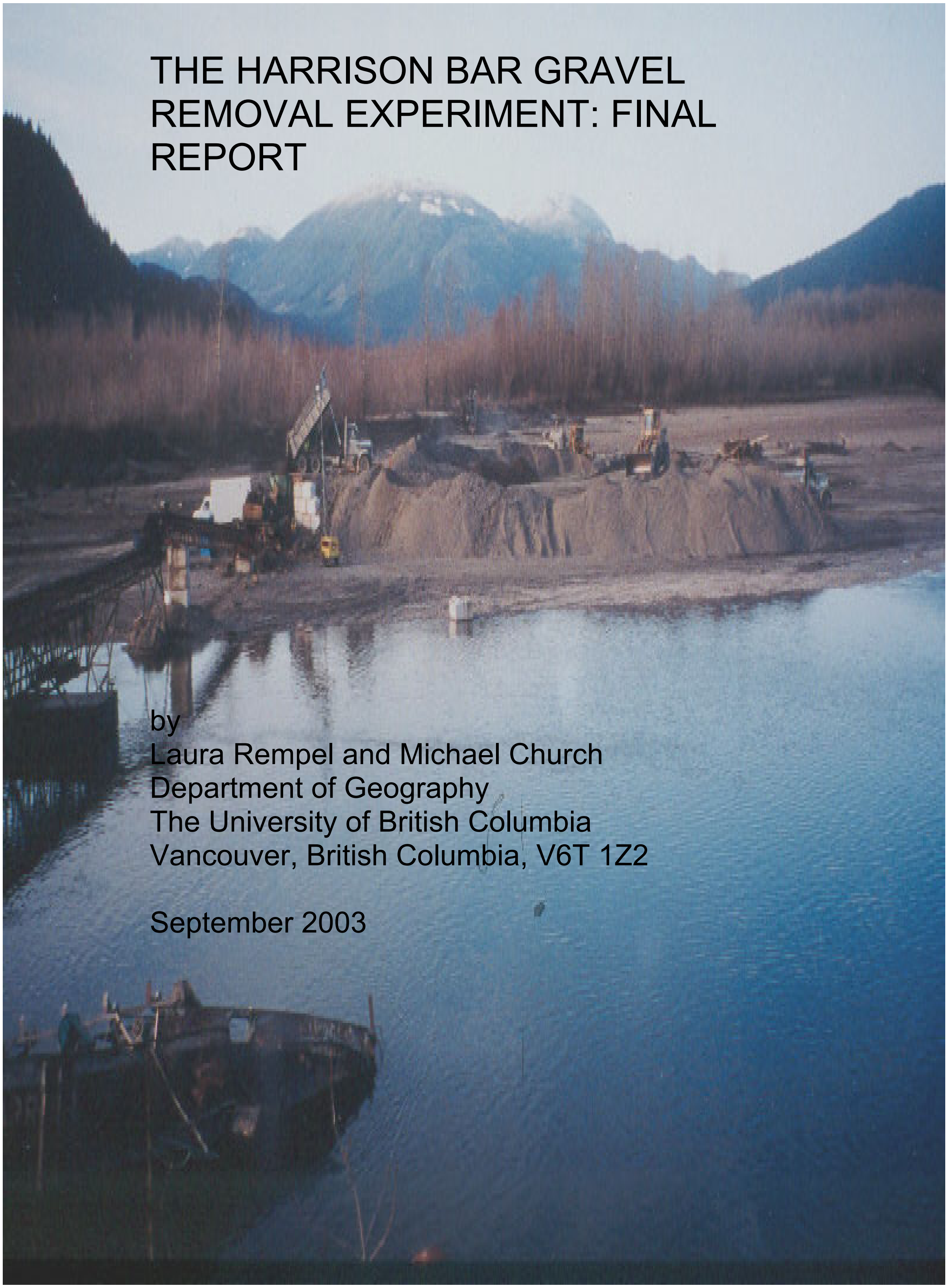

THE HARRISON BAR GRAVEL REMOVAL EXPERIMENT: FINAL REPORT

by
Laura Rempel and Michael Church
Department of Geography
The University of British Columbia
Vancouver, British Columbia, V6T 1Z2

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Executive Summary

There is increasing concern that the natural processes of bed aggradation and seasonal flooding pose an unacceptable risk to the people and investment along lower Fraser River. As a result, gravel mining from within the main channel is currently being investigated as part of an effective strategy to reduce flood risk. For many decades, Fraser River has been exploited by the local aggregate industry as a source of gravel for construction and industrial purposes. However, observations from other rivers where gravel extraction occurs have found that mining can induce major morphological and ecological changes.

This report summarises research that examined the short-term (over three freshet cycles post-mining) physical and ecological impacts of an experimental gravel removal at Harrison Bar, Fraser River. The lower corner of Harrison Bar was chosen for bar scalping because it had been the site of persistent sediment deposition over the past 15 years and flood security in the vicinity was being compromised. The removal operation took place in February 2000 and involved scalping 70,000 m^3 of gravel from the surface of the exposed gravel bar at low flow. Systematic monitoring began in August 1999, prior to the removal, and continued for 18 months following the removal. Four components of the river system were examined: bar topography, physical habitat characteristics, the macroinvertebrate assemblage; and fish species assemblages and distributions with respect to habitat availability at Harrison Bar.

Data were collected at the scalped site (Har-S) and three upstream reference sites (upper Harrison Bar, Foster Bar, Carey Bar) that were chosen for their physical similarity to Har-S. Sampling for benthic invertebrates occurred twice before and eight times after bar scalping. Fish sampling by beach seine took place three times before and eight times after scalping. Topographical surveys of the removal area took place prior to scalping, immediately after, and on three occasions after subsequent freshet events (2000, 2001, 2002) to document changes in bar configuration and to estimate sediment replenishment to the removal area.

Sediment was extracted to an average depth of less than 1 m at Har-S, producing notable instantaneous changes. The scalped area was left topographically simple with unconsolidated fine gravel and sand replacing a coarse and relatively stable bar surface. Average sand cover increased from 11% to 32% and median grain size decreased from 25 mm to 13 mm. Also notable was the decrease in grain size of the coarsest fraction (D_{95}) from 66 mm to 40 mm. The proportion of the area of lower Harrison Bar at greater than 8 m elevation was reduced from 71% to 4% and the area >9 m elevation was reduced from 24% to 0%.

These physical changes were relatively short-lived: two subsequent freshets of below-average discharge in 2000 and 2001 transformed the loose and sandy surface into a moderately coarse substrate with negligible sand cover. Median grain size (D_{50}) increased to 35 mm and the coarsest fraction (D_{95}) increased in size along the water's edge but remained lower than prior to scalping (82 mm versus 91 mm).

The below-average freshets of 2000 and 2001 produced negligible volumetric change at the scalped site (8311 m^3 net erosion over the lower bar); however, topographical changes were notable and resulted in deposition of an isolated gravel bar at the lower corner and erosion of a summer channel that flowed diagonally across the lower bar. The channel had irregular geometry with high habitat diversity. Some rebuilding of high bar area was observed in 2000 and 2001: the proportion by area of lower Harrison Bar >9 m surface elevation was 15% after freshet in 2001 compared with 0% immediately after scalping. However, a loss in high bar habitat remained evident as the area of lower Harrison Bar >9 m elevation prior to scalping was 24%.

The above-average freshet in 2002 deposited 27,630 m^3 of sediment over lower Harrison Bar. Considering volumetric change within the boundaries commonly surveyed in all years, 31% of the scalped volume was replenished over three freshets. The lower bar was further transformed into an irregular surface of variable elevation that offered greater topographical variability in comparison with pre-scalp conditions. However, the proportion of area over lower Harrison Bar >9 m elevation remained 6% less than before scalping (18% post-scalping versus 24% before scalping, corresponding to 44,750 m^2 and 58,925 m^2, respectively). The range of flows over which the loss of high bar habitat was most significant was between 4000 and 7000 m^3/s. These flows typically occur between May and August, during the period when fish are rearing in the gravel reach.

At flows less than 3000 m^3/s, lower Harrison Bar offered higher habitat diversity and smaller-sized habitat units after scalping. Bar edge remained the most common habitat type, however, units were shorter in length and spaced between open nooks. The increase in habitat diversity was observed both along the main channel edge and within a summer channel that crossed the lower corner of Harrison Bar. The new channel increased the amount of wetted area available for fish and presented a variety of habitat types including eddy pool, open nook, and bar edge. Recently, the channel appears to be infilling, however, it provided valuable aquatic habitat in the short-term after scalping as the bar was changing toward its new configuration.

The characteristics of bar edge units, the most common habitat type in the gravel reach, changed at Har-S after scalping in comparison with the three reference sites. The short-term change was statistically significant and was interpreted to be a shift towards reduced bank slope and sandier substrate. The change was only observed during summer months.

Asymmetrical analysis of variance (ANOVA), the most rigorous approach available to detect environmental impacts, was used to determine whether or not bar scalping had a significant impact on benthic invertebrates and juvenile fish at lower Harrison Bar.

Asymmetrical ANOVA was applied to five parameters characterizing juvenile fish at the removal site compared with the three reference sites: total density, proportion of salmonid species, species richness, Simpson's diversity, and Simpson's evenness. When data from all habitat types were pooled at the bar-scale, only evenness recorded a short-term impact at Har-S: values were more variable at Har-S after scalping compared with reference sites. An examination at the habitat-scale limited to bar edge units found a significant short-term impact in the proportion of salmonid species at Har-S. In this case, salmonid representation (consisting of chinook and chum salmon) was *higher* at Har-S than reference sites in winter and spring post-scalping. Statistical power to detect an impact was low for all analyses, however, it was higher for bar-scale analyses due to the larger number of beach seine samples.

Six parameters characterizing the invertebrate community were examined by asymmetrical ANOVA: total density, proportion of mayflies, stoneflies, caddisflies (EPT), taxon richness, the number of EPT taxa, Simpson's diversity, and Simpson's evenness. Results of the analyses were identical when data were examined at the bar-scale (all habitats) or habitat-scale (bar edge only). A short-term significant impact was detected for 3 of 6 parameters. Total density and the proportion of EPT were lower at Har-S in May and August after scalping compared with reference sites. Evenness was more variable after scalping at Har-S. Statistical power was relatively high for these analyses.

An examination of the abundances of the seven most common invertebrate taxa found a significant short-term reduction at Har-S due to scalping for two taxa: Chironomidae and Oligochaeta. A significant change for Baetidae was also detected, however, abundance of the common mayfly increased at Har-S after scalping. Statistical power to detect an impact was moderate for those taxa for which an impact was not detected.

Invertebrate density at the scalped site was lower than reference sites immediately after mining in April 2000 and remained lower until August 2000, less than one freshet cycle. Lower invertebrate density at the scalped site suggested that physical conditions may have been less favourable than at other gravel bars affected by spring flooding. The rate of sediment transport across Harrison Bar was likely higher due to the loose substrate framework left by scalping, and these conditions may have deterred settlement by some taxa. The fact that all impacts associated with the invertebrate community due to scalping were short-lived is consistent with observations that the fine gravel/sand surface at lower Harrison Bar was transitory, lasting only through the first freshet.

We are unable to rule out the possibility that the improvement in habitat diversity at flows <3000 m^3/s after scalping was fortuitous. In other circumstances, post-scalp sedimentation patterns might have sustained or even further simplified the existing topography. It does appear certain that processes of sediment transport and deposition assisted site recovery because the scalped surface of Harrison Bar became topographically complex after one freshet event. However, an above-average freshet was necessary for substantial sediment deposition and areas of high surface elevation to rebuild. We expect that sediment replenishment will be necessary for a removal site to continue to offer high quality habitat that favours recolonization by benthic invertebrates and rearing by fish. A large removal in 1995 from the upstream head of nearby Foster Bar has continued to degrade in the absence of sediment deposition since scalping and habitat quality has been notably impacted.

Eight recommendations, summarized below, are given for future gravel removals based on the experience gained in this study in order to minimize the likelihood of negative morphological and ecological change. Minimum sampling requirements are also listed for future monitoring studies along with a discussion on ways to improve statistical power to detect an impact.

1. *Site selection and planning for future removals should give due consideration to the need to preserve areas of high bar habitat as well as local patterns of sediment transport and the likelihood of gravel replenishment to the site.*
2. *In general, the removal volume at a site should not exceed the best estimate of local gravel deposition in a year of mean annual flood discharge (derived from volumetric or sediment transport estimates). This is to ensure that physical changes to a site fall within the range of change that might be observed at a non-removal site in a large freshet.*
3. *The haul road surface should be mechanically scarified once a removal operation is complete and prior to freshet.*
4. *It is important to preserve bars within the gravel reach exclusively as reference sites to allow for comparisons between scalped and undisturbed reference sites*.
5. *Future removals should be treated as "experiments" with a structured monitoring program.*
6. *When the goal of a monitoring program is to examine mining impacts using statistically rigorous methods, due consideration must be given to the timing of permit approval to allow necessary pre-scalp samples to be collected.*
7. *There remains a need to learn about the ecological and morphological impacts of linear excavations, bar edge scalping, and riffle dredging.*
8. *There remains a need to learn about the cumulative impacts of multiple removals or single but large removals, as well as the response to gravel mining over an extended period of long-term monitoring.*

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4.0 Discussion

4.1 Bar-Scale Physical Changes

Immediate physical changes to Harrison Bar as a result of gravel mining were substantial. Approximately 70,000 m^3 of sediment was removed to an average depth exceeding 1 m and from a large area (~600 m x 150 m), which corresponded to roughly 40% of the lower bar. Within the scalped boundary, the proportion of bar area at greater than 8 m elevation was reduced from 71% to 4% and the area >9 m elevation was reduced from 24% to 0%. The scalped area was left topographically simple and graded to a slope of approximately 2%. The evenly graded, homogeneous area of unconsolidated fine gravel and sand replaced a pre-existing coarse and relatively stable bar surface. Average sand cover increased from 11% to 32% and median grain size decreased from 25 mm to 13 mm. Also notable was the decrease in grain size of the coarsest fraction (D_{95}) from 66 mm to 40 mm.

The dramatic change in surface sediment texture due to scalping was relatively short-lived. Flooding in spring 2000 transformed the loose and sandy substrate into a moderately coarse surface with negligible sand cover. Sand cover in the scalped and reference areas of Harrison Bar was similar (~1%) after flooding, which indicated that a significant amount of sand was entrained from across the entire bar surface. Flooding in 2001 produced additional surface coarsening within the removal area, particularly along the water's edge where median grain size increased from 25 mm before scalping to 35 mm after scalping and after two freshets. The coarsest fraction (D_{95}) increased in size along the water's edge after scalping, but to a lesser extent: the grain size after two freshets remained lower than prior to scalping (82 mm versus 91 mm). The D_{95} grain size along the waterline of the reference area decreased over the same period.

Topographical changes after scalping of lower Harrison Bar occurred concurrently with sedimentary changes as a result of flooding. Flood discharge in 2000 and 2001 was below average and produced negligible volumetric change, both over the entire lower bar (8311 m^3 net erosion) and locally within the removal area (3123 m^3 net deposition). However, there was a relatively large and balanced exchange of sediment (deposition and erosion) over the lower bar in each freshet that resulted in topographical changes. It remains uncertain whether or not this amount of sediment exchange is typical of gravel bars in Fraser River or if the destabilized bar surface after scalping was more easily entrained. Topographical changes after two freshets included an increase in maximum bar surface elevation but a slight decrease in average bar elevation, deposition of an isolated gravel bar at the lower corner, and erosion of a summer channel that flowed diagonally across the lower bar. The channel had irregular geometry with high habitat diversity, and established a flow connection between the main channel and inner side channel during summer months. Some rebuilding of high bar area was observed during this period: the proportion of bar area >9 m elevation was 15% after freshet in 2001 compared with 0% immediately after scalping and 24% prior to scalping.

Flood discharge in 2003 was above average and deposited 27,630 m^3 of sediment over lower Harrison Bar, approximately 31% of the scalped volume. The material was deposited over much of the area including upstream of the removal boundary, where bar surface elevation increased to >10 m. Total bar area >10 m was in fact higher in 2003 than before scalping (2,450 m^2 versus 25 m^2, respectively). Two small, high points >9 m developed on the inside middle bar, and further deposition on the lower corner resulted in infilling of the summer channel at its top end. The bar surface was transformed from a simple and homogeneous surface into an irregular surface of variable elevation that offered greater topographical variability in comparison with pre-scalp conditions. Average bar surface elevation increased to within 11 cm of the average prior to scalping, and maximum bar elevation exceeded pre-scalp conditions by 35 cm in 2003. However, the proportion of bar area >9 m was 18%, which remained 6% less than before scalping. The range of flows over which the loss of high bar habitat was most significant was between 4000 and 7000 m^3/s, corresponding to bar surface elevations between 8.5 and 10 m. These flows typically occur between May and August, during the period when fish are rearing in the gravel reach.

It should be noted that total bar area >10 m elevation, which would become inundated at flows exceeding 8000 m^3/s, was higher in 2003 than prior to scalping. This high-bar area was situated immediately upstream of the removal boundary. We do not believe that scalping was responsible for the increase and speculate that the area of bar >10 m would have been at least as large in the absence of scalping because of the natural tendency for sediment deposition over Harrison Bar. Nevertheless, this finding demonstrates that vertical bar growth and island building can proceed in proximity to a removal operation so long as sediment continues to be recruited to the area.

Clearly, multiple freshet events of above-average peak discharge will be necessary for areas of high surface elevation to rebuild on Harrison Bar after scalping. Such events also appear necessary for notable sediment recruitment to the lower bar. Given the rapid increase in bed material transport at higher flows, this condition is apt to be general along the river.

4.2 Habitat Availability and Use By Fish

The lowering of bar surface elevation and reduction in total area of high bar 8.5 – 10 m directly reduced the amount of shallow water habitat available between 4000 and 7000 m^3/s. Areas >8.5 m elevation before scalping would now have deeper water and higher velocity during summer months, which includes the period when fish are rearing in the gravel reach. Such conditions are not favourable for most species of juvenile fish and, consequently, habitat availability over this range of flow was reduced as a result of scalping. Habitat value in the gravel reach has been shown naturally to decrease in summer months as discharge increases (**Figure 54**). The additional reduction in high elevation bar area as a consequence of scalping would have further reduced habitat value during a period when it is already limiting.

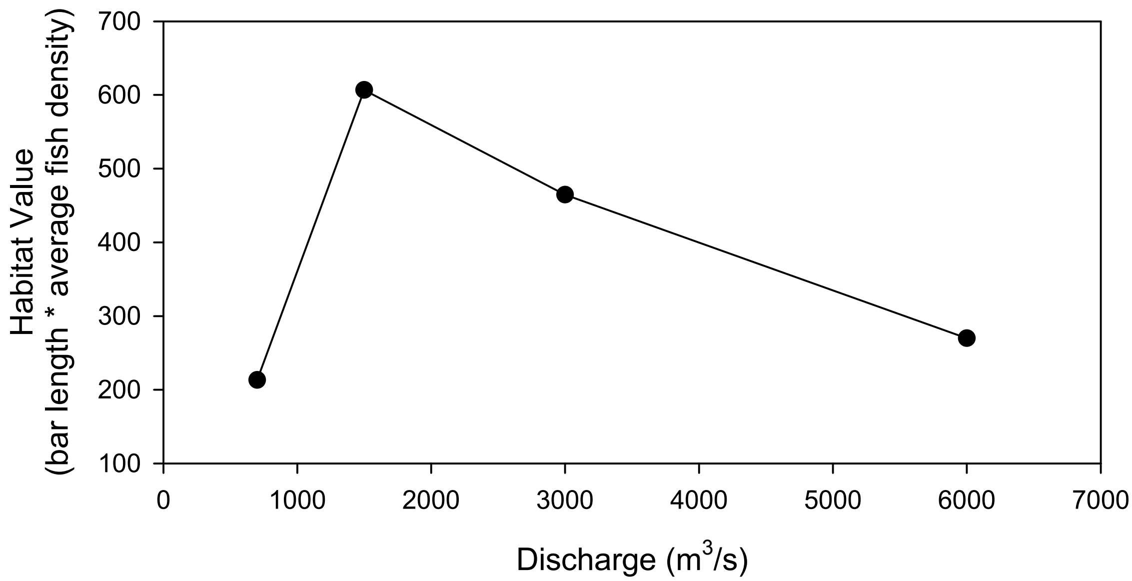

Figure 54. The relation between habitat value (total bar length * mean fish density grouped according to season) and discharge for bars in the gravel reach (adapted from Church et al. 2000).

The surface of lower Harrison Bar had greater topographic variability after scalping, which increased habitat diversity at flows less than 3000 m^3/s. The increase was not statistically significant, but the pattern of habitat diversification after scalping was consistent for several water levels examined by photography. Prior to scalping, the bar surface was an expansive, flat area of simple topography. Particularly at low flow, units of the most common habitat type, bar edge, were large (>700 m in length) and other habitat types were generally rare. Bar edge remained the most common habitat type at low flow one year after scalping, however, units were shorter in length and spaced between open nooks.

From the perspective of a fish, smaller and more diverse habitat units offer a wider choice in the range of habitat conditions available and support a greater number of species. This situation is energetically favourable because animals can disperse over short distances and select from a range of physical conditions and food sources (Rosenfeld and Boss 2001). It is also favourable for sustaining populations over the long term because reaches of river with high habitat diversity can support multiple life stages of animals with variable habitat requirements (Galat and Zweimüller 2001). In contrast, long-distance dispersal over extensive areas is necessary in a more simplified reach of river with few habitat types available (Nicolas and Pont 1997). Such a reach, ultimately, may lack the capacity to support some species of fish and high fish density (Ward et al. 2002).

The smaller size and greater diversity of habitat units after scalping was most notable during late summer months (discharge <3000 m^3/s) both along the main channel edge and within a summer channel that crossed the lower corner of Harrison Bar. The new channel increased the amount of wetted area available for fish and was host to a variety of habitat types including eddy pool, open nook, and bar edge. The channel conveyed flow through November 2000 but fresh sediment deposited by the 2001 freshet cut off flow into the channel after September 15, 2001. In 2002, the channel carried flow through August but was cut off prior to September 15. Although the channel appears to be infilling, it provided valuable aquatic habitat in the short-term after scalping as the bar was changing toward its new configuration.

Fish density, along with several other metrics characterizing the fish community, showed no detectable impact at lower Harrison Bar as a result of scalping. The statistical analyses were relatively sensitive because reference sites varied in a consistent manner over time. Density was lower in the scalped area *prior* to scalping relative to reference sites, but was higher in 7 of 8 periods of sampling post-scalping. This pattern was consistent regardless of whether the spatial scale of examination was the whole lower bar (all habitat types pooled) or bar edge units only.

There were 2 cases of 10 in which a significant impact was detected after scalping: Simpson's evenness and the proportion of fish belonging to the family Salmonidae. The former impact was detected at the bar scale and the latter result was obtained from the analysis of bar edge units only. In each case, the detected impact was short-lived (less than one freshet cycle). In the case of salmonid representation, average values before scalping were lower at the scalped site than all reference sites; however, there was a significant increase in salmonid representation at the scalped site in May 2000 and February 2001, after scalping. The significantly higher representation in May 2000 consisted of chinook salmon, whereas chum salmon fry were significantly more common at the scalped site in February 2001.

Diet choice by chinook salmon was relatively consistent among sites in each year of sampling, both before and after bar scalping. The majority of these fish originated from the Nechako and Stuart drainages (L. Rempel, unpublished data) and spent up to a year rearing in the gravel reach before migrating to the ocean. Stomach contents of chinook salmon collected during summer months included a range of aquatic and terrestrial insects, with nymph and adult chironomids making up the majority of food by volume in the stomachs of fish at all sites. Mayfly nymphs were common in the stomachs of chinook salmon from upper and lower Harrison Bar in most years as well, but had low representation in the stomachs of fish at Carey Bar.

4.3 Site Recolonization by Benthic Invertebrates

Benthic invertebrates recolonized lower Harrison Bar immediately after scalping as water inundated the site with the onset of freshet. Samples collected in April 2000 had above average density and included a high proportion of mayfly, stonefly, and caddisfly (EPT) nymphs. Several of these taxa (e.g., *Ameletus* sp.) are known to be highly mobile and have good swimming ability (Mackay 1992). These behavioural tactics are practical for survival in the gravel reach where the water edge shifts over several hundred meters across the surface of gravel bars during freshet (Rempel et al. 1999). However, subsequent months of sampling (May, August 2000) revealed lower than average invertebrate density and proportions of mayflies, stoneflies, and caddisflies at the scalped site. This reduction was statistically significant and indicated a short-term impact due to scalping at Harrison Bar. Recall that samples in these months were among those collected from sediment disturbed by scalping, whereas winter samples were collected at elevations below the removal boundary. In all months after August 2000, invertebrate density at the scalped site was higher than the average of reference sites.

Taxon richness, the number of EPT taxa, and species diversity showed variable trends after scalping at Harrison Bar and no short-term impact was detected due to scalping. Statistical power was relatively high for these analyses conducted both at the bar scale and within bar edge habitat units. The sensitivity of the analyses to detect an impact, however, was reduced because of the temporal variability observed at reference sites. Underwood (1993) states that a significant temporal interaction among reference sites after scalping indicates that an impact would have to be large to be ecologically "important". Presumably, populations are resilient to some disturbances in a variable environment, and an environmental impact "must be relatively large, otherwise it is simply within the population's capacity to recover". The fact that density, %EPT, taxon richness, and diversity were mostly similar at the scalped site in summer 2001 compared with pre-scalp conditions presumably indicates the system's capacity to recover from a modest removal of gravel from lower Harrison Bar.

Abundances of the most common mayfly, Baetidae, were higher at the scalped site than the average of reference sites on all dates before and after scalping. Abundance was significantly higher at the scalped site almost one year after scalping, in January 2001, and a short-term impact (positive) due to bar scalping was detected. Other common mayfly taxa (Ephemerellidae and Heptageniidae) showed a short-term decrease in abundance immediately after scalping but the decrease was not statistically significant and abundances were higher than reference sites after one summer post-scalping.

Chironomid midges (mostly Orthocladiinae) were the most abundant taxon at all sites in the gravel reach, and showed a significant reduction in abundance immediately after scalping. The impact was reflected in May and August samples that were collected from within the former removal boundary. Abundance was higher at the scalped site in all subsequent months of sampling relative to reference sites. Overall, a significant impact due to gravel mining was detected in the abundance of 3 of the 7 most common taxa in the gravel reach. The impact was short-lived for both taxa and was positive for the family Baetidae and negative for Chironomidae. Statistical power to detect an impact was moderate for those taxa for which an impact was not detected.

Lower taxon richness at the scalped site compared with reference sites immediately after mining suggested that physical conditions may have been less favourable than at other gravel bars affected by spring flooding. The rate of sediment transport across Harrison Bar was likely higher due to the loose substrate framework left by scalping, and these conditions may have deterred settlement by some taxa. But the disturbed surface sediment did not deter settlement by invertebrates such as *Ameletus* sp. The fact that all impacts associated with the invertebrate community due to scalping were short-lived, lasting up to one freshet cycle in duration, is consistent with observations that the fine gravel/sand surface at lower Harrison Bar was transitory, lasting only until the first freshet.

Recolonization by invertebrates of the scalped site depended on an abundant source population existing upstream. These animals would have arrived at Harrison Bar by a combination of passive and active drift in the flow as flooding inundated the site (Rader 1997). The term "drift" is given to the assemblage of animals found drifting in the flow, and previous drift sampling in the main channel of the gravel reach found high taxon richness (27 unique taxa on average) and moderate density (2.7 animals/m^3; L. Rempel, unpublished data). Drift samples consisted of a mixture of aquatic and terrestrial insects that would have dropped in from riparian areas. We do not know to what amount single or multiple scalping operations may reduce the source population of invertebrates in the gravel reach. But persistent removals extending throughout the gravel reach might reduce the source population and ultimately delay site recovery.

A dramatic shift in the proportions of functional feeding groups in April 2000 was not a signal of physical site disturbance but rather was driven by the life cycle of Orthocladiinae. Larval Orthocladiinae (collector-gatherers) hatch in late autumn (October/November) and mature through the winter months, emerging as terrestrial adults in March. They were significantly more abundant than all other taxa in March but were relatively rare in April. At this time, *Ameletus* sp. (scraper) had proportionately high abundance. A similar shift in dominance observed in September 2000 was due to an abundance of newly hatched oligochaetes (scrapers). The increase in Oligochaeta and shift from predominantly collector-gatherer taxa to scrapers was observed at all sites and was therefore independent of scalping. On all dates except April and September 2000, collector-gatherers feeding on fine particulate organic matter were the most common feeding group represented in samples. Previous benthic sampling in the gravel reach found collector-gatherers to be significantly more common than all other feeding groups combined (Rempel et al. 1999).

A notable observation from benthic sampling over three years in the gravel reach is that invertebrate abundance exhibited a high level of spatial variability. This pattern was prominent with Orthocladiinae; density was more than four times higher at Har-R than at all other sites in September 1999 and was almost twice as high at Fos-S than at other sites in February 2001. The abundances of other taxa such as Heptageniidae and Baetidae showed a similar degree of variability on some dates.

4.4 Synthesis and General Recommendations

Two freshets of below-average peak discharge resulted in some reorganization of surface sediment and adjustments in surface topography across lower Harrison Bar. However, an above average flood exceeding 10,000 m^3/s peak discharge was necessary for sediment recruitment and rebuilding of high bar habitat at the site. After two modest freshets and one large event, the proportion of bar area >9 m in elevation and inundated between 4000 and 7000 m^3/s remained 6% less than prior to scalping (44,750 m^2 versus 58,925 m^2 before scalping). Repeated topographic surveys were needed to detect this impact, which directly affected juvenile fish because the amount of shallow water habitat during summer months was reduced. Interestingly, a comparison of average and maximum bar surface elevation from before to after scalping found negligible differences. Only by comparing the elevation-to-area relation and then relating it to the specific range of flows over which fish would be affected was the impact to fish habitat identified.

The exchange of sediment by erosion and deposition over the bar surface appeared to assist in site recovery because the scalped surface of Harrison Bar was uniformly graded to a 2% slope but developed topographical variability after one freshet event. Topographical change continued over subsequent freshets and the transformation highlighted the role of sediment transport throughout the gravel reach in habitat creation and maintenance. Even in the absence of scalping, gravel bars undergo changes in sediment texture and configuration on an annual basis, creating alternating zones of sediment deposition and erosion that are relatively transient on the time scale of decades. Gravel deposits divert the flow around them and the fact that these deposits shift in space causes episodic lateral instability that is important for maintaining a diverse array of channel networks and habitats. On a local scale, sediment transport maintains fish habitat of high quality by producing topographic irregularities across a bar surface and by episodically reworking and cleaning the substrate.

Various factors operating both at the local and reach scales will influence the physical and ecological response to gravel mining; these factors likely vary between gravel bars. Foster Bar provides an example of the impact of bar scalping in the absence of sediment replenishment. In 1995, a substantial amount of gravel was removed from the bar head where flow patterns are predominantly erosional and the likelihood of gravel deposition is low. Removal depth averaged 3 m and, in the absence of sediment recruitment, bar surface elevation has degraded an additional 1 m over six years since scalping (see Appendix B). Scalping likely accelerated degradation by the removal of the coarse surface sediment layer. A change in flow patterns upstream of Foster Bar due to a change in channel alignment at Carey Point is partially responsible for the lack of coarse sediment recruitment and infiltration of fine sediment to the bar head. Bar topography has simplified and the habitat is of poorer quality compared with other sites in the gravel reach (L. Rempel, unpublished data).

These observations highlight the most significant impact of gravel mining: the loss of quality habitat units such as bar head, riffle, and eddy pool for use by fish and invertebrates. Current habitat conditions at Foster Bar are very simple (mostly bar edge) relative to other sites. Areas of clean, coarse sediment, which are typical at the upstream ends of gravel bars, are rare. Further degradation over the removal area since scalping has eliminated shallow, bar top habitat that is important for juvenile fish at high discharge. Although benthic invertebrate density was comparable with reference sites in localized areas with clean, coarse sediment, these areas were rare along the bar flank of upper Foster Bar after six years post-scalping.

On the basis of these findings, the following recommendations are presented for consideration in the planning of future removals in the gravel reach of Fraser River.

1. *Site selection and planning for future removals should give due consideration to the need to preserve areas of high bar habitat as well as local patterns of sediment transport and the likelihood of gravel replenishment to the site.*

Complex bar topography is essential for making available a variety of habitats at all levels of discharge. Although our analysis of habitat availability examined only a range of flows <3000 m^3/s, water levels fluctuate over several metres on the rising and declining limb of the flood hydrograph (McLean et al. 1999). Juvenile fish rearing in the reach depend on habitat being available over this entire range of flows. Strictly targeting areas of highest elevation to maximize removal depth is not recommended because of the importance of these areas for providing shallow zones of reduced hydraulic stress at high discharge. Scalping of lower Harrison Bar resulted in a reduction in the available area of shallow water between 4000 and 7000 m^3/s, and even after 3 freshet cycles the total area of high bar habitat had not recovered to its original pre-scalp extent.

2. *In general, the removal volume at a site should not exceed the best estimate of local gravel deposition in a year of mean annual flood discharge (derived from volumetric or sediment transport estimates). This is to ensure that physical changes to a site fall within the range of change that might be observed at a non-removal site in a large freshet.*

The impacts of bar scalping on the juvenile fish community and benthic invertebrate community were relatively short-lived. These results are not in themselves surprising given that approximately 285,000 m^3/yr of material is recruited to the gravel reach downstream of Agassiz, and an additional 2-3 million m^3/yr of material is redistributed locally (Church et al. 2001). Freshet therefore represents a major physical disruption on an annual basis to which organisms residing in the gravel reach are habituated. In comparison, the removal of 70,000 m^3 from lower Harrison Bar was relatively modest. Within the vicinity of Harrison Bar, gravel deposition in the past 15 years has averaged between 65,000 m^3/yr (based on gravel transport estimates; Figure 19 of Church et al. 2001) and 112,800 m^3/yr (based on volumetric calculations for gravel only; Table A2 of Church et al. 2001).

Underwood's (1993) prediction that populations residing in highly variable environments are resilient and can recover rapidly from disturbances appears to apply for the one-time gravel removal at Harrison Bar. The modest volume of gravel removed from a site that is geomorphologically favourable for sediment recruitment probably helped to achieve this goal at Harrison Bar. We recognize, however, that the improvement in habitat diversity after scalping may have been fortuitous. In other circumstances, post-scalp sedimentation might have sustained or even further simplified the topography, with consequent impacts on habitat quality and the abundances of animals.

3. *The haul road surface should be mechanically scarified once a removal operation is complete and prior to freshet.*

A location where the impact of gravel mining at Harrison Bar was less transient was along the road surface. It was left hard-packed after bar scalping and consisted mostly of fine, crushed gravel. Areas of road surface, compacted and blanketed with sand, remained discernible from photographs taken after two freshet events since scalping.

4. *It is important to preserve bars within the gravel reach exclusively as reference sites to allow for comparisons between scalped and undisturbed reference sites*.

Preserving multiple undisturbed bars as reference sites is absolutely necessary if the impacts of future removals are to be investigated following statistically rigorous methods. Very few gravel bars have escaped gravel removal and the value of these sites for future monitoring studies will increase as the pressure for bar scalping continues to grow.

5. *Future removals should be treated as "experiments" with a structured monitoring program.*

Results of the one-time gravel removal study at Harrison Bar cannot be generalized to all other removal operations within the gravel reach of Fraser River. Further studies are necessary to determine if the patterns of response by the physical habitat, fish, and benthic invertebrates are characteristic of removals at other sites. A monitoring program incorporating physical and ecological observations before and after mining should accompany future removals. Observations should address "structural" attributes of the fish community such as diversity and density, but should also emphasise "functional" attributes of the ecosystem by examining lower trophic levels and the energy base on which fish depend.

There is potential for this study to be used in conjunction with future removal studies as a time block in a repeated measures analytical framework. Each removal study would serve as an independent replicate for the analysis, allowing conclusions to be generalized beyond the site-scale to a larger area of the gravel reach. Such a design is more rigorous than asymmetrical ANOVA because the treatment effect is replicated. Prior consultation with a statistician is recommended to formulate the experimental framework and estimate the power of such a design to detect treatment effects at different levels of replication. Measures of variances estimated in this study will be useful in the early planning stages of future studies to determine the necessary sampling effort for a desired level of statistical power.

6. *When the goal of a monitoring program is to examine mining impacts using statistically rigorous methods, due consideration must be given to the timing of permit approval to allow necessary pre-scalp samples to be collected.*

The effectiveness of this study was limited by the short time period between permit approval and the start of removal operations. It was only fortuitous that sampling had been carried out at Harrison Bar and the three reference sites in August and September 1999, prior to bar scalping, as part of a different study. Typically, proponents interested in gravel mining initiate permit submission only months before scalping is to begin. Time for review by regulatory agencies is often several weeks or months and together, these factors result in an inadequate period for pre-removal data collection. The planning and approval processes must be modified if the desired outcome of a monitoring study is a rigorous statistical analysis of gravel mining impacts.

7. *There remains a need to learn about the ecological and morphological impacts of linear excavations, bar edge scalping, and riffle dredging.*

These techniques have not been evaluated but may be considered in the future for river management.

8. *There remains a need to learn about the cumulative impacts of multiple removals or single but large removals.*

The impacts of multiple removals likely are not simply additive, but rather multiplicative, and may not be immediately detectable. The results of this study should not be generalized to predict the outcome of these scenarios, nor should they be casually applied to others bars in the gravel reach without careful geomorphological consideration.

4.5 Sampling Recommendations

4.5.1 Statistical Power

Statistical power is a well-established concept (Zar 1984) that is being applied increasingly for studies in which the results have important implications for the management of fisheries or other natural resources (Peterman 1990). It is most appropriately carried out before initiating a study as a means to determine the necessary sampling effort for a desired level of power, given knowledge of the system's natural variance. Similarly, it can be used to solve for the minimum detectable effect size when the feasible sample size and natural variance are known. These applications of power analysis are highly useful in the planning of studies to ensure that resources are allocated most appropriately for data collection. The estimates of variance yielded by our study may be useful in this regard for future studies in the gravel reach of Fraser River.

Power analysis also can be used to interpret a statistical analysis of previously collected data that did not detect a difference among groups (as was done in this study). This application is termed retrospective power analysis, and has received strong criticism from some authors (Thomas 1997, Lenth 2001). The basis for these criticisms is that as the p-value increases, retrospective power analysis will decrease because it is simply a transformation of the p-value. It is argued that retrospective power calculations add no new information to an analysis, except to rationalize a non-significant result when it is not expected (Lenth 2001).

Despite these criticisms, we chose to calculate power for those analyses in which an impact due to bar scalping was not detected in order to help differentiate between a strong null-result and an analysis with low probability of revealing an effect. This application is of particular use to managers needing to make decisions and formulate policies based on study results. We believe that the low power values obtained for some analyses do not undermine the results of the asymmetrical ANOVA, but instead serve to reveal a high level of variance in the parameter being analyzed. This is because power is inversely related to the amount of residual variance unexplained in the analysis (see Appendix **E**).

The results of power analysis for the various fish metrics examined by asymmetrical ANOVA indicated low power when all habitats were pooled (0.08 to 0.37). Power was further reduced when sample size was lower and only bar edge habitat units were analyzed (0.001-0.09). These results indicated a large amount of variance in the data, both in space and time, relative to the amount of sampling effort. Natural variability inherent to fish distributions may reduce statistical power to detect impacts due to bar scalping (or due to another factor) without very great sampling effort. We expect that greater replication (larger number of beach seines at a site during each sampling episode) and a greater number of sampling episodes *before* gravel mining would have helped to better estimate the natural variance and thereby increase power to detect an impact.

Power to detect an impact was substantially higher for the analyses of benthic invertebrate metrics, ranging between 0.54 and 0.67 for bar edge units and 0.23-0.49 when all habitats were pooled (in contrast to fish results). Statistical power was also relatively high for the analysis of common taxon abundances (0.07-0.79). Because the distribution of invertebrates is also highly variable in space and time, we speculate that increased sampling replication would have improved statistical power to detect an impact. Sampling effort for invertebrates, in particular, comes at a high cost because of the laboratory processing time. Hence, desired statistical precision and the cost of laboratory processing time are conflicting but important factors to consider for future monitoring studies.

The most effective sampling strategy (i.e., the strategy that returns the most discriminating results for a given overall level of effort) will depend on the temporal and spatial structure of variance in the data. We briefly explored the properties of one variable analyzed by asymmetrical ANOVA to help establish a suitable sampling strategy for future studies given the high natural variance in Fraser River data. We chose to examine *invertebrate taxon richness* because no impact was detected and statistical power was approximately average. As well, a decline in richness at Har-S was noted immediately after scalping.

First, we simulated an increase in the effect magnitude in April 2000 immediately after scalping by systematically reducing taxon richness. Asymmetrical ANOVA was run three times, each time with taxon richness reduced at Har-S only (original values were successively reduced by a factor of 1 for three analyses from an average of 3 taxa/sample to 0 taxa/sample). Power increased from 0.23 (original), to 0.40 (minus 1), 0.65 (minus 2), and 0.84 (minus 3) based on the simulated data. The significance of each analysis was similar (no short-term impact detected), however, the power to detect an impact was substantially increased by an increase in effect magnitude.

Second, we examined the effect of an adding a fourth reference site to the analysis. Data from Calamity Bar were used because the site had been included in all monitoring activities. The additional reference site increased statistical power only marginally, from 0.23 to 0.31, based on original data. When both effect size was increased (as described above) and four reference sites were included, power substantially increased: 0.52 (minus 1), 0.76 (minus 2), and 0.91 (minus 3).

We also ran an analysis based on hypothetical data provided by Underwood (1993) to examine the effect of an unbalanced number of sampling episodes before and after the impact. Underwood's original data included an equal number (four) of observations collected before and after a simulated disturbance. We randomly eliminated two sampling episodes before the disturbance and power was virtually unchanged between the balanced and unbalanced sampling design. The variance among replicates in the example was lower than for Fraser River samples, but the exercise is nevertheless instructive because it suggests that our unbalanced design was not fatally weakened.

Collectively, these exploratory results suggested that when large-scale (i.e., bar to bar) spatial variability is great, the addition of another reference site may not improve resolution greatly. An additional reference site will improve power, however, when the effect size is very large. We expect that when there is high temporal variability, the addition of one or two sampling episodes may not greatly increase resolution. In such cases, it is probably most efficient to increase sample replication at each site in order to improve as much as possible the estimates of mean values, hence improving the ability of the analysis to distinguish among them. In this study, fewer post-scalp sampling periods and an increase in sample replication during each period may have improved overall statistical power. Of course, such insights can only be drawn once knowledge of the system's natural variance has been gained.

4.5.2 Minimum Sampling Recommendations

Substantial sampling effort and expense were undertaken for this study both in field data collection and laboratory processing time. This amount of effort may not be realistic for the monitoring of future removals; therefore, the following recommendations are made as *minimum* sampling requirements. If a statistically rigorous analysis is desired, we recommend consultation with a statistician to ensure that sampling effort will be adequately distributed given the natural level of variance quantified in our study.

- At least two reference sites undisturbed by bar scalping and other unnatural factors, and subject to the same flow conditions, should be included in all monitoring activities and sampled simultaneously with the removal site.
- At least two, and preferably three sampling episodes should be scheduled prior to gravel removal. These episodes should be spaced apart in time (preferably chosen at random) to ensure independence. Consideration should be given to the timing of key life cycle events (late winter for invertebrates emerging and spring/summer for fish rearing) to ensure that the animals of interest are present in the system. The same or greater number of sampling episodes should take place after the removal operation is complete. It is not necessary that the number of episodes matches with pre-impact sampling, but it may be desirable to match the timing of sampling episodes before and after impact. Post-removal sampling should extend over a minimum of one freshet cycle, and preferably one above-average freshet event, when the greatest degree of physical and biological change is likely to occur.

<u>Biological Sampling</u>

- Collect benthic invertebrates using a consistent and standard sampling technique (e.g., Surber net or kick net). Sample from only one habitat type or stratify effort equally among habitat types to minimize habitat-specific variability. Collect samples in groups of six replicates at a given location due to the inherent variability of invertebrate distributions. Taxonomic identification to family is adequate for most analytical purposes.
- Sample juvenile fish using a consistent technique (preferably by beach seine). Stratify effort by habitat type and collect a minimum of ten replicate samples from each sample unit during sampling episodes. Accurate catch estimates will require substantial effort due to the mobility of fish and habitat-specificity of their distributions. Additional sampling effort is recommended if budget allows.

<u>Physical Habitat Sampling</u>

- The grain size distribution of surface sediment should be characterized within the removal area and one reference area before mining and after one freshet, according to the Wolman or photographic method (Church et al. 2000). Sediment sampling should be carried out within identifiable sedimentary units at each site and these units categorized for each set of samples taken.

- Habitat mapping of the removal site should take place before and one freshet after mining at similar discharges. Mapping over a range of discharges is desired and should include at least one date of above average mean annual discharge (>3000 m^3/s). Mapping can be carried out by ground surveys or photographic analysis by a trained technician.
- Concurrent with fish sampling, descriptive information on habitat characteristics should be collected at fish sampling locations. This information should include surface sediment texture, embeddedness, near-shore and off-shore water velocity and depth, and bank slope.