SEDIMENT MANAGEMENT IN LOWER FRASER RIVER

CRITERIA FOR A SUSTAINABLE LONG-TERM PLAN FOR THE GRAVEL-BED REACH

Michael Church
Department of Geography
The University of British Columbia
Vancouver, British Columbia V6T 1Z2

A report for
Emergency Management BC, Flood Protection Program
Ministry of Public Safety and Solicitor General

March 30, 2010

EXECUTIVE SUMMARY

A program of planned sediment removals from the gravel-bed reach of lower Fraser River was initiated in 2004 with the objective to maintain or lower flood water levels in the reach. To date, annual licensing difficulties have prevented the program from achieving gravel removal targets in all but one year. This report is intended to define criteria for a program that might be licensed for multi-year sediment removals in a sustainable long-term sediment management program. “Sustainable”, in this context, means achieving the goals for flood hazard mitigation without creating deleterious consequences for the riverine ecosystem. A number of lessons have been learned as the result of 2004-2009 and earlier experience. These include:

- Sediment removal at a rate that approximates gravel influx has no immediately major effect on river processes and morphology;
- Sediment removal by bar top scalping has little effect on local water levels;
- The actual sediment removals to date appear to have had no lasting impact on fish or invertebrate populations in the vicinity of the removals, but monitoring effort has been insufficient to qualify this as a robust conclusion;
- Sediment removal that is not properly planned and/or executed can have immediate and serious effects on fish populations;
- Effective environmental monitoring of fish and invertebrate organisms requires a large continuing effort because of the very large natural variability in their occurrence, both spatially and temporally;
- We still lack sufficiently robust baseline information of both the sediment budget and the aquatic ecosystem to be able to confidently establish an assuredly sustainable long-term sediment management program.

A program of sediment removals from the river to counteract the effects of aggradation might be based on either of two distinct strategies:

1) routine removal, at convenient places along the river, of a volume of sediment that, over a period of years, approximates the bed material influx to the reach, with the effect of eliminating net aggradation. Such a strategy might be termed “profile maintenance”, meaning maintaining the flood water surface profile elevations;

2) targeted removal, from specifically identified sites, of volumes of sediment in order to counteract the effects of local sediment accumulation with consequent rise of water levels immediately upstream. Such a strategy might be termed “profile control”, meaning the management of flood water levels locally along the river.

Experience to date suggests that only the first objective is feasible in a program that is sustainable – that is, a program that respects ecological values along the river. Such a program also requires measures of effectiveness, which currently are lacking. Direct observation of water levels along the river – possible because there is an extant network of manual gauges – is the most effective measure of the desired objective, but will be indicative only over a period of several years. Measures of habitat quantity and quality along the river are a second measure, also assessed over a period of years. Site monitoring remains important to ensure no direct damage to the aquatic ecosystem. All of

these measures are most effectively appraised on a time scale comparable with the time scale for morphological and ecological changes along the river, which is of order 10 years. Hence, a program planned for a 10-year horizon and operated in an adaptive and precautionary fashion appears most appropriate.

Accordingly, a sustainable long-term program of sediment removal from Fraser River in the gravel-bed reach will observe the following circumstances and criteria.

- It will recognise that a sustainable long-term program of sediment removal may limit or eliminate general bed aggradation in the gravel-bed reach over a period of years, but that it cannot be used to eliminate local water level problems.
- It will recognise that for the program to operate in the long-term in a sustainable way additional information is required, in particular more precise knowledge of the sediment budget needs to be developed and knowledge of the annual pattern of fish activities within the reach needs to be detailed. The program should proceed only if there is a commitment to conduct the research to acquire this knowledge.
- The program should be planned and approved on a 10-year period, with more frequent review, as monitoring outcomes dictate.
- Sediment removals will be focused in those sub-reaches where chronic sediment accumulation occurs. Four such zones can be defined today but these may change over a period of years; indeed, there is some evidence that some changes may currently be under way.
- Within these zones, sites for sediment removal should be identified on a year-to-year basis, according to recent sediment deposition, the recent history of removals, and perceived (lack of) impact on current activities of fishes.
- Volumes removed should conform with recommendations given in Church et al. (2001), as discussed in Appendix B of this report, using 230 000 m^3a^{-1} as the current estimate of average annual bed material recruitment.
- Site-scale monitoring should follow the prescription given in G3 Consultants (2009) with emphasis on benthic invertebrates and on physical habitat measures.
- Reach-scale monitoring should be undertaken on an annual or biennial basis using aerial photography, as described in this report.
- The program must be adaptive and precautionary, with provision to change any elements of the program as soon as monitoring activities identify unfavourable changes to river morphology and/or the riverine ecosystem, or as soon as it becomes clear that secular changes in flow and sediment influx are affecting the river.
- It will be recognised that there may be reasons to make sediment removals from particular sites along the river on a special basis (e.g., to maintain side channels; to facilitate navigation). Such needs should be considered outside the long-term sediment management program, but sediment removals should be considered as part of the volume removed for purposes of the program.

Table of contents

1. INTRODUCTION

1.1. Contract Obligation

This report is written to respond to a request from Emergency Management BC, Flood Protection Program, "to provide a report to assist with the creation of a long-term sediment management plan for the Lower Fraser River". It is understood that 'Lower Fraser River' means the so-called 'gravel-bed reach' between the mouth of Sumas River (km 99[1] upstream from Sand Heads) and the settlement of Laidlaw (km 148).

Sediment management is necessary in this reach because the deposition of gravel leads to aggradation (that is, raising the streambed), with consequent effects on the level of flood waters and the protection provided by the river dykes. It is understood that 'sediment management' will include a continuing program of planned gravel removals from critical sites along the river.

1.2. Problem Statement[2]

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 its natural state, this range of flows was sufficient to flood extensive portions of the restricted floodplain of the river within the Lower Mainland. After the great flood of 1894, efforts commenced to protect developing settlements and the occupied floodplain from the river, efforts that continue after more than a century.

The river follows a steep, confined course through the mountains and interior plateaux, where it picks up rocks, gravel, and finer sediments from the banks and from tributaries. Within the Lower Mainland, the gradient of the river quickly declines as it approaches the sea. It cannot continue to move the larger material on the reduced gradient. Consequently, the material is deposited, mainly between Laidlaw and Sumas Mountain. These deposits form a confined 'alluvial fan' – a wedge of sediment restricted within the confines of the relatively narrow valley northeast of Sumas Mountain.

An alluvial fan is an accumulation of river-transported sediment deposited 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

---

[1] River kilometres quoted in this report are based on river kilometres above Sand Heads established by McLean and Church (1986) and Church and Ham (2004), and displayed in figure 1. Because the river channel changes over time, nominal distances may not accurately reflect current chainage. However, they represent a consistent set of distances and positions for reference purposes. The limit distances for the study reach reported here are different than those reported in Church et al. (2001).

[2] This section is in large part abstracted from Church et al. (2001), pp. 2-5.

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 because the deposited sediment fills the current channel bed, creating an obstruction to the conveyance of water downstream. The water then finds a new course around the deposits. How unstable a river is depends upon the volume of sediment 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 20th century, the chief means to protect adjacent land from flooding has been a program of river dyking. In addition, extensive bank protection works have been undertaken to protect the dykes and to prevent erosion of the increasingly valuable floodplain land. As a result, the river has been confined within a channel zone that is considerably narrower than it originally was. The confinement is not extreme. The chief effects have been the cutoff of side channels 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. The contemporary problem of river aggradation has been partially created by human restriction of the channel zone of the river.

There is an additional important dimension to the problem on Lower Fraser River. 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[3] habitat of exceptionally high quality. Habitat renewal is an essential process for the maintenance of habitat quality. The modest river instability renews aquatic habitat at a rate to which the river fauna can easily adapt. Hence, the ecological wealth of Fraser River in the gravel-bed reach – which contributes substantial economic value through various fisheries and is a culturally significant feature of the environment for First Nations – is the product of the modest rate of gravel transport and deposition. There is, furthermore, increasing public appreciation of the recreational and aesthetic qualities of the river that stem in significant degree from the morphological complexity and habitat values, hence from processes associated with the transport and deposition of the gravel. Therefore, actions taken to mitigate flood hazard and effects of river instability must reckon with possible consequences for the habitat, environmental quality and cultural significance of the river.

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. As the result of a series of studies (UMA, 2001; 2001; nhc, 2006; 2008) it is known that at various places along the river the dykes today are not sufficiently high to assure protection against the water level for which the dyke system was nominally designed; that is, the 1894 flood of record. The real problem underlying the sediment management program is mitigation of the flood hazard, hence management of water levels.

[3] "riparian" refers, literally to the river bank. Practically, it refers to land immediately adjacent to the river the quality of which is substantially influenced by the presence of the river.

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 by sediment removal to lower the stream bed;
- maintaining or lowering high water levels locally by channel re-alignment;
- adopting institutional and social actions to maintain social protection (such actions would include some mix of restrictive land use zoning, insurance, and emergency measures planning).

Amongst these possibilities, official attention has been focused on sediment removal so the bed is prevented from rising. This action appears to directly confront the source of the problem. However, it may significantly affect on the riverine ecosystem which is a valued element of the river. In order to develop a sustainable long-term strategy for sediment removal from the river, it is necessary then to have answers to a set of linked questions:

- How quickly is the river bed aggrading (i.e., what is the gravel budget of the river)?
- Where is sediment being deposited?
- How does sediment deposition influence the morphology and ecology of the river?
- How much sediment needs to be removed in order to mitigate the flood hazard?
- From where should sediment be removed in order to mitigate the flood hazard?
- How might sediment best be removed from the river?
- How might the river morphology and ecosystem be affected by sediment removal from the river?

The answers to these questions are critical to the establishment of a long-term, sustainable strategy for gravel management in Lower Fraser River. “Sustainable”, in this context, means achieving the goals for flood hazard mitigation without creating deleterious consequences for the riverine ecosystem.

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 taken now about the river may eventually be reinforced or confounded by environmental change so it is important to foresee, so far as we can, trends in flow and sediment supply that might occur in the future, and those of the past that have created the present situation. Such trends must be considered in developing long-term plans for river management. A planned program of sediment removals from the river to counteract the effects of aggradation might be based on either of two distinct strategies:

1) routine removal, at convenient places along the river, of a volume of sediment that, over a period of years, approximates the bed material[4] influx to the reach, with the effect of eliminating net aggradation. Such a strategy might be termed “profile maintenance”, meaning maintaining the flood water surface profile elevations;

2) targeted removal, from specifically identified sites, of volumes of sediment in order to counteract the effects of local sediment accumulation, with consequent rise of water levels immediately upstream. Such a strategy might be termed “profile control”, meaning the management of flood water levels locally along the river.

Both strategies are considered in this report.

1.3. Objectives

It is the objective of this report to contribute toward the development of a sustainable long-term sediment management plan for Lower Fraser River by answering the questions posed above within the context set by the decision that gravel removal from the river is the preferred strategy. Important specific objectives are as follows:

- to examine the current status of the sediment budget and to recommend activities that will lead to improvement of sediment budget knowledge necessary to ensure the success of the management plan;
- to review the effect of sediment removals to date in order to appraise the effectiveness of current and planned activities;
- to appraise what may be efficient measures of the effectiveness of a sediment removal program to mitigate the flood hazard;
- to propose an effective program for ecological monitoring based on experience to date.
- to recommend candidate sites, volumes and methods for gravel removal in a long-term program in light of current knowledge of the sediment budget and morphological trends along the river;

These elements respond to the problem statement given above and should contribute toward the development of a sound technical basis for a sustainable long-range program for sediment management in Lower Fraser River.

[4] “Bed material” is that portion of the sediment load that may settle on the bed and lower banks of the channel. It determines the channel form. In the gravel-bed reach of Fraser River it is approximately synonymous with ‘bed load’, that portion of the sediment load that moves on the bed of the river. It is that part of the river’s sediment load that is deposited in the gravel-bed reach, leading to aggradation there. However, a certain amount of sand that may move in suspension in the water column is trapped in the interstices of the gravel bed sediments and sand is also deposited as ‘cover sand’ on bar tops. The bed material load of the river, amounting to about 400 000 tonnes per year, is only a small fraction of the 18 million tonne total sediment load of the river, almost all of which is fine sediment that moves in suspension through the gravel-bed reach.

2. THE STATUS OF THE SEDIMENT BUDGET

2.1. What do we know?

Rational sediment management in a river channel must be predicated on knowledge of the sediment budget of the reach because removal of too little material will render the program ineffective whilst the consequence of removing too much, invariably, is collapse of the channel into a ditch-like form and dramatic change in the riverine ecosystem (see Church et al., 2001, for a detailed discussion). In active gravel-bed rivers, the exposure of more or less extensive areas of bar surface at low flows gives rise to the notion that the sediment transport in the channel must be large. In Fraser River, the annual influx of gravel is estimated to be in the order of 190 000 to 240 000 cubic metres (bulk measure: see further discussion below) per annum in the long term. In comparison, an amount approaching 10x these figures is moved by the river *within* the reach in each year, contributing to the notion of a large sediment flux.

A number of sediment budget estimates for the reach have been made (summarized in Appendix A). Leaving aside early estimates based on sediment transport measurements at Agassiz, which may very well be biased, the estimates for gravel influx at Agassiz between 1952 and 1999 vary from 180 000 m^3a^{-1} to 240 000 m^3a^{-1} (bulk measure; rounded figures), while figures for Laidlaw vary from 113 000 m^3a^{-1} to 226 000 m^3a^{-1}. (The Laidlaw figures are smaller than the Agassiz figures because the intervening reach has mainly been degrading – that is, losing more material to onward transport than is gained by sediment influx.)

Some reasons for continuing uncertainty of the sediment budget are the following:

- The budget estimates are based on a comparison of successive digital elevation models of river morphology derived from field and remote sensing surveys. In particular, they include a combination of bathymetric survey of the river, airborne Lidar survey of exposed riparian areas and, in some earlier surveys, ground measurements. A very small systematic error in the reference elevations for any one of the survey components (of order centimetres) would accumulate to a large summary error in the inter-survey comparisons. Such an error is suspected, for example, in a 2004 airborne Lidar survey, rendering the digital elevation model for the 2003 river morphology unreliable and disqualifying sediment budget estimates based on the 2003 survey;
- The transport of gravel in the reach is small in comparison with the transport of sand (which is of order 6 million tonnes), yet sand forms a significant part of the gravel-reach sediment body. Small errors in appraising the sand exchange might entirely swamp the gravel exchange estimates;
- To account for river bank erosion and deposition, assumptions (based on field sampling) must be made about the proportion of sand in bank and river bar deposits. Further, the proportion of the sand deposits that is truly ‘bed material’ (that is, larger than about 0.18 mm) must be estimated. Sampling remains limited and these proportions are not known in detail throughout the reach;

- It is visually evident that significant volumes of "cover sand" (extensive sheets of sand) occur on bar surfaces within the reach. Erosion and deposition of these materials may account for a significant part of the observed morphological changes in the gravel reach, but they are not separately tracked in the sediment budget;
- The transport of sand and gravel at the downstream end of the gravel-bed reach (that is, in the vicinity of the mouth of Sumas River) are not well known, so that the assignments of gravel and sand transport in this part of the reach may introduce errors that are carried through the upstream directed computations of changes in sediment storage and of sediment flux;
- Numerical computations conducted by Ferguson and Church (2009) show that, even in high floods, the sediment transport in the downstream part of the reach selectively favours sand over gravel. This process may include the substitution of gravel for sand in deposits in that part of the reach, which would introduce a further negative bias into the estimated gravel budget;

The recently completed 1999-2008 sediment budget update (nhc, 2009) illustrates very well some of the problems raised by these circumstances. It shows negative sediment transport (that is, upstream directed sediment flux) through 27 km of the 65 km study reach, a physically impossible circumstance. The result for gravel alone is even more biased. This artifactual result might be realised if a large volume of sand were mobilised and removed from the reach[5]. In the period, there were three above-average floods, and it is known (McLean et al., 1999) that there is indeed net evacuation of sand from the gravel-bed reach during large floods. However, absent sediment transport measurements at Mission (which were suspended in 1986), the effect cannot be quantitatively assessed.

I conclude that the most reliable estimates of long-term gravel influx into the reach remain those of the 1952-1999 period. The 1952 survey, using classical ground surveying and photogrammetric techniques, yielded relatively sparse but almost certainly unbiased information. So far as we know, the 1999 survey is not subject to serious error (analysis in Church et al., 2001). The range of gravel influx estimates for this period, derived from steadily improved methods of analysis, is 1.4x, which is quite good in the field of sediment transport estimates. The corresponding range of estimates of total bed material influx is 200 000 m^3a^{-1} to 260 000 m^3a^{-1} (bulk measure; rounded figures), a 1.3x range. On these figures, we cannot be said to know the sediment budget precisely. Furthermore, the estimates are derived from a historical period and may no longer be current. The circumstances described above demand a precautionary approach to sediment management in the river.

For purposes of river profile management, longer term estimates of the sediment budget are more reliable than shorter term ones because the net morphological change is larger, hence more easily measured, and because transient effects such as appear to have occurred in 1999-2008 are apt to be averaged away. The 1952-1999 sediment budget remains the most reliable basis for designing a long term sediment management program.

[5] Since much of this sand would be transported past the Mission gauge, the downstream extremity of the reach, where it is assumed that the transport of gravel-reach bed material approaches zero, the net effect is to negatively bias the total budget.

2.2. What do we need to know?

The sediment management program for the gravel-bed reach has been developed on the basis that the sediment budget is sufficiently well known, subject to the periodic acquisition of a new survey. This represents a mismatch between ‘scientific information’ and information to underpin practical planning. Science always proceeds by degrees of approximation, with regard for errors of measurement and errors associated with the necessarily simplified view of the processes under study. This is especially true in field science and most particularly true on rivers, where all measurements are difficult. In comparison, practical planning requires firm figures upon which to base the plan, so the science-based estimate comes to be interpreted as a firm figure.

A sustainable program of sediment management requires an ongoing program of field observations designed to improve both the measure and the basis for measuring the sediment budget. At present, two urgent requirements are

1) to improve our knowledge of sediment textures (grain size) throughout the reach, but particularly toward the downstream end, where our present information is least detailed, so that sand and gravel components of the budget may more confidently be separated;

2) to understand what happens in the ‘gravel to sand transition’ that occurs downstream from the Sumas River confluence so that the gravel budget may confidently be established there.

Both of these requirements are the object of current UBC research. In addition,

3) to continue to analyze error specification in the periodic river surveys so that the accuracy and precision of the estimates of morphological change that underlie the budget calculations can be improved.

It is particularly important to understand possible sources of bias in the measurements and GIS-based analysis. Since the sediment influx estimated for each survey period is the relatively small residual from the difference of two large numbers – volumes of erosion and of deposition, mostly representing sediment shifted within the reach – it is possible that modest biases, in particular ones associates with the specification of reference elevations, may disproportionately affect the final figures. This consideration is of comparatively greater importance as the period for budget estimation becomes shorter since the real volumetric change in sediment resident in the reach is then smaller. To base a continuing program of sediment management on something like decennial river surveys, errors that may introduce bias into the results need to be more closely specified.

In summary, it is necessary to continue to improve the basis for establishing the sediment budget of the gravel-bed reach in order to provide information that may underpin a sustainable long-term program of sediment management.

3. WHAT HAS HAPPENED?

3.1. Sediment removals since 2000

Sediment removals during the decade 2000-2009 are shown in Table 1 and located in Figure 1. Until 2003, a nominal moratorium on gravel removals remained in place pending the formulation of a strategy to manage them. In 2004, a letter of understanding was signed between the Province of British Columbia and the federal Department of Fisheries and Oceans setting, as a "flood control measure", an annual target for removal of 500 000 m^3 per year in 2005-06 and 420 000 m^3 per year in 2007-09. These values were in excess of the estimated annual influx of bed material to the reach and presented a potential opportunity to observe the sensitivity of the river to removal of such volumes. In the event, difficulties were encountered in the annual issue of licences for removals and only in 2008 was the annual target for removal even approached. Over five years, removals totalled 228 400 m^3a^{-1} (bulk measure), just one-half of the projected amount and nearly exactly equal to the median estimated bed material influx. Only 4 removals have individually exceeded 100 000 m^3 in bulk volume (Table 2).

The method of removal has, in the main, been bar top scalping during low water (January to March period) when operations can be carried out entirely on dry surfaces. There have been two bar edge removals. At the back of Tranmer Bar (mouth of Maria Slough) in 2004, less than 10 000 m^3 were excavated; there was no monitoring. In 2006, at Gill Bar (the "Gill East" site) the bar edge was cut back with removal of more than 50 000 m^3; the operation was dry with a berm left along the low water edge. There has been one deep pit excavation (Spring Bar, 2008).

The effect of these sediment removals on the flood profile is difficult to ascertain but certainly small.

3.2. Measures of effectiveness

In a rational program, there must be some measure of the effectiveness of actions undertaken. There is no such measure in the present sediment management program.

The purpose of the program ostensibly is to maintain or lower water levels during flood flows. Hence, measures of water level at the same flow before and after sediment removal, in the vicinity of the removal would appear to be a relevant measure. 2-D hydraulic modelling of the effect of sediment removals at specific sites, using before and after excavation topography, have persistently shown that local water level effects are small – in fact, comparable with the probable error of the hydraulic computations. A reach-length study by UMA Engineering (2004) reported that sand and gravel removal between 1952 and 1999, amounting to more than 4 million m^3, appeared to have lowered the flood profile by 20 cm[6]. In comparison, a direct estimate of average bed level change due to sediment deposition during the same period, derived by distributing the net accumulation from the sediment budget over the area of the channel, indicates 8.6 cm rise

[6] Gravel removal records are incomplete before 1974, hence the recorded 4.1×10^6 m^3 is an underestimate by an unknown but probably significant amount.

of the bed, reduced to 2.1 cm after gravel removals in the period are factored in (Church et al., 2001), implying 6.5 cm lowering due to sediment removal. The difference between the two figures is in part due to the fact that bed level changes do not simply translate into water surface level changes, but it will also be affected by errors in both the water level computations and the sediment budget.

For long-term assessments of the effectiveness of a program to manage water levels along the river, 2-D hydraulic modelling appears to be attractive as a measure of effectiveness. To be a valid measure, however, the computations must be undertaken with the same computational model and with input data of comparable precision and accuracy. The second requirement implies that the modelling must be based on river surveys conducted to the same level of resolution and precision at the two times for which the comparison is desired. The outcome will not, however, directly demonstrate the effect of sediment removal, for changes in channel alignment and other factors that influence water conveyance through the channel will also be reflected in the results.

It is possible that, for a long-term assessment of a sediment removal program, flow modelling using topography adjusted to reflect only the sediment extractions, as undertaken by UMA Engineering (2004), may give an approximate picture of effectiveness. However, over such a long term the river would not realistically preserve details of individual excavations and the results would be approximate at best. The exercise conducted by UMA Engineering, appropriately interpreted, suggests that the benefits of sediment removal at rates comparable with gravel influx are at best modest.

The best (and simplest) measure would be a direct observation of water level at various places along the reach, and an observation of trends through time at a given flow. There has for many years been a network of staff gauges in the gravel reach, maintained by the province for water level readings during high freshets as part of flood management operations (cf. Dignan, 1994). This network is augmented by additional gauges maintained along the river for similar purposes by the municipalities. The most recent documentation of this network is given in Figure 2. The organisation of regular observations from these gauges during moderate to high flows each year, and analysis of water level trends, would be a relatively inexpensive and highly effective means of studying water level changes along the river. Water level trends, however, reflect the effects of changing flow alignment and (locally) obstructions to flow other than gravel accumulation, however, so – as with hydraulic modelling – they cannot be interpreted straightforwardly as a measure of the effect of a sediment removal program. These measurements would, however, be an effective measure of the actual program objective – management of water levels.

No simple measure of water levels, then, isolates the reach-wide effect of sediment removal because of the confounding effect of other factors (such as channel alignment and obstructions) that influence water levels along the river. It is potentially possible to determine water level effects locally, in the vicinity of a removal site, by measurement or by modelling, but indications are that the effect of individual sediment removals is small. These circumstances lead to the conclusion that sediment removal in quantities that might do no lasting harm to the riverine ecosystem is not a practical means to achieve water level ‘control’ locally and in the short term.

3.3. Environmental monitoring

An important objective of the sediment management program on Fraser River – the criterion for sustainability – is to demonstrate no net harm to the aquatic or riparian ecosystems, which are exceptionally rich and economically important in this reach of the river. A program to monitor environment and habitat conditions, and on-site benthic and fish communities, has been in effect since the inception of the current sediment removal program in 2004. The sampling design is based on protocols established by Rempel and Church (2003) to study an experimental sediment removal at Harrison Bar in February-March, 2000, and specified by Rempel (2003; also published in Rempel and Church, 2009). A review of the monitoring reports from 2004-2008 was undertaken by G3 Consulting (2009; hereafter referred to as 'G3') for Emergency Management British Columbia. Initial comments here broadly follow that comprehensive report.

Rempel and Church (2009) found that inherent variability of the biological data produced low statistical power to detect persistent effects of sediment removal even after an intensive sampling program. Subsequent monitoring studies have, in general, expended less effort than was made in the Harrison Bar experiment and the G3 meta-analysis confirms that monitoring to date does not resolve the magnitude and extent of the effect of sediment removals. To the extent that the data are interpretable, it appears that seasonal effects on populations dominate variance, as one might expect.

G3 introduces some notable innovations in analysis and important recommendations for continuation of the monitoring program. In particular, a form of cluster analysis was used on selected habitat factors to identify properly matched reference and treatment sites, thus sharpening the prospect to achieve a meaningful discrimination. The report also makes some important recommendations for the program. First, it notes that what would constitute a significant "effect" needs to be precisely defined before meaningful analysis can be undertaken. Two statements (somewhat paraphrased here) bearing on such a definition are:

- Once sediment is removed, how long is required for a site to recover in physical terms and in terms of the biological community, or does it fully recover at all?
- Can a site be adequately characterised, prior to treatment, such that an estimate of loss can be made and can commensurable habitat compensation be specified in terms of the time scale for the original habitat to recover?

The report also makes recommendations for the sampling program:

- Consider focusing on fewer sites deemed to be representative;
- Increase the number of samplings, particularly for the 'before treatment' period [in order to more adequately characterise the important seasonal variations];
- Survey site-scale ecological habitat characteristics comprehensively;
- Focus attention on habitat measures and benthos [bottom dwelling invertebrates].

The purpose of the first point is to permit more intensive study within the practical limitations of monitoring effort, which is achieved by the increase of statistical sensitivity that will be gained by the second point. This implies that not all sites will be studied for ecological impact (which does not mean that site operations would not be monitored).

The third and fourth points emphasize placing attention on more consistently repeatable and more sensitive measures. The report also makes important recommendations for standardizing the various measures and reporting protocols so that analyses can be undertaken with confidence that the underlying data are of sufficient quality and so that data can be incorporated into larger data sets for retrospective analysis.

There are larger issues implied by these recommendations. The focus of most people's interest in the riverine ecosystem is the fishery. Controversies that have surrounded the sediment management program have largely focused on supposed impacts on fish communities. Yet the recommendation is to de-emphasize sampling that community. The reason given in G3 (aside from the observed lack of discrimination provided by fish sampling) is that fishes are highly mobile so that it is difficult to say how a sampled animal relates to the particular place where it was caught.[7] Certain benthic invertebrate species (or genera), in comparison, appear to be somewhat sensitive indicators of site condition. Certain fish species, furthermore (those of main public interest), are subject to other population pressures such that it may be difficult to make an unequivocal interpretation of observed trends in any case. In the end, it is suitable habitat that is most important, and it is suitability of habitat that is directly and most significantly disturbed by sediment removals. Hence, measures of habitat quality should take precedence.

The G3 report emphasizes measures of site habitat suitability, that is habitat suitability in the immediate vicinity of the sediment removal. There are, however, significant larger scales. Church et al. (2000) defined 12 nearshore habitat types, at least 8 of which are distinguished in bar environments that may be subject to sediment removal. They also showed that these habitats host somewhat distinctive communities of juvenile fishes. Subsequently, Perkins (2007) has shown that the quantity of each habitat varies significantly with flow but is, historically, relatively stable. The occurrence and distribution of habitat types is, then, of substantial significance to overall habitat suitability for the communities of Fraser River fishes. The habitat types are defined by bar edge (or bank) and nearshore sedimentary morphology and gravel texture, and induced flow conditions. Topographic manipulation of the bars – as in sediment removal – directly affects the occurrence of these units. Hence, a second kind of effective environmental monitoring is to ask for the quantity and distribution of habitat types in the environs of sediment removals. The habitat classification was designed to be applied using aerial photography (and has been so applied; see KWL Associates, 2002), so that such a measure of environmental impact would be relatively easy to realise.

At still larger scale, the overall range of habitats in the river is influenced by the amount of perennial secondary channels, by the amount of seasonal channels, by total vegetated shoreline length and by overall channel zone width. These, again, are measures that are easily recovered from aerial photography. They are measures that might be influenced, in the long term, by persistent sediment removals, but they equally are affected by the general river regime (that is, by trends in flows and sediment influx). As long term measures of habitat quality, however, they are both significant and easy to collect.

[7] This is not entirely a straightforward issue. Church et al. (2000) have shown that juvenile fishes do tend to select particular habitat units in the river, but the data are not sharply discriminatory so that, again, a very large sampling effort would be required to gain any sensitivity with respect to questions about species presence or absence.

4. BASES FOR A SUSTAINABLE LONG-TERM PROGRAM FOR SEDIMENT MANAGEMENT IN THE GRAVEL-BED REACH

4.1. What have we learned?

During the six years that the current program of planned sediment removals from Fraser River have been in operation, we have learned certain lessons:

- Sediment removal at a rate that approximates gravel influx has no immediately major effect on river processes and morphology;
- Sediment removal by bar top scalping has little effect on local water levels;
- The actual sediment removals to date appear to have had no lasting impact on fish or invertebrate populations in the vicinity of the removals, but monitoring effort has been insufficient to qualify this as a robust conclusion;
- Sediment removal that is not properly planned and/or executed can have immediate and serious effects on the fishery[8];
- Effective environmental monitoring of fish and invertebrate organisms requires a large continuing effort because of the very large natural variability in their occurrence, both spatially and temporally;
- We still lack sufficiently robust baseline information of both the sediment budget and the aquatic ecosystem to be able to confidently establish an assuredly sustainable long-term sediment management program.

4.2. How can a long-term program be rationalised?

Church et al. (2001) pointed out that sediment removal from rivers in quantities that significantly exceed the incoming sediment supply causes significant changes in river morphology and riverine ecosystems. Ratios of removal/supply as low as 1.6:1, applied persistently, have been observed to have notable effects. It was proposed, therefore, that removals be limited, on average, to quantities that exceeded the supply rate by only a modest amount (specifically, by about 25% of the current best estimate of bed material influx[9]), that any such program be regarded as experimental, and that an assessment of the outcome be made after 5 or 10 years. Furthermore, it was recommended that removal at any one site not exceed one-half of the normal bed material transport past that site.

We have learned, by observation and by numerical modelling, that such removals do not significantly affect water levels locally. Therefore, a long-term sediment removal program cannot be regarded as an effective strategy to resolve local instances of high water along the dykes, that is, to achieve ‘profile control’. On the other hand, experience before 1999 indicates that a program that removes from the river a quantity of river bed material equivalent to the long-term bed material supply might reduce or eliminate

---

[8] cf., for example, the Big Bar pink salmon incident of 2006.

[9] In the event, larger volumes were mandated to be removed, but were achieved in only one year.

sediment aggradation as a contributor to a rise in the floodwater profile along the river. Such a program is a program for ‘water profile maintenance’ in the long term.

From our consideration of sediment budget and monitoring constraints we can draw some useful observations. The bed material budget is most reliably estimated on time scales of order 10 years (or more) because of issues related to data resolution. Considering reach-wide water profile maintenance, a similar time scale is required to identify trends. Significant trends in reach-wide river morphology and habitat are similarly identified on such a time scale in Fraser River. We conclude that a sustainable program for sediment management should be planned and executed on a similar time scale. This implies some additional information requirements.

4.3. What do we need to learn to operate the program?

The lack of certain information about the river, important to ensure proper planning and to ensure the sustainability of a program of water profile maintenance by sediment removal, has been noted throughout this report. We need:

- to continue to study and refine the sediment budget in order to improve the accuracy and precision of sediment budget estimates: this is the necessary basis for planning a sustainable program of sediment removal;
- to learn much more about the way in which organisms, especially the fishes, use space in the river: this is the necessary basis for planning a program that is sustainable in the sense that it does no lasting harm to the aquatic ecosystem;
- to develop an effective program for monitoring immediate and long-term impacts of sediment removal on the aquatic ecosystem;
- to develop an effective program for monitoring the long-term impact of sediment removal on the riverine morphology and habitat.

What needs to be done to accomplish the first item (sediment budget) is reasonably well understood but, beyond continuing surveys to estimate the sediment budget, no program to systematically improve sediment budget estimates has been undertaken.

The second item (how fishes use the river) is important for direct assessment of the possible impact of a proposed removal on current activities of river fishes. Each species has preferred foraging areas and strategies, specific spawning requirements and areas, and preferred holding areas. How might these intersect with proposed removal sites? At present, for nearly all species, this question can be answered only by applying very general knowledge about the fishes’ movements and requirements. More refined information is required in order to answer the questions confidently. The requirement will be difficult and expensive to achieve because it will require years of study. We simply do not know enough about the behaviour patterns of the fishes in the river, particularly of the critical juvenile stocks, hence we cannot guarantee being able to plan sediment removal operations that will certainly avoid any significant harm[10].

The third item is addressed in the G3 (2009) report, while the bases for the fourth item are contained in Church et al. (2000) and in Ham and Church (2002).

4.4. How should the program be operated?

A program to remove sediment from the river for profile maintenance should take advantage of the sedimentation process in the river to remove sediment in the least obtrusive way.

The bed material load transported into the reach by Fraser River is not deposited uniformly along the reach. It is deposited preferentially in locations where currents slacken and the river can no longer move the gravel farther on. Such places occur at a variety of scales, most notably at the scale of hundreds of metres along bar edges, and at the scale of kilometres at ‘constriction points’ in the river. These are local areas along the channel where constriction or sharp bends choke the flow, so that water levels must rise upstream to gain the gradient to drive the flow through the constriction or around the sharp bend (Figure 3). They are the major points of persistent sedimentation over periods commensurable with the decennial time scale discussed above for a sustainable program of sediment management.

In the gravel reach of Fraser River, there are currently four identifiable zones of major constriction and persistent sedimentation. These are:

- Tranmer Bar – Lower Herrling Island, upstream from the relatively narrow channel at Rosedale;
- Outer Hamilton and Gill Bars, where the river turns sharply in front of Mt. Woodside;
- Harrison Bar, where the river turns sharply against Harrison Knob;
- Webster – Yaalstrick Bars, where most of the remaining gravel load is deposited as the river encounters a reduced gradient at the downstream limit of the gravel reach.

These zones develop and persist for decades because their location depends on the alignment of the river at the largest scale, which changes only very slowly. They were the zones where most sediment deposition and the greatest aggradation occurred in the 1952-1999 survey interval, with up to 1 metre or more net aggradation over more than one kilometre length of channel. The first two of these areas continued to accumulate sediment in the 1999-2008 period, but the downstream two did not. However, significant aggradation appears to have occurred since 2000 in the upper Spring Bar and Seabird Island areas. Channel avulsions since 2000 in the Tranmer and Gill Bar areas are a consequence of the continued aggradation there.

---

[10] Questions that were raised during the 2010 permitting process concerning possible interference of sediment removal with White Sturgeon in the vicinity of Big Bar represent an example of the problem that is addressed in this paragraph.

Major sediment removals should be focused within these zones. A decision for this will facilitate the approval of multi-year removals and it will facilitate the provision of access. It will also facilitate the requirement that much more needs to be learned about fish behaviour in zones targeted for gravel removal, since it will limit the length of river that needs to be studied in detail in the relatively short term. If aggradation persists in the Spring-Seabird area it could become another zone for limited removals. Within each of these zones a number of sites may be chosen for sediment removal. These sites will vary from year to year according to the recent pattern of sediment deposition and preceding year's activities. Consequently, sites should be selected on a year-to-year basis and cannot reasonably be prescribed in a long-term planning discussion.

A potential problem with focusing activity in a limited area of the river is that only a limited amount of sediment can be removed by shallow scalping of bar tops. In any case, this method of removal can be ecologically damaging (further comments below). More consideration should be given to alternative methods of gravel removal, principally by "pullback" of lateral bar edges. This reverses the pattern in which gravel is deposited and so is most in keeping with natural processes in the river. Ecologically sensitive application of this method will require assurance that, at the time of removal, there are no critical fish activities in the vicinity. It will also require intensive monitoring to determine the impact on resident benthic invertebrates. Individual removals should be designed in accordance with the guidelines given in Church et al. (2001; restated in Appendix B).

A long range program must be accompanied by continual assessment of effective indicators of changes in river state. These have been identified as:

- regular seasonal measurement of water levels in the network of manual gauges along the river and annual analysis of the trends;
- continuation of the site-scale monitoring program, with focus on selected sites;
- annual or biennial analysis using up-dated aerial photography of larger scale habitat trends and morphological changes along the river;
- resurvey of the river and updating of the sediment budget on a 10-year cycle, or at such time as the information to be gained appears vital (such as after a notably high flood).

The first and third elements of this assessment program may be influenced by factors other than sediment removal, including changes in channel alignment and secular changes in flows or sediment delivery to the reach. Therefore, the application of expert geomorphological judgment to the observed trends will be essential. Resurvey is not recommended more frequently than once per decade because it is evident that, in comparison with possible errors, short-term reassessments lack resolution.

All elements of the program should continue to be regarded as experimental. If unfavourable trends appear to be emerging in river morphology or ecology, then the program must be modified to control those trends. Hence the program must be both adaptive and precautionary. Monitoring for morphological change is particularly important because the river in the gravel-bed reach currently lies close to a transition between multiple channel and single channel form, the latter providing much less diverse habitat possibilities (Church et al., 2001).

4.5. Some additional considerations

There are reasons other than profile maintenance why one may wish to remove gravel from the river.

Perennial and seasonal side channels play important ecological roles in the river. However, chronic gravel accumulation at the upstream end of such channels can change their flow regime or even cut the channels off. This also reduces flood stage conveyance of the river. At specifically identified sites, it may be worthwhile to encourage the maintenance of seasonal or perennial circulation through a side channel by making a one-time gravel removal to lower the entrance sill of the channel.

At certain sites along the river, high riffles interfere with commercial towboat navigation. It may be worthwhile to cut passage through riffles in such cases. Such a program was carried on for many years until the early 1990s using scuffle dredges. Gravel was pushed off the riffles but not actually removed from the river. This program has not been carried out for two decades and a problem today is to find equipment capable of doing navigation dredging in the gravel reach at reasonable cost.

Neither of these activities should be regarded as integral parts of a long-range program for profile maintenance. However, gravel removed from the river in the course of these activities should be included in the gravel removal sum for profile maintenance.

It has been remarked that the preferred method of gravel removal – bar top scalping in the dry – has little hydraulic benefit. It furthermore disturbs large areas for recovery of modest volumes of gravel. It is preferred because it is supposed to have minimal ecological impact. Whilst it presumably does have minimal immediate impact in comparison with other extraction methods, the longer term consequences are probably not benign. Bar top areas represent the areas of slackest water in high flow: they are escape and holding areas for fishes from flood currents. The amount of slack water in the river is relatively limited and is most limited at flood stage (Perkins, 2007). Scalping of bar tops increases depths and flow velocities. Whilst the change is not sufficient to confer significant hydraulic benefit, it may very well represent a critical difference for fishes seeking escape from river currents. So far as I know, the effect has not been critically examined.

In comparison, pullback of bar edges, without significant change of the overall topographic range of the bar, preserves high bar escape terrain. It also removes gravel from the channel edge, where flood velocities are substantially higher, hence may have greater hydraulic benefit. Introduction of an alternative means of sediment removal might, in consideration of fish activities, open different seasonal windows for sediment removal as well. Assessments need to be made of the relative merits of minimizing immediate ecological disturbance versus the preservation of long-term ecological advantage, with possibly different hydraulic outcomes as well.

Large, deep excavations (such as the 2008 Spring Bar removal) are not recommended. They have the potential to intercept a large fraction of the entire bedload moving downstream and to create significant downstream changes in river processes and stability.

5. SUMMARY OF RECOMMENDATIONS

To establish a sustainable long-term program of sediment removal from Fraser River in the gravel-bed reach, the following circumstances and criteria should be observed.

- It will recognise that a sustainable long-term program of sediment removal may limit or eliminate general bed aggradation in the gravel-bed reach over a period of years, but that it cannot be used to eliminate local water level problems in the short term: that is, the program may serve for general ‘water profile maintenance’ but not for local ‘water profile control’.
- It will recognise that for the program to operate in the long-term in a sustainable way additional information is required, in particular more precise knowledge of the sediment budget needs to be developed and knowledge of the annual pattern of fish activities within the reach needs to be detailed. The program should proceed only if there is a commitment to conduct the research to acquire this knowledge.
- The program should be planned and approved on a 10-year period, with more frequent review, as monitoring outcomes dictate.
- Sediment removals will be focused in those sub-reaches where chronic sediment accumulation occurs. Four such zones can be defined today but these may change over a period of years; indeed, there is some evidence that some changes may currently be under way.
- Within these zones, sites for sediment removal should be identified on a year-to-year basis, according to recent sediment deposition, the recent history of removals, and perceived (lack of) impact on current activities of fishes.
- Volumes removed should conform with recommendations given in Church et al. (2001), as discussed in Appendix B of this report, using 230 000 m^3a^{-1} as the current estimate of average annual bed material recruitment.
- Site-scale monitoring should follow the prescription given in G3 Consultants (2009) with emphasis on benthic invertebrates and on physical habitat measures.
- Reach-scale monitoring should be undertaken on an annual or biennial basis using aerial photography, as described in this report.
- The program must be adaptive and precautionary, with provision to change any elements of the program as soon as monitoring activities identify unfavourable changes to river morphology and/or the riverine ecosystem, or as soon as it becomes clear that secular changes in flow and sediment influx are affecting the river.
- It should be recognised that there may be reasons to make sediment removals from particular sites along the river on a special basis (e.g., to maintain side channels; to facilitate navigation). Such needs should be considered outside the long-term sediment management program, but sediment removals should be considered as part of the volume removed for purposes of the program.

6. REFERENCES[11]

*Church, M. and Ham, D.G. 2004. *Atlas of the alluvial gravel-bed reach of Fraser River in the Lower Mainland.* The University of British Columbia, Department of Geography. Available at http//www.geog.ubc.ca/fraserriver/reports.

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

*Church, M., Ham, D.G. and Weatherly, H. 2001. *Gravel management in lower Fraser River*. Report prepared for the City of Chilliwack.

Dignan, T.M. 1994. *Fraser River gauges.* British Columbia Ministry of Environment, Hydrology Branch, Technical Support Section. Project 93 5 R 029.

Ferguson, R. and Church, M. 2009. A critical perspective on 1-D modeling of river processes: Gravel load and aggradation in lower Fraser River. *Water Resources Research* **45**: W11424. doi: 10.1029/2009WR007740. 15pp.

G3 Consulting Ltd. 2009. Fraser River gravel extraction surveys: statistical meta-analysis. Report for the British Columbia Ministry of Public Safety and the Solicitor General, Emergency Management BC.

*Ham, D. and Church, M. 2002. *Channel island and active channel stability in the lower Fraser River gravel reach*. Report. The University of British Columbia, Department of Geography.

KWL Associates (Kerr Wood Leidal). 2002. *2003 Fraser River potential gravel removals.* Report for the Fraser Basin Council.

nhc (northwest hydraulic consultants). 2006. *Final report – Lower Fraser River hydraulic model.* Report prepared for the Fraser Basin Council.

nhc (northwest hydraulic consultants). 2008. *Fraser River hydraulic model update – final report.* Report prepared for the British Columbia Ministry of the Environment.

nhc (northwest hydraulic consultants). 2009. *Fraser River sediment budget phase 2. Final report.* Report prepared for Emergency Management BC.

Rempel, L.L. 2003. Recommendations for Fraser River gravel monitoring. Report for the British Columbia Integrated Land Management Bureau.

Perkins, A.A.H. 2007. *Distribution and abundance of nearshore aquatic habitat, Fraser River, British Columbia.* M.Sc. thesis, The University of British Columbia.

*Rempel, L. and Church, M. 2003. The Harrison Bar gravel removal experiment: final report. Report for the Habitat Conservation Trust Fund of British Columbia.

Rempel, L.L. and Church, M.2009. Physical and ecological response to disturbance by gravel mining in a large alluvial river. *Canadian Journal of Fisheries and Aquatic Sciences* **66**: 52-71.

UMA Engineering Ltd. 2000. *Fraser River gravel reach hydraulic modelling study.* Report prepared for the City of Chilliwack.

[11] References marked by an asterisk are available at www.geog.ubc.ca/fraserriver/reports

UMA Engineering Ltd. and Ward and Associates Ltd. 2001. *Fraser and Harrison rivers hydrologic and hydraulic investigations.* Report prepared for the City of Chilliwack.

UMA Engineering Ltd. 2004. *Fraser River gravel reach sediment scenario modelling.* Report for the British Columbia Ministry of Water, Land and Air Protection.

Table 1

Gravel removals, 2000-2009

Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
			(thousands of cubic metres bulk measure)							
Seabird					85					
Spring						*8*		25	340	
Tranmer		*10*			*5*					146
Lwr Herrling						33	133			
Powerline									19	
Big					50		60			
Hamilton	*2*	22	*10*	*10*			*10*		42	
Gill				60		51	70			
Harrison	70				45					148
Queen's						58				
Total	72	32	10	70	185	150	273	25	401	294

Values in italics are estimated; no formal survey. Values are rounded to the nearest thousand cubic metres

Table 2

Distribution of individual removals by size

Size range (10^3 m^3 bulk)	No. of removals
≤10	7
10 – 50	7
50 – 100	7
100 – 300	3
>300	1

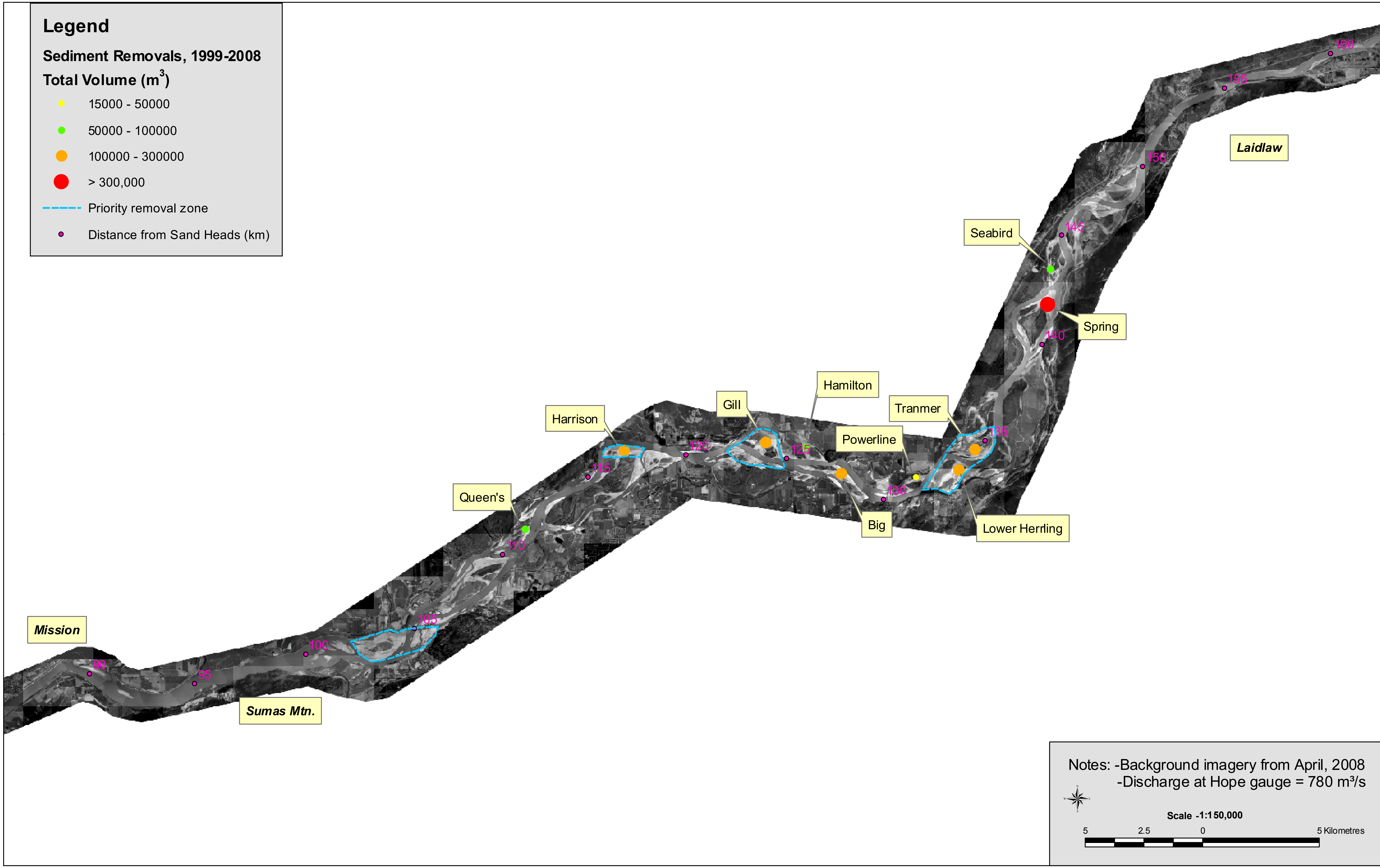

Figure 1: Location of sediment removals, 2000 - 2009 (modified from nhc, 2009; their Figure 2.1)

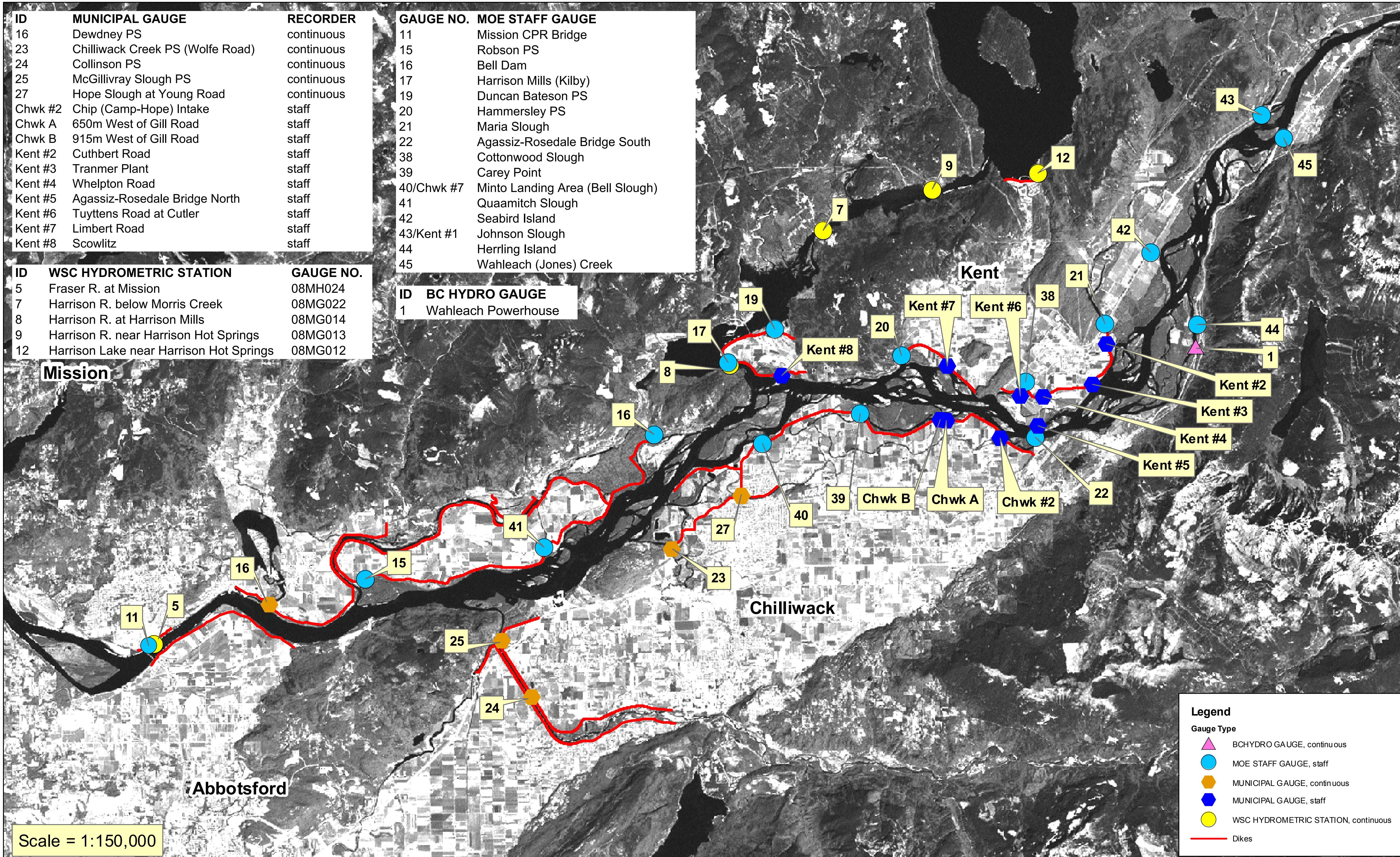

Figure 2: Fraser River gauge locations (extracted from nhc, 2008; their Figure 1)

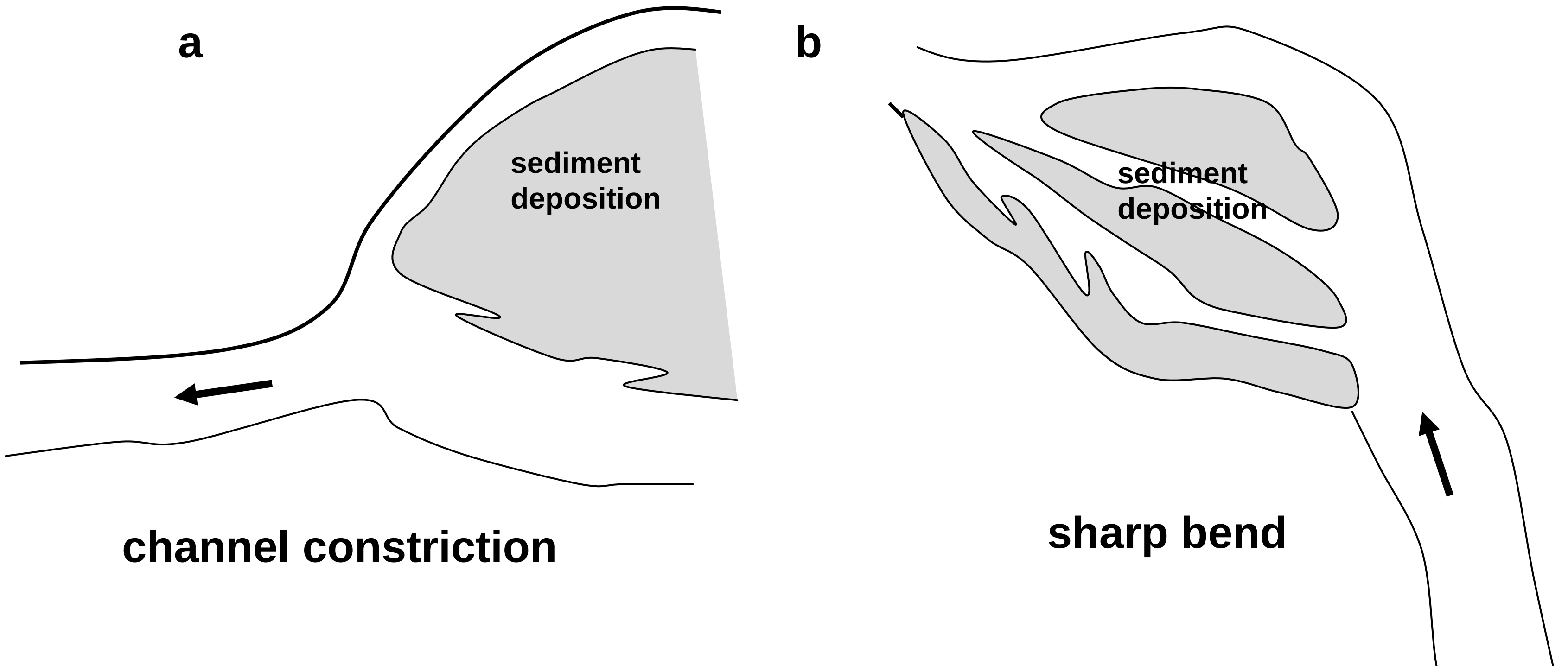

Figure 3. Cartoons showing characteristic situations where sediments accumulate: (a) flow constriction where channel zone narrows; (b) sharp bend where upstream backwater induces sediment deposition

APPENDIX A. A review of bed material influx estimates for lower Fraser River

Table A1. Gravel influx estimates at Agassiz (10^3 m^3a^{-1} bulk measure)[1]

Source	1952-1984	1984-1999	1952-1999	1999-2009	Remarks
1) *McLean et al. (1999)*	*130*				*1966-1986*
2) McLean and Church (1999)	125				
3)*Church et al. (2001)*	*135*	*110*	*125*		*using Hope flows*
range	*115-185*	*85-168*	*110-165*		
4) Church et al. (2001)	175	220	188		the 1952-1999 estimate is based on the sum of the two shorter periods
range	157-190	185-252	170-205		
5) Ham and Church (2003)	157	290	200		
6) Ham (2005)	171	294	179		gravel only
6) Ham (2005)	180	378	212		gravel only. 52-99 by direct difference[2]
corrected for error and bias			243		52-99 by sum of shorter periods[2]
7) Church (2008), unpublished			224		gravel only: 52-99 by direct difference
8) nhc (2009)				0	see notes
adjusted				0	see notes

1. Entries in italic are based on sediment rating curves constructed from WSC measurements at Agassiz, originally analyzed in McLean and Church (1986) and in McLean (1990). All other entries are based on sediment budget estimates derived from observations of morphological change along the channel. Unit conversions between tonnes, sometimes reported in the original documents, and cubic metres bulk volume assume sediment bulk density is 1.75 tonnes/m^{-3}, based on a limited number of direct measurements of bar gravels.

2. "52-99 by direct difference" means that a sediment budget estimate was made by directly difference the 1952 and 1999 DEMs. "52-99 by sum of shorter periods" means that results for 1952-1984 and 1984-1999 were summed.

Table A2. Total bedload/bed material influx estimates at Agassiz (10^3 m^3a^{-1} bulk measure)[1]

Source	1952-1984	1984-1999	1952-1999	1999-2009	Remarks
1) *McLean et al. (1999)*	*160*				*1966-1986*
2) *Church et al. (2001)*	*160*	*125*	*145*		
5) Ham and Church (2003)	144	385	197±77		52-99 by direct difference[2]
			221		52-99 by sum of shorter periods[2]
6) Ham (2005)	145	385	197±77		as Ham and Church (2003)
6) Ham (2005)	153±16	494±33	237±11		all bed material: 52-99 by direct difference
corrected for error and bias			262±15		52-99 by sum of shorter periods
7) Church (2008), unpublished			197		smaller than gravel influx
8) nhc (2009)				0	see notes
adjusted				61	see notes

1. Entries in italic are based on sediment rating curves constructed from WSC measurements at Agassiz, originally analyzed in McLean and Church (1986) and in McLean (1990) and are rounded to the nearest 5000 m^3. All other entries are based on sediment budget estimates derived from observations of morphological change along the channel. Unit conversions from bulk volume change assume sediment bulk density is 1.75 tonnes/m^{-3}, based on a limited number of direct measurements of bar gravels.

2. "52-99 by direct difference" means that a sediment budget estimate was made by directly difference the 1952 and 1999 DEMs. "52-99 by sum of shorter periods" means that results for 1952-1984 and 1984-1999 were summed.

Table A3. Gravel influx estimates at Laidlaw (10^3 $m^3 a^{-1}$ bulk measure)[1]

Source	1952-1999	1999-2008	Remarks
4) Church et al. (2001)	113		
5) Ham and Church (2003)	174		1952-99 by direct difference
6) Ham (2005)	181		
7) Church (2008), unpublished	226		
8) nhc (2009)		72	see notes
adjusted		72	see notes

1. All estimates by direct difference of bathymetries

Table A4. Total bedload/bed material influx estimates at Laidlaw (10^3 $m^3 a^{-1}$ bulk measure)[1]

Source	1952-1999	1999-2008	Remarks
4) Church et al. (2001)	115		
5) Ham and Church (2003)	193		1952-99 by direct difference
6) Ham (2005)	193		
7) Church (2008), unpublished	193		smaller than gravel influx
8) nhc (2009)		130	see notes
adjusted		248	see notes

1. All estimatres by direct difference of bathymetries

Notes on the estimates

1) McLean et al. (1999) estimated bedload transport by convolving flow frequency with a bedload rating curve based on 75 bedload measurements made at Agassiz, mostly in the late 1960s and early 1970s. They performed a detailed error analysis of the measurements and of the rating curve, and reported that annual loads were estimated to within ±40%, hence, the 21 year mean would be estimated to within ±9%. Annual data are in their table 4.

2) McLean and Church (1999) estimated the gravel influx at Agassiz on the basis of volumetric change in the channel and floodplain on the basis of surveys conducted in 1952 and 1984. The datum given above differs from that in their paper as they used 1.6 t m^{-3} for volume conversion. They imply in their paper, but do not state explicitly, that the estimate is for gravel only. They also make a direct comparison with the gravel only figure given by McLean et al. (1999). In McLean et al (1999) sand in the bed (that is, +0.177 mm sand) comprised 17.7% of the estimated total bedload. Applying this figure to the datum of McLean and Church would increase the estimated bed material influx to 266 000 t a^{-1}. Data in their table 1.

3) Church et al. (2001) constructed a rating curve based on the estimated annual total gravel influx (data from McLean et al. 1999). They obtained the 95% confidence range for the period-average sediment influx estimates, as reported above. Hope flows were used because the Agassiz gauge did not operate before 1966 nor after 1986. Data in their table 3. They estimated total bed material influx by assuming that the load included 30% of bed material sand (data in their table A5).

4) Church et al. (2001) essentially repeated the morphological analysis of McLean and Church (1999) but with higher resolution and much more highly developed GIS technology.

5) Ham and Church (2003) is based on DEM reanalysis. In particular, volume estimates along banklines were substantially improved by hand interpolation to overcome a difficult problem in DEM automated surface fitting: volume change estimates at abrupt topographic breaks remains an important problem in DEM analysis with no general solution.

6) Ham (2005) differs from Ham and Church (2003) only insofar as refined topographic analysis resulted in a somewhat different division between gravel and sand. Overall volumes have not changed.

6) Ham (2005) performed substantial additional error analysis, including the incorporation of a residual gravel transport figure at Mission, consideration of the possibility for survey errors near Sumas Mountain (later discounted), and consideration of a cumulative bias over time as the result of compensating erosion and deposition, resulting in corrected estimates for Agassiz influx.

7) The unpublished 2008 estimates by Church derive from a reassessment of bed material texture in the reach between Lower Yaalstrick bar and Mission. The gravel-sand transition is now placed at the downstream limit of Lower Yaalstrick bar. This eliminates from the gravel budget a large inter-period scour/fill episode downstream from there which significantly affected estimates between 1984 and 2003. The total

budget is smaller than the gravel budget due to presumed net sand loss (advected out of the reach).

8) The nhc (2009) estimates arise from a new survey of the river undertaken in 2008. As the result of this survey it was determined that the 2003 survey probably included a significant bias in the reference elevation for the terrestrial (Lidar) portion of the survey, so 1999-2003 budget estimates have been dropped. The 1999-2008 survey indicates that the gravel influx at Laidlaw was entirely deposited above Agassiz. This is possible, since Tranmer Bar intercepted a large volume of gravel during this period. Hence gravel influx at Agassiz is estimated as zero. Gravel flux farther downstream would be the result of movement within the reach below Agassiz. The actual budget shows negative transport in some subreaches: this is a numerical artifact that might arise from net loss of sand, mobilized in the reach and advected out of it.

8) nhc (2009) adjusted results arise from a recalculation in which the sand content of eroded overbank deposits was ignored. Nhc (2009) recommends the median figure 190 000 m^3a^{-1} as the best estimate of the influx of bed material at Laidlaw for the period. Applying the standard estimate of 20% sand, this would yield a gravel input of 152 000 m^3a^{-1}. This is double the directly estimated number.

Discussion

There are some notable aspects of the data. First, the rating estimates, constructed from two distinct approaches, are consistent and imply an average annual recruitment of about 130 000 m^3a^{-1} gravel. The McLean et al. (1999) estimate applies to the period 1966-1986 during which the underlying bedload samples were taken by WSC. The Church et al. estimates comprise the period 1952-1999. Sub-period estimate for 1952-1984 and 1984-1999 indicate higher transport, on average, during the earlier period, which would be expected from the flows (and is the consequence of using the flows in the estimates). Total bed material load is estimated to be about 145-155 000 m^3a^{-1}, which implies that 12-18% of the load is sand, consistent with the assumption of McLean and Church (1999).

The estimates from sediment budget methods are more variable. The first estimate (McLean and Church, 1999) is 127 000 m^3a^{-1} gravel, consistent with the rating estimates but much lower than all other estimates. Unadjusted estimates made between 2001 and 2005 are consistent at about 190 000 m^3a^{-1} gravel, despite incremental improvements in the DEM interpolation techniques. All of these estimates are based on the same basic data. This is 1.5x the 1999 estimates.

Ham (2005) performed corrections to account for gravel passing Mission and for bias due to compensating erosion and deposition. The bias correction was prompted by the observation that the 1952-1999 budget calculated as the sum of 1952-1984 and 1984-1999 components is always greater than the direct 1952-1999 budget. His result increases the gravel budget by a further 22%. (Percentages are based on comparison with the direct 1952-1999 results.) The 2008 figures, which revise grain sizes in the river following new sampling in the gravel-sand transition near Sumas Mountain, reduces the long term estimate for influx at Agassiz to about 225 000 m^3a^{-1} gravel, still 80% above the original estimates of 1999.

The earliest sediment budget-based estimates of McLean and Church (1999) were made with a home-constructed DEM. Furthermore, the coverage of the 1984 survey was restricted due to flows and survey technology available at the time. (The 1984 survey was improved for the 2001 and subsequent estimates by photogrammetric interpolation of many additional points.) Incremental improvements in DEM software and interpretation methods make the 2005 and later estimates the most comprehensive ones.

A peculiarity of the sediment budgets, however, is that the 1984-1999 results exceed the 1952-1984 results (the consistency is unexceptional: the same basic surveys are analyzed in all cases). This outcome is entirely possible. The rating curve results conform with the flow history, of course, because the calculations are based on the flows. However, the result could also be a manifestation of compensating erosion/sedimentation bias, which is possible because the sand budget is not closed at Mission and because gravel may undetectably exchange with sand in sediment deposits in the reach.

The total bed material flux estimates are less reliable because the total throughput of sand in the reach is of order 6 million tonnes, so the assessment of the deposited portion becomes difficult. The McLean-Church estimates are based on multiplying up the gravel result by the fraction of sand observed in gravel deposits. The later results are based on observed changes in the volume of sand resident in the reach. These calculations depend upon identifying bed material sand, including interstitial sands in gravel, bar cover sands, and the fraction of +0.177 mm sand in topset sands in the islands. Ham and Church (2003) and Ham (2005) lay out the assumptions used, but the results remain very approximate. The outcome is to reduce the estimated total influx of bed material below the gravel component for the 1952-1984 period and again in some later periods, which is plainly nonsense (it indicates only that more sand apparently left the reach than arrived in it).

The results present two major problems:

1) discounting the earliest sediment budget analysis, why are the results from the sediment transport measurements in the order of one-half to two-thirds of the sediment budget estimates?

2) are the sediment budget estimates subject to a significant integration bias due to compensating erosion and deposition?

It is quite possible that the sediment transport measurements are biased. Measurements were obtained using basket traps in 6 verticals in a 500 m wide channel. It is apparent that the transport is, overall, at low to moderate rate most of the time, whence it occurs discontinuously across the bed and may easily have been missed in sparse sampling. It is also likely that the traps failed to settle properly on the bottom on some occasions, leading to a low or zero catch in the presence of transport (many zero catches were reported). The samples were corrected for known hydraulic bias of the samplers, but that does not cover inadequate sampling in the presence of large spatial and temporal variations in transport, nor unsuccessful deployment of the samplers.

Integration bias in the sediment budget estimates is difficult to assess. The sediment budget method was applied to Fraser River since the lateral style of instability in the river gave the appearance that, over a significant period, the occurrence of compensating erosion and deposition would remain relatively minor. We do not have morphological evidence for large-scale compensating effects, but the pattern of budget estimates makes it appear likely. On the other hand, the reach is assumed to be an endpoint sink for gravel, so all the gravel influx ought to be detectable even if some sites experience compensating erosion and deposition – that is compensation should not be a problem in this case. This raises three further possibilities:

1) significant volumes of gravel are moving downstream, beyond the end of the "gravel reach";

2) gravel removal from the river over the years has been significantly larger than is documented (documented removals are accounted for in the sediment budget);

3) there is a significantly higher, and growing, proportion of sand in the gravel reach deposits than has been determined.

Item (1) seems very unlikely (there is no evidence for it – corrections have now been made for the known amount of gravel that passes Mission). Item (2) is probable, but it is not clear that undocumented removals could be so large as to cover the problem. It would be consistent with the appearance of greater bias in the past since gravel removal has been increasingly closely monitored since 1984, and almost completely controlled since 1998. Item (3) is possible and would present a severe problem to resolve. Again, the pattern of bias is plausible since the pattern of dominantly lower floods of the late 20^{th} century is consistent with sand accumulation in the reach.

References

Church, M., Ham, D. and Weatherly, H. 2001. *Gravel management in lower Fraser River.* Department of Geography, The Universtiy of British Columbia. Report prepared for The City of Chilliwack, 110pp. Available online at *www.geog.ubc.ca/fraserriver.*

Ham, D. G. 2005. *Morphodynamics and sediment transport in a wandering gravel-bed channel: Fraser River, British Columbia*. Ph.D. thesis. The University of British Columbia, 272pp. Available online at *www.geog.ubc.ca/fraserriver.*

Ham, D. G. and Church, M. 2003. *The sediment budget in the gravel-bed reach of Fraser River: 2003 revision*. Department of Geography, The University of British Columbia, 19pp. Available online at *www.geog.ubc.ca/fraserriver.*

McLean, D. G. 1990. *Channel instability on lower Fraser River.* Ph.D. thesis. 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 Section. *Report* **IWD-HQ-WRB-86-62**, 56pp + figures and tables.

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.

nhc (northwest hydraulic consultants). 2009. *Fraser River sediment budget phase 2. Final report.* Report prepared for Emergency Management BC.

APPENDIX B. The recommendations for sediment removals in Church et al. (2001)

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 judgment indicates that larger extractions must be made to improve water levels locally to assure flood security.*

   [Subsequent experience indicates that the italicized portion of this recommendation is not practical because individual extractions have no significant impact on local water levels.]

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.*

   [Experience suggests that it is difficult to estimate bed material recruitment over a period as short as 5 years. I now suggest a ratio of 1.25 over 10 years.]

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 river-wide 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 [i.e., in Church et al., 2001] should be reviewed and revised.

   [The text in italics is effectively replaced by more specific recommendations in G3 Consultants (2009).]

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).

   [km 110 is at Wellington Bar.]

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.

   ["Types 1 and 2" correspond with channel constrictions and sharp bends, as described in the present report. Comments in the present report modulate this 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.

[This recommendation addresses shoals at riffles which are considered, in the present report, to fall outside the considerations of a long-term sediment management plan.]

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.

   [It should also consider potential impacts on current activities of fishes.]

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

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*.

   [Experience suggests that the circumstance described in italics is unlikely to be unambiguously demonstrable.]

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 over the next 30 years. *The plan should not rely on industrial-scale gravel extraction from Fraser River*.

   [The remark in italics seems somewhat more remote now than it did in 2001.]

References

Church, M., Ham, D.G. and Weatherly, H. 2001. *Gravel management in lower Fraser River.* Report prepared for the City of Chilliwack. Available at http//www.geog.ubc.ca/fraserriver/reports.

G3 Consulting Ltd. 2009. Fraser River gravel extraction surveys: statistical meta-analysis. Report for the British Columbia Ministry of Public Safety and the Solicitor General, Emergency Management BC.

APPENDIX C. Persons interviewed for this report

Ms. Erica Ellis
Kerr Wood Leidal Associates, Ltd.

Dr. Victor Galay, P.Eng.
Northwest Hydraulic Consultants, Ltd.

Dr. Darren Ham
Northwest Hydraulic Consultants, Ltd.

Dr. David McLean, P.Eng.
Northwest Hydraulic Consultants, Ltd.

Dr. Laura Rempel
Canada Department of Fisheries and Oceans, Vancouver.

Mr. Hamish Weatherly, P.Geo.
BGC Engineering, Inc.