martin and Church, 1995), so that the sediment transport intensity is about 5x greater on this river than on the Fraser. Furthermore, sediment delivery is even more episodic on this river than on the Fraser; as much as 200 000 m^3 influx has been experienced in the greatest floods. The method for gravel extraction is the excavation of relatively deep pits in the river bed, which are observed to refill after one or a few major floods. There has been only one deep excavation on Fraser River, in lower Minto Channel, which was worked commercially for years. A decade after closure of operations there, the deep pool in lower Minto Channel has propagated upstream, but has not refilled. Since little bed material is transported into Minto Channel, this is not surprising. But the modest intensity of bed material flux in Fraser River suggests that deep excavations would persist for some years almost anywhere in the river. Therefore, the technique cannot be recommended for use on Fraser River. Hence, the Vedder River experience has not been pursued for this report. However, a review of Vedder experience should be conducted with a view to comparing conditions there with those in Fraser River.

4.3 LESSONS LEARNED

The case histories reviewed above provide a consistent view of the effects of gravel mining on river morphology. They also show that other river management actions may have a compounding effect on river channel changes. Important results are as follows:

- Gravel removal from a channel at rates larger than the rate of gravel recruitment produces lowering of the channel bed (degradation). The extraction ratio needs be only modestly larger than 1.0 to realize degradation (cf. Satsop River, Washington).

* Gravel removal at a point, or within a limited reach, creates upstream and downstream propagating degradation. Galay (1983) systematically reviews degradation due to gravel removal and gives further cases.

In gravel-bed rivers, the increase of gradient upstream created by the removal of material increases the competence (size of the largest stone that can be moved) and sediment transporting capacity of the stream, so that upstream degradation propagates fairly quickly. Downstream, water deprived of sediment entrains additional material. This reduces the gradient downstream and, by selective removal of the smaller and more readily entrained material, increases the armour surface of large stones on the streambed. Armouring tends to arrest the downstream propagation of degradation fairly quickly. These effects are most evident when material is removed from a pit in the riverbed. Upstream propagating degradation has been observed in Minto Channel on Fraser River (Church and Weatherly, 1999).

* Gravel removal from a bar causes loss of gravel from neighbouring bars upstream and downstream (cf. Skykomish River, Washington).

This is an example of the upstream and downstream propagation of degradation referred to in the last point.

* Gravel removal from bars creates a wider, more uniform channel section with less lateral variation in depth (cf. Cowichan River: see Figure 36), and reduces the prominence of the pool-riffle sequence in the channel (Mamquam River).

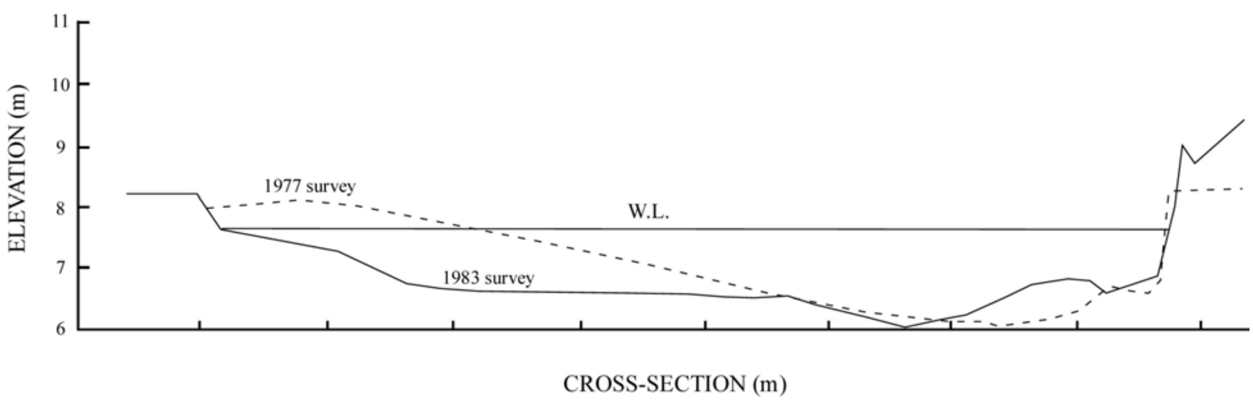


Figure 36. Channel cross-section change after gravel removal, Cowichan River, British Columbia.

An additional case of this phenomenon is reported by Collins and Dunne (1990) from Redwood Creek, in northern California. A multiple-year study there with repeated surveys showed that only a fraction of bar topography was restored in subsequent flood seasons. Similar experiences have occurred on Fraser River (for example, at Foster Bar, following gravel extraction in 1996). Much may depend upon the location of the extraction in relation to currently active zones of sedimentation.

* Channel morphology is simplified as the result of degradation following gravel removal.

Degradation creates a deeper, narrower channel. Back channels are cut off and river-edge wetlands are dewatered. Initially complex channels tend to regress toward being single-thread channels. These effects amount to reduction in habitat diversity. An experiment reported by Lisle et al. (1993) illustrates the degradation process. A channel with sand and fine gravel was established in a laboratory flume as a model of a gravel-bed river. A series of alternate bars was established by a flow with sediment feed. The sediment feed was then reduced to one-third of its former rate (simulating gravel extraction at the feed point). The channel incised by twice its former mean depth and bed particle size increased (increased armouring due to selective removal of the finer grains). The distal bars became emergent.

The efficacy of the process depends upon the competence of the flows to erode the river channel bed. In gravel-bed rivers carrying modest sediment loads, the main channel is often relatively heavily armoured with large material. If the flows are not competent to move this material, erosion to make up the sediment load lost at the point of extraction may instead occur on channel bars and banks. Often, as in Lisle's experiment, limited degradation occurs, and then armouring stops further lowering of the bed

- The pattern of channel erosion downstream from a point of sediment extraction is often attack on alternate banks in turn, leading to the establishment of a meandering tendency in the river.

In several of the case studies, a tendency is mentioned for the river to take up a meandering habit in association with degradation (cf. the Miribel channel). Meandering is a relatively efficient way for a river to reduce its gradient (by increasing channel length). A river with reduced sediment load, which will stabilise with a reduced gradient, takes up such a pattern. Successive erosion and deposition points along each bank build up a pattern of alternate scour and fill to create the meandering channel (Figure 37).

- Gravel removal from the river channel may accelerate erosion and sediment transport locally in the short term.

This happens when the gravel removal destroys the bed surface armour of coarse stones, which mediates the rate of entrainment of bed material. Until the armour is reestablished, sediment may be entrained at an accelerated rate. Bars are often heavily armoured at their upstream end. Removal of this armour may prompt substantial additional erosion after a limited gravel extraction.

- A reduction in sediment load introduced into a river can have effects similar to those associated with gravel extraction.

This point is illustrated in several of the long-term European histories where changed land-use practices have affected sediment yield and river behaviour. In British Columbia, similar histories have been observed casually in relation to forest land use. Dams impose such a change abruptly.

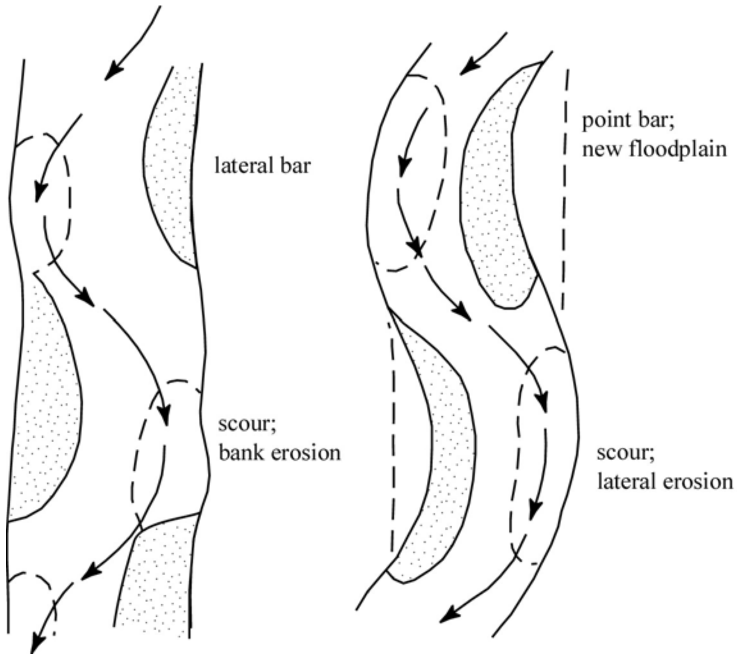


Figure 37. Establishment of a meander channel by alternating scour and fill.

- Constriction of a river channel may have effects similar to those caused by extraction of gravel.

Confinement of a river creates a narrower, deeper channel with higher flow velocities and a greater competence to move bed material. The result is degradation. In this case, however, gravel is not extracted from the channel, so the result is deposition of the mobilized material farther downstream and the onset there of problems associated with aggradation. The case of the Miribel channel on the Rhone River is essentially an experiment on these effects.

This example, along with the examples of up- and downstream propagating degradation, establishes the point that it is not possible to isolate effects of changed sediment supply to a local site along a river channel.

5 RECOMMENDATIONS FOR GRAVEL MANAGEMENT IN FRASER RIVER

In this section, recommendations are made for managing river flood hazard by selective removal of gravel from the channel -- in effect, by lowering the channel bed. This report is restricted to considering gravel removal for purposes of assuring flood security and so gravel removal for other purposes is not considered as a primary activity. It should be recognized, as well, that gravel removal is not the only means by which flood security may be addressed. Gravel removal should be considered in the context of a management plan that examines other actions as well. Such actions might include raising or reconstructing dykes, channel training, land-use zoning, land recovery (into the public domain), structural floodproofing, insurance, and public emergency measures programs. Not all of these actions may be advisable or feasible.

5.1 HOW MUCH GRAVEL SHOULD BE REMOVED FROM THE RIVER?

In sections 2 and 3 of this report, the importance of the bed material transport for the maintenance of the river morphology, hence of the riverine ecosystem, is explained. The implication of these discussions is that large volumes of gravel should not be removed from the river in a relatively short period. In particular, section 3.1 presents evidence that significant changes in the movement of bed material through a river produces significant degradation accompanied by radical changes in channel morphology.

Histories of gravel removal from river channels mostly demonstrate the dramatic effects of removing quantities far in excess of supply. Major degradation and trenching of the channel follow. A small number of cases have been found in which the gravel extraction rate is comparable with supply. Lillooet River has been subject to channelization and base level adjustments as well, so is not an easy case to interpret. Satsop River, Washington, and Fraser River itself are the most significant cases. Satsop River may be compared with neighbouring rivers with similar sediment supply that have been more heavily mined. They all have degraded significantly. Satsop River has a reported extraction ratio of 1.6:1, but neither the sediment supply nor the extraction rate are known very precisely, so the extraction ratio should not be regarded as a precise figure. It indicates merely that extraction has been comparable with sediment supply or has exceeded it by a modest amount. All three of the Washington state rivers, in their distal gravel reaches, are morphologically simpler channels than Fraser River today as the result of river management activities during more than a century.

Fraser River has been subject to a modest rate of gravel extraction for nearly half a century. The extraction ratio is estimated to be between 0.3 and 0.4. The river has continued to aggrade. If gravel extraction is to be used as a means to eliminate aggradation along the river, it appears as if the rate of removal should be increased by 2.5 to 3x. The best estimate of the gravel budget (p.23) downstream from Agassiz -- the reach where significant aggradation occurs -- falls in the range 170 000 - 230 000 m^3a^{-1} (bulk volume). Allowing a sand fraction of 30% in the deposits, the gross volume deposited is estimated to be in the range 245 000 - 325 000 m^3a^{-1}. The median figures are 200 000 m^3a^{-1} gravel and 285 000 m^3a^{-1} gross. In the present state of our knowledge, 285 000 m^3a^{-1} appears to be a prudent limit figure for annual removal of bed material from the gravel-bed reach of the river.

However, the supply of gravel to the river is highly variable (see Figure 13). Sometimes, a considerable number of years pass when flow fails to reach mean annual flood level. In these years, small quantities of gravel are recruited into the reach. Maintenance of a steady rate of extraction through such a period may not be desirable. Nor, on the other hand, should extraction rates be increased automatically in response to a major flood. Such an action, in combination with a steady base rate of removal will result in removing more than the intended volume from the river. These issues may be addressed by relating gravel removals over a relatively short period to the pattern of sediment influx predicted from the Agassiz rating curve.

The rates of gravel removal discussed in these paragraphs should be recognized as limit amounts. If there appears to be no reason rooted in the mitigation of flood hazard to remove so much sediment from the river, then only smaller amounts should be taken. From the perspective of riverine habitat maintenance, the most desirable amount would be zero (except, possibly, in the case of excessive siltation in productive side-channels). However, it may also be desirable that some individual extractions exceed the limit rate in a particular year in order to economically resolve problems of flood security presented by excessive gravel accumulation at a particular site.

Recommendation 1

The rate of bed material removal for the next several years should not exceed 285 000 m^3a^{-1}, on average, although individual operations might exceed that figure when best engineering judgement indicates that larger extractions must be made to improve water levels locally to assure flood security.

Recommendation 2

The bed material extraction ratio should not exceed 1.5 in comparison with the best estimate of gravel recruitment over the most recent 5 year period.

The best estimate of sediment influx to the reach downstream from Agassiz in any short-term period -- indeed the only estimate available -- is derived from the annual rating curve (Figure 12). Figure 38 shows the 5-year running mean of the record as it would be applied following recommendation 2. In Recommendation 2, the factor 1.5 is applied in view of the apparent negative bias of the rating curve (cf. the gravel influx estimates in Table 3). This leads to a lower recommended limit for extraction in periods of minor gravel recruitment (e.g., the decade from 1978 through 1997), but higher levels may be possible following major gravel influx (e.g., the mid-1970s).

The value 285 000 m^3a^{-1} is selected as a limit figure for bed material extraction in comparison with the median of the best range of estimates of the 47-year recruitment rate of bed material. It yields an extraction ratio of about 1.0. However, none of the figures is precise. Therefore,

Recommendation 3

Recommendation 1 should be implemented in a precautionary and adaptive manner. Each extraction should be regarded as an experiment, with physical and biological surveys conducted at each extraction site before and after removal, and follow-up monitoring to determine the net impact over several succeeding years. In addition, monitoring of riverwide morphological conditions should be undertaken. As soon as the results from several sites are consistently interpretable and trends in mean channel condition are discernible, recommendations 1 and 2, and all others in this report should be reviewed and revised.

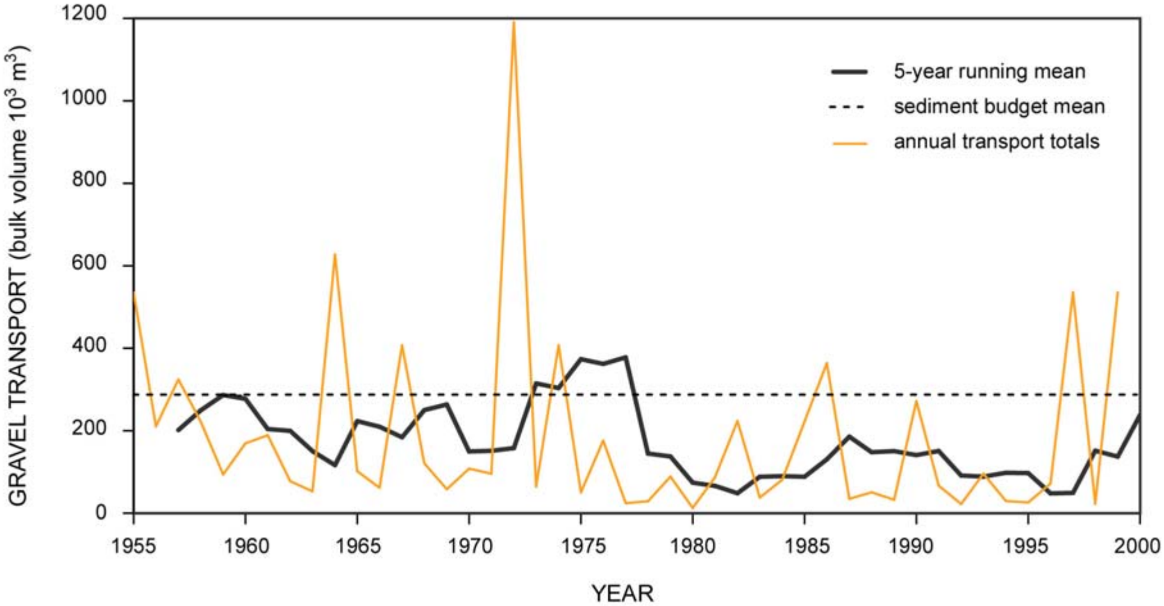


Figure 38. Annual bed material influx at Agassiz (m^3 bulk volume) as observed in the WSC program or estimated from the rating curve. Also shown, a 5-year running mean. The running mean is plotted in the year following the end of the 5-year averaging period to simulate the 5-year average in recommendation 2. The dashed straight line indicates 285 000 m^3a^{-1}. It exceeds the transport figure in most years because of suspected bias in the transport figures.

Implementation in a precautionary manner implies caution in predicting the consequences in the environment of anticipated actions (in this case, predicting the impact on the river environment of removing bed material from the river) (Stebbing, 1992), in order to ensure that actions remain within the bounds of the system to absorb them without significant loss of character or quality. Caution in this case is necessary because we do not know the sediment budget precisely (and are unlikely to acquire precise knowledge in the near future) but, more importantly, because we do not know the level at which the rate of gravel extraction would begin to degrade the quality of the riverine ecosystem.

Proceeding in an adaptive manner implies a readiness to review and modify procedures as soon as accumulated experience indicates the necessity or opportunity to modify actions so as to achieve the major goals of assuring security from flooding and maintaining or enhancing the riverine ecosystem in a more effective manner than under current procedures. It also implies deliberately monitoring current procedures and outcomes to ensure that experience is accumulated and appraised in a systematic way.

Riverwide monitoring implies periodic surveys to determine morphological characteristics such as mean channel width, braid ratio (ratio of total length of channels to length of the main thalweg), island area, and exposed bar area at low flow. Most of these measures can be obtained from air photographs.

Constraints on the rate of gravel removal should be applied locally, as well. The gravel transport declines along the reach. The rate of gravel removal should not approach the total transport rate, on average, in the upstream part of the reach, in order that sufficient material may continue downstream to maintain normal turnover and renewal of gravels. This constraint becomes less imperative near the downstream end of the reach where gravel is no longer moved on.

Recommendation 4

The rate of gravel removal in any short sub-reach along the river should not exceed one-half the estimated local bed material transport rate in a sequence of three consecutive years, except near the downstream limit of gravel deposition (downstream of km 110).

This recommendation prevents massive removal of gravel in the short term from a single site. A problem with implementing it is that the bed material transport rate is not known on a year-to-year basis along the river. The best approximation available is to take the 47-year average of sediment transport along the river and to scale it by the transport at Agassiz. This result is presented in Figure 39. Actual values can be recovered by multiplying the scale factor at any place along the channel by the transport estimated at Agassiz during the preceding three years. It would be sufficient to approximate the scale factor shown in Figure 39 with a linear trend.

5.2 WHERE SHOULD GRAVEL BE REMOVED?

The conditions established at the end of section 3 impose fairly stringent limitations on gravel removal activities from any river in which it is desired to maintain a viable ecosystem. These limitations are to preserve the full range of topographic variability in the channel and to avoid dramatic change in the duration or severity of stressful flows. They immediately place two constraints on any gravel management plan for the river:

- systematic lowering of bar tops along an extended reach should not be contemplated;
- persistent removal of bed material at one place equivalent to the transport there, so as to interrupt the downstream progression of the entire bed material load, should not be contemplated.

The reason for the first constraint is that systematic lowering of bartops would eliminate bartop habitats that are important during high flows. It would also eliminate the possibility for new island development in the affected reach. The second mentioned practice would lead to degradation immediately upstream and downstream with channelization of all flows and significant reduction in topographic variability within the affected reach. Bartop environments and bar-edge environments with low lateral gradients would be significantly reduced over a period of years.

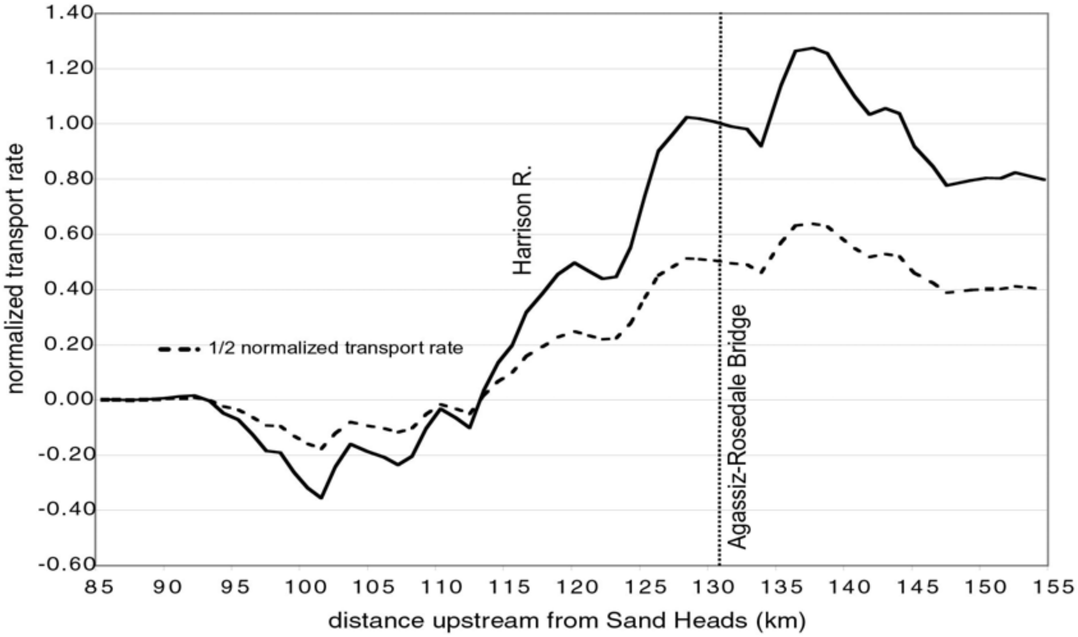


Figure 39. Scaled distribution of bed material transport in the gravel-bed reach of Fraser River. The scale is based on the 47-year average transport estimated from the sediment budget. The transport at the Agassiz-Rosedale bridge is assigned a value of 1.0

A prominent feature of sedimentation in the river allows these constraints to be respected without preventing gravel removal. Section 2.6 describes how major gravel buildup occurs at a restricted number of places along the river where the overall configuration of the channel causes much of the bed material load to be deposited. In these places and immediately upstream, water levels may be increased as the result of channel blockage by the deposited sediments and increased resistance to flow that may result from the channel constriction or modified channel alignment. Three characteristic situations occur:

1. Narrowing of the channel zone caused by the presence of erosion resistant banks. At high flows, the river backwaters upstream until the drop in water level through the constriction is sufficient to drive the flow through. Bed material is deposited in the backwater. An example of this situation is the constriction at the Agassiz-Rosedale Bridge (Figure 40) caused by the high banks on the left (south) side upstream of the bridge (composed of landslide earth) and the heavily protected right (north) bank. The protection was established to secure the bridge and powerline crossings. Persistent aggradation occurs on lower Herrling Island.

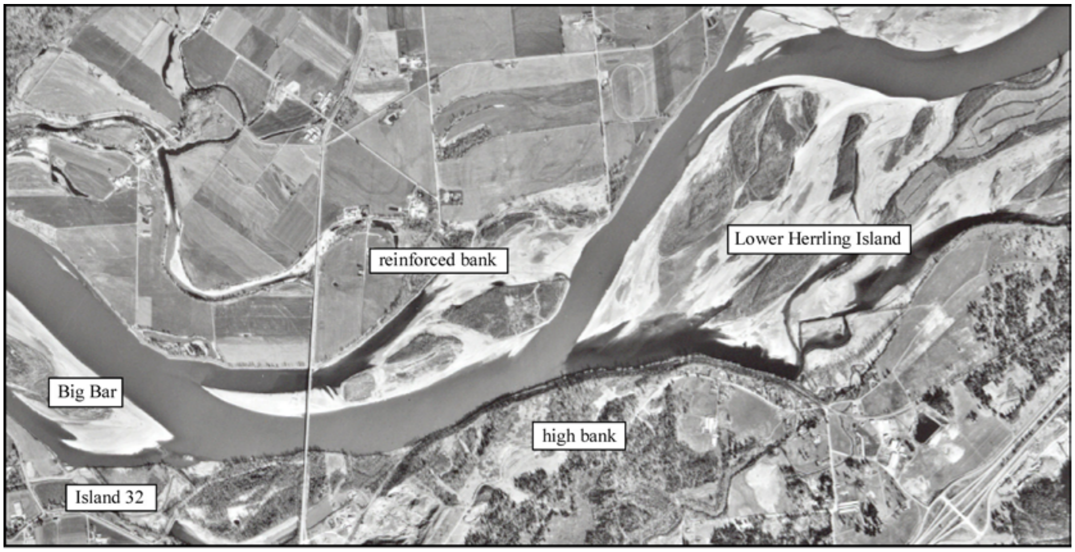


Figure 40. Air photograph (1999) showing the constricted channel at the Agassiz-Rosedale Bridge and the sediment accumulation upstream on Lower Herrling Island.

2. High flow resistance, and possibly channel narrowing as well, where the river is forced to turn abruptly or to find a course through extensive island and bar topography. The current channel at the mouth of Harrison River is an example of this situation (see Figure 18). Sedimentation occurs on Harrison Bar. Another example of complex river morphology upstream of a sharp bend occurs in the Gill Island/Hamilton bar area (Figure 41).

3. High flow resistance where the river crosses a high riffle. An example of this situation occurs downstream of Wellington Bar in the area known as Chilliwack Rock. Here the river crosses a very long diagonal riffle (that incorporates Wellington Bar and the bars downstream to the Sumas River mouth) in several small, shallow channels (Figure 42). Backwater above this bar and excessive flow divergence lead to persistent shoaling of the channels here.

Situations of the first type will persist so long as the river remains confined downstream. The confinement at the Agassiz-Rosedale Bridge is effectively permanent, but the channel zone upstream is very wide, providing a large capacity to store material. Situations of the second and third types are transient. Eventually, changes in river alignment will eliminate the problem, but not before the passage of some years or, perhaps, the occurrence of a large flood. To deal with these situations, the following recommendations are made.

<u>*Recommendation 5*</u>

In situations of types 1 and 2, gravel should be removed from the bar surface and riverward flank within the downstream two-thirds of the bar area in order to increase high flow conveyance of the channel and reduce local and upstream water levels.

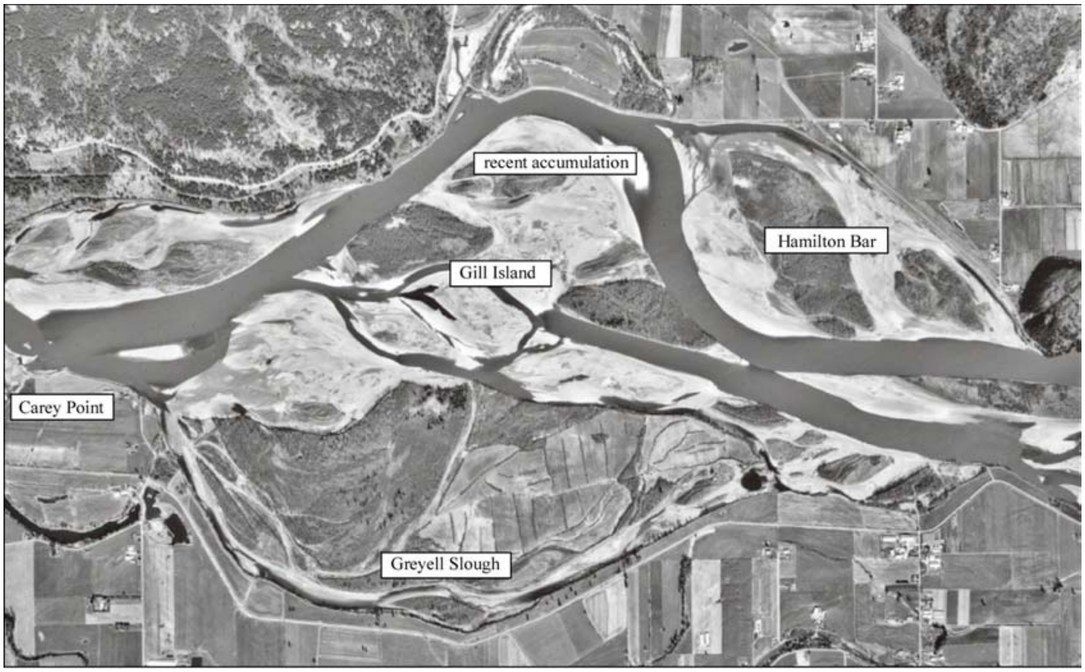


Figure 41. Air photograph (1999) showing the complex channel morphology and sediment accumulation in the vicinity of Gill Island and Hamilton Bar.

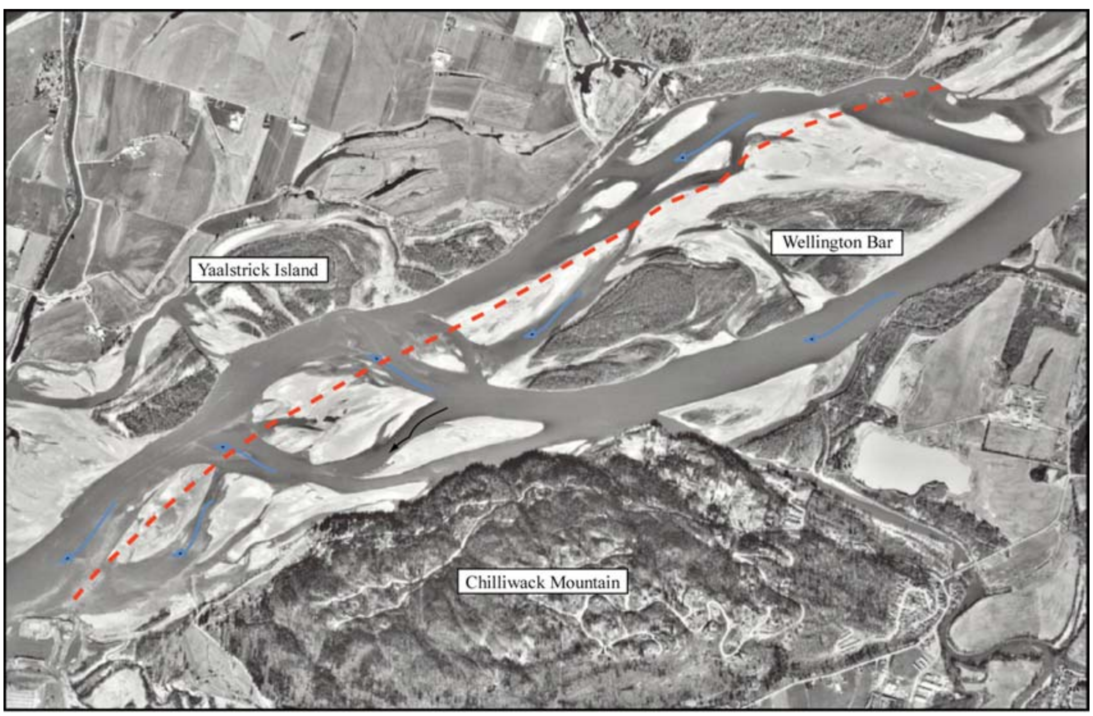


Figure 42. Air photograph (1999) showing the long diagonal riffle downstream from Wellington Bar with several shoal channels carrying the flow and intermediate flows through the riffle.

Material should not be removed from the headmost portion of the bar. This is an area of high flow attack, which customarily is relatively heavily armoured with larger material at the surface. The removal of this surface might destabilize the bar and river channel in unforeseen and undesirable ways. In addition, the highest points on the bar should not systematically be removed, for reasons discussed above.

Recommendation 6

In situations of type 3, a major bar-crossing channel should be developed by removing gravel from the wetted channel on a favourable alignment. These cases will be related to navigation requirements on the river. Choice of alignment should consider the likelihood that the river will maintain the selected alignment for some time; the practical needs for navigation; and the likely effects downstream of the resulting alignment of the current. Likely alignments are apt to be already present in the form of chutes across the bar.

In this case, river bottom armoured surface may be disrupted. However, riffles are points of persistent exchange of gravel, so that armour development is not heavy. Material might be removed from the channel or scuffled into the downstream pool, according to the needs of the program.

Another circumstance in which it may seem desirable to remove gravel is when gravel accumulation affects the river current so that the river threatens to erode banks that are deemed important to maintain. The principal situation in which this might occur is where the river threatens to impinge on the main dykes, or on some significant public facility (such as the railway). The gravel accumulation and consequent water levels may not be particularly high. In this situation, it should be recognized that the accumulation might be the consequence of river alignment established by other factors, and not the cause of the problematic river alignment. Gravel removal in these cases may relieve the severity of the immediate attack by the river but may not solve the problem of unfavourable alignment. Thorough studies will be necessary to find the best strategy to assure the integrity of the threatened feature. Gravel removal should not be regarded as the automatic solution to the problem.

5.3 WHAT IS THE BEST MANNER BY WHICH TO REMOVE GRAVEL?

Strategies for removing gravel from the active channel zone of a river can be reduced to three broad categories: (1) deep pits dug in or immediately adjacent to the main thread of the channel; (2) continuous dredging of the channel bottom; and (3) bar scalping (see Figure 43a). The second of these strategies is usually associated with navigation improvements. A modification of this strategy is to remove gravel from shallow places, such as riffles, but to leave it in the channel for onward transport and redeposition. All three strategies have been applied in the gravel reach of Fraser River, but the dominant one has been bar scalping. Kellerhals et al. (1987) reviewed gravel extraction experience on the river up to the mid-1980s.

Deep pits are economical from a gravel mining perspective, since access can be arranged and equipment can be committed for recovery of a substantial volume of material. For control of gravel aggradation, the strategy may also be effective where the influx of sediment is relatively high and it can be intercepted in the pit. This strategy has been followed on Vedder River for some years. The interception of a substantial portion of the bed material load creates sediment "starvation" downstream and may lead to degradation that progressively alters channel morphology in the manner described in various case studies (see section 3). On Fraser River, a deep pit was mined for a number of years in lower Minto Channel. A secondary channel is the most feasible location in which to locate such an operation on Fraser River since currents in the main channel would make operations difficult. In the short run, a deep pit in a secondary channel may not relieve problems of sediment buildup along the river since relatively little bed material transport may be directed into the secondary channel. This is the case in Minto Channel where, some years after cessation of mining, a deep pool still exists and has migrated upstream in the channel (Church and Weatherly, 1998).

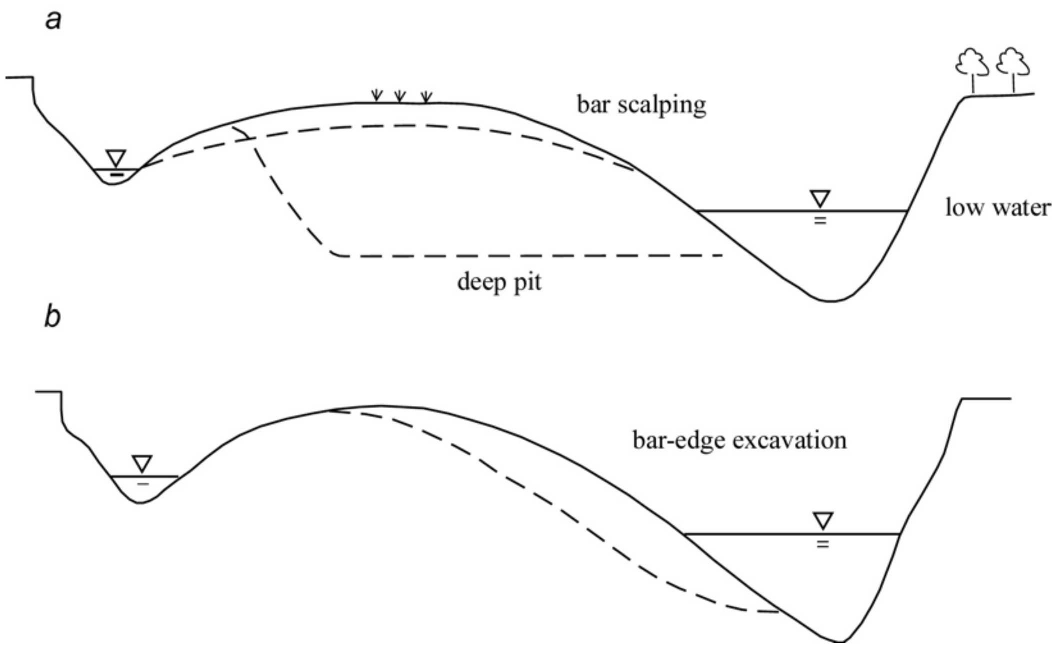


Figure 43. Alternative geometries for gravel extraction from the channel zone: cross-section through a bar with minor secondary channel.

"Continuous dredging" of the channel bottom in Fraser River has been restricted to scuffle dredging or excavation of relatively short reaches (200-500 m) through riffles to facilitate tow boat and log boom navigation. Only recently excavation has occurred (at Chilliwack Rock/ Webster Bar, in September, 2000) and, even in this case, the material was left nearby in the channel. Insofar as this activity facilitates drawdown of water over the riffles it should have a minor effect on upstream water levels. The environmental effects of many years of scuffle dredging have not been studied but there is no reported major effect on the channel morphology or habitat.

Bar scalping has been the only method approved for systematic removal of gravel from the channel zone in recent years. This activity can be conducted during the low-water time of year (January 15-March 15) entirely on dry surfaces, hence has no immediate effect on water quality. Suitably constrained, it avoids spawning sites. The usual strategy has been to lower the bar top to a smoothly convex surface with continual slopes of 1^{o} to 2^{o} toward the water (in order to avoid fish stranding during subsequent declining stages). A featureless, semi-planar surface is left. The technique presents several problems from a habitat perspective:

- It disturbs a relatively large area of channel bed in comparison with the volume of material removed. This activity leaves a loose surface that is subject more readily to entrainment, especially of fine material, on the next freshet than is the normal, armoured bar surface.
- It eliminates irregularities created by sedimentation on the bar surface that constitute the microhabitats where juvenile fishes congregate (cf. section 3.3).
- It reduces the elevation of the bartop area, which provides the available habitat at normal high water stage in the river.
- Persistent elimination of bartops will eventually eliminate island formation and reduce shoreline length, hence reduce the incidence of important nearshore habitat.

The third point is particularly important since alternative habitat niches are most limited during high water.

On balance, bar scalping appears less favourable for habitat protection than has been supposed. Since a relatively shallow excavation is made, it may also have little effect on water levels nearby because relatively little water moves across bar tops, even in high flows. Persistent scalping eventually reduces both onward transport of bed material and general water levels through a reach (cf. the example of the Washington rivers; section 4.1).

Insofar as gravel removal can be an effective tool for reducing water levels locally, it must affect a substantial increase in channel conveyance in the short term. This requires the removal of a significant amount of material from the main channel. A strategy to achieve this consistent with maintaining the morphological features of the river could be called *bar-edge scalping*. This would consist of removing a wedge of material from the bar face to widen the main channel (see Figure 43b). The excavated section is a parallelogram that preserves the previously existing bar-face gradients and top elevations. The thickness of the slice can be varied to suit design needs for increased conveyance. The excavation could run most of the length of the bar and continue to the bar tail, but it should not remove the barhead area, which is usually both shallow and heavily armoured. The overall stability of the bar, hence of the channel, depends strongly on the continued stability of the barhead. Design details would vary with the morphology of individual bars.

An obvious disadvantage of this proposal is the need for excavation in the water. There are three reasons why this is a significant concern. First, it affects water quality downstream by releasing quantities of silt from the bed; second, it may disturb areas with high potential for spawning; and third, it may impact populations of benthic organisms. In comparison with other desiderata, the need to maintain water quality by avoiding all mobilization of silt may have been overemphasized. During excavation (using a hydraulic clamshell bucket) of a riffle crossing at Chilliwack Rock in September, 2000, turbidity measurements showed that incremental turbidity dissipated within about 500 m downstream (L.Rempel, personal communication, March, 2001). Interference with spawned sites is a significant concern, to be avoided by careful scheduling. However, alteration of gravel quality in potentially spawnable sites may be less serious. It is natural sedimentation processes in the river that create spawning quality gravel and so, provided sedimentation processes are reestablished at the site after excavation, there should be no permanent damage. Potential impact on benthic invertebrates remains the most difficult issue to judge. These organisms move and colonize sites by a variety of strategies. Species that can move only locally (i.e., on the order of 10s of metres) may be strongly affected for some time. On the other hand, species that can swim strongly, ones that drift into position, or ones that are inoculated onto a site from airborne adults may recover quickly. Rempel et al. (1999) found that most species in Fraser River appear to move many tens of metres at least in a season simply to avoid untoward effects of seasonal flooding but, in that study, origins and destinations of individuals were not determined.

<u>*Recommendation 7*</u>

The technique of 'bar-edge scalping' should be investigated as a relatively effective gravel extraction method for improving channel conveyance whilst maintaining characteristic river morphology. Trial excavations should incorporate monitoring programs to investigate silt release, effects on subsequent gravel quality for spawning, and impacts on benthic invertebrates.

Further steps may be taken to maintain suitable bar-face geometries for juvenile fish. Nooks and bays are important features along the channel edge. By "stepping" the excavation down by 0.5 to 1 metre at several positions along the excavation, and by producing longitudinal undulations on the excavated surface (as sketched in Figure 44), such features will be maintained at the water edge over a range of stages. These features are particularly important on the intermediate and upper faces of the bar, when offshore currents are relatively strong.

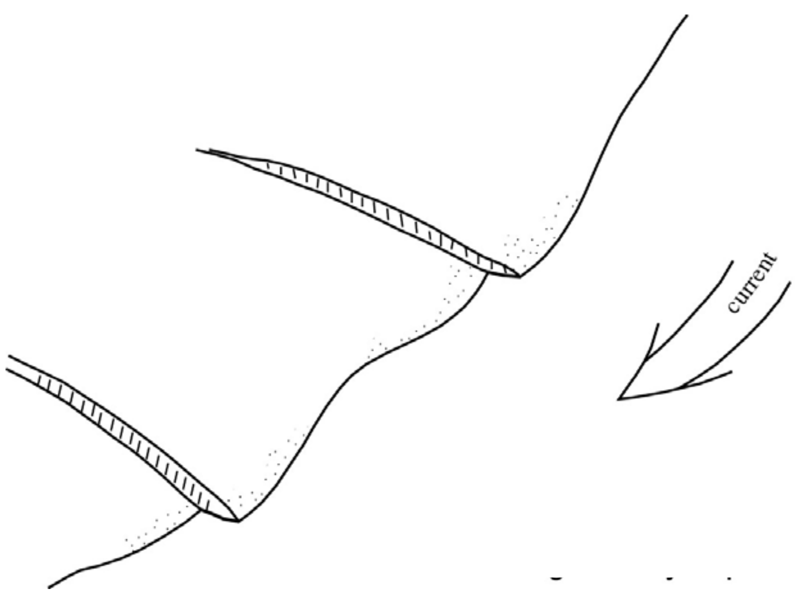


Figure 44. Detail of proposed bar-face excavation geometry to preserve microhabitat features.

<u>*Recommendation 8*</u>

Extractions should be designed to mimic sedimentary features that create irregular bar edges in order to maintain physical microhabitat features.

The methods recommended here have not been tried before in a systematic way, so far as the authors are aware. Therefore, both extraction operations and subsequent habitat characteristics should be monitored closely to determine the costs and feasibility of designing and executing such excavations, and to determine their ecological effect (following recommendation 3). Some conventional bartop scalping might still be conducted to yield comparative information.

5.4 HOW FREQUENTLY SHOULD GRAVEL BE REMOVED FROM A SITE?

The answer to this question depends upon three criteria:

- the effect of gravel extraction on subsequent site morphology;
- the effect of repeated extractions at a site on downstream bed material transfer and river morphology;
- the effect of repeated disturbance at a site on fishes and benthic organisms.

At sites where sedimentation is still active, excavated material may be replaced relatively quickly (cf. Harrison Bar, which recovered an estimated 10 000 m^3 in the moderate 2000 freshet after an excavation of 70 000 m^3) but, at other sites, material and elevation may not be recovered for a long time. Foster Bar has not recovered material to replace that removed during a large excavation in 1996.

The second issue can be addressed by considering experience elsewhere. When the quantity removed approaches or exceeds the bed material transport past the site, onward sediment transfer is interrupted and significant degradation occurs downstream (cf. the examples from Washington state quoted in section 4.1). If the practice continues, channel morphology will become simplified. In most cases, chronic accumulation of sediment continues at a particular site for only a few years, after which the channel alignment is sufficiently modified by the fact of the local aggradation to change conditions and end the accumulation. The recent history at Harrison Bar appears to be a case where a large volume of sediment has accumulated for natural reasons and significant erosion is occurring immediately downstream.

There is very little information with which to address the third issue. The work of Brown et al. (1998) showed that persistent extraction of gravel modifies the aquatic environment and occurrence of both benthic organisms and fishes, but these results were observed in relatively small streams subject to a substantial rate of gravel extraction. In Fraser River, ecological studies are currently underway to assess the effect of gravel extraction on the occurrence fishes and benthic organisms at a number of sites paired with ones that have no history of extraction. No outstanding effects have been detected so far (L. Rempel, personal communication, March 2001), but none of the sites has been subject to repeated heavy extraction. The major pit excavation in Minto Channel, which was worked for many consecutive years, contains good numbers of fishes today.

In face of imperfect information, it is appropriate to proceed in a precautionary way.

Recommendation 9

Gravel should not be extracted in consecutive years at any site. Repeat extraction should not be considered at any site where there is evidence for ecological stress in the form of significantly changed occurrence of benthic organisms or fishes except in the case of chronic aggradation that presents a significant risk of breaching flood security.

“Significantly changed” should be judged in comparison with the total relevant data set obtained from research and monitoring activities in order to define normal sampling and temporal variance. “Significant risk” means that that a freshet with moderately frequent probability for recurrence appears likely to breach flood security.

5.5 HOW MUCH GRAVEL CAN BE REMOVED BEFORE MORPHOLOGICAL AND ECOLOGICAL EFFECTS BECOME SIGNIFICANT?

In section 5.1 it was noted that there is a gap in observations between rivers that have suffered heavy extraction of gravel and consequently exhibit dramatic changes in both morphology and ecology, and ones that have had only light extraction (extraction ratio significantly less than 1.0) and exhibit no obvious effects. A program to manage flood hazard on Fraser River that includes planned extraction of gravel would therefore be an experimental program.

It is important to recognize three complicating factors in assessing how much gravel might be removed from the river:

1. Other activities along the river, notably persistent hardening of banks, are contributing to morphological simplification. These activities themselves influence the pattern of downstream sediment transfer (because bar deposition and bank erosion are characteristic processes in the staging of bed material along the channel). They also have ecological consequences in the long term with or without gravel extraction. The combined effect of all activities along the river may affect the ecosystem out of proportion to the effects of the individual activities.

2. Some of the most valued elements of the ecosystem (for example, salmonine fishes) are under heavy exploitive stress. This may confound attempts to isolate the effect on them of gravel extraction activities alone.

3. Appraisal of the limit extraction ratio depends upon knowledge of the sediment budget. In Fraser River, we have better knowledge now than in almost any other major river, but we still do not know the sediment budget precisely, and we do not know in quantitative detail how it may change in the longer term due to changes in sediment supply.

These considerations suggest that the extraction ratio should not be allowed to exceed the long-term rate of supply until knowledge of both the sediment budget and the effects of gravel extraction are substantially improved as the result of experience and monitoring. Nor should it be allowed to exceed the apparent rate of recruitment in a relatively short period, say 5 years. These recommendations are already incorporated in recommendations 2 and 3.

6 THE LONG TERM

A century is not very long in the life of Fraser River. However, it encompasses the period of significant human modification of the riverine environment, and it represents an outer strategic planning horizon that we are apt to allow ourselves for managing the river. This period is long enough to raise a number of additional questions concerning the sediment budget and the riverine ecosystem.

6.1 THE LONG TERM PAST

Lower Fraser River appears to retain a satisfactorily functioning ecosystem. But it is by no means a pristine ecosystem. Healey (1997) has summarized major environmental and social changes within the Lower Mainland over the past 150 years. Human modifications of the riverine environment have already worked major changes. Amongst significant changes are the following:

- clearance of natural vegetation from most of the riverbanks;

The natural riparian vegetation would have been cottonwood forest with heavy undergrowth in areas of relatively recent floodplain construction (< 150 years), and cedar-hemlock forest in old-established floodplain areas. Only fragments of these forests are left along the river. Their removal has drastically changed the quality of near-bank habitat and local recruitment of carbonaceous matter to the river.

- drainage and filling of floodplain wetlands;

The Fraser River floodplain formerly included many major wetlands, the most prominent of which was the former Sumas Lake. These flooded regularly during freshet and provided important "escape" terrain for rearing fishes from the fast waters of the flood. (On the other hand, it is likely that many fishes became stranded in these areas in late summer, as well.) These areas were also recruitment areas for carbon and nutrients of major importance for the riverine ecosystem. Drainage and dyking have isolated Fraser River from its floodplain and have thereby dramatically simplified the ecosystem:

- isolation of back channels and side channels from the river by dyking;

According to Rosenau and Angelo (2000) 103.5 km of minor channels have been isolated from the river by dyking (some with the provision of control gates to maintain water flows). Again, this represents loss or dramatically reduced effectiveness of significant escape and rearing habitat, and nutrient recruitment. These channels were possibly the most productive waters of all in their original state.

- elimination of large woody debris from the channel;

This effect is the consequence of a century of snagging on the river and, in recent years, the operation of a debris trap at Hope. The original purpose of this activity was to facilitate riverboat navigation. In more recent years it has been continued for the safety of navigation and on the theory that it represents sound (and tidy) environmental management. In fact, it represents bad environmental management. Large woody debris is an important morphological feature, habitat feature, and source of carbon in Pacific Northwest rivers. Its elimination is another aspect of the simplification of the riverine environment.

- hardening of banks;

About half of the outer banklines of the river are now hardened (Table 5; 46% if natural bedrock sections are excluded). Most of the hardening is by rock riprap. The tabulated figures are probably a minimum estimate because there are sections of old, severely degraded bank protection along the river that probably were not all identified in the mapping exercise that led to Table 5. The practice today, furthermore, remains prescription of additional bank hardening wherever the river approaches the dykes or threatens property, so this trend is apt to continue. The practice not only reduces the quality of near-bank habitat (see the review by Schmetterling et al., 2001), it also interferes with the transfer of bed material through the gravel-bed reach. Successful bank hardening eliminates erosion, which interferes with the process of sediment exchange by which bed material is moved through the river. The remaining unprotected banks -- largely in islands -- accordingly come under increased attack, and sediment is remobilized more rapidly from bars within the channel zone. The results are increased instability within the channel zone, reduction in island area, and more rapid movement of bed material into the distal parts of the reach.

- gravel extraction;

This factor has been extensively reviewed in this report.

- noise and traffic;

This factor, particularly the extensive use of motors on the water and the dramatic increase of human traffic along shorelines, has not been systematically evaluated in relation to riverine wildlife. Noise and traffic have increased substantially within the past 30 years. There is no doubt that traffic has some effect on fish behaviour; casual observation is sufficient to show that fish exhibit avoidance behaviour whenever they are approached. Noise in the marine environment is only just beginning to be recognized as a problem for mammals; whether it systematically affects fish is unknown.

The net effect of these factors has been to create a riverine ecosystem already substantially simplified and less productive than it originally was. How much less productive cannot be known. The only long records of system productivity are those associated with commercial fish catches which themselves represent an additional and confounding effect.

All of these factors also confound attempts to isolate the effect on the riverine ecosystem of gravel removal. There is no practical way to isolate the effects of the known 35-year history of gravel removal from the channel. Contemporary studies may isolate elements of the processes that affect the system, but even these cannot be entirely isolated from some of these other influences.

6.2 THE LONG TERM FUTURE: SETTLEMENT AND SOCIETY

The future of lower Fraser River is tied up with the future of human settlement and activity in the Lower Mainland (see Healey, 1997). Urbanization will continue to increase as the area will continue to be a magnet for immigrants. Accordingly economic activity and transport will continue to increase. These trends mean that land will become more valuable and the importance of maintaining flood security will become even more urgent (at least in terms of potential financial loss). For the river, there are several likely consequences:

- continued pressure to harden banklines and confine the channel in order to protect property and facilities;
- increased pressure to extract gravel as the apparently most cost-effective way to assure flood security;
- continuing pressure to develop and maintain a navigation channel on the river;
- continuing pressure for commercial gravel extraction;
- increased human traffic along the river.

The first four of these factors impinge on the question of gravel extraction from the river. As described above, hardening of banklines and confinement of the channel inhibits the lateral exchange of sediment by which the river stages bed material downstream. This activity will, then, result in either (or probably both) of increased gravel accumulation at certain points of high flow resistance that are created along the river, and more rapid transfer of bed material downstream to the distal part of the gravel-bed reach, where aggradation will be increased. There are signs of both tendencies already. Both effects will increase the channelization and simplify morphology in the upper part of the reach, with unfavourable effect on the riverine ecosystem.

Proposals to manage the extraction of gravel for flood security have been extensively discussed in this report and recommendations have been provided in the preceding section.

Dredging to artificially maintain a navigation channel may have direct effects on channelization of the river. In the past, navigation requirements have been modest and dredging has been limited to providing shallow-draft passage through certain riffles. Plans to increase draft or to provide a more direct navigation route along the river, with consequent increase in dredging requirements should be subject to environmental impact review, since they may have significant effects on channel morphology, hence on the ecosystem.

Commercial gravel extraction might have dramatic effects on the river. The current aggregate requirement in the Lower Mainland is in the order of 20 million tonnes per annum (Hora, 1998). As a low-value commodity, it cannot be transported far. Yet the spread of settlement in the region is leading to systematic withdrawal of terrestrial sources from production or access. In this circumstance, the river, with a large accumulation of gravel, appears to be an attractive source. Furthermore, river gravel is superior for many uses because the material is relatively strong and relatively clean. This report has endeavoured to make clear, however, that despite the large stock of gravel in the river -- the product of 10 000 years of postglacial sedimentation -- the character of the riverine environment depends upon the contemporary sediment exchange along the river, and that this involves only a modest gravel recruitment each year. Large volumes cannot be removed without having a serious impact on the riverine environment.

It remains important to recognize the problem faced by the aggregate industry in the region. Aggregate is a basic resource in our society and must be found somewhere. An important activity to help ensure sound planning of the riverine environment is to develop a rational plan for the provision of aggregate resources in the Lower Mainland region, and to take planning steps to ensure the viability of the plan. This plan would likely have to include land use and zoning provisions, since aggregate resources of acceptable quality and economic quantity are localized in their occurrence. Kondolf (1994b) has emphasized the importance of planning for environmentally sound provision of aggregate supplies.

Two additional recommendations arise from this brief discussion.

Recommendation 10

A proposal to increase the draft for navigation in the gravel-bed reach or to provide a more extensively engineered navigation route than has been the past custom should be subject to environmental impact assessment with respect to possible effects on the riverine ecosystem.

Recommendation 11

A plan should be developed to assure adequate sand and gravel supplies for the Lower Mainland region over the next 30 years. The plan should not rely on industrial scale extraction of gravel from Fraser River.

Recommendation 11 replicates on a regional scale a recommendation (concerning long range planning) contained in the report of the Aggregate Advisory Panel (2001).

The issues raised in this section are of particular importance in view of the fact that Fraser River is only conditionally stable in its current morphological state (cf. Figure 22 and discussion in section 2.7). It is possible that continuing action to confine the channel or to engineer a larger navigation channel could push the river into a single-thread state.

6.3 THE LONG TERM FUTURE: ENVIRONMENT

The regional environment determines the primary conditions of hydrology and sediment supply that determine the morphology of Fraser River. The environment is not constant. Figure 45 shows the flow history at Hope since 1912. The major structure in the record is an oscillation of roughly 60 years' length, which is most apparent in the mean flow. Cumulative departures reveal abrupt regime shifts in 1925, 1948 and 1977 which created periods of dominantly above-normal flows and some major floods in the period 1948-1977, and dominantly below average flows and floods before and since. These shifts coincide with the Pacific Decadal Oscillation [Mantua et al., 1997] -- a quasi-periodic climate signature of the North Pacific Ocean. The time period of the sediment budget discussed in this report, between 1952 and 1999, is evenly divided between epochs of above and below normal flows. It is also apparent that, since the middle of the 20th century, interannual variability has been much greater than the long-term changes in flow. Because of the characteristically nonlinear relations between flow and sediment transport, we expect that the high variability dominates the sediment signal.

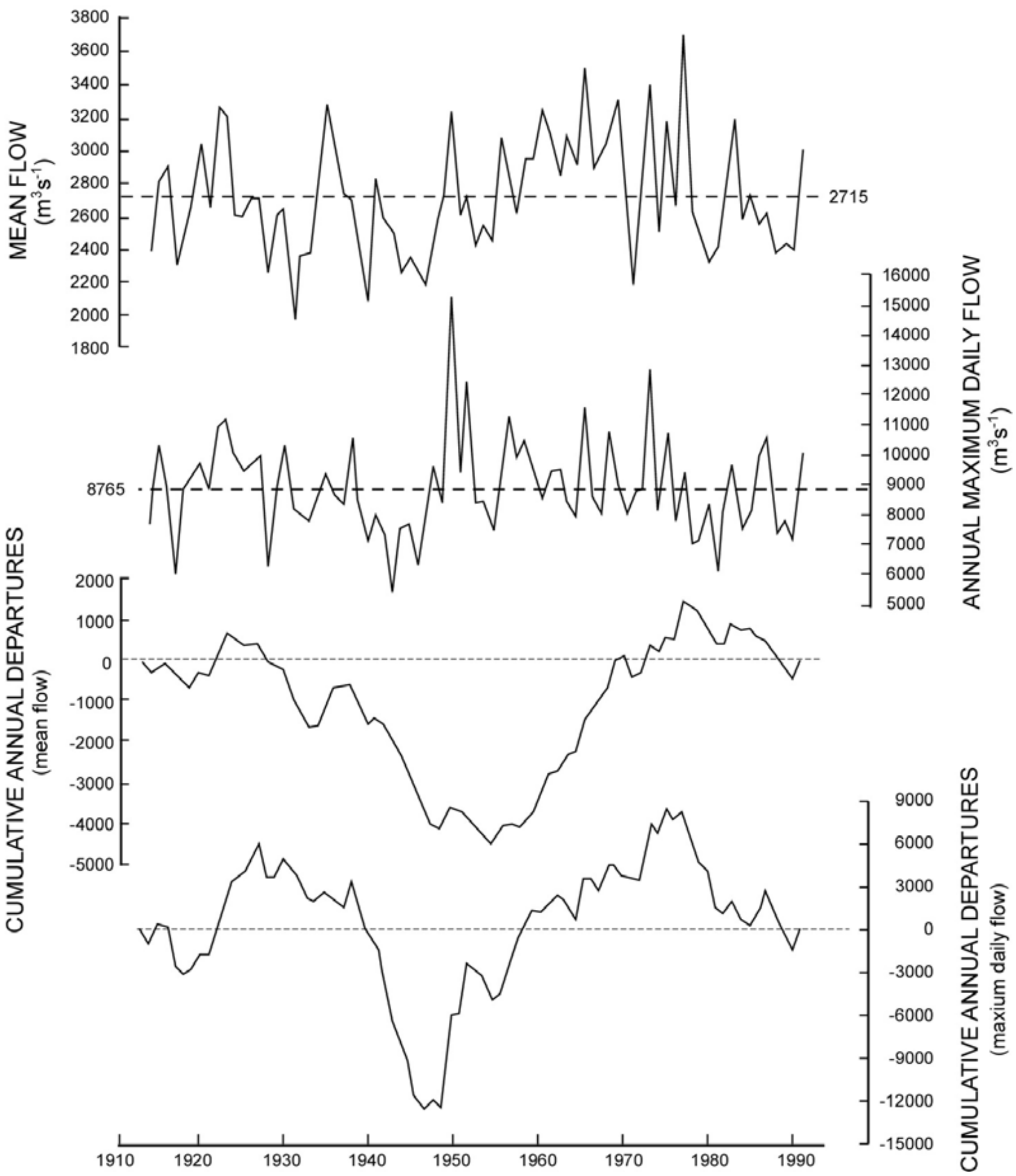


Figure 45. Mean annual flow and annual maximum daily flow at Hope (WSC station 08MF005) from 1912 to 1990, and cumulated departures from the means. The winter of 1976-77, indicated in the diagram, witnessed a dramatic change in characteristic weather in western North America (cf. Trenberth and Horrell, 1994; Mantua et al., 1997), the effect of which is evident in hydrometric records.

We suppose that these decadal fluctuations in weather and runoff will continue in the future. But human agency has superimposed a secular shift in climate on top of that. Whilst it is now reasonably established that humans are influencing global mean climate, principally by changing the composition of the atmosphere so that the world is becoming warmer (Houghton et al., 2001), the regional implications of this primary effect remain unclear. We may make the following speculations concerning regional effects of secular climate change and their possible impact on Fraser River flows (cf. Ashmore and Church, 2001):

- higher precipitation in the Coast Mountains, the consequence of warmer and more energetic weather systems moving onshore from the North Pacific Ocean may increase mean runoff;
- warmer winter temperatures may shift the balance of winter precipitation toward greater rainfall and smaller snow accumulation, so that winter flows are increased and spring freshet flows (the consequence mainly of regional snowmelt) are reduced;
- higher summer temperatures in the British Columbia interior may hasten the decline of post-freshet flows.

At present, none of these possible effects can be quantified. The impact of a reduction in snow accumulation has been studied by Moore (1991), who examined the character of warm winters. His results are displayed in Figure 46 and clearly show that reduced snow accumulation is associated with reduced freshet flows. Such an effect of changing mean climate should not, of course, be interpreted to mean that major floods could no longer occur. However, they might signify a reduced capacity, on average, to deliver bed material to the lower river, so they might affect the mean gravel budget.

The environment of the region has also been affected by human activity and has almost certainly influenced the gravel budget in the past. The influx of European settlers to the region after 1850 led to extensive disturbance of gravel bars all along the river in the search for placer gold. This activity is known to have had significant effects on sand accumulation in the Fraser delta (Hales, 2000) and must have had a significant influence on gravel yield to the lower river. After 1880, the successive engineering of two railroads and a major highway through Fraser Canyon, and the more recent engineering of the Coquihalla Highway, along with various pipeline and transmission line projects across the mountains along tributaries of the river, have maintained a high rate of sediment delivery to the rivers -- higher than the natural rate of sediment delivery from a mainly undeveloped landscape. These factors probably mean that the past 150 years has seen an elevated rate of sediment delivery to the gravel-bed reach of lower Fraser River. However, the time scale for this effect to dissipate is not known. Whether sediment yield rates have already recovered from these disturbances, or whether they continue to be elevated, is not clear. But it appears unlikely that gravel yield to the river in the future will remain as high as it has been in the recent past.

The future water and gravel supplies to the river cannot be predicted quantitatively. But it appears fairly clear that the mean conditions will be for reduced freshets and reduced gravel delivery. These factors will, by themselves, push the river closer to the regime change from multi-thread wandering channel to single-thread channel that has been discussed in this report.

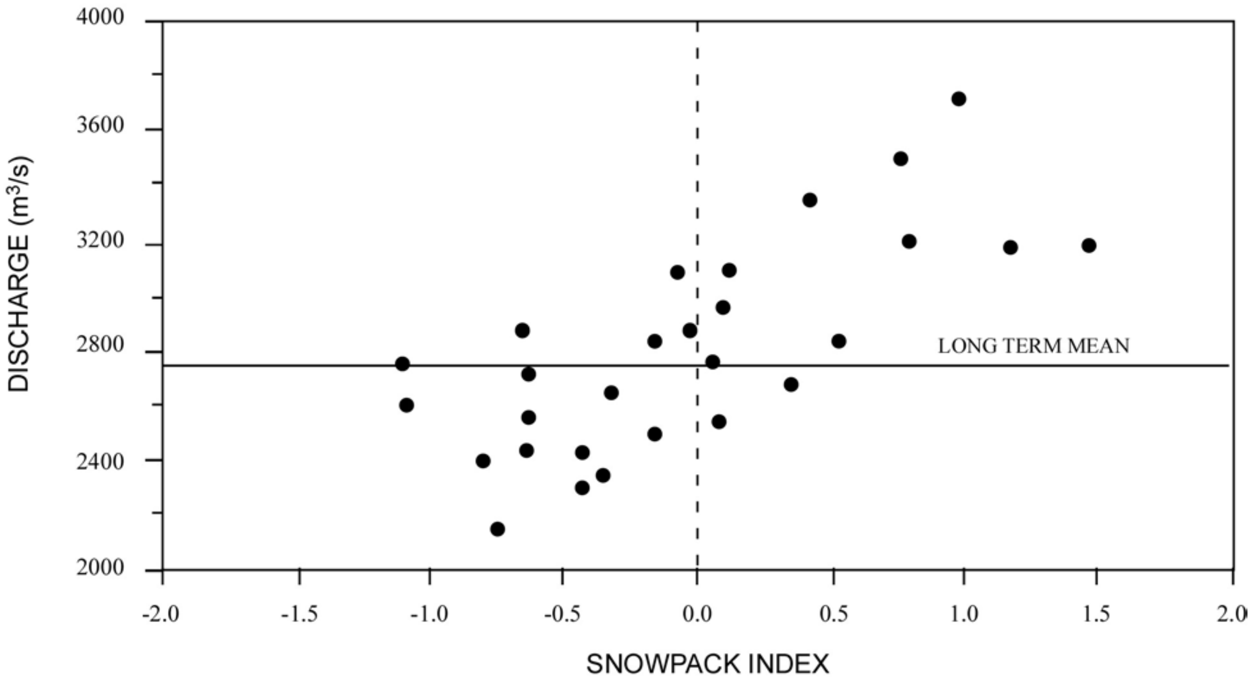


Figure 46. Mean annual streamflow in Fraser River plotted against snowpack index. The snowpack index is a pooled measure of snow accumulation derived from many snow courses in the basin. Positive values indicate high snow accumulation. The graph shows that as snowpack decreases, mean annual flow decreases (Moore, 1991).

At the same time, it does not eliminate the possibility for individual major floods and accompanying high gravel transport. It leaves river managers with the responsibility to monitor gravel accumulation and extraction rates in light of the likelihood that future trends will reduce gravel influx to the system.

The gravel-bed reach of Fraser River remains a riverine environment in a state of conditional stability.

REFERENCES

Aggregate Advisory Panel. 2001. *Managing aggregate: cornerstone of the economy.* Report to the Government of British Columbia, March 2001: 47pp.

Amoros, C., Rostan, J.-C., Pautou, G. and Bravard, J.-P. 1987. The reversible process concept applied to the environmental management of large river systems. *Environmental Management* **11**: 607-617.

Ashmore, P. and Church, M . 1998. Sediment transport and river morphology: a paradigm for study. *In* Klingeman, P.C, Beschta, R.L., Komar, P.D. and Bradley, J.B., editors, *Gravel-bed rivers in the environment.* Highlands Ranch, Colorado, Water Resources Publications: 115-140.

Ashmore, P. and Church, M. 2001. The impact of climate change on rivers and river processes in Canada. Geological Survey of Canada *Bulletin* **555**: 58pp.

Brown, A.V., Lyttle, M.M. and Brown, K.B. 1998. Impacts of gravel mining on gravel bed streams. *Transactions of the American Fisheries Society* **127**: 979-994.

Church, M. and Weatherly, H. 1998. *Historical changes of Minto Channel during the twentieth century.* Report for District of Chilliwack, 1 December, 1998: 19pp.+19 figs.

Church, M., Ham, D. and Weatherly, H. 2000. Sedimentation and flood hazard in the gravel reach of Fraser River: Progress report 2000. *Report for District of Chilliwack, September 2000: 28pp+7 figs.*

Church, M., Rempel, L. and Rice, S. 2000. *Morphological and habitat classification of the Lower Fraser River gravel-bed reach.* Report prepared for the Fraser Basin Council, November 2000: 77pp.

Collin, B.D. and Dunne, T. 1989. Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic Mountains, Washington, U.S.A. *Environmental Geology and Water Science* **13**: 213-224.

Collin, B. and Dunne, T. 1990. Fluvial geomorphology and river gravel mining: a guide for planners, case studies included. California Department of Conservation, Division of Mines and Geology, *Special Publication* **98**: 29pp.

Desloges, J.R. and Church, M. 1989. Wandering gravel-bed rivers. *Canadian Geographer* **33**: 360-364.

Florsheim, J., Goodwin, P. and Marcus, L. 1998. Geomorphic effects of gravel extraction in the Russian River, California. *In* Bobrowsky,P.T., editor, *Aggregate resources: a global perspective*. Rotterdam, A.A.Balkema: 87-99.

Galay, V.J. 1983. Causes of river bed degradation. *Water Resources Research* **19**: 1057-1090.

Harvey, M.D. and Schumm, S.A. 1987. Response of Dry Creek, California, to land use change, gravel mining and dam closure. International Association of Hydrological Science, *Publication* **165** *(Erosion and Sedimentation in the Pacific Rim)*: 451-460.

Hales, W.J. 2000. *The impact of human activity on deltaic sedimentation, Marshes of the Fraser River Delta, British Columbia*. The University of British Columbia, Ph.D. dissertation: 153pp.

Healey, M.C. 1997. *Prospects for sustainability: integrative approaches to sustaining the ecosystem function of the lower Fraser Basin.* The University of British Columbia, Westwater Research Unite, Institute for Resources and Environment: 91pp.

Hora, Z.D. 1998. Aggregate resources of the Greater Vancouver and Lower Mainland market, B.C., Canada: problems and future outlook. *In* Bobrowsky,P.T., editor, *Aggregate resources: a global perspective*. Rotterdam, A.A.Balkema: 397-408.

Houghton, J.T. et al., editors. 2001. *Climate change 2001: the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, Cambridge University Press.

Kanehl, P. and Lyons, J. 1992. Impacts of in-stream sand and gravel mining on stream habitat and fish communities, including a survey on the Big Rib River, Marathon County, Wisconsin. Wisconsin Department of Natural Resources, *Research Report* **155**. (quoted by Brown et al., 1998)

Kellerhals, R., Miles, M. and Zallen, M. 1987. *Effects of gravel mining on the salmonid resources of the lower Fraser River*. Report for Canada Department of Fisheries and Oceans, Habitat Management Division, Vancouver. Kellerhals Engineering Services, Ltd.: various pagination.

Kondolf, G.M. 1994a. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* **28**: 225-243.

Kondolf, G.M. 1994b. Environmental planning in regulation and management of instream gravel mining in California. *Landscape and Urban Planning* **29**: 185-199.

Kondolf, G.M. 1998a. Environmental effects of aggregate extraction from river channels and floodplains. *In* Bobrowsky,P.T., editor, *Aggregate resources: a global perspective*. Rotterdam, A.A.Balkema: 113-129.

Kondolf, G.M. 1998b. Large-scale extraction of alluvial deposits from rivers in California: geomorphic effects and regulatory strategies. *In* Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B., editors, *Gravel-bed rivers in the environment*. Highlands Ranch, Colorado, Water Resources Publications: 455-470.

Kondolf, G.M. and Swanson, M.L. 1993. Channel adjustments to reservoir construction and gravel extraction along Stony Creek, California. *Environmental Geology* **21**: 256-269.

Lagasse, P.F., Winkley, B.R. and Simons, D.E. 1980. Impact of gravel mining on river system stability. American Society of Civil Engineers*, Proceedings: Journal of the Waterway, Port, Coastal and Ocean Division* **106**: 389-403.

Lane, E.W. 1955. The importance of fluvial morphology in river hydraulic engineering. American Society of Civil Engineers*, Proceedings* **81**: 1-17.

Ligon, F.K., Dietrich, W.E. and Trush, W.J. 1995. Downstream ecological effects of dams. *BioScience* **45**: 183-192.

Lisle, T.E., Iseya, F. and Ikeda, H. 1993. Response of a channel with alternate bars to a decrease in supply of mixed-size bed load: a flume experiment. *Water Resources Research* **29**: 3623-3629.

Mantua, N.L., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069-1079.

McLean, D.G. 1990. *Channel instability on lower Fraser River*. Ph.D. thesis (unpublished). The University of British Columbia: 290pp.

McLean, D.G. and Church, M. 1986. A re-examination of sediment transport observations in the lower Fraser River. Environment Canada, Water Resources Branch, Sediment Survey, Ottawa. *Report IWD-WRB-HQ-SS-86-5*: 56pp.

McLean, D.G. and Tassone, B. 1987. Discussion of 'Bedload sampling and analysis' by D.Hubbell. *In* Thorne, C.R., Hey, R.D. and Bathurst, J.S., editors, *Sediment Transport in Gravel-bed Rivers*, Chichester, John Wiley & Sons: 109-113.

McLean, D.G. and Church, M. 1999. Sediment transport along lower Fraser River. 2. Estimates based on the long-term gravel budget. *Water Resources Research* **35**: 2549-2559.

McLean, D.G., Church, M. and Tassone, B. 1999. Sediment transport along lower Fraser River. 1. Measurements and hydraulic computations. *Water Resources Research* **35**: 2533-2548.

Moore, R.D. 1991. Hydrology and water supply in the Fraser River basin. *In* Dorcey,A.H.J., editor, *Water in sustainable development: exploring our common future in the Fraser River basin.* University of British Columbia, Westwater Research Centre: 21-32.

Northcote, T.G. and Larkin, P.A. 1989. The Fraser River: a major salmonine production system. *In* Dodge, D.P., editor, *Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Science* **106**: 172-204.

Petit, F., Poinsart, D., and Bravard, J.-P. 1996. Channel incision, gravel mining and bedload transport in the Rhone River upstream of Lyon, France ("canal de Miribel"). *Catena* **26**: 209-226.

Rempel, L.L., Richardson, J.S. and Healey, M.C. 1999. Flow refugia for benthic macroinvertebrates during flooding of a large river. *Journal of the North American Benthological Society* **18**: 34-48.

Rinaldi, M. and Simon, A. 1998. Bed-level adjustments in the Arno River, central Italy. *Geomorphology* **22**: 57-71.

Rosenau, M.L. and Angelo, M. 2000. *Sand and gravel management and fish-habitat protection in British Columbia salmon and steelhead streams*. Pacific Fisheries Resource Conservation Council, Vancouver. *Background Paper* **2000/3**: 70pp.

Roux, A.L., Bravard, J.-P., Amoros, C. and Pautou, G. 1989. Ecological changes of the French Upper Rhone River since 1750. *In* Petts, G.E., editor, *Historical change of large alluvial rivers: western Europe.* Chichester, John Wiley & Sons: 323-350.

Sandecki, M. 1989. Aggregate mining in river systems. *California Geology* **42**: 88-94.

Sear, D.A. and Archer, D. 1998. Effects of gravel extraction on stability of gravel-bed rivers: the Wooler Water, Northumberland, U.K. *In* Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B., editors, *Gravel-bed rivers in the environment*. Highlands Ranch, Colorado, Water Resources Publications: 415-432.

Schmetterling, D.A., Clancy, C.G. and Brandt, T.M. 2001. Effects of riprap bank reinforcement on stream salmonids in the western United States. *Fisheries* **26**(7): 6-11.

Stebbing, A.R.D. 1992. Environmental capacity and the precautionary principle. *Marine Pollution Bulletin* **24**: 287-295.

Sterling, S.M. and Church, M. in review. Sediment trapping characteristics of a pit trap and a Helley-Smith sampler in a cobble-gravel bed river. *Water Resources Research.*

Surian, N. 1999. Channel changes due to river regulation: the case of the Piave River, Italy. *Earth Surface Processes and Landforms* **24**: 1135-1151.

Sutek Services, Ltd. and Kellerhals Engineering Services, Ltd. 1989. *Assessing gravel supply and removal in fisheries stream*. Report prepared for Canada Department of Fisheries and Oceans and British Columbia Ministry of Environment. various pagination.

Trenberth, K.E. and Hurrell, J.W. 1994. Decadal atmospheric-ocean variations in the Pacific. *Climate Dynamics* **9**: 303-319.

UMA Engineering Ltd. 2000. *Fraser River gravel reach hydraulic modeling study: final report.* Report to the City of Chilliwack, March 2000: 65 pp.+figures+appendices.

UMA Engineering Ltd. 2001. *Fraser and Harrison Rivers: hydrologic and hydraulic investigations.* Report for the City of Chilliwack, January 2001: 54 pp. + figures, appendices.

Weatherly, H. and Church, M. 1999. *Gravel extraction inventory for lower Fraser River (Mission to Hope) -- 1964 to 1998.* Report to the District of Chilliwack, March 15: 10 pp + tables, figures.

Appendix A - Determining the sediment budget

A1 GENERAL APPROACH

The purpose of this appendix is to describe the methods that have been adopted to estimate sediment transport along lower Fraser River. The updated sediment budget presented in this report is based largely upon procedures previously described (Church et al., 2000). However, a number of significant modifications have been made in an effort to improve the reliability of the budget (gravel and coarse sand) estimates for lower Fraser River. The complete procedure to establish the sediment budget is described below, including the newly adopted modifications.

The sediment budget is based primarily upon repeated topographic surveys of the channel bed (bathymetry) to detect changes associated with sediment erosion and deposition. On Fraser River, changes occur over years to decades, with erosion and deposition occurring largely in distinct zones. Therefore, repeat bathymetric surveys at some years separation can be used to describe these changes provided the temporal and spatial resolution of the surveys is sufficiently high. Full hydrographic surveys of all study reaches are available for 1952 and 1999 with partial surveys from 1984 (Mission to Agassiz) and 1991 (Mission to Harrison River). Surveys from 1952 and 1984 have been re-analyzed to validate the methodological approach adopted in this study by comparing results with those given in McLean (1990) using the same data. In addition, the recent (1999) resurvey of the channel has been used to provide an updated transport rate estimate to Agassiz, with an extension to Laidlaw. The additional surveys allow the spatial and temporal variability of storage and transport zones along the river to be determined more reliably than was possible using a single 32 year intersurvey period (McLean, 1990).

A2 GRAVEL TRANSPORT RATES FROM CHANGES IN MORPHOLOGY

The basis for relating morphology to sediment transport is the sediment budget, which can be expressed for a defined channel reach as:

$$V_o = V_i - (1-p)\Delta V$$

where V_o is volumetric sediment output and V_i is volumetric sediment input to the reach during some specified time period. The change in storage, ΔV, is measured as the net difference between scour and fill of the channel bed, as estimated from the change in bathymetry over the period, adjusted for sediment porosity by (1-p) to express all terms as mineral volumes. The equation can be reduced to a mean transport rate by dividing by the time between successive channel surveys. The complete budget must also take into account removals of sediment through dredging and changes in storage associated with erosion and deposition of island and floodplain deposits. Finally, total volumetric changes can be converted to bed material volume changes by adjusting for the proportion finer than medium sand (< 0.25 mm in diameter). Within the channel, this adjustment is negligible, but it may be considerable in floodplain and island deposits. The complete gravel budget can therefore be expressed as:

$$V_o = V_i - V_d - (1-p)(\Delta V_c) - (1-p)(1-\Phi)\Delta V_f$$

where V_d is the volume removed by dredging, ΔV_c is the net scour and fill of active channel sediments which is adjusted by the known porosity, p, and ΔV_f is the net change due to erosion and deposition of island and floodplain deposits, adjusted by p and by Φ, the fraction of fine sand and silt. Positive values for ΔV_c or ΔV_f indicate net erosion (i.e. $V_o > V_i - V_d$ for the reach). Dividing through by Δt, the time between successive surveys, yields the sediment budget expressed as a mean transport rate, or

$$Q_o = Q_i - Q_d - (1-p)\Delta V_c/\Delta t - (1-p)(1-\Phi)\Delta V_t/\Delta t$$

The value of Q represents the transport (flux) rate per unit time.

In this study, the transport into any 1-km reach is equal to the transport rate out of the reach immediately upstream. On lower Fraser River, there is no gravel transport past Mission, hence Q_o at that location can be assigned a value of 0 for gravel and gravel budget calculations can be extended upstream on a cell-by-cell basis. This technique allows the gravel transport rate to be estimated at any location along the entire reach. This approach follows the conventions given by McLean and Church (1999), although that study used 2-km cells. Furthermore, the deposition and erosion of medium and coarse sands -- those parts of the total sand load of the river that constitute bed material -- can be estimated provided the portion of the deposits that constitutes sand is known.

A3 COMPILATION OF AVAILABLE BATHYMETRIC DATA

The earliest complete channel survey of the gravel reach was undertaken in 1952 by Public Works Canada and extended from Barnston Island to Yale. River bathymetry was surveyed by sonar, while exposed (above waterline) surfaces were mapped photogrammetrically (McLean and Church, 1999). The second major survey was completed in 1984 using a combination of automated hydrographic survey, conventional cross sectional surveys, and terrestrial ground mapping (McLean, 1990). Data from both surveys had been archived on magnetic tapes, but the physical deterioration of the tapes necessitated data recovery by alternative means.

To recreate the 1952 survey, data have been digitized manually from the series of 1:4800 mylar maps of the survey (approximately 12,000 points). As depths were given to chart datum (geodetic mean sea level) no additional adjustment for water level was required. In addition, contour lines from bar and island surfaces along the active channel zone and adjacent floodplain margins were digitized to provide nearly complete spatial coverage of the channel. The data were imported into Arc/Info where elevations were converted to metres and positions were adjusted to the UTM (NAD83) datum. A TIN model (surface of irregular triangles) was created from the data to visually examine the output for elevation coding errors. Obvious discrepancies were then corrected by hand. Contour line elevations were also verified, but small positional errors could not be detected (hence corrected) as dense spacing of the drawn lines hindered interpretation in some regions.

The 1984 survey was recovered in two parts. A copy of the original HYDAC sounding survey was available in ASCII format on CD-ROM from Environment Canada in Ottawa. Data were imported into the GIS and plotted on the 1983 planimetric base map (from aerial photography) to visually compare the spatial extent of the survey with maps given in McLean (1990). The conventional cross sectional and terrestrial ground mapping surveys needed to complete the 1984 survey were obtained directly from D. McLean as ASCII files. The amended sounding file consists of 66,600 individual elevation points. Despite the large number of data points, the 1984 survey was found to be more spatially limited than either the 1952 or 1999 surveys between Mission and Agassiz, as the relatively low water conditions in 1984 precluded access to several areas along the channel. This effectively limits the precision of the sediment budget, as no bathymetric surface can be modeled in regions with insufficient topographic data (hence no surface comparison can be made). Rather than exclude these regions, it was decided to amend the original survey with photogrammetrically derived elevation data. Aerial photographs from 1979 were selected as the large scale (1:10 000) allowed bar and island topography to be clearly discernable. Ideally, the selected photos would be available closer to the date of the survey, but the potentially 'best' photos (1983) were too small scale to reliably map surface topography. In total, 13,000 points were digitized and appended to the 1984 sounding file. This procedure introduces bias if photogrammetrically mapped regions were subject to erosion or deposition between 1979 and 1984, as change volumes would be incorrectly estimated.

The 1999 bathymetric survey data were delivered by Public Works and Government Services, Canada in October 1999. The complete data set consisted of 301,500 sounding points, also in ASCII format. Although survey lines were spaced roughly 200 metres apart, elevations were obtained at sub-metre spacing along each line, thus accounting for the large total number of points. To reduce the density of the sounding points along each line, a subset of the original data was created using a specially written Fortran program to retain points at 20 metre spacing between the start and end points of each individual survey line (additional data were deemed redundant for the intended bed surface model construction). The edited dataset consists of roughly 12,000 points, comparable with the 1952 survey.

To complete the 1999 dataset, elevation points from exposed bars and floodplain surfaces were incorporated from a laser profiling topographic survey completed in March 1999. Outliers in the data (e.g., trees, buildings) were removed using a Fortran program to search for adjacent points at least 3 metres higher than the immediate 2 neighbours. The filtered dataset was then overlaid with the 1999 channel map, so each topographic point could be assigned a channel map classification code (i.e., water, gravel bar, floodplain). Within the GIS, points falling on either the river surface, backchannels, or bar edges were deleted, as these points obviously do not represent the actual bed of the river. The final dataset of laser altimetry data was reduced from the original 60,000 points to 55,700 points.

A4 CONSTRUCTION OF 3-DIMENSIONAL SURFACES

In order to calculate erosion and deposition volumes of channel sediment between channel surveys, it is first necessary to compute a topographic surface for each date. There is no known, universally accepted technique by which to model complex river bed topography. Several recent studies have suggested that TIN models (specifically Delaunay triangulation) present the most appropriate technique for representing complex river bed topography (Lane *et al*., 1994; Milne and Sear, 1997; Brasington *et al*., 2000). Triangulated irregular network models (TINs) are often used to represent a continuous surface because the method preserves known spot elevations and the density of the triangulated mesh can be adjusted during data collection to reflect the complexity of the surface (Burrough and McDonnell, 1998). As well, interpolation can be restricted across breaks of slope (i.e. river banks) to limit topographic distortion (Lane *et al*., 1994). Delaunay triangulation appears to provide a realistic representation of a surface where the data are well distributed. However, the bathymetric data (as with conventional cross-sections) are heavily biased in the cross-stream direction. This often results in an unrealistic representation of the bed surface, mainly in the form of thin, elongated triangles, despite the inclusion of breaklines.

The most common alternative to a TIN is the grid model, in which the irregularly spaced points of the original survey are replaced with a regular array of cells, each having a single interpolated value. The advantage of grid models is that they are computationally more efficient and can be manipulated with a variety of visualization and surface analysis tools (Milne and Sear, 1997) both within and external to the GIS. Grid models are commonly generated directly from TIN models, though most GIS software offers several analytical techniques by which to produce a regular interpolated grid independently. McLean (1990) used a combination of Laplacian and spline interpolation to represent the bed surface, the results of which were interpreted visually. As there is no directly comparable interpolation technique in Arc/Info GIS, available alternatives were explored. These methods included spline, inverse distance weighting and trend surface analysis. Kriging was attempted but the procedure failed due to computing limitations. Although each method was found to provide an adequate representation for part of the channel, none produced satisfactory results for the entire surface. These judgements are mainly qualitative as there is no independently acquired true surface on which to base a comparison. They are largely based on a visual comparison of contour lines (produced from each grid model) with topographic channel features, including the sharp bend near Mission, known scour holes, and floodplain and island banklines.

The technique finally accepted was the TOPOGRID function in Arc/Info, an interpolation method specifically designed for the creation of hydrologically correct digital elevation models. TOPOGRID is essentially a discretized thin plate spline technique, in which an exact spline surface is replaced with a locally smoothed average (Burrough and McDonnell, 1998). One of the main criticisms of spline techniques is that they produce an unrealistically smooth surface, but smoothing tolerances can be adjusted in the GIS to produce sharper, less generalized output, though this increases the possibility of spurious sinks and peaks (Arc/Info 8.0.2 online help). In general, model output from TOPOGRID was visually more realistic than all other methods, although small pits and peaks were created in regions of complex terrain. The observed number of pits and peaks has since been reduced by increasing smoothing tolerances to recommended model limits for elevation point density, accuracy and error inherent in converting point and line elevations into a regularly spaced grid. In addition, the number of iterations used to compute an elevation value for each grid cell location has been increased to reduce the number of interpolated sinks, such as occur midway between sounding lines. This also improves the fit to stream and ridge lines when using contour data (refer to following paragraphs).

Initially, the model was found to estimate a 'wavy' elevation surface along island and floodplain boundaries (i.e. for 1999) where sounding transects did not coincide with the altimetry transects (see Figure A 1). To eliminate the edge-effect problem, it was necessary to incorporate contour data into all of the models. In effect, this means modeling the channel bed, islands and the adjacent floodplain as a single continuous surface for each date. This approach differs from that described by McLean (1990) who estimated bank erosion and construction as a separate term in the sediment budget. Contour data are preferred over additional spot heights in the TOPOGRID model as the program can incorporate these data into the modeling routine as a form of breakline, thereby increasing the reliability of the interpolated surface. However, contour data were available only for the 1952 surveys. To generate contours for the other dates, common island and floodplain surfaces were delimited for 1952-84, 1984-99 and 1952-99 from the planimetric mapping. These common areas were overlaid with the 1952 contour data to simulate 1984 and 1999 contours. The overlays were also used to add the laser altimetry from 1999 to the 1952 and 1984 surveys. This procedure entails the assumption that the elevation of stable island and floodplain surfaces has remained fairly constant over the 47 year period of study.

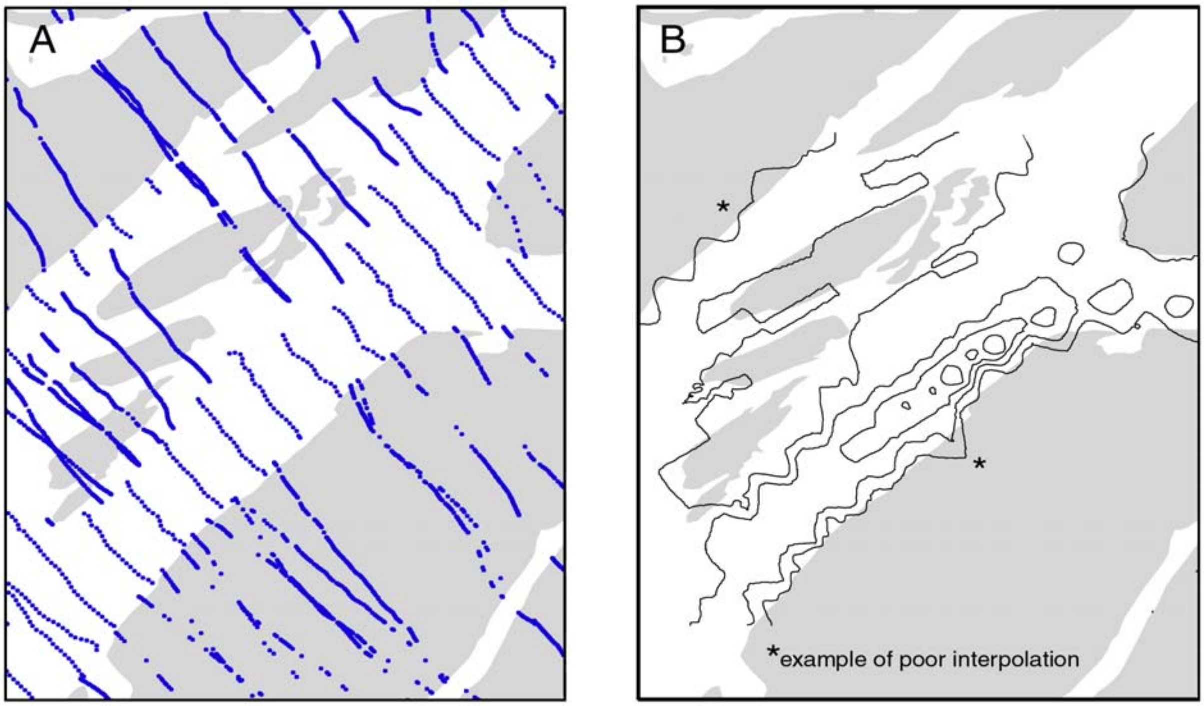


Figure A 1. (a) Bathymetry and laser altimetry data (dark points and lines) with (b) interpreted 4-metre contour lines. Note how contours appear 'wavy' between bankline and channel bed. Shaded areas indicate vegetated island and floodplain surfaces.

For each survey date, additional contours were hand-digitized in the GIS where existing contours did not conform to banklines. The main benefit of these procedures is that all surveys have a similar spatial extent, thereby eliminating the need to mask out areas with insufficient data (cf. McLean, 1990). For each date, a 25 metre (625 m^2) grid cell surface was produced, roughly the average density of the 1984 survey. A complete model (Mission to Laidlaw) consists of roughly 163,500 individual cells.

For the updated budget, additional contours have been added along the channel and bar surface for each date. These contours have been hand-digitized using existing bathymetric and contour data as a guide. Contours were created at 5 metre intervals starting from the deepest scour hole near Mission by displaying all points having an elevation greater than or less than the desired interval (e.g., –20 m) and placing contours between the observed division. The additional bed surface contours further eliminate spurious pits and peaks along the bed between survey lines, help preserve the modeling of real scour holes and better reflect the transition in elevation between the bed and adjacent banks -- the latter point is particularly critical near the submerged base of channel banks where sounding lines typically do not extend. In general, the updated model appears to provide a more realistic picture of bed topography than previous models, particularly in the transition from bed to adjacent channel banks.

The accuracy of the updated models is difficult to quantify directly. McLean (1990) tested the precision of volumetric calculations by comparing the predicted value at each grid cell with the value of actual surveyed values where the data were coincident. Such a comparison may be misleading, however. For example, surface interpolators such as TIN models implicitly preserve the value of the original data in the output model and so no error difference is apparent. By comparison, TOPOGRID models a surface that does not necessarily pass through the surveyed data values, resulting in a larger (on average) deviation at data points. The main consideration in evaluating model performance should be the behaviour of predicted values where there are no surveyed points. TIN models assume that elevations between adjacent points can be approximated by a linear slope or triangular surface whereas TOPOGRID applies knowledge of local slope changes and can model a curved surface such as occurs naturally along a river bed. This becomes important where surveyed data do not conform to local elevation maxima or minima (i.e., bar surface top; bottom of a scour hole). If the original data were taken at regular intervals along and between sounding lines, each model would provide similar output. Model accuracy at surveyed data value locations is further limited where a single modeled grid cell overlaps elevation values from multiple soundings, altimetry or contour lines values. Since each interpolated grid cell contains only a single associated elevation (e.g., 10 m), there can be significant apparent deviations where local slope changes are large (e.g., surveyed sounding points with elevations of 7 and 13 metres), even though the model has estimated the "average" elevation of the cell.

A5 CALCULATING THE GRAVEL BUDGET

A5.1 Computation of unadjusted volumetric changes and bed level changes

The gravel budget requires information on the net difference between scour and fill of the channel bed, changes in storage along island and floodplain deposits and removals of gravel from each reach by dredging/mining. Volumetric changes between any two surveys were initially calculated in Arc/Info GIS using the command CUTFILL, which simply subtracts one cell value from another and writes this information to a third file. First, each topographic model was "clipped" to correspond with a polygon coverage known as a "replace" coverage, which contains one of two numeric codes (0 or 1). The replace coverage serves as a mask which is used to replace interpolated elevations with a no-data value where the modeling is known to be weak or otherwise should not be included (because it is outside the region of interest: for example, lower Vedder Canal; several of the prominent sloughs).

The same mask was used for all 3 modeled surfaces to ensure that the same areas exactly are included or excluded from the computations. Since the 1984 survey covers a shorter reach of the river than the other two surveys, a separate mask was used to compare the 1952 and 1999 surveys upstream of Agassiz Bridge. Polygons that were classified as stable island and flood-plain surfaces on *all* dates were assigned the no-data value. This was done to ensure that the computing areas for 1952-84, 1984-99 and 1952-99 are exactly the same, and that they correspond so far as possible with the region that has formed the active channel within the past 50 years. The comparison area is 55.4 million m^2. Upstream of Agassiz, the comparison area is 33.6 million m^2.

The next step was to use CUTFILL to compute the difference between surveys. This was done in 25x25 m *grid cells* over the entire domain (the dimensions are comparable with the resolution of the surveys -- see section A4). Because the same coordinate system was used for all surveys, the grid cells correspond exactly from survey to survey and can be superimposed for intersurvey comparisons. There are 88 660 cells in the Mission-Agassiz reach, and an additional 53 735 cells upstream of Agassiz. Volumetric differences for 1952-84, 1984-99,1952-99 (Mission to Agassiz) and 1952-99 (Agassiz to Laidlaw) were then computed as the product of polygon area and interpolated change in elevation, and aggregated into new polygon coverages corresponding with the 1-km *computing cells* along the river (as shown in figures 3 and 15 of the main report) and the data were exported to a spreadsheet. In the spreadsheet, the volumetric differences were divided by the area of cell in order to arrive at an estimate of the change in bed level. This determines simply that an individual computing cell was higher or lower in elevation, on average, at the end of one survey period compared with another, irrespective of whether the elevation change could be attributed to gravel, coarse sand or fine sand, or whether a portion of the change involved the addition to or loss of channel bank, which would change the currently active channel zone.

The results of these calculations are presented in table A6 as *unadjusted bed level changes*. Since no adjustments have been made to the observed volumetric differences they are consistent between periods, and they sum properly to the reported reach average when appropriately weighted by cell area.

A5.2 Computation of bed material changes and associated bed level changes

In this section, a detailed explanation is given of the procedures followed to arrive at the results reported in Table A 1-A 4.

The initial topographic models are the same ones used in the previous calculations. However, a procedure was now introduced to classify the 25x25 m grid cells within the study reach. Each cell was classified according to the type of morphological change that occurred in the cell between successive surveys. These changes were determined from planimetric mapping for the years 1949, 1983 and 1999 from available air photography. The dates do not correspond exactly with the timing of the bathymetic surveys so small coding errors remain possible. Successive maps were overlaid (e.g. 1949 to 1983) and the grid cells were coded as one of 6 possible types of channel change transitions based on the interpreted channel maps, as follows:

1. channel scour/ fill (water, bar, bar-edge on both dates)
2. bank erosion (island or floodplain at earlier date; water or bar-edge at later date)
3. bank deposition (water or bar-edge at earlier date; island or floodplain at later date)
4. floodplain stripping (island or floodplain at earlier date; bar at later date)
5. floodplain recovery (bar at earlier date; island or floodplain at later date), and
6. stable island/ floodplain (island or floodplain on both dates)

These codes are mutually exclusive and they include all mapped polygons for each intersurvey comparison (i.e. every overlay polygon is classified as 1 of 6 transitions only and there are no unclassified overlay polygons remaining).

Polygons that were classified as stable island and floodplain surfaces between two dates were assigned the no-data value. This means that the computing areas vary between comparisons (48.9 million m^2 in 1952-84; 46.1 million m^2 in 1984-99; and 49.5 million m^2 in 1952-99 in the Mission-Agassiz reach). The comparison area for the unadjusted difference calculations is larger (55.4 million m^2) since the area of stable island/ floodplain surfaces that was excluded from those calculations is smaller; that is, the stable area common to all 3 mapping dates is much smaller than the stable area between either the 1952-84, 1984-99 or 1952-99 periods. The 1952-99 comparison may seem surprising: it indicates that there are areas along the river (amounting to 1.07% of the total active area) that constituted island or floodplain in both 1952 and 1999, but changed within the intervening period.

At this point, the original elevation difference maps were overlaid with the channel change maps to produce a new summary coverage wherein each individual cell recording elevation change was additionally coded with a channel change (transition) attribute. Individual cells were sometimes divided into more than one smaller cell depending on mapping boundaries but each individual 'cell piece' was coded with only a single transition code. An additional database field 'volume' was also added to the summary overlay coverage where volume was calculated as the product of the cell area and the average computed elevation difference. Volumes were subsequently summarized for each channel change transition type along each 1-km computing cell and the data were imported into a spreadsheet for further analysis. Those calculations followed individual components of the sediment budget, as allowed by the grid cell coding, and excluded from the calculations of the bed material budget some portions of the sediments eroded or deposited. The excluded sediments were fine sands and silts deposited on or removed from floodplain and island surfaces when they were eroded or deposited. This material is judged not to form part of the "bed material". The adjustment is the source of the apparent discrepancies in the bed elevation changes reported in table A6 under "bed level change from sediment budget".

Table A1. Sediment budget - 1952 to 1984

Cell	river km	length (m)	width (m)	bed changes (deposition): channel change	bed changes (deposition): % sand	bed changes (deposition): channel gravel	bed changes (deposition): channel sand
1	85.5	820	560	-100,534	95	-5,027	-95,507
2	86.3	1,000	500	-248,529	95	-12,426	-236,102
3	87.3	1,000	450	-175,697	95	-8,785	-166,912
4	88.3	950	400	200,598	95	10,030	190,568
5	89.3	990	640	401,184	95	20,059	381,125
6	90.3	1,000	750	360,947	95	18,047	342,900
7	91.3	1,000	750	299,529	80	59,906	239,623
8	92.3	1,150	730	362,126	80	72,425	289,700
9	93.4	1,000	660	-514,343	80	-102,869	-411,474
10	94.4	1,090	750	-375,085	60	-150,034	-225,051
11	95.5	1,070	1,090	128,009	60	51,204	76,806
12	96.6	1,000	670	-261,367	40	-156,820	-104,547
13	97.6	1,030	680	-513,685	30	-359,579	-154,105
14	98.6	1,000	600	668,194	30	467,736	200,458
15	99.6	1,000	960	783,569	30	548,498	235,071
16	100.6	1,000	1,270	260,992	30	182,694	78,298
17	101.6	1,030	1,240	330,118	30	231,083	99,035
18	102.7	1,100	1,220	902,639	30	631,848	270,792
19	103.8	1,260	1,160	-80,800	30	-56,560	-24,240
20	105.0	1,250	1,320	-428,619	30	-300,033	-128,586
21	106.3	1,020	1,440	-489,820	30	-342,874	-146,946
22	107.3	1,020	1,270	-683,645	30	-478,551	-205,093
23	108.3	1,030	1,220	-32,258	30	-22,580	-9,677
24	109.3	1,040	1,390	786,657	30	550,660	235,997
25	110.4	1,160	1,100	652,772	30	456,940	195,832
26	111.5	1,010	990	439,874	30	307,912	131,962
27	112.5	1,020	1,040	-284,617	30	-199,232	-85,385
28	113.6	1,070	920	104,520	30	73,164	31,356
29	114.6	1,020	730	216,242	30	151,369	64,872
30	115.6	1,020	1,040	716,395	30	501,477	214,919
31	116.7	1,220	830	-189,112	30	-132,378	-56,734
32	117.9	1,120	1,170	173,546	30	121,482	52,064
33	119.0	1,240	890	216,334	30	151,434	64,900
34	120.2	1,020	590	36,853	30	25,797	11,056
35	121.3	1,020	700	-345,990	30	-242,193	-103,797
36	122.3	1,010	1,190	-273,608	30	-191,526	-82,083
37	123.3	1,060	1,240	-504,086	30	-352,861	-151,226
38	124.4	1,020	1,520	1,293,146	30	905,203	387,944
39	125.4	1,010	1,370	395,271	30	276,689	118,581
40	126.4	1,020	980	1,401,122	30	980,786	420,337
41	127.4	1,090	800	307,202	30	215,042	92,161
42	128.5	910	700	1,046,079	30	732,255	313,824
43	129.4	1,130	560	125,003	30	87,502	37,501
R1-43		1,047	932	7,107,126		4,716,912	2,390,214

Cell	bank changes: erosion (sub 3m)	bank changes: deposition (sub 0.84m)	bank changes: bank total	bank changes: bank gravel	bank changes: bank sand	bank changes: O/B sand (>0.177 mm)
1	0	32	32	2	30	-474
2	0	709	709	35	673	-1,050
3	0	0	0	0	0	733
4	0	0	0	0	0	658
5	-252,736	21,408	-231,328	-11,566	-219,762	-52,962
6	-85,891	401	-85,490	-4,274	-81,215	-46,266
7	0	0	0	0	0	-13,523
8	0	0	0	0	0	-20,822
9	-265	0	-265	-53	-212	-25,085
10	-6,879	0	-6,879	-2,752	-4,128	-38,578
11	-52,915	0	-52,915	-21,166	-31,749	-25,036
12	-43,845	0	-43,845	-26,307	-17,538	-47,817
13	0	0	0	0	0	291
14	-79,570	15,881	-63,688	-44,582	-19,107	-43,895
15	-296,759	4,835	-291,923	-204,346	-87,577	-88,496
16	-49,205	0	-49,205	-34,444	-14,762	-55,087
17	-63,669	0	-63,669	-44,568	-19,101	-111,532
18	-286,261	0	-286,261	-200,383	-85,878	-133,401
19	-47,390	15,221	-32,170	-22,519	-9,651	-132,185
20	0	29,878	29,878	20,915	8,963	-107,467
21	-424,686	0	-424,686	-297,281	-127,406	-160,053
22	-126,687	0	-126,687	-88,681	-38,006	-128,066
23	0	130,883	130,883	91,618	39,265	-8,610
24	-23,062	113,377	90,315	63,220	27,094	-108,207
25	-16,201	0	-16,201	-11,341	-4,860	-31,088
26	0	151	151	106	45	-56,022
27	0	0	0	0	0	1,386
28	0	16,431	16,431	11,502	4,929	-16,146
29	0	13,956	13,956	9,769	4,187	5,583
30	0	17,320	17,320	12,124	5,196	-14,688
31	-107,594	59,308	-48,285	-33,800	-14,486	-64,052
32	-13,255	0	-13,255	-9,278	-3,976	-386,156
33	-113,981	47,959	-66,022	-46,215	-19,807	-258,916
34	0	107	107	75	32	-22,921
35	-182,773	0	-182,773	-127,941	-54,832	-57,715
36	0	0	0	0	0	-48,234
37	-94,723	0	-94,723	-66,306	-28,417	-198,377
38	-91,678	0	-91,678	-64,175	-27,503	-353,132
39	0	204,832	204,832	143,382	61,449	-119,268
40	0	108,252	108,252	75,776	32,476	-83,846
41	0	38,033	38,033	26,623	11,410	-136,823
42	-188,325	1,390	-186,935	-130,855	-56,081	-198,457
43	0	0	0	0	0	-57,924
R1-43	-2,648,349	840,364	-1,807,985	-1,037,684	-770,301	-3,443,725

Cell	vegetation stripping and recovery: stripping (sub 3m)	vegetation stripping and recovery: recovery (sub 0.84m)	vegetation stripping and recovery: gravel	vegetation stripping and recovery: sand	vegetation stripping and recovery: O/B sand (>0.177 mm)
1	0	0	0	0	0
2	0	82	4	78	354
3	0	0	0	0	31
4	0	179	9	170	89
5	0	19,748	987	18,760	3,109
6	0	200	10	190	261
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	-149
11	0	0	0	0	1,593
12	0	0	0	0	23,478
13	0	94,199	65,939	28,260	92,819
14	0	1,027	719	308	3,264
15	0	0	0	0	0
16	0	0	0	0	-4,599
17	0	35	25	11	31
18	0	0	0	0	0
19	0	12,875	9,012	3,862	18,505
20	0	15,896	11,127	4,769	35,430
21	-8,863	0	-6,204	-2,659	48,807
22	0	0	0	0	-8,995
23	0	0	0	0	9,526
24	0	40,583	28,408	12,175	33,671
25	0	12,641	8,849	3,792	10,883
26	0	425	298	128	349
27	0	44,612	31,229	13,384	16,799
28	0	69,609	48,726	20,883	24,493
29	0	31,922	22,346	9,577	34,822
30	0	104,875	73,413	31,463	22,210
31	0	0	0	0	10,847
32	0	70,507	49,355	21,152	34,237
33	0	7,375	5,163	2,213	-1,139
34	0	50,040	35,028	15,012	9,690
35	0	0	0	0	482
36	0	0	0	0	1,468
37	0	0	0	0	8,042
38	0	0	0	0	7,908
39	0	152,594	106,816	45,778	108,802
40	0	0	0	0	16,933
41	0	0	0	0	0
42	0	21,859	15,301	6,558	4,936
43	0	0	0	0	2,485
R1-43	-8,863	751,285	506,560	235,863	571,472

stable fldpln total sand	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
-16346	0	0	-5,025	-95,952	-100,977	1
81982	0	0	-12,387	-236,047	-248,434	2
382517	0	0	-8,785	-166,147	-174,932	3
451433	0	0	10,039	191,485	201,524	4
195258	0	0	9,480	130,270	139,750	5
-144377	0	0	13,783	215,870	229,653	6
-73944	0	0	59,906	226,100	286,006	7
-117652	0	0	72,425	268,879	341,304	8
-87721	0	0	-102,922	-436,771	-539,692	9
-88750	0	0	-152,786	-267,905	-420,691	10
26887	0	0	30,038	21,614	51,652	11
-46176	0	0	-183,127	-146,424	-329,551	12
19020	0	0	-293,640	-32,736	-326,376	13
324611	0	0	423,873	141,029	564,901	14
38580	0	800	344,152	59,797	403,949	15
-78922	0	0	148,251	3,850	152,101	16
-32128	0	0	186,539	-31,556	154,983	17
-75759	0	0	431,465	51,513	482,978	18
-38107	5,880	2,520	-64,186	-141,188	-205,374	19
19633	0	0	-267,991	-186,891	-454,883	20
12282	53,200	22,800	-593,158	-365,457	-958,615	21
-33999	0	0	-567,232	-380,160	-947,392	22
-62370	0	0	69,037	30,504	99,541	23
-51273	0	0	642,288	200,730	843,019	24
9399	0	0	454,448	174,559	629,007	25
46980	0	0	308,315	76,462	384,777	26
191822	0	0	-168,003	-53,816	-221,820	27
326883	457,100	195,900	590,492	261,415	851,907	28
447114	379,120	162,480	562,604	281,521	844,125	29
209817	32,200	13,800	619,214	272,899	892,113	30
-75833	0	0	-166,178	-124,424	-290,602	31
-17498	0	0	161,559	-282,680	-121,122	32
-78365	107,100	45,900	217,481	-166,849	50,632	33
13593	107,100	45,900	168,000	58,769	226,769	34
104236	0	0	-370,134	-215,862	-585,996	35
141639	0	0	-191,526	-128,848	-320,374	36
30169	0	0	-419,166	-369,978	-789,144	37
351280	82,950	35,550	923,978	50,767	974,745	38
416288	136,850	58,650	663,737	273,993	937,730	39
250877	2,660	1,140	1,059,222	387,039	1,446,261	40
319283	0	0	241,665	-33,253	208,412	41
194176	0	0	616,702	70,780	687,482	42
81843	0	0	87,502	-17,939	69,564	43
3,568,385	1,364,160	585,440	5,549,947	-431,037	5,118,910	R1-43

Table A2. Sediment budget - 1984 to 1999

Cell	river km	length (m)	width (m)	bed changes (deposition): channel change	% sand	channel gravel	channel sand	bank changes: erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)	vegetation stripping and recovery: stripping (sub 3m)	recovery (sub 0.84m)	gravel	sand	O/B sand (>0.177 mm)	stable fldpln total sand	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
1	85.5	820	560	-22,001	95	-1,100	-20,901	0	0	0	0	0	21	0	0	0	0	0	37886	0	0	-1,100	-20,881	-21,981	1
2	86.3	1,000	500	48,434	95	2,422	46,013	0	0	0	0	0	412	0	0	0	0	0	69016	0	0	2,422	46,425	48,847	2
3	87.3	1,000	450	29,274	95	1,464	27,811	0	0	0	0	0	443	0	0	0	0	-6	87300	0	0	1,464	28,248	29,712	3
4	88.3	950	400	9,152	95	458	8,694	0	0	0	0	0	-244	0	0	0	0	0	-71420	0	0	458	8,451	8,908	4
5	89.3	990	640	86,017	95	4,301	81,716	0	0	0	0	0	-1,261	0	0	0	0	1,144	-106127	0	0	4,301	81,599	85,899	5
6	90.3	1,000	750	204,127	95	10,206	193,920	0	0	0	0	0	-395	0	0	0	0	147	-9552	0	0	10,206	193,673	203,880	6
7	91.3	1,000	750	-124,984	80	-24,997	-99,987	0	0	0	0	0	-1,197	0	0	0	0	0	-75390	0	0	-24,997	-101,184	-126,181	7
8	92.3	1,150	730	-289,179	80	-57,836	-231,343	0	0	0	0	0	-1,669	0	0	0	0	0	-39111	0	0	-57,836	-233,012	-290,847	8
9	93.4	1,000	660	-135,699	80	-27,140	-108,560	0	301	301	60	241	-120	0	0	0	0	0	77195	0	0	-27,080	-108,439	-135,519	9
10	94.4	1,090	750	-363,972	60	-145,589	-218,383	0	0	0	0	0	247	0	0	0	0	-266	6850	0	0	-145,589	-218,402	-363,991	10
11	95.5	1,070	1,090	-550,419	60	-220,168	-330,251	0	0	0	0	0	-5,720	0	0	0	0	733	-4715	0	0	-220,168	-335,238	-555,406	11
12	96.6	1,000	670	-293,271	40	-175,963	-117,309	0	0	0	0	0	-9,067	0	0	0	0	2,351	49001	0	0	-175,963	-124,024	-299,987	12
13	97.6	1,030	680	-367,234	30	-257,063	-110,170	0	0	0	0	0	-1,468	0	0	0	0	2,735	250044	0	0	-257,063	-108,903	-365,966	13
14	98.6	1,000	600	-668,195	30	-467,736	-200,458	0	0	0	0	0	-2,936	0	0	0	0	0	-56121	0	0	-467,736	-203,394	-671,130	14
15	99.6	1,000	960	-1,204,732	30	-843,313	-361,420	0	0	0	0	0	956	0	0	0	0	0	-15424	0	0	-843,313	-360,463	-1,203,776	15
16	100.6	1,000	1,270	-161,564	30	-113,095	-48,469	-348,458	0	-348,458	-243,920	-104,537	-80,715	0	0	0	0	0	-15522	0	0	-357,015	-233,721	-590,737	16
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-60,475	0	-60,475	-42,332	-18,142	-31,820	0	0	0	0	-1,253	-66325	0	0	-414,434	-210,688	-625,122	17
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	20,134	20,134	14,094	6,040	9,454	0	0	0	0	153	-108211	0	0	320,560	146,990	467,550	18
19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	92,724	92,724	64,907	27,817	34,489	0	112,506	78,755	33,752	16,588	100797	3,400	3,400	526,560	278,688	805,248	19
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	12,304	12,304	8,613	3,691	7,030	0	0	0	0	2,528	126498	0	0	189,394	90,727	280,121	20
21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-91,006	19,403	-71,603	-50,122	-21,481	-82,467	0	10,373	7,261	3,112	-17,540	10914	23,750	23,750	463,392	112,161	575,553	21
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-16,803	5,844	-10,959	-7,671	-3,288	-21,691	0	0	0	0	-1,273	129872	0	0	434,428	163,219	597,647	22
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	3,287	3,287	2,301	986	5,719	0	17,547	12,283	5,264	13,214	154885	0	0	125,235	72,605	197,841	23
24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	10,932	0	0	0	0	15,625	115806	0	0	169,243	99,090	268,332	24
25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	-187	0	0	0	0	161	36843	0	0	39,480	16,894	56,374	25
26	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	-19,708	0	0	0	0	-33,779	27948	14,000	6,000	-298,984	-181,623	-480,607	26
27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	7,824	0	0	0	0	6,157	-8789	0	0	-19,931	5,439	-14,492	27
28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	26,728	0	0	0	0	6,802	19275	449,400	192,600	373,675	193,676	567,351	28
29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	11,369	11,369	7,958	3,411	45,468	0	0	0	0	39,858	-72517	204,085	87,465	108,321	131,749	240,070	29
30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-39,021	36,359	-2,663	-1,864	-799	40,365	0	0	0	0	26,321	-78315	0	0	-124,614	13,280	-111,334	30
31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	117,528	117,528	82,270	35,258	31,672	0	0	0	0	84,006	128670	0	0	1,074,542	576,196	1,650,738	31
32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	3,512	0	0	0	0	11,776	23119	0	0	617,286	279,839	897,124	32
33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	-10,342	0	0	0	0	-6,398	-34090	105,000	45,000	325,785	122,882	448,668	33
34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	3,574	0	0	0	0	-562	-38905	105,000	45,000	168,238	75,114	243,352	34
35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-341,979	40,393	-301,586	-211,110	-90,476	-58,502	0	46,616	32,631	13,985	10,890	-266647	0	0	306,756	83,855	390,611	35
36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	12,360	12,360	8,652	3,708	23,074	0	0	0	0	16,546	-136145	0	0	157,580	107,155	264,735	36
37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	-11,555	0	0	0	0	3,325	-68285	0	0	646,975	269,045	916,020	37
38	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-26,535	0	-26,535	-18,575	-7,961	-83,763	0	0	0	0	-46,438	-62165	0	0	164,014	-59,910	104,104	38
39	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-130,469	0	-130,469	-91,328	-39,141	-67,089	0	0	0	0	776	191254	0	0	236,098	34,872	270,970	39
40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	2,610	0	0	0	0	-4,055	73985	30,891	13,239	102,082	42,305	144,387	40
41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	18,005	18,005	12,603	5,401	2,102	0	0	0	0	1,885	117490	0	0	269,158	119,340	388,498	41
42	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	2,133	0	0	0	0	-9,538	52307	0	0	-30,204	-20,350	-50,554	42
43	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	216	216	151	65	-10,561	0	0	0	0	-638	-19223	0	0	-92,284	-50,749	-143,033	43
R1-43		1,047	932	3,329,109		2,678,200	650,909	-1,054,745	390,226	-664,520	-465,314	-199,206	-243,709	0	187,043	130,930	56,113	141,975	533,958	935,526	416,454	3,279,342	822,536	4,101,878	R1-43

Table A3. Sediment budget - 1952 to 1999

Cell	river km	length (m)	width (m)	bed changes (deposition): channel change	% sand	channel gravel	channel sand
1	85.5	820	560	211,549	95	10,577	200,971
2	86.3	1,000	500	-212,425	95	-10,621	-201,804
3	87.3	1,000	450	-138,423	95	-6,921	-131,501
4	88.3	950	400	214,113	95	10,706	203,407
5	89.3	990	640	647,982	95	32,399	615,583
6	90.3	1,000	750	616,443	95	30,822	585,621
7	91.3	1,000	750	190,202	80	38,040	152,162
8	92.3	1,150	730	98,039	80	19,608	78,431
9	93.4	1,000	660	-660,880	80	-132,176	-528,704
10	94.4	1,090	750	-747,228	60	-298,891	-448,337
11	95.5	1,070	1,090	-354,298	60	-141,719	-212,579
12	96.6	1,000	670	-454,937	40	-272,962	-181,975
13	97.6	1,030	680	-884,660	30	-619,262	-265,398
14	98.6	1,000	600	2,270	30	1,589	681
15	99.6	1,000	960	-422,890	30	-296,023	-126,867
16	100.6	1,000	1,270	-185,308	30	-129,716	-55,592
17	101.6	1,030	1,240	-91,051	30	-63,735	-27,315
18	102.7	1,100	1,220	1,260,942	30	882,660	378,283
19	103.8	1,260	1,160	641,236	30	448,865	192,371
20	105.0	1,250	1,320	-554,629	30	-388,241	-166,389
21	106.3	1,020	1,440	153,483	30	107,438	46,045
22	107.3	1,020	1,270	-99,232	30	-69,463	-29,770
23	108.3	1,030	1,220	55,668	30	38,968	16,700
24	109.3	1,040	1,390	337,295	30	236,106	101,188
25	110.4	1,160	1,100	615,157	30	430,610	184,547
26	111.5	1,010	990	-485,984	30	-340,189	-145,795
27	112.5	1,020	1,040	-509,062	30	-356,343	-152,719
28	113.6	1,070	920	-311,694	30	-218,186	-93,508
29	114.6	1,020	730	-163,540	30	-114,478	-49,062
30	115.6	1,020	1,040	159,772	30	111,840	47,931
31	116.7	1,220	830	24,556	30	17,189	7,367
32	117.9	1,120	1,170	377,290	30	264,103	113,187
33	119.0	1,240	890	422,775	30	295,943	126,833
34	120.2	1,020	590	37,113	30	25,979	11,134
35	121.3	1,020	700	207,766	30	145,436	62,330
36	122.3	1,010	1,190	-310,584	30	-217,409	-93,175
37	123.3	1,060	1,240	171,849	30	120,295	51,555
38	124.4	1,020	1,520	1,137,869	30	796,508	341,361
39	125.4	1,010	1,370	866,941	30	606,859	260,082
40	126.4	1,020	980	783,557	30	548,490	235,067
41	127.4	1,090	800	261,622	30	183,135	78,487
42	128.5	910	700	338,282	30	236,798	101,485
43	129.4	1,130	560	-93,424	30	-65,397	-28,027
44	130.5	1,180	520	-390,032	30	-273,022	-117,010
45	131.7	1,220	690	-45,203	30	-31,642	-13,561
56	132.9	1,020	1,300	-482,396	30	-337,677	-144,719
47	133.9	1,460	1,140	-580,913	30	-406,639	-174,274
48	135.4	1,070	1,650	1,305,994	30	914,196	391,798
49	136.5	1,280	1,050	315,063	30	220,544	94,519
50	137.8	1,070	790	-53,093	30	-37,165	-15,928
51	138.8	1,000	620	-207,303	30	-145,112	-62,191
52	139.8	1,000	1,040	-781,575	30	-547,102	-234,472
53	140.8	1,070	880	-721,558	30	-505,091	-216,468
54	141.9	1,190	900	-618,554	30	-432,988	-185,566
55	143.1	1,020	900	122,399	30	85,679	36,720
56	144.1	1,110	780	-349,942	30	-244,959	-104,982
57	145.2	1,360	770	-1,092,998	30	-765,099	-327,899
58	146.6	1,020	820	-595,731	30	-417,012	-178,719
59	147.6	1,800	820	-488,271	30	-341,789	-146,481
60	149.4	1,100	810	-60,472	30	-42,331	-18,142
61	150.5	1,080	670	59,718	30	41,803	17,915
62	151.6	1,040	480	-15,015	30	-10,511	-4,505
63	152.6	1,010	420	199,631	30	139,741	59,889
64	153.6	1,160	440	-111,716	30	-78,201	-33,515
65	154.8	1,430	400	-187,476	30	-131,233	-56,243
R1-17		1,008	747	-2,171,501		-1,828,285	-343,216
18-43		1,073	1,053	5,325,024		3,727,517	1,597,507
44-65		1,168	813	-4,779,443		-3,345,610	-1,433,833
total		1,088	892	-1,625,921		-1,446,379	-179,542

Cell	bank changes: erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)
1	0	0	0	0	0	-614
2	0	3,774	3,774	189	3,585	1,539
3	0	0	0	0	0	3,003
4	0	0	0	0	0	336
5	-385,394	18,436	-366,957	-18,348	-348,609	-57,690
6	-140,568	5,861	-134,707	-6,735	-127,972	-47,147
7	0	0	0	0	0	-18,880
8	0	0	0	0	0	-26,630
9	0	0	0	0	0	-21,441
10	0	0	0	0	0	-36,934
11	-37,115	0	-37,115	-14,846	-22,269	-53,855
12	-147,606	0	-147,606	-88,564	-59,042	-63,090
13	0	0	0	0	0	161
14	-86,011	28,139	-57,871	-40,510	-17,361	-45,375
15	-268,413	5,627	-262,786	-183,950	-78,836	-94,763
16	-359,511	0	-359,511	-251,658	-107,853	-102,039
17	-262,956	25	-262,930	-184,051	-78,879	-124,607
18	-222,423	6,297	-216,126	-151,288	-64,838	-119,605
19	-144,461	70,491	-73,970	-51,779	-22,191	-100,531
20	-29,784	142,155	112,371	78,660	33,711	-59,064
21	-556,338	0	-556,338	-389,437	-166,902	-181,216
22	-156,481	0	-156,481	-109,537	-46,944	-111,388
23	0	233,184	233,184	163,228	69,955	7,807
24	0	336,505	336,505	235,554	100,952	-42,181
25	0	1,922	1,922	1,345	577	-37,196
26	0	120,714	120,714	84,500	36,214	-22,857
27	0	35,049	35,049	24,534	10,515	6,231
28	0	39,137	39,137	27,396	11,741	1,568
29	0	86,116	86,116	60,282	25,835	26,214
30	-76,002	88,401	12,400	8,680	3,720	-9,711
31	-64,061	1,092,806	1,028,745	720,122	308,624	30,756
32	-118,351	31,804	-86,547	-60,583	-25,964	-135,243
33	-188,083	111,885	-76,198	-53,339	-22,859	-156,347
34	0	1,506	1,506	1,055	452	-4,498
35	-670,594	168,859	-501,735	-351,215	-150,521	-97,788
36	0	42,466	42,466	29,726	12,740	12,397
37	-148,886	45,754	-103,131	-72,192	-30,939	-67,254
38	-465,399	147,344	-318,055	-222,638	-95,416	-227,481
39	0	371,641	371,641	260,149	111,492	-238,732
40	-75,356	693,724	618,368	432,858	185,510	-40,923
41	0	175,435	175,435	122,805	52,631	-76,481
42	-131,340	243,269	111,929	78,350	33,579	-135,780
43	0	35,895	35,895	25,127	10,769	-45,456
44	-12,950	105,789	92,839	64,987	27,852	-377
45	-463,188	1,682	-461,506	-323,054	-138,452	-107,282
56	0	176,610	176,610	123,627	52,983	-82,518
47	0	0	0	0	0	-33,689
48	0	190,007	190,007	133,005	57,002	-114,884
49	0	299,617	299,617	209,732	89,885	-108,526
50	0	17,656	17,656	12,359	5,297	-28,485
51	0	2,662	2,662	1,863	799	-36,874
52	0	0	0	0	0	-769
53	0	1,984	1,984	1,389	595	-4,884
54	0	0	0	0	0	-10,624
55	-1,516	5,159	3,643	2,550	1,093	3,656
56	-10,689	51,568	40,879	28,616	12,264	11,724
57	-135,860	18,693	-117,167	-82,017	-35,150	-61,841
58	-100,066	0	-100,066	-70,046	-30,020	-57,172
59	-182,151	107,581	-74,570	-52,199	-22,371	-46,046
60	-14,201	4,373	-9,828	-6,880	-2,948	-36,381
61	-7,370	0	-7,370	-5,159	-2,211	-16,191
62	0	0	0	0	0	-1,482
63	0	0	0	0	0	13
64	0	0	0	0	0	529
65	0	0	0	0	0	277
R1-17	-1,687,573	61,862	-1,625,711	-788,473	-837,237	-688,025
18-43	-3,047,558	4,322,360	1,274,802	892,361	382,441	-1,824,759
44-65	-927,992	983,383	55,391	38,774	16,617	-731,825
total	-5,663,123	5,367,605	-295,518	142,662	-438,179	-3,244,609

Cell	vegetation stripping and recovery: stripping (sub 3m)	recovery (sub 0.84m)	gravel	sand	O/B sand (>0.177 mm)	stable fldpln total sand
1	0	0	0	0	0	36884
2	0	0	0	0	385	160869
3	0	0	0	0	187	474337
4	0	0	0	0	124	374000
5	0	22,135	1,107	21,028	3,912	92310
6	0	1,300	65	1,235	255	-206303
7	0	0	0	0	0	-159655
8	0	0	0	0	0	-194702
9	0	0	0	0	0	-19508
10	0	0	0	0	-295	-88669
11	0	0	0	0	6,325	15991
12	0	0	0	0	57,901	-119326
13	0	325,202	227,641	97,561	90,312	32890
14	0	0	0	0	2,090	247751
15	0	0	0	0	0	2523
16	0	0	0	0	6,332	-92297
17	0	475	332	142	-15,766	-71071
18	0	42,146	29,503	12,644	1,207	-211167
19	0	205,073	143,551	61,522	34,859	-53626
20	0	179,128	125,389	53,738	77,167	32614
21	0	95,433	66,803	28,630	-21,326	14298
22	0	0	0	0	763	-16984
23	0	0	0	0	44,379	-14404
24	0	289,676	202,773	86,903	59,815	18585
25	0	69,339	48,537	20,802	32,927	4774
26	0	26,215	18,351	7,865	15,396	80192
27	0	137,533	96,273	41,260	45,534	189090
28	0	265,349	185,745	79,605	75,515	323218
29	0	206,033	144,223	61,810	114,943	346041
30	0	383,606	268,524	115,082	121,679	118424
31	0	91,458	64,021	27,437	83,613	49696
32	0	361,280	252,896	108,384	-56,994	-25396
33	0	14,518	10,162	4,355	-101,561	-64586
34	0	54,960	38,472	16,488	18,476	-20979
35	-607	15,100	10,145	4,348	3,386	3429
36	0	0	0	0	37,625	471
37	0	0	0	0	-9,628	-226429
38	0	87,724	61,406	26,317	-92,397	284057
39	0	328,727	230,109	98,618	64,041	448670
40	0	114,806	80,364	34,442	16,358	326967
41	0	113,985	79,790	34,196	-10,626	490230
42	0	174,737	122,316	52,421	5,940	244002
43	0	0	0	0	2,404	53771
44	0	0	0	0	8,995	-75418
45	0	0	0	0	-99,632	-63097
56	0	207,596	145,317	62,279	131,291	-44132
47	0	0	0	0	37,782	87977
48	0	446,921	312,845	134,076	122,769	-67225
49	0	515,565	360,896	154,670	143,056	204927
50	0	150,281	105,197	45,084	77,435	135966
51	0	13,454	9,418	4,036	110,155	-84329
52	0	0	0	0	31,566	-176325
53	0	0	0	0	-194,899	-326662
54	0	0	0	0	-14,349	-301991
55	0	82,750	57,925	24,825	24,180	-149845
56	0	139,596	97,717	41,879	38,725	-121231
57	0	71,965	50,375	21,589	59,822	-212443
58	0	0	0	0	-49,576	-182815
59	-100,147	4,148	-67,199	-28,800	-157,310	-191463
60	0	240,573	168,401	72,172	72,838	194970
61	0	33,064	23,145	9,919	-11,668	100055
62	0	0	0	0	-5,118	-104334
63	0	0	0	0	3,025	10721
64	0	1,400	980	420	7,157	15635
65	-9,200	64,435	38,665	16,571	-2,036	-7737
R1-17	0	349,112	229,146	119,966	151,764	486,024
18-43	-607	3,256,825	2,279,352	976,865	563,494	2,394,956
44-65	-109,346	1,971,748	1,303,681	558,720	334,211	-1,358,797
total	-109,953	5,577,685	3,812,179	1,655,552	1,049,469	1,522,184

Cell	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
1	0	0	10,577	200,357	210,935	1
2	0	0	-10,433	-196,295	-206,728	2
3	0	0	-6,921	-128,311	-135,233	3
4	0	0	10,706	203,868	214,574	4
5	0	0	15,158	234,223	249,381	5
6	0	0	24,152	411,993	436,145	6
7	0	0	38,040	133,281	171,322	7
8	0	0	19,608	51,801	71,408	8
9	0	0	-132,176	-550,144	-682,320	9
10	0	0	-298,891	-485,566	-784,457	10
11	0	0	-156,565	-282,377	-438,943	11
12	0	0	-361,526	-246,205	-607,731	12
13	0	0	-391,620	-77,364	-468,984	13
14	0	0	-38,921	-59,965	-98,886	14
15	0	800	-479,973	-299,666	-779,639	15
16	0	0	-381,373	-259,153	-640,526	16
17	0	0	-247,454	-246,425	-493,879	17
18	0	0	760,874	207,691	968,565	18
19	9,280	5,920	549,918	171,950	721,868	19
20	0	0	-184,191	-60,836	-245,028	20
21	76,950	46,550	-138,246	-248,220	-386,465	21
22	0	0	-178,999	-187,339	-366,338	22
23	0	0	202,196	138,842	341,038	23
24	0	0	674,433	306,676	981,110	24
25	0	0	480,492	201,656	682,148	25
26	14,000	6,000	-223,339	-103,178	-326,516	26
27	0	0	-235,536	-49,179	-284,715	27
28	906,500	388,500	901,455	463,421	1,364,876	28
29	583,205	249,945	673,232	429,684	1,102,916	29
30	32,200	13,800	421,244	292,501	713,745	30
31	0	0	801,331	457,797	1,259,128	31
32	0	0	456,416	3,370	459,786	32
33	212,100	90,900	464,866	-58,679	406,187	33
34	212,100	90,900	277,605	132,952	410,558	34
35	0	0	-195,634	-178,245	-373,879	35
36	0	0	-187,682	-30,413	-218,095	36
37	0	0	48,103	-56,267	-8,164	37
38	82,950	35,550	718,226	-12,066	706,160	38
39	136,850	58,650	1,233,967	354,152	1,588,118	39
40	33,551	14,379	1,095,263	444,833	1,540,095	40
41	0	0	385,729	78,206	463,935	41
42	0	0	437,463	57,645	495,108	42
43	0	0	-40,270	-60,311	-100,581	43
44	140,000	60,000	-68,035	-20,540	-88,575	44
45	238,105	102,045	-116,591	-256,881	-373,473	45
56	0	0	-68,733	19,317	-49,416	56
47	0	0	-406,639	-170,182	-576,821	47
48	109,900	47,100	1,469,946	637,861	2,107,807	48
49	37,800	16,200	828,971	389,803	1,218,775	49
50	0	0	80,391	83,403	163,794	50
51	0	0	-133,831	15,925	-117,906	51
52	0	0	-547,102	-203,676	-750,778	52
53	0	0	-503,702	-415,655	-919,357	53
54	0	0	-432,988	-210,538	-643,526	54
55	0	0	146,155	90,474	236,628	55
56	0	0	-118,627	-390	-119,017	56
57	0	0	-796,740	-343,479	-1,140,219	57
58	0	0	-487,058	-315,487	-802,545	58
59	0	0	-461,187	-401,007	-862,194	59
60	0	0	119,191	87,539	206,730	60
61	0	0	59,788	-2,235	57,553	61
62	0	0	-10,511	-11,104	-21,615	62
63	0	0	139,741	62,927	202,669	63
64	0	0	-77,221	-25,408	-102,629	64
65	0	0	-92,568	-41,431	-134,000	65
R1-17	0	800	-2,387,613	-1,595,948	-3,983,561	R1-17
18-43	2,299,686	1,001,094	9,198,917	2,696,642	11,895,559	18-43
44-65	525,805	225,345	-1,477,351	-1,030,764	-2,508,115	44-65
total	2,825,491	1,227,239	5,333,953	69,930	5,403,883	total

Table A4. Sediment volume changes and bed level changes in individual subreaches between Agassiz and Mission - 1952-99 as sum of 1952-84 and 1984-99 budgets

Cell	river km	length (m)	width (m)	bed changes (deposition): channel change	% sand	channel gravel	channel sand
1	85.5	820	560	-122,536	95	-6,127	-116,409
2	86.3	1,000	500	-200,095	95	-10,005	-190,090
3	87.3	1,000	450	-146,422	95	-7,321	-139,101
4	88.3	950	400	209,750	95	10,487	199,262
5	89.3	990	640	487,201	95	24,360	462,841
6	90.3	1,000	750	565,074	95	28,254	536,820
7	91.3	1,000	750	174,545	80	34,909	139,636
8	92.3	1,150	730	72,947	80	14,589	58,357
9	93.4	1,000	660	-650,042	80	-130,008	-520,034
10	94.4	1,090	750	-739,057	60	-295,623	-443,434
11	95.5	1,070	1,090	-422,410	60	-168,964	-253,446
12	96.6	1,000	670	-554,638	40	-332,783	-221,855
13	97.6	1,030	680	-880,918	30	-616,643	-264,276
14	98.6	1,000	600	-1	30	-1	0
15	99.6	1,000	960	-421,163	30	-294,814	-126,349
16	100.6	1,000	1,270	99,428	30	69,599	29,828
17	101.6	1,030	1,240	-201,456	30	-141,019	-60,437
18	102.7	1,100	1,220	1,340,448	30	938,313	402,134
19	103.8	1,260	1,160	461,342	30	322,940	138,403
20	105.0	1,250	1,320	-170,361	30	-119,252	-51,108
21	106.3	1,020	1,440	199,471	30	139,629	59,841
22	107.3	1,020	1,270	-52,074	30	-36,452	-15,622
23	108.3	1,030	1,220	125,816	30	88,071	37,745
24	109.3	1,040	1,390	1,028,432	30	719,902	308,530
25	110.4	1,160	1,100	709,172	30	496,421	212,752
26	111.5	1,010	990	-7,246	30	-5,072	-2,174
27	112.5	1,020	1,040	-313,090	30	-219,163	-93,927
28	113.6	1,070	920	-3,660	30	-2,562	-1,098
29	114.6	1,020	730	68,067	30	47,647	20,420
30	115.6	1,020	1,040	541,037	30	378,726	162,311
31	116.7	1,220	830	1,228,420	30	859,894	368,526
32	117.9	1,120	1,170	1,055,383	30	738,768	316,615
33	119.0	1,240	890	531,742	30	372,219	159,523
34	120.2	1,020	590	127,192	30	89,035	38,158
35	121.3	1,020	700	347,203	30	243,042	104,161
36	122.3	1,010	1,190	-60,853	30	-42,597	-18,256
37	123.3	1,060	1,240	420,164	30	294,115	126,049
38	124.4	1,020	1,520	1,553,987	30	1,087,791	466,196
39	125.4	1,010	1,370	863,022	30	604,116	258,907
40	126.4	1,020	980	1,502,823	30	1,051,976	450,847
41	127.4	1,090	800	673,709	30	471,596	202,113
42	128.5	910	700	1,002,929	30	702,051	300,879
43	129.4	1,130	560	-7,047	30	-4,933	-2,114
R1-43		1,047	932	10,436,235		7,395,112	3,041,123

Cell	bank changes: erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)
1	0	32	32	2	30	-454
2	0	709	709	35	673	-637
3	0	0	0	0	0	1,177
4	0	0	0	0	0	415
5	-252,736	21,408	-231,328	-11,566	-219,762	-54,223
6	-85,891	401	-85,490	-4,274	-81,215	-46,661
7	0	0	0	0	0	-14,720
8	0	0	0	0	0	-22,490
9	-265	301	36	7	29	-25,205
10	-6,879	0	-6,879	-2,752	-4,128	-38,331
11	-52,915	0	-52,915	-21,166	-31,749	-30,755
12	-43,845	0	-43,845	-26,307	-17,538	-56,884
13	0	0	0	0	0	-1,177
14	-79,570	15,881	-63,688	-44,582	-19,107	-46,830
15	-296,759	4,835	-291,923	-204,346	-87,577	-87,540
16	-397,663	0	-397,663	-278,364	-119,299	-135,802
17	-124,144	0	-124,144	-86,901	-37,243	-143,352
18	-286,261	20,134	-266,127	-186,289	-79,838	-123,946
19	-47,390	107,944	60,554	42,388	18,166	-97,696
20	0	42,183	42,183	29,528	12,655	-100,437
21	-515,693	19,403	-496,290	-347,403	-148,887	-242,520
22	-143,490	5,844	-137,646	-96,352	-41,294	-149,757
23	0	134,169	134,169	93,919	40,251	-2,890
24	-23,062	113,377	90,315	63,220	27,094	-97,275
25	-16,201	0	-16,201	-11,341	-4,860	-31,275
26	0	151	151	106	45	-75,730
27	0	0	0	0	0	9,210
28	0	16,431	16,431	11,502	4,929	10,582
29	0	25,325	25,325	17,728	7,598	51,051
30	-39,021	53,679	14,658	10,261	4,397	25,677
31	-107,594	176,836	69,243	48,470	20,773	-32,380
32	-13,255	0	-13,255	-9,278	-3,976	-382,645
33	-113,981	47,959	-66,022	-46,215	-19,807	-269,258
34	0	107	107	75	32	-19,346
35	-524,751	40,393	-484,358	-339,051	-145,307	-116,217
36	0	12,360	12,360	8,652	3,708	-25,160
37	-94,723	0	-94,723	-66,306	-28,417	-209,932
38	-118,213	0	-118,213	-82,749	-35,464	-436,895
39	-130,469	204,832	74,363	52,054	22,309	-186,357
40	0	108,252	108,252	75,776	32,476	-81,236
41	0	56,037	56,037	39,226	16,811	-134,721
42	-188,325	1,390	-186,935	-130,855	-56,081	-196,324
43	0	216	216	151	65	-68,486
R1-43	-3,703,095	1,230,590	-2,472,505	-1,502,999	-969,506	-3,687,434

Cell	vegetation stripping and recovery: stripping (sub 3m)	recovery (sub 0.84m)	gravel	sand	O/B sand (>0.177 mm)
1	0	0	0	0	0
2	0	82	4	78	354
3	0	0	0	0	25
4	0	179	9	170	89
5	0	19,748	987	18,760	4,252
6	0	200	10	190	409
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	-414
11	0	0	0	0	2,326
12	0	0	0	0	25,829
13	0	94,199	65,939	28,260	95,554
14	0	1,027	719	308	3,264
15	0	0	0	0	0
16	0	0	0	0	-4,599
17	0	35	25	11	-1,222
18	0	0	0	0	153
19	0	125,381	87,767	37,614	35,092
20	0	15,896	11,127	4,769	37,957
21	-8,863	10,373	1,057	453	31,267
22	0	0	0	0	-10,268
23	0	17,547	12,283	5,264	22,740
24	0	40,583	28,408	12,175	49,296
25	0	12,641	8,849	3,792	11,044
26	0	425	298	128	-33,430
27	0	44,612	31,229	13,384	22,956
28	0	69,609	48,726	20,883	31,295
29	0	31,922	22,346	9,577	74,680
30	0	104,875	73,413	31,463	48,531
31	0	0	0	0	94,853
32	0	70,507	49,355	21,152	46,012
33	0	7,375	5,163	2,213	-7,538
34	0	50,040	35,028	15,012	9,128
35	0	46,616	32,631	13,985	11,372
36	0	0	0	0	18,014
37	0	0	0	0	11,367
38	0	0	0	0	-38,530
39	0	152,594	106,816	45,778	109,579
40	0	0	0	0	12,879
41	0	0	0	0	1,885
42	0	21,859	15,301	6,558	-4,601
43	0	0	0	0	1,847
R1-43	-8,863	938,328	637,489	291,976	713,447

stable fldpln total sand	gravel removal	sand removal	gravel sum	sand sum	total sand+gravel	Cell
21,540	0	0	-6,125	-116,832	-122,958	1
150,999	0	0	-9,965	-189,622	-199,587	2
469,817	0	0	-7,321	-137,899	-145,220	3
380,013	0	0	10,496	199,936	210,432	4
89,131	0	0	13,781	211,868	225,649	5
-153,929	0	0	23,989	409,543	433,533	6
-149,334	0	0	34,909	124,916	159,825	7
-156,763	0	0	14,589	35,867	50,456	8
-10,526	0	0	-130,001	-545,210	-675,211	9
-81,900	0	0	-298,374	-486,307	-784,681	10
22,172	0	0	-190,130	-313,624	-503,754	11
2,826	0	0	-359,090	-270,448	-629,538	12
269,064	0	0	-550,703	-141,638	-692,341	13
268,490	0	0	-43,864	-62,365	-106,229	14
23,156	0	800	-499,161	-300,666	-799,827	15
-94,444	0	0	-208,765	-229,871	-438,636	16
-98,453	0	0	-227,895	-242,244	-470,138	17
-183,969	0	0	752,024	198,503	950,528	18
62,690	9,280	5,920	462,374	137,499	599,874	19
146,131	0	0	-78,597	-96,164	-174,761	20
23,196	76,950	46,550	-129,766	-253,296	-383,062	21
95,873	0	0	-132,804	-216,941	-349,745	22
92,516	0	0	194,273	103,109	297,382	23
64,533	0	0	811,531	299,820	1,111,351	24
46,242	0	0	493,928	191,452	685,381	25
74,928	14,000	6,000	9,331	-105,161	-95,830	26
183,033	0	0	-187,934	-48,377	-236,312	27
346,157	906,500	388,500	964,166	455,092	1,419,258	28
374,597	583,205	249,945	670,926	413,270	1,084,196	29
131,502	32,200	13,800	494,599	286,179	780,778	30
52,837	0	0	908,364	451,772	1,360,135	31
5,621	0	0	778,845	-2,842	776,003	32
-112,455	212,100	90,900	543,267	-43,967	499,300	33
-25,312	212,100	90,900	336,237	133,883	470,121	34
-162,411	0	0	-63,378	-132,007	-195,385	35
5,494	0	0	-33,946	-21,694	-55,639	36
-38,116	0	0	227,809	-100,933	126,876	37
289,115	82,950	35,550	1,087,992	-9,143	1,078,849	38
607,541	136,850	58,650	899,836	308,865	1,208,701	39
324,861	33,551	14,379	1,161,303	429,344	1,590,648	40
436,772	0	0	510,822	86,087	596,909	41
246,484	0	0	586,497	50,431	636,928	42
62,620	0	0	-4,782	-68,688	-73,470	43
4,102,343	2,299,686	1,001,894	8,829,289	391,499	9,220,788	R1-43

Table A 5. Comparison between sediment budget and sediment transport estimates: total bed material influx at Agassiz ($10^3\ m^3 a^{-1}$, bulk measure)[1]

	1952-84	1984-99	1952-99[2]	1952-99[3]
Sediment budget				
by survey	250	310	205	270
upper bound[4]	270	360		295
lower bound[4]	225	265		245
bias-corrected estimate				335
upper bound[5]				360
lower bound[5]				310
Sediment transport	195	155		180
upper bound[6]	265	235		235
lower bound[6]	165	120		155

1 *Based on gravel influx (table 3, p.22) x 1.0/0.7, to incorporate included sand.*
2 *By direct difference of surveys.*
3 *By sum of the constituent periods.*
4 *Outside error estimate derived as the pooled sum of errors estimated for the individual sediment budget computing cells.*
5 *Error estimates derived as the range of estimates adjusted for 2 to 10-year intersurvey periods.*
6 Outside error estimate derived as the pooled sum of 2s error ranges for individual years from the regression equation for the annual sediment load.

Table A6. Summary of bed level changes

Cell	river km	length (m)	width (m)	sediment budget s+g totals (m3)			bed level changes from sediment budget (m)					
				1952-84	1984-99	1952-99	1952-84		1984-99		1952-99	
							gross	net	gross	net	gross	net
1	85.5	820	560	-100,977	-21,981	210,935	-0.220	-0.220	-0.048	-0.048	0.459	0.459
2	86.3	1,000	500	-248,434	48,847	-206,728	-0.497	-0.497	0.098	0.098	-0.413	-0.413
3	87.3	1,000	450	-174,932	29,712	-135,233	-0.389	-0.389	0.066	0.066	-0.301	-0.301
4	88.3	950	400	201,524	8,908	214,574	0.530	0.530	0.023	0.023	0.565	0.565
5	89.3	990	640	139,750	85,899	249,381	0.221	0.221	0.136	0.136	0.394	0.394
6	90.3	1,000	750	229,653	203,880	436,145	0.306	0.306	0.272	0.272	0.582	0.582
7	91.3	1,000	750	286,006	-126,181	171,322	0.381	0.381	-0.168	-0.168	0.228	0.228
8	92.3	1,150	730	341,304	-290,847	71,408	0.407	0.407	-0.346	-0.346	0.085	0.085
9	93.4	1,000	660	-539,692	-135,519	-682,320	-0.818	-0.818	-0.205	-0.205	-1.034	-1.034
10	94.4	1,090	750	-420,691	-363,991	-784,457	-0.515	-0.515	-0.445	-0.445	-0.960	-0.960
11	95.5	1,070	1,090	51,652	-555,406	-438,943	0.044	0.044	-0.476	-0.476	-0.376	-0.376
12	96.6	1,000	670	-329,551	-299,987	-607,731	-0.492	-0.492	-0.448	-0.448	-0.907	-0.907
13	97.6	1,030	680	-326,376	-365,966	-468,984	-0.466	-0.466	-0.523	-0.523	-0.670	-0.670
14	98.6	1,000	600	564,901	-671,130	-98,886	0.942	0.942	-1.119	-1.119	-0.165	-0.165
15	99.6	1,000	960	403,949	-1,203,776	-779,639	0.421	0.420	-1.254	-1.254	-0.812	-0.813
16	100.6	1,000	1,270	152,101	-590,737	-640,526	0.120	0.120	-0.465	-0.465	-0.504	-0.504
17	101.6	1,030	1,240	154,983	-625,122	-493,879	0.121	0.121	-0.489	-0.489	-0.387	-0.387
18	102.7	1,100	1,220	482,978	467,550	968,565	0.360	0.360	0.348	0.348	0.722	0.722
19	103.8	1,260	1,160	-205,374	805,248	721,868	-0.141	-0.146	0.551	0.546	0.494	0.483
20	105.0	1,250	1,320	-454,883	280,121	-245,028	-0.276	-0.276	0.170	0.170	-0.149	-0.149
21	106.3	1,020	1,440	-958,615	575,553	-386,465	-0.653	-0.704	0.392	0.360	-0.263	-0.347
22	107.3	1,020	1,270	-947,392	597,647	-366,338	-0.731	-0.731	0.461	0.461	-0.283	-0.283
23	108.3	1,030	1,220	99,541	197,841	341,038	0.079	0.079	0.157	0.157	0.271	0.271
24	109.3	1,040	1,390	843,019	268,332	981,110	0.583	0.583	0.186	0.186	0.679	0.679
25	110.4	1,160	1,100	629,007	56,374	682,148	0.493	0.493	0.044	0.044	0.535	0.535
26	111.5	1,010	990	384,777	-480,607	-326,516	0.385	0.385	-0.481	-0.501	-0.327	-0.347
27	112.5	1,020	1,040	-221,820	-14,492	-284,715	-0.209	-0.209	-0.014	-0.014	-0.268	-0.268
28	113.6	1,070	920	851,907	567,351	1,364,876	0.865	0.202	0.576	-0.076	1.387	0.071
29	114.6	1,020	730	844,125	240,070	1,102,916	1.134	0.406	0.322	-0.069	1.481	0.362
30	115.6	1,020	1,040	892,113	-111,334	713,745	0.841	0.798	-0.105	-0.105	0.673	0.629
31	116.7	1,220	830	-290,602	1,650,738	1,259,128	-0.287	-0.287	1.630	1.630	1.243	1.243
32	117.9	1,120	1,170	-121,122	897,124	459,786	-0.092	-0.092	0.685	0.685	0.351	0.351
33	119.0	1,240	890	50,632	448,668	406,187	0.046	-0.093	0.407	0.271	0.368	0.094
34	120.2	1,020	590	226,769	243,352	410,558	0.377	0.123	0.404	0.155	0.682	0.179
35	121.3	1,020	700	-585,996	390,611	-373,879	-0.821	-0.821	0.547	0.547	-0.524	-0.524
36	122.3	1,010	1,190	-320,374	264,735	-218,095	-0.267	-0.267	0.220	0.220	-0.181	-0.181
37	123.3	1,060	1,240	-789,144	916,020	-8,164	-0.600	-0.600	0.697	0.697	-0.006	-0.006
38	124.4	1,020	1,520	974,745	104,104	706,160	0.629	0.552	0.067	0.067	0.455	0.379
39	125.4	1,010	1,370	937,730	270,970	1,588,118	0.678	0.536	0.196	0.196	1.148	1.006
40	126.4	1,020	980	1,446,261	144,387	1,540,095	1.447	1.443	0.144	0.100	1.541	1.493
41	127.4	1,090	800	208,412	388,498	463,935	0.239	0.239	0.446	0.446	0.532	0.532
42	128.5	910	700	687,482	-50,554	495,108	1.079	1.079	-0.079	-0.079	0.777	0.777
43	129.4	1,130	560	69,564	-143,033	-100,581	0.110	0.110	-0.226	-0.226	-0.159	-0.159
44	130.5	1,180	520			-88,575					-0.144	-0.470
45	131.7	1,220	690			-373,473					-0.444	-0.848
46	132.9	1,020	1,300			-49,416					-0.037	-0.037
47	133.9	1,460	1,140			-576,821					-0.347	-0.347
48	135.4	1,070	1,650			2,107,807					1.194	1.105
49	136.5	1,280	1,050			1,218,775					0.907	0.867
50	137.8	1,070	790			163,794					0.194	0.194
51	138.8	1,000	620			-117,906					-0.190	-0.190
52	139.8	1,000	1,040			-750,778					-0.722	-0.722
53	140.8	1,070	880			-919,357					-0.976	-0.976
54	141.9	1,190	900			-643,526					-0.601	-0.601
55	143.1	1,020	900			236,628					0.258	0.258
56	144.1	1,110	780			-119,017					-0.137	-0.137
57	145.2	1,360	770			-1,140,219					-1.089	-1.089
58	146.6	1,020	820			-802,545					-0.960	-0.960
59	147.6	1,800	820			-862,194					-0.584	-0.584
60	149.4	1,100	810			206,730					0.232	0.232
61	150.5	1,080	670			57,553					0.080	0.080
62	151.6	1,040	480			-21,615					-0.043	-0.043
63	152.6	1,010	420			202,669					0.478	0.478
64	153.6	1,160	440			-102,629					-0.201	-0.201
65	154.8	1,430	400			-134,000					-0.234	-0.234
R1-43		1,047	932	5,118,910	4,101,878	7,911,998	0.121	0.075	0.097	0.065	0.187	0.109
R44-65		1,168	813			-2,508,115					-0.120	-0.156
Total		1,088	892			5,403,883					0.086	0.021

unadjusted computing cell sediment totals (m3)			unadjusted bed level changes (m)			
1952-84	1984-99	1952-99	1952-84	1984-99	1952-99	Cell
-100,982	-22,846	-123,262	-0.220	-0.050	-0.268	1
-248,206	49,631	-199,846	-0.496	0.099	-0.400	2
-169,949	32,125	-138,247	-0.378	0.071	-0.307	3
205,223	9,628	214,765	0.540	0.025	0.565	4
17,332	86,566	104,025	0.027	0.137	0.164	5
101,487	203,257	305,296	0.135	0.271	0.407	6
239,210	-131,502	107,209	0.319	-0.175	0.143	7
257,196	-278,019	-21,186	0.306	-0.331	-0.025	8
-627,247	-122,440	-750,539	-0.950	-0.186	-1.137	9
-514,339	-371,404	-887,294	-0.629	-0.454	-1.085	10
6,423	-555,117	-550,623	0.006	-0.476	-0.472	11
-410,063	-177,186	-588,059	-0.612	-0.264	-0.878	12
-109,601	-129,438	-239,962	-0.156	-0.185	-0.343	13
479,478	-686,196	-208,245	0.799	-1.144	-0.347	14
184,886	-1,208,731	-1,023,126	0.193	-1.259	-1.066	15
-12,636	-858,392	-871,675	-0.010	-0.676	-0.686	16
-135,705	-705,023	-841,638	-0.106	-0.552	-0.659	17
160,795	488,709	650,620	0.120	0.364	0.485	18
-488,358	1,021,551	534,755	-0.334	0.699	0.366	19
-610,742	411,773	-197,794	-0.370	0.250	-0.120	20
-1,369,817	376,211	-991,946	-0.933	0.256	-0.675	21
-1,286,141	633,499	-652,453	-0.993	0.489	-0.504	22
104,095	355,341	459,277	0.083	0.283	0.365	23
662,651	379,536	1,043,804	0.458	0.263	0.722	24
585,877	70,079	656,732	0.459	0.055	0.515	25
240,579	-627,957	-388,073	0.241	-0.628	-0.388	26
-180,594	24,471	-155,358	-0.170	0.023	-0.146	27
222,421	25,536	248,916	0.226	0.026	0.253	28
425,933	175,917	602,769	0.572	0.236	0.810	29
872,268	51,984	924,983	0.822	0.049	0.872	30
-514,872	2,058,537	1,545,543	-0.508	2.033	1.526	31
-956,898	985,241	29,730	-0.730	0.752	0.023	32
-774,442	257,554	-516,040	-0.702	0.233	-0.468	33
24,917	101,439	126,605	0.041	0.169	0.210	34
-875,244	281,358	-594,489	-1.226	0.394	-0.833	35
-436,094	363,877	-71,105	-0.363	0.303	-0.059	36
-1,256,236	1,005,861	-247,977	-0.956	0.765	-0.189	37
-5	-170,009	-168,767	0.000	-0.110	-0.109	38
804,739	294,303	1,101,161	0.582	0.213	0.796	39
1,327,349	118,942	1,446,287	1.328	0.119	1.447	40
-141,212	414,296	273,621	-0.162	0.475	0.314	41
242,224	-51,493	191,446	0.380	-0.081	0.301	42
-9,553	-167,133	-177,065	-0.015	-0.264	-0.280	43
		-273,294			-0.445	44
		-1,197,032			-1.422	45
		62,930			0.047	46
		-573,753			-0.345	47
		1,964,607			1.113	48
		1,240,039			0.923	49
		290,414			0.344	50
		58,133			0.094	51
		-681,223			-0.655	52
		-1,380,013			-1.466	53
		-702,185			-0.656	54
		316,235			0.344	55
		-902			-0.001	56
		-1,146,574			-1.095	57
		-1,064,131			-1.272	58
		-1,337,854			-0.906	59
		294,549			0.331	60
		-3,015			-0.004	61
		-36,630			-0.073	62
		210,538			0.496	63
		-89,452			-0.175	64
		-145,882			-0.255	65
-4,063,858	4,014,332	-37,220	-0.096	0.095	-0.001	R1-43
		-4,194,495			-0.195	R44-65
		-4,231,715			-0.067	Total

It is worth emphasis that, although we have preferred the available sum of 1952-1984 and 1984-1999 sediment budgets for estimating the total sediment budget in the Agassiz-Mission reach, the appropriate results for estimating bed level change remain the direct 1952-1999 survey differences. The actual surveys are not biased by sediment coincident scour/fill. In what follows, it must be realized that the selection of input data for summary presentations differs between the preferred estimates of the sediment budget, and those that lead to the estimates of bed level changes.

A5.3 Some example calculations

Upon close examination of the different columns presented in Table A 6, it becomes obvious that the bed-level changes reported for some reaches do not change appreciably between the two calculations, while for others, the differences appear to be surprisingly large. In order to make the procedures more transparent, some sample calculations will be given for selected computing cells along the river. We give one example of a "simple cell", one in which there were negligible bankline changes so that the computing areas were the same for all inter-survey comparisons, and in which exchange of wash material was, accordingly, small. The summary numbers in both bed elevation change exercises should be consistent and very similar to each other. We give a second example of a "complex cell", one in which significant bankline changes have occurred so that floodplain/island areas have been created or destroyed, or there has been significant floodplain stripping and/or recovery. In this case, significant wash material deposits will have been present, leading to systematic differences in the sediment volume recorded between the unadjusted and bed material calculations, thence to different results. In the case of the bed material calculations, furthermore, results may not sum between periods because the observed wash material adjustments may differ amongst the periods due to compensating erosion and deposition.

A5.3.1 Simple cell

We first review the calculations for a reach in which the computed bed-level changes remain essentially the same between the two analyses and, in addition, there has been no known sand and gravel removal. A suitable reach for this review is cell 2, located near the downstream end of the study reach at Mission, where the volumetric and bed level changes are as reported in Table A 7. In this comparison, we compare the unadjusted bed level changes with bed level changes estimated from the sediment budget for the full period 1952-1999. (In the main report, the preferred sediment budget is based on an adjusted sum of the 1952-1984 and 1984-1999 budgets. Taking account of the sum procedure would complicate the comparison given here, but would not change the principles to be demonstrated.)

Table A 7. Volume and bed level changes in cell 2*

period	1952-84	1984-99	1952-99
unadjusted volume (m^3 bulk measure) (table A6)	**-248,206**	**49,631**	**-199,846**
unadjusted bed level change (m)	-0.50	0.10	-0.40
sediment budget (m^3 bulk measure) (table A3)	-248,434	48,847	-206,728
bed material level change (m)	-0.50	0.10	-0.41

* negative values indicate degradation (erosion volume exceeds deposition volume)

In the sediment budget calculations the direct sum of the 1952-84 and 1984-99 figures (-0.40 m) does not equal the summary value for 1952-99 (-0.41 m) partly because the areas over which the individual period data are calculated are not exactly the same in each case. The sum does, however, correspond with the unadjusted result for 1952-1999. Furthermore, the result for cell 2 based on the sum of component sediment budgets (Table A 4) is also -0.40 m.

To further review how these data were derived, we need to examine the raw summary data from the GIS. In the case of the unadjusted bed level changes, the volume results are simply the sum of the interpolated elevation differences recorded between two successive surveys in each grid cell (there are n = 813 grid cells in computing cell 2) multiplied by the area of a grid cell (625 m^2). The mean bed level change is, then, simply $\Delta V/A$, as given in equation (1). A is 625n.

In the case of Table A 1-A 3, the total volumes are based on additions of gravel and sand whose proportions are determined by the location within the channel, but also by the type of transition observed between the two survey dates. Raw (GIS-calculated) volumes for each transition type (sums over the number of grid cells tagged with the particular transition type code) are given in Table A 8. Differences between the bolded intersurvey period totals given in Table A 7 and Table A 8 derive only from roundoff errors (due chiefly to transforming small elevation differences into large volumes via multiplication by large areas), and from the slightly different masking areas.

Table A 8. Volume changes (m^3 bulk measure) in cell 2 by transition type

transition type	1	2	3	4	5	Total volume
1952-84	-248,529	-3,888	1,098	0	1,261	**-250,058**
1984-99	48,434	2,258	-884	0	0	**49,809**
1952-99	-212,425	3,076	5,828	0	1,282	**-202,239**

The sediment budget tables (Table A 1 - A3) are broken into different sections according to the summary treatment of the transitional changes. Values that are found in these tables are italicized in the following discussion for emphasis.

The first major section of the tables summarizes the *bed changes*, which are based on the transition 1 (active channel scour/fill) volume. The volumetric calculations are straightforward in this case. This material is simply divided into *channel gravel* and *channel sand* according to the percentage of gravel in the bed and lower banks. All of this material is bed material and is counted in the *total sand+gravel* column at the end of the table.

The next major section of the table, *bank changes*, summarizes bank erosion and deposition (transitions 2 and 3). The calculations are considerably more complex because there is a 1-3 metre layer of sands and silts on island and floodplain surfaces that must be removed, or estimates of bed material transfer rates will be inflated. McLean (1990) estimated bank erosion volumes by multiplying eroded areas by the thickness of the basal gravel layer as estimated from direct field measurement, though this depth had to be extrapolated when islands were completely eroded. Deposition thickness was estimated using similar procedures. These depths have now been estimated within the GIS by subtracting the volume of overbank (sand and silt) deposits from the total observed volumetric change under island and floodplain surfaces. Appropriate thicknesses of sand and silt were obtained from Figure 7 . That figure was constructed by overlaying the channel map for 1999 with the 1999 survey to identify island/floodplain areas, then spatially averaging island/floodplain elevations for each reach and plotting them as a function of distance upstream from Mission. Separate exercises were conducted for old floodplain, recently established floodplain, and old bar tops. Best-fit exponential lines are shown in Figure 7 to average scatter or anomalies that may be present due to insufficient elevation data (i.e. a young island polygon may have few or no spot heights).

It is assumed that the difference in elevation between old bar and young island surfaces represents the thickness of recent overbank deposition, estimated as 0.84 metres, or half the maximum observed depth since newly deposited island surfaces will be under various stages of construction at the time of observation. The difference between old bar and old islands, 3 metres on average, is taken to represent the thickness of eroded overbank deposits. (Our previous sediment budget estimates adopted values of 1 m and 2 metres respectively, following McLean (1990)). In general, the deposition thickness is considerably less than the erosion thickness, a difference likely attributable to age (eroded sediments may be considerably older than deposited sediments where vertical accretion rates are limited). Boniface (1985) and McLean (1990) found an association between overbank thickness and the age of vegetation along island and floodplain surfaces on Fraser River. The thickness of overbank sands may require further confirmation through direct field sampling, though the sampling requirements over such a large area may be prohibitive. An alternative method would be to estimate the erosional and depositional age of island and floodplain deposits based upon the historic mapping that has been completed. Polygons of different ages could be overlaid with elevation data to test whether an age-thickness relation can be determined from existing data.

The conventions just described do not lead to a simple adjustment for erosion and deposition volumes. For example, removing 3 metres of sand from a polygon observed to be eroded, multiplied by the erosional area, may result in a larger volume to be subtracted than the total eroded volume calculated by the GIS. In such cases, the total erosional volume observed is assigned to sand. Similar adjustments are made for transitions coded as stripping (island to bar) which is an erosional sediment transfer, and re-vegetation (bar to island) which is a depositional sediment transfer. (These two transitions were ignored in previous sediment budget estimates.) Where the product of the stripping area and the 3 m overbank thickness was found to be smaller than the stripping volume recorded by the GIS, gravel was also assumed to have been eroded. Similarly, measured revegetation volumes in excess of 0.84 m times the revegated area were assumed to have resulted from additional gravel deposition.

Accordingly, bank erosion (island or floodplain at the earlier date) is assumed to include 3 m of overbank sands above the basal gravel layer. The area of bank erosion is multiplied by 3 m and compared to the measured volumetric change. In the example of cell 2, 3 m times the eroded area of 15,337 m^2 in the period 1952-84 exceeds the 3888 m^3 measured volume, so all of the eroded volume is considered to be overbank sand. The remainder (in this case 0) would be considered to be channel sand and gravel (the value 0 is entered at *erosion, sub 3m*). Bank deposition is computed in a similar manner, except that only the top 0.84 metres of sediment is overbank sand. In this example, the product of 0.84 and the depositional area of 464 m^2 is less than the total measured volume, so there is 390 m^3 of overbank sand and 709 m^3 of bed material sand and gravel: the value 709 is entered at *deposition sub 0.84m*. *Bank total* represents the difference between erosion and deposition of bed material in the banks. This total is divided into *bank gravel* and *bank sand* using the same gravel fraction as in the bed. These values are also included in the *total sand+gravel* column at the end of the table.

The total volume change of overbank sand (390 m^3 – 3888 m^3) is then multiplied by 0.3 to estimate the fraction that is coarser than 0.177 mm (the fraction is defined from analyzed samples of overbank sands obtained from along the river, but not necessarily from cell 2). This value (-1050 m^3) is entered as *O/B sand >0.177* and is also included in the *total sand+gravel* column. **The remaining 2449 m^3 of fine overbank sands is considered wash material and is discarded from sediment budget calculations.** In cells where there has been significant bank erosion and deposition over time, this elimination of wash material represents a considerable adjustment which means that the bed-level changes computed from the sediment budget and based on bed material change (Table A 1 - A 3) are systematically different than the unadjusted bed level changes reported in Table A 6.

The final major section of the sediment budget tables summarizes transitions 4 and 5, *vegetation stripping and recovery*. In this example, there was no measured stripping of sand (top 3 m of surface) or gravel (volume below 3 m). The recovery volume was measured as 1261 m^3 and the recovery area was 1403 m^2. Since only the top 0.84 metres is considered O/B sands, this material is subdivided into 1179 m^3 of O/B sands and the remaining 82 m^3 is considered bed material (recovery sub 0.84 m). The bed material volume is subdivided into sand and gravel using the percentage of gravel in the bed and banks. These volumes are found in the *gravel* and *sand* columns and are included in *total sand+gravel*. The overbank sand volume is again multiplied by 0.3 to estimate the coarse sand fraction. This value (354 m^3) is entered into the *O/B sand >0.177* mm column. The remaining 825 m^3 is also considered wash material and discarded from the bed material budget.

The sediment budget also includes a column for overbank sands on stable island and floodplain surfaces (*stable fldpln total sand*). These volumes summarize transition 6 but are not included in sediment budget calculations. The volumes are simply presented as a reflection of measurement errors as volumetric changes are expected to have been minimal on these surfaces (though strictly speaking, some wash material may be deposited or removed). The errors are greatest along the floodplain (areas outside the main channel banks) where the data are less dense and are maximum at the margins of the survey data where the topographic modeling is subject to interpolation errors, as we would expect.

The final term required for the sediment budget is the volume of gravel removed from each reach by dredging or mining activities (V_d). These volumes are included as a positive term in the budget (i.e. they are added to each reach as a depositional volume) as it is assumed that this volume represents material that would have remained in each reach had it not been removed. Weatherly and Church (1999) found that an average of 130,000 m^3 has been removed from the gravel reach between 1964 and 1998 at a variety of different sites, although the records are incomplete prior to 1974 (when the industry became regulated). It is not possible to provide an accurate estimate of earlier removals, though total amounts were probably small except during 1949-52 (approximately) when river gravels were used to repair and upgrade channel dykes. The incomplete knowledge of gravel removal volumes represents a negative bias in the sediment budget (meaning transport estimates represent a minimum) although the magnitude of this bias remains unknown. Gravel removals are incorporated into the sediment budget by plotting the locations of individual documented removals on the base map to determine the affected reach in each case.

These quantities are recorded in the sediment budget tables under *gravel removals* and *sand removals*. As there were no known removals in computing cell 2, a value of 0 is entered in both columns.

The summary of all gravel and coarse sand volumetric changes in given in the columns *gravel sum*, *sand sum* and *total sand+gravel*. The *gravel sum* includes gravel eroded or deposited within the bed (transition 1), channel banks (transitions 2 and 3) and associated with vegetation stripping and recovery (transitions 4 and 5), as well as gravel removed by mining. The *sand sum* includes the sand fraction associated with the gravel erosion and deposition (all transitions) as well as the coarse fraction of overbank sands associated with bank erosion and deposition (transitions 2 and 3) and vegetation stripping and recovery (transition 4 and 5). Sand volumes removed by mining are also included. The bed-level changes are subsequently calculated as the *total sand and gravel* volume change calculated for each cell, divided by the active channel area of the cell (cell width x length).

As reported earlier, the sediment budget total (-248 434 m^3) compares very well with the direct survey difference total (-248 206 m^3) because most of the material exchange occurs within the channel bed (transition 1) and only a small fraction is 'lost' as overbank wash material. In this example, the 2449+825 m^3 of wash material excluded from final calculations occurs entirely within stable floodplain surfaces and so was not included in the direct survey calculation. In addition, an equivalent volume of coarse sand was eroded outside the channel bed (transitions 2-5) as was deposited so no bias is introduced as a result of the assumed 3 m overbank sand erosion thickness or 0.84 m sand deposition thickness.

A5.3.2 Complex cell

We now review a case in which the reported bed-level changes are very large. A suitable computing cell for this comparison is Cell 33 where the sediment budget shows an apparent bed-level change of +5 cm (aggradation), compared to the direct survey comparison which shows a change of –70 cm (degradation) between 1952 and 1984. There have been historic sand and gravel removals from this reach, however, which are included in the sediment budget results as a depositional term. If this volume is removed from the sediment budget calculations, there was an apparent bed change of –9 cm, still much smaller than the direct survey comparison.

Net volumetric changes for all periods in cell 33 are given in Table A 9 (in this table, gravel and sand removals have been included in the sediment budget figures in order to make the change "equivalent" to that detected from the unadjusted survey). The raw data values that are used in the sediment budget calculations are given in the Table A 10. As before, the highlighted figures, constituting the unadjusted survey differences (Table A 6) and the unprocessed data for the sediment budget, are equivalent to within roundoff error associated with the different calculations used to construct them and to different masking areas.

Table A 9. Volume and bed level changes in cell 33*

period	1952-84	1984-99	1952-99
unadjusted volume (m^3 bulk measure) (table A6)	**-774,442**	**257,554**	**-516,040**
unadjusted bed level change (m)	-0.70	0.23	-0.47
sediment budget (m^3 bulk measure) (table A1 - A3)	-102,368	298,668	103,187
bed material level change (m)	-0.09	0.27	0.09

* negative values indicate degradation (erosion volume exceeds deposition volume)

Table A 10. Volume changes (m^3 bulk measure) in cell 33 by transition type

transition type	1	2	3	4	5	6	Total volume
1952-84	216,334	-986,290	57,215	-7,880	11,457	-78,365	**-787,529**
1984-99	315,408	-44,615	10,143	-13,899	-7,428	-34,090	**225,518**
1952-99	422,775	-740,827	143,473	-357,358	33,339	-64,586	**-563,184**

As previously discussed, the large discrepancy between the previously reported figures (that is, –102 368 m^3 in 1952-84) compared with the direct survey (-774 442 m^3) can be attributed to the treatment of the overbank wash material. In this example, there was a net loss of 604 137 m^3 of wash material associated with bank changes, and a further loss of 2659 m^3 of wash material associated with vegetation and recovery processes that was ignored in the sediment budget calculations. If this total (606 796 m^3) had been included, the figure reported in Table A 1 would be –709 164 m^3 or –787 529 m^3 if the degradation on stable island/bar surfaces is considered (which would largely account for the slightly different masking regions used).

A5.3.3 Summary difference

Between Mission and Agassiz during the period 1952-84, the total volume of wash material eliminated from bank changes was 8.04 million m^3 (erosional volume). This volume is in fact negative for all computing periods and reflects the observation that bank erosion volumes consistently exceed bank deposition volumes. The total volume of wash material eliminated from the bed material budget due to vegetation stripping and recovery changes was 0.57 million m^3 (depositional volume). Since these wash material losses are included in the unadjusted survey difference comparison (Table A 6) the unadjusted bed-level changes are smaller or more negative for most computing cells.

There remains the question which is the more appropriate set of figures to use to establish trends of bed level change along the river. The overbank changes are large, and tend to decrease apparent aggradation if included (since they are mainly degradational), but they should not have any material impact on raising the level of the channel bed since these sediments are found on island and floodplain surfaces above the normal channel zone. Their removal should increase the channel conveyance in the very highest floods (those that flood over the floodplain and island surfaces). It appears most prudent to adopt the original values for change in channel bed elevation, the ones based on the bed material budget, for examining potentially significant changes within the channel.

It remains to ask why those numbers do not even sum from survey to survey. The reason for this is the changing mask that is used from survey to survey in the sediment budget calculations. This adjusts the marginal areas where most overbank sediment adjustments occur, so that overbank sediments are not considered on the basis of equivalent areas from survey to survey. The directly differenced 1952-99 volumes and elevation changes, then, do not equal the sum of the component intersurvey changes.

A6 Appendix References

Boniface, C. 1985. *Vegetation succession on mid-channel bars of the Fraser River, British Columbia*. Unpublished M.Sc. thesis, Department of Geography, Simon Fraser University, 137pp.

Brasington, J., Rumsby, B.T. and McVey, R.A. 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. *Earth Surface Processes and Landforms* **25**: 973-990.

Burrough, P.A. and McDonnell, R.A. 1998. *Principles of Geographic Information Systems*. Oxford University Press: 333pp.

Church, M., Ham, D. and Weatherly, H. 2000. *Sedimentation and flood hazard in the gravel reach of Fraser River: Progress Report 2000.* Report prepared for the District of Chilliwack, 25 September, 2000.

Lane, S.N., Chandler, J.H. and Richards, K.S. 1994 . Developments in monitoring and modelling small-scale river bed topography. *Earth Surface Processes and Landforms* **19**: 349-368.

McLean, D.G. 1990. *Channel Instability on lower Fraser River*. Unpublished Ph.D. thesis, The University of British Columbia: 290pp.

McLean, D.G. and Church, M. 1999. Sediment transport along lower Fraser River 2. Estimates based on the long-term gravel budget. *Water Resources Research* **35**: 2549-2559.

Milne, J.A. and Sear, D.A. Modelling river channel topography using GIS. *International Journal of Geographical Information Science* **11**: 499-519.

Weatherly, H. and Church, M. 1999. *Gravel extraction inventory for lower Fraser River (Mission to Hope) -- 1964 to 1998.* Report to the City of Chilliwack, March 15.