Analysis of Sedimentation and Sediment Mitigation Strategies for Mission Creek

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"*The design process is most challenging when the project reach is unstable due to straightening, channelization, or changing hydrologic or sediment inflow conditions"*

(Shields et al. 2008)

i. Executive summary

The Mission Creek channel as it flows through the city of Kelowna is highly disturbed by channelization. High sediment loads in Mission Creek have the potential to damage fish restoration works proposed for the channel. Therefore, a study of sedimentation, the causes of sedimentation and mitigation of sedimentation within Mission Creek was conducted.

This report investigates the spatial and temporal patterns of sediment deposition in Mission Creek. An analysis of the frequency and intensity of large flows that transport the sediment was conducted. An analysis of the long profile and grain size pattern from the exit from Ghallaghar's Canyon to Okanagan Lake is presented. An analysis of 18 reaches in Mission Creek was conducted. These reaches were grouped into natural, channelized, sedimentation, and downstream sections for interpretation. Mission Creek displayed a braided or wandering channel pattern on a 1938 orthophoto. Therefore, each reach was assessed to determine if it had the same energy and grain size characteristics as a braided or meandering river channel. The restoration plan presented by Gaboury and Slaney (2003) and Gaboury et al. (2004) is reviewed in light of the new analyses. Recommendations are presented in the final section.

Sedimentation downstream of KLO Bridge has been a significant problem since at least 1967. Since 1990, sediment has been extracted from Mission Creek downstream of KLO Bridge three times (1990, 1997, and 2006). The average time between sediment extractions to maintain channel capacity during this period is every 8 years. Since 1937, large flow events have occurred every 6.4 years on average, with recent large flows occurring in 1986, 1990, 1997, and 2006.

The analysis contained in this report yielded a number of recommendations for the mitigation of sedimentation and the restoration of Mission Creek. The setting back of dykes to form a floodplain within the new dyke location to improve the geomorphic and ecological functioning of the river is sound. Land should be purchased where possible to allow for the setback of the dykes.

Three reaches showed potential for degradation and release of sediment from the channel bed. Where and if degradation is occurring needs to be determined. This could be determined through a sediment budget for Mission Creek. One way of calculating a sediment budget is using appropriate software such as SAM Design Package for Channels as recommended by Shields et al. (2008).

Once the sediment budget of the channel has been determined, the appropriate channel design methodology should be used. If the channel is shown to have an active bed, channels should be designed using the active bed method (Shields et al. 2006). If possible a channel should be designed to transfer the sediment supplied to it so that aggradation or degradation do not occur.

The option of designing a braided or wandering channel upstream of the KLO Bridge should be explored as a number of the reaches within this section displayed energy and sediment characteristics within the transition between meandering and braiding.

The channel downstream of the KLO Bridge could be used as a sediment trap to contain sediment from upstream. If the overall channel design for Mission Creek cannot accommodate the amount of sediment supplied to the channel, this section can be used as

a sediment trap to protect downstream restoration works. The advantages of using this location as a sediment trap are that it already traps sediment, is already disturbed by excavation and is easy to access from a main road.

Within the downstream section, land should be purchased to set back the dykes. If possible, a channel should be designed to carry the sediment supplied to it from upstream using the active bed method if the channel bed sediment is mobile (Shields et al. 2008). The approach to channel design outlined in Gaboury and Slaney (2003) is appropriate if the channel is found to be a threshold channel with little sediment movement according to (Shields et al. 2008).

ii. Table of contents

iii. List of tables

iv. List of figures

v. Acknowledgments

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Funding for this project was provided through the Okanagan Water Board. The Mission Creek Habitat Restoration Project involves a partnership (Restoration Working Group) that presently includes BC Ministry of Environment (MOE), the City of Kelowna, Central Okanagan Regional District (CORD), Okanagan National Alliance (ONA), Westbank First Nation, Department of Fisheries and Oceans Canada, the Friends of Mission Creek and the Central Okanagan Land Trust. The primary objective of the Working Group is to implement restoration projects on Mission Creek.

1. Introduction

Mission Creek is a highly disturbed river system flowing through Kelowna B.C. There are a number of serious management problems associated with the creek. Two of the most important problems on Mission Creek are habitat degradation and channel bed stability (specifically sedimentation). To address the habitat degradation of Mission Creek a working group was formed. The Mission Creek Habitat Restoration Project involves a partnership (Restoration Working Group) that presently includes BC Ministry of Environment (MOE), the City of Kelowna, Central Okanagan Regional District (CORD), Okanagan National Alliance (ONA), Westbank First Nation, Department of Fisheries and Oceans Canada, the Friends of Mission Creek and the Central Okanagan Land Trust.

Mission Creek has been heavily modified through narrowing of the channel by the building of dikes for flood control from East Kelowna Bridge to the river mouth at Okanagan Lake. The channel narrowing has modified the channel pattern, hydraulic patterns, bed sediment patterns, and energy levels within the channel at bankfull flows and above. These changes have decreased the fish habitat value for important species such as Kokanee and Rainbow trout (Gaboury and Staney 2003). However, the changes to the river channel have also disrupted the natural sediment transport patterns within the river. Of particular concern is sediment deposition occurring at and downstream of the KLO Bridge.

In 2003, the feasibility of restoring the habitat on Mission Creek through river restoration was completed (Gaboury and Slaney 2003). This report provides a well reasoned argument as to why the habitat within Mission Creek should be restored. They note that the Mission Creek channel has lost natural fluvial geomorphic processes and patterns (riffles and pools, meanders and sediment sorting), connection to the floodplain and wetlands, fish spawning and incubation habitats, diverse fish rearing habitats, diverse overwintering habitats, and fish refuge from high velocity water (Gaboury and Slaney 2003). The report also assessed the feasibility of returning the creek to a more natural state through setting back the dykes to widen sections of the river, constructing riffle-pool sequences, and realigning portions of the channel to a more meandering route. In 2004, a follow up report provided a detailed feasibility study of habitat restoration on Mission Creek (Gaboury et al. 2004).

Mission Creek is the most important spawning tributary for Kokanee and Rainbow trout on Okanagan Lake and its restoration is critical to the recovery of the sports fishery and overall system health. A restoration program involving set-back dyking, re-meandering of the river channel, and installation of sediment control measures has been outlined in Gaboury and Slaney (2003). Current sediment control recommendations however do not include a complete analysis of bedload quantities, cost effectiveness, feasibility and long- term benefits to the aquatic and riparian habitats.

There are a number of important factors in assessing sedimentation within a river system. One important factor driving sediment transport and deposition is the frequency, magnitude and duration of flow events capable of transporting and depositing sediment. Other important factors include the shape of the long profile because it controls the channel slope, channel energy conditions and, in part, the sediment transport rate. The grain size on the bed is another important factor that controls the sediment transport rate and can indicate bed stability (degradation or aggradation).

During the summer of 2007 and the summer and fall of 2008 channel surveys and grain size measurements were made on Mission Creek by Okanagan College students working as research assistants. Two students (Zoe Masters and Erin Courtney) used these data for directed studies courses. This data is used to analyse the long profile and grain size patterns of Mission Creek. Hydraulic and sediment mobility values were calculated from these data. The analysis of these results is very useful in reviewing restoration strategies and recommending sediment mitigation strategies.

This report provides:

- a review of sediment mitigation strategies for Mission Creek
- an analysis of the sedimentation patterns on Mission Creek
- an analysis of the frequency of sediment transport/deposition flow events
- an analysis of the temporal sedimentation patterns on Mission Creek
- an analysis of the long profile of Mission Creek downstream of Gallagher's Canyon to the mouth
- an analysis of the bed sediment grain size pattern of Mission Creek downstream of Gallagher's Canyon to the mouth
- an analysis of the hydraulic, and sediment mobility patterns of Mission Creek downstream of Gallagher's Canyon to the mouth
- an analysis to determine if Mission Creek channels are close to the braiding to meandering threshold
- an independent review of the recommendations for restoration in Gaboury and Slaney (2003) and Gaboury et al. (2004)
- recommendations on strategies to mitigate excessive sediment deposition and restore Mission Creek

1.1. Study site

Mission Creek is situated within the confines of the City of Kelowna. Specifically, the project site is located between the East Kelowna road Bridge downstream to the confluence with Okanagan Lake. The study area was expanded to include the natural section from where Mission Creek exits from Gallagher's Canyon to the East Kelowna Bridge. Mission Creek is a fourth-order stream with 38.9 km of fish-bearing streams. Numerous fish species have been identified in Mission creek including Kokanee, Rainbow trout, Brown trout, Prickly sculpin, Longnose dace and Finescale sucker (Anonymous 1997). Mission Creek has a drainage basin area of 858.8 km^2 and relief of 1829 m, with elevations ranging from 2,171 m at the summit of Little White Mountain to 342 m at the confluence with Okanagan Lake. The average annual total precipitation at Kelowna is 329.7 mm, with approximately 25% falling as snow. At an elevation of 1,250 m at McCulloch near Hydraulic Lake, the annual precipitation increases to 702.6 mm with 52% falling as snow. Approximately the middle of the watershed, at Joe Rich, the annual precipitation is 579.4 mm with 52% as snow (Anonymous 1997).

2. Sedimentation, channelization, and sediment extraction

The three most important impacts on the Mission Creek river system are sedimentation, channelization and sediment extraction. The scientific understanding of these processes and potential management actions will be discussed.

A river channel adjusts to several key factors that determine the river's pattern, size (width and depth), bed grain size and stability. We can think of these factors as driving forces and resisting forces. The driving forces are primarily controlled by channel slope and discharge that drive the energy terms specific stream power (ω), the energy at the channel bed and the shear stress τ_o, the stress applied to the channel bed to move sediment. The driving force in the river channel increases with larger discharge and slope. The resisting force works against the driving force within the river channel to decrease sediment transport. The resisting force is primarily represented by the grain size on the channel bed. Larger grain size material offers more resistance than smaller grain size material. An additional factor is the sediment load or volume of sediment transported experienced by a channel.

Channels are dynamically stable when the discharge and slope are in balance with the sediment load and the sediment grain size (Figure 2-1). Channel bed erosion (degradation) occurs when the driving forces become larger than the resisting forces. Channel bed deposition (aggradation) occurs when the resisting forces become larger than the driving forces.

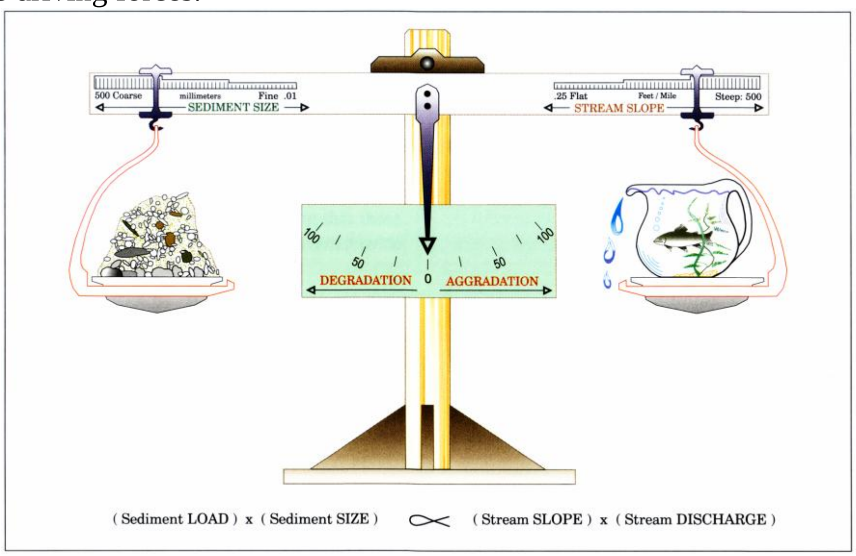


Figure 2-1. The bed of a river is the balance of river forces (From Lane 1957).

More specifically, the bed of a river is stable (in grade) when the amount of sediment entering a reach exactly equals the amount exiting the reach (Figure 2-2). When the sediment discharge Qs (m^3/s), the total amount of sediment transported downstream passed a channel cross-section, is constant downstream, the bed elevation will remain stable. Usually this occurs where the average bed slope, width and depth are constant downstream. The river channel has reached equilibrium with the present conditions.

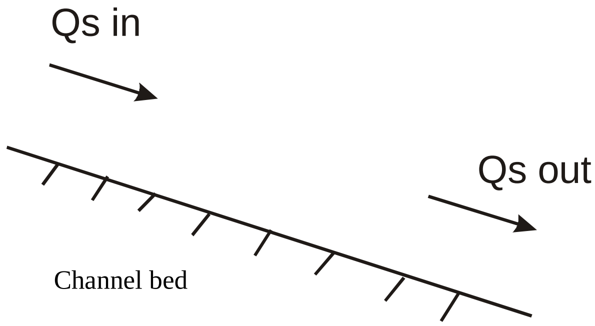


Figure 2-2. Downstream sediment discharge patterns for a stable river bed (Qs in = Qs out). Qs (m^3/s) is the sediment discharge; the total amount of sediment transported downstream passed a channel cross-section.

A river system can be thought of as a simple conveyor belt with sediment being supplied from an erosion zone in the mountains (Figure 2-3). The supplied sediment is transported through the river system through the transfer zone. Finally, sedimentation occurs downstream in the deposition zone. It is important to note that all three processes occur in each zone. That is that erosion, transfer and deposition of sediment occur in each zone but a single process dominates over the others.

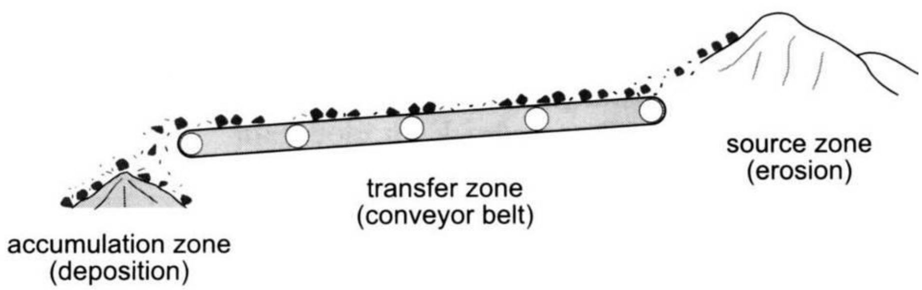


Figure 2-3. Simple model of a river system with three zones (From Brierley and Fryis 2005).

It is important to understand how sediment is supplied to a river channel for proper river management. For Mission Creek the sediment is supplied in the mountains from the valley sides through which Mission Creek flows. It should be noted that although sediment is being transported downstream in the sections upstream of the East Kelowna Bridge, sediment input and the interaction of the channel with the valley walls control channel processes. Sediment is supplied to the Mission Creek channel by natural landslides and extensive bank erosion by the creek channel itself upstream of Pearson creek (Anonymous 1998). The landslide hazard on Mission Creek has been rated as high (Anonymous 1998). A large number of landslides (95) have been identified as active or in-active within the watershed. These landslides are thought to be natural and ongoing since deglaciation and not due to logging activities because approximately 75% of the landslides occurred in unlogged portions of the watershed. The report recommended that since the majority of the landslides were natural and likely to reactivate, that no remediation efforts be conducted (Anonymous 2000). It is clear that minimizing the input of sediment from the upper basin would be difficult because the landslides producing the sediment are natural and distributed throughout the system.

The main transportation zone on Mission Creek occurs between where the channel curves south downstream of the East Kelowna Bridge and KLO Bridge. The section begins where the Mission Creek channel leaves the confinement of the valley and therefore there is no further input of sediment from the valley walls.

Another sediment source within the transportation reach is the channel banks and the channel bed. Sediment may be added to the channel as it migrates laterally. However, it is most common that sediment is deposited on point bars at an equal rate to compensate for the bank erosion. This maintains the channel width.

An additional source of sediment within the transfer zone is the channel bed. The erosion of the bed (degradation) can release large volumes of sediment. This occurs when the channel energy to transport sediment exceeds the amount of sediment entering the river reach or when the amount of energy is great enough to break the armour layer of larger sediment that forms and protects finer material underneath.

The deposition zone for Mission Creek occurs near Okanagan Lake. This area is nearest the delta downstream of KLO Bridge. Generally, the deposition of sediment within the depositional zone will cause the elevation to build up over time. This causes the slope of the river to decrease and the deposition to intensify. This may cause the channel to switch locations periodically when there is a higher slope route for the river to take. In Mission Creek this process has caused the numerous abandoned channels seen in Figure 2-10 and discussed in a later section.

2.1. Sedimentation

Sedimentation occurs when there is a change in the sediment transport capacity within a river. This means that the sediment discharge entering a river reach is greater than the amount of sediment exiting the reach (Figure 2-4). This often occurs when the channel bed slope decreases abruptly. The decrease in slope decreases the specific stream power which cause the sediment transport rate to decrease and sedimentation results. It may also occur where a channel widens, causing the specific stream power and shear stress to decrease.

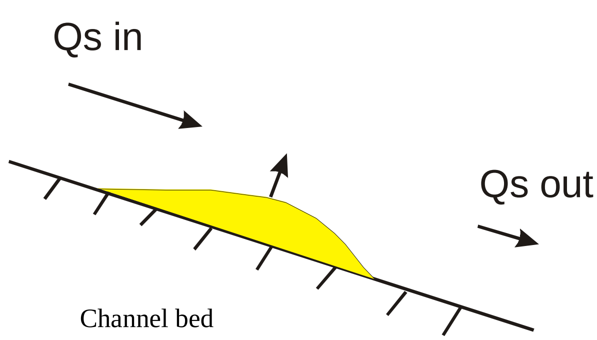


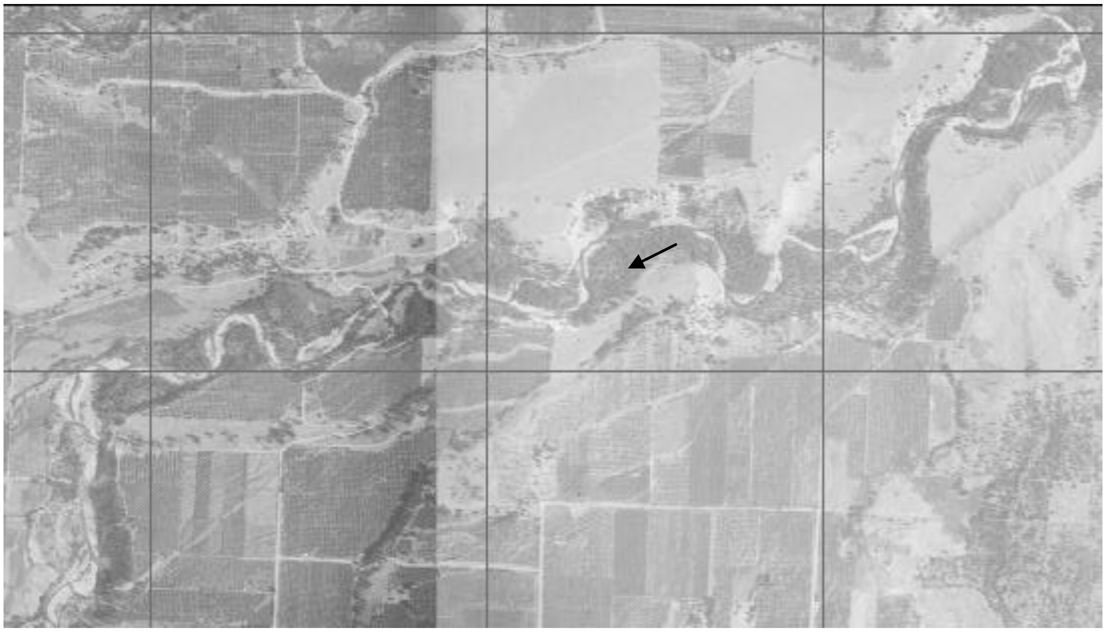
Figure 2-4. Downstream sediment discharge patterns for an aggrading river bed (Qs in > Qs out). Qs (m^3/s) is the sediment discharge; the total amount of sediment transported downstream passed a channel cross-section.

Generally, coarse bed sediment is supplied to the river bed from landslides, the erosion of channel banks as rivers migrate or the erosion of the channel bed during degradation. Sedimentation within the channel can also occur downstream of a major input of sediment to a river channel. Landslides, tributary channels, upstream bed degradation or placer mining can cause major sedimentation within the channel.

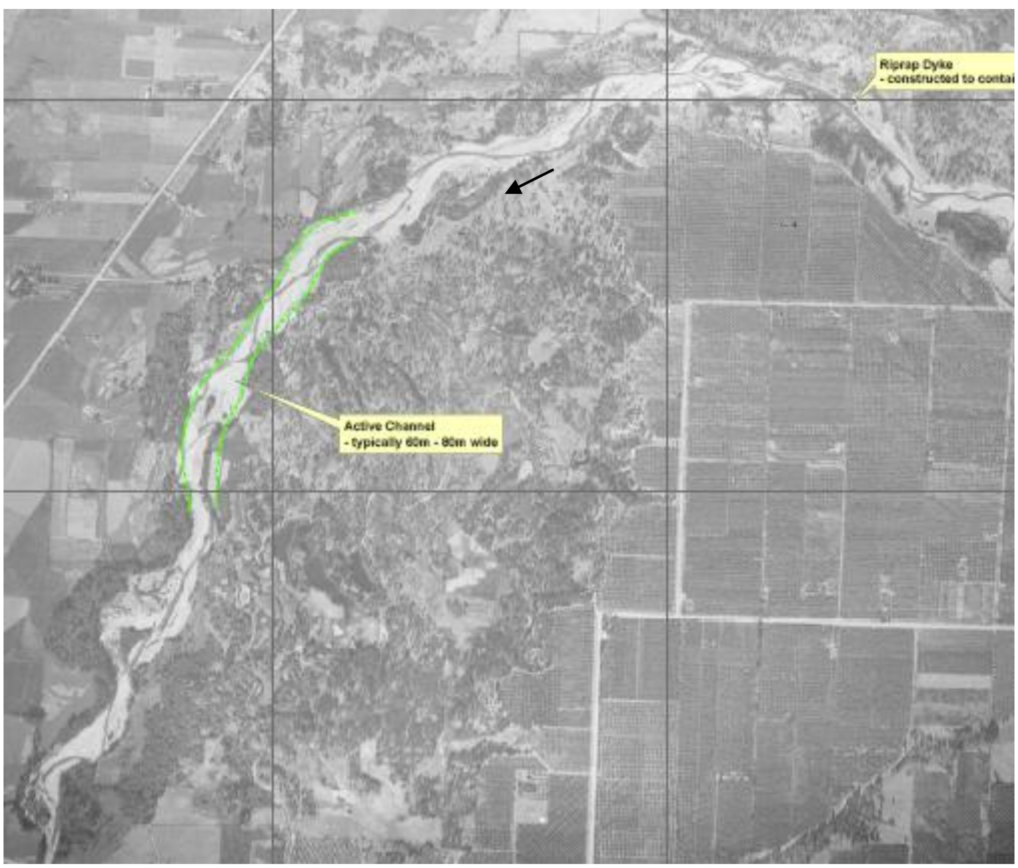
2.1.1 Sediment deposition patterns in Mission Creek

A historical analysis of sedimentation patterns on Mission Creek was conducted using aerial photographs. Mission Creek displayed many changes during the historical period. Much of Mission Creek displayed a braided pattern in 1938 (Figure 2-5). The braided section began near Gallagher's Canyon and ended 750 m downstream of the KLO Bridge. The channel was wide (~80 m) and surface gravel and in-channel bars can be seen (Figure 2-5 AB). Braided channels indicate high sediment transport rates, active channel bars and in-channel deposition of sediment. Sediment is stored within the channel as gravel bars.

Placer mining occurred in Mission Creek around the early 20th century. These mining operations would have produced a large supply of gravel to Mission Creek. Some of these mine works can be seen today near where Mission Creek exits from Gallagher's Canyon. A large input of gravel to a channel from placer mining can change the river pattern from meandering to braided by overloading the channel with sediment, causing the deposition of the mid-channel bars that define the braided pattern. The extra sediment supplied to the Mission Creek channel due to placer mining would have changed the character of the creek. However, it is impossible to tell from the 1938 orthophotographs whether the braiding in the Mission Creek channel is natural or due to the sediment released by placer mining.



A.



B.

Figure 2-5. 1938 Mission Creek Channel displaying the (A) upper section downstream of Gallagher's Canyon, and (B) the middle section that is currently dyked.

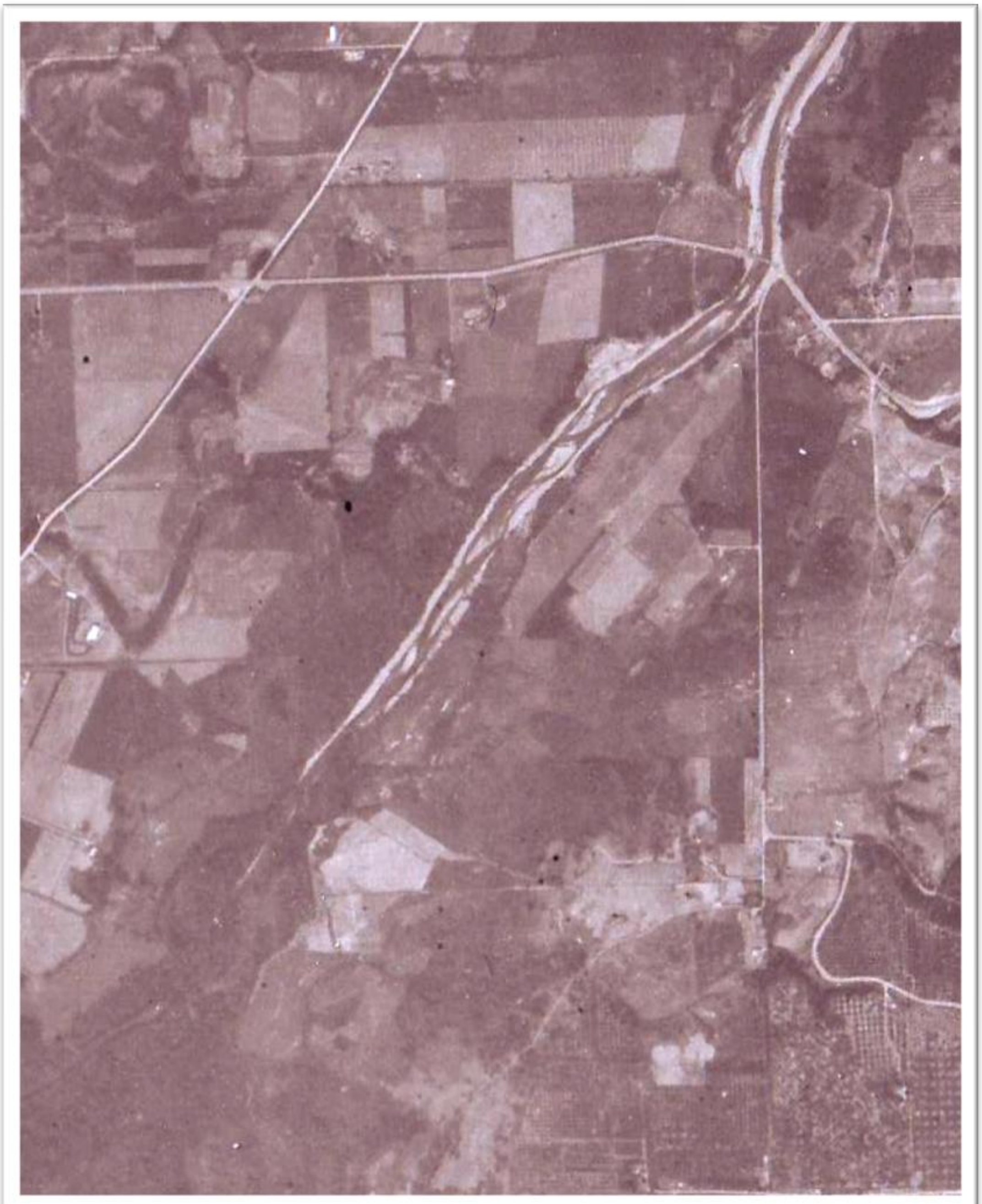
The section of channel just downstream of KLO Bridge is a location of significant sedimentation and gravel extraction and is therefore a focus of this study. The history of this section was investigated in detail using aerial photography from 1938, 1951, 1963, 1973, 1986, 1996, and 2006 (Figure 2-6 A-G).

In 1938, the channel from KLO Bridge to 750 m downstream was unconfined and up to 120 m wide (Figure 2-6A). The channel displayed a braided pattern with numerous in channel bars and several smaller wetted channels at low flow. The stream bed was covered by bar surfaces. Upstream of the bridge also displayed a wide braided channel. At 750 m downstream of the bridge the channel narrowed to 32 m into what appeared to be dykes that were already constructed. By 1951 the dykes can be seen beside the channel, narrowing the channel to 50 m (Figure 2-6B). Six in-channel bars are clearly visible within the channel at this time. In 1963, the channel continued to display five channel bars within the KLO Bridge section (Figure 2-6C). In 1973, the section had six mid-channel and lateral bars (Figure 2-6D). The channel in 1986 had five mid-channel bars (Figure 2-6E). The number of bars had decreased to four in 1996 (Figure 2-6F). In 2006, the number and size of the mid-channel bars had been greatly reduced by the gravel extraction (Figure 2-6G).

This analysis indicates that the Mission Creek channel downstream of KLO Bridge has been a location of significant sedimentation since at least 1938. In 1938 much of the Mission Creek channel was significantly wider than it is currently, however, the section below KLO Bridge was wider than average even at that time. Channels are generally wider where sediment is deposited. The gravel bars force flow to each side causing the channel to be shallower and wider. The channel has narrowed significantly in this section due to the construction of the dykes. The unconfined channel reached a maximum of 120 m in width in 1938. The channel was narrowed to ~50 m through dyking and this has decreased to ~30 m in 2006. The channel remained ~50 m from when the dyking was completed in 1951 until sometime between 1973 and 1986 when the channel narrowed to ~ 35 m. This may be associated with the in stream works that were conducted in 1981 and 1985. In 1985, 5350 m^3 of gravel was side cast within the channel. This could account for some of the channel narrowing. If this gravel was pushed to the side of the channel to a depth of 1 m for 750 m downstream of KLO Bridge it would narrow the channel by 7 m. The channel width would therefore decrease from ~50 m to ~43 m.

A. 1938

B. 1951



C. 1963

D. 1973

E. 1986

F. 1996

G. 2006

Figure 2-6. Aerial photographs of reaches number 14 and 15 for (A) 1938, (B) 1951, (C) 1963, (D) 1973, (E) 1986, (F) 1996, and (G) 2006.

In 1938, the channel changed from braided to a single channel at 750 m downstream of the KLO Bridge (Figure 2-5). It appears that the channel enters dykes at this point. These dykes were therefore constructed before 1938. The channel widens slightly (~50 m) again at Casorso Rd Bridge near Okanagan Lake, probably due to sedimentation related to the decrease in the competence of the water to carry sediment due to the decrease in slope related to the lake level.

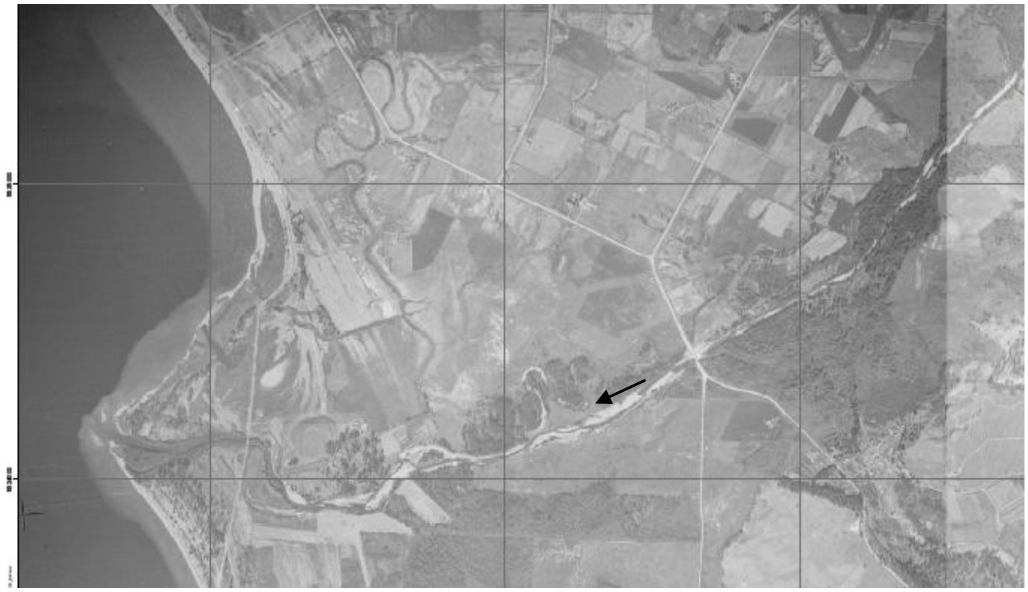


Figure 2-7. 1938 Mission Creek channel displaying the abandoned channels on the floodplain near KLO road. Arrows indicated flow direction.

2.2. Channelization

Channelization has often been used to protect valley floors adjacent to rivers from flooding. Typically river channels are straightened and dyked to maintain flood flows within the channel. Other effects included draining wetlands near channels. Channelization and draining of wetlands have decreased the hydrological connectivity between the river channel and the floodplain. This hydrological connectivity is important for river ecosystem functioning but also effects the erosion potential on the bed. Where channels are dyked the water depth, and also the shear stress exerted on the bed, increases quickly with increasing discharge. In natural systems where the floodplain is connected to the river the water depth increases quickly until the river overtops its banks. Any additional increase in discharge flows over the floodplain. Because the water is flowing over the floodplain, water depth increases more slowly with increasing discharge. The largest floods are thereby less erosive on the beds when the flood waters are dispersed over a large floodplain.

Straightening rivers causes changes to bed slope. The bed slope increases if meanders are cutoff. Channelization manipulates one or more important hydraulic variables (depth, width, slope, roughness), while feedbacks promote adjustments towards a new geomorphic state (Brooks 1988). This causes the sediment discharge to increase out of the channelized reach while the sediment discharge into the reach stays the same (Figure 2-8). This causes the bed to erode and channel degradation to occur (Brooks 1989, Talbot and Lapointe 2002a, Talbot and Lapointe 2002b). It should be noted that this eroded sediment is transferred downstream where it is deposited.

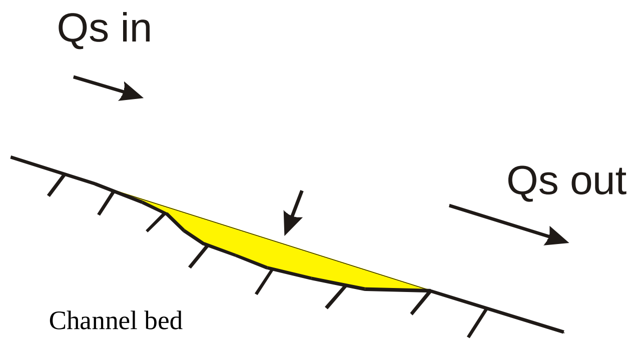


Figure 2-8. Downstream sediment discharge patterns for a degrading river bed (Qs in < Qs out). Qs (m^3/s) is the sediment discharge; the total amount of sediment transported downstream passed a channel cross-section.

Channelization may cause instability in the channelized reach but also upstream and downstream. Impacts are particularly pronounced in response to channel slope modifications or straightening programs that increase local bed steepness and the erosive potential. The channelized section may act as a fulcrum with net degradation upstream and net aggradation downstream (Brierely and Fryis 2005). Degradation tends to be at a maximum immediately upstream of the area of maximum disturbance as the upstream progression of headcuts accentuates unit stream power. Over time armouring may increase resistance and inhibit further bed erosion.

These changes are most dramatic on rivers that carry a significant amount of bedload (Brierley and Fryis 2005), like Mission Creek. Transfer of excess bedload downstream of the area of maximum disturbance may result in accelerated channel aggregation, reducing channel capacity. This secondary response progressively works its way upstream over time. Areas of reduced velocity promote deposition of sediments, and the response times for stabilization and channel contraction may be enhanced by revegetation of sediment stores. Increased flow resistance promotes accelerated rates of sedimentation.

These changes decrease a number of important natural geomorphic features within the river channel. The decreases in these features are summarized in Figure 2-9. Most importantly, channelized rivers become less variable with a decrease in pools, gravel sorting, and cover. The channel becomes more homogenized with riffle like habitat and unsorted gravels.

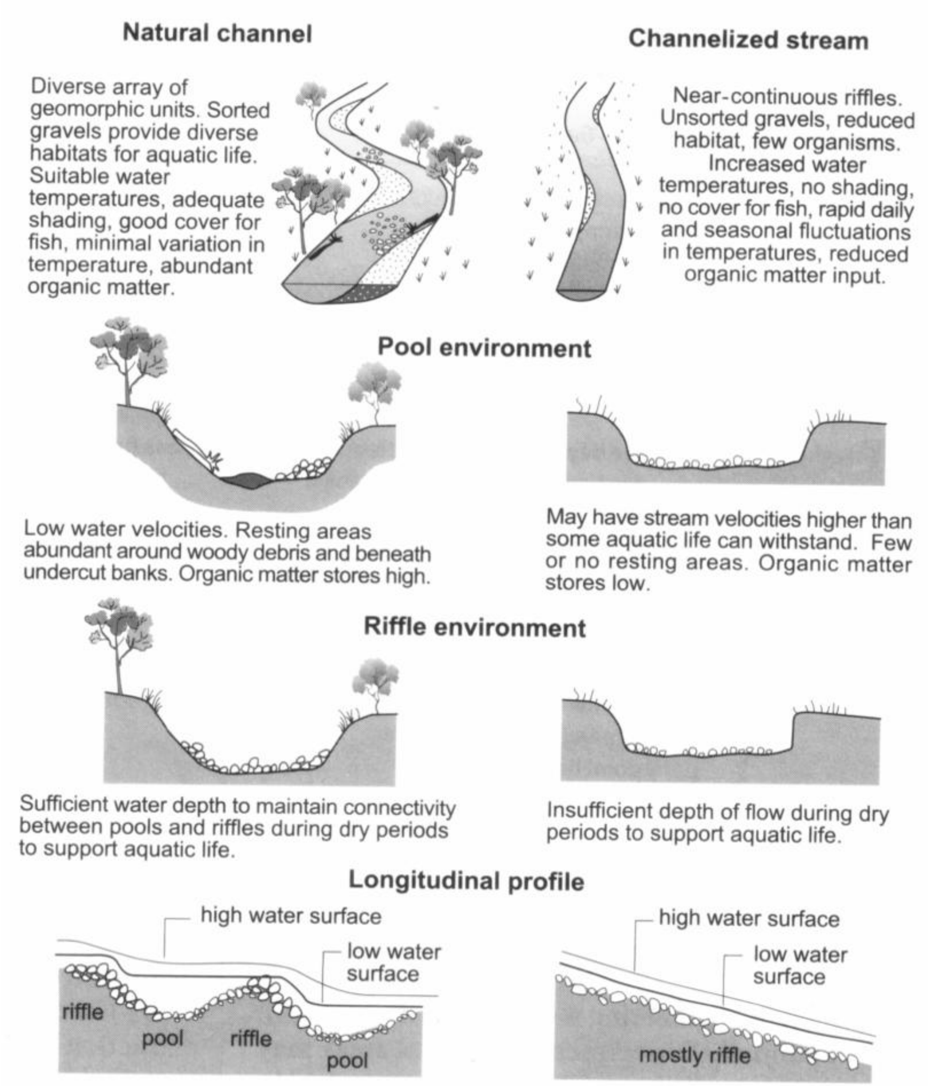


Figure 2-9. Impacts of channelization (from Brierely and Fryis 2005)

2.3. Effect of channelization on Mission Creek

Aerial photographs show that the area that the city of Kelowna is presently located was the active floodplain of Mission Creek at sometime in the past (Figure 2-10). Numerous abandoned channels are present throughout the floodplain. Most of the abandoned channels are very sinuous, indicating that the lower portion of Mission Creek had been a meandering channel. Two of the abandoned channels are seen in the 1938 orthophoto map (Figure 2-10). The youngest of these abandoned channels located closest to the active channel (A) displays a sinuosity (P = channel length/valley length) of 2.4 (Figure 2-10). This abandoned channel connected to the present channel just downstream of KLO Bridge before being cut-off. This suggests that this section was recently active. An older abandoned channel (B) located further north of KLO road has a sinuosity of 1.8 Figure 2-10).

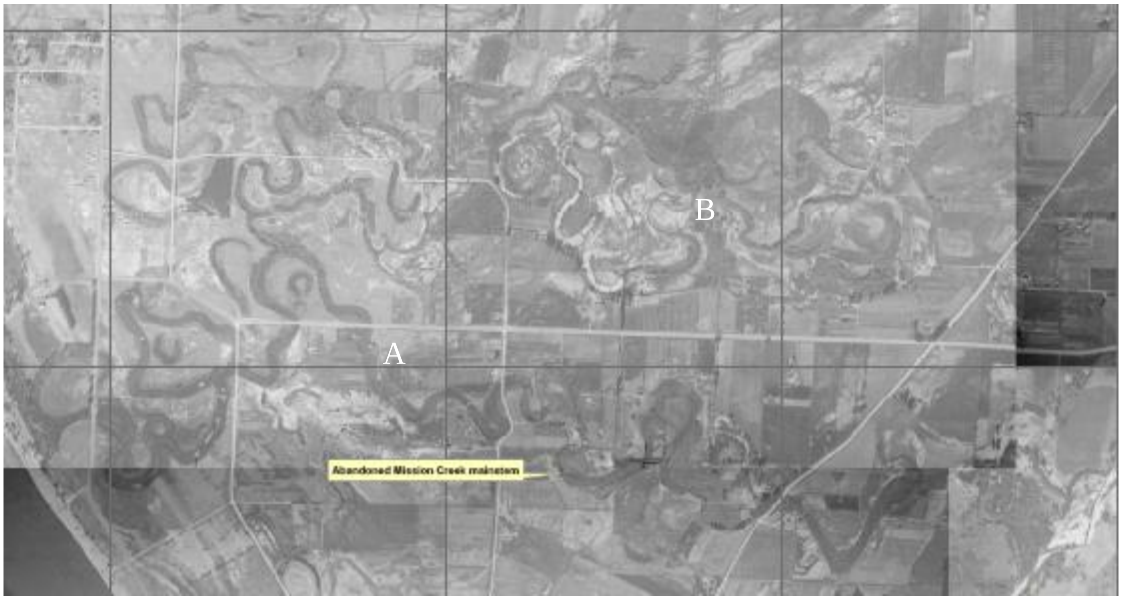


Figure 2-10. The 1938 Mission Creek channel displaying the floodplain containing numerous abandoned channels near KLO Road.

Historically, the Mission Creek floodplain linked more closely to the riparian and channel hydrological system. From the aerial photographs it appears that the floodplain was connected to the channel at this time. For example, paleochannels can be seen in the floodplain near the location where Mission Creek leaves its valley and flows towards the lake. This indicates that the floodplain and the channel were at similar elevations at that time. Currently, the channel bed is significantly below the level of the floodplain in many areas. When the floodplain and channel are at similar elevations, during floods water flows over the floodplain thereby decreasing the water depth within the channel. Having an active floodplain decreases the shear stress and stream power within the channel during floods. This increases the stability of the channel bed and causes the deposition of finer gravel size sediment on the channel bed.

The effect of channelization on the slope and grain size patterns and hydraulic conditions within the channel are discussed in section 4.

2.4. Gravel extraction

Gravel extraction has several unintended and problematic consequences. Gravel extraction can take the form of instream mining where sediment is extracted from instream bars and bed surfaces or open floodplain pits. In many instances, sediment extraction has been applied without due regard for sustainable rates of bedload transport. By removing sediment from the channel, the pre-existing balance between sediment supply and transport capacity is disrupted, basically interrupting the downstream conveyor belt. A summary of the processes that occur when sediment is extracted from a river channel is presented in Figure 2-11.

Before extraction, the river is stable and the bed is armoured by larger sediment (Figure 2-11). The rivers' sediment load and the forces available to transport sediment are balanced through the reach (Figure 2-2).

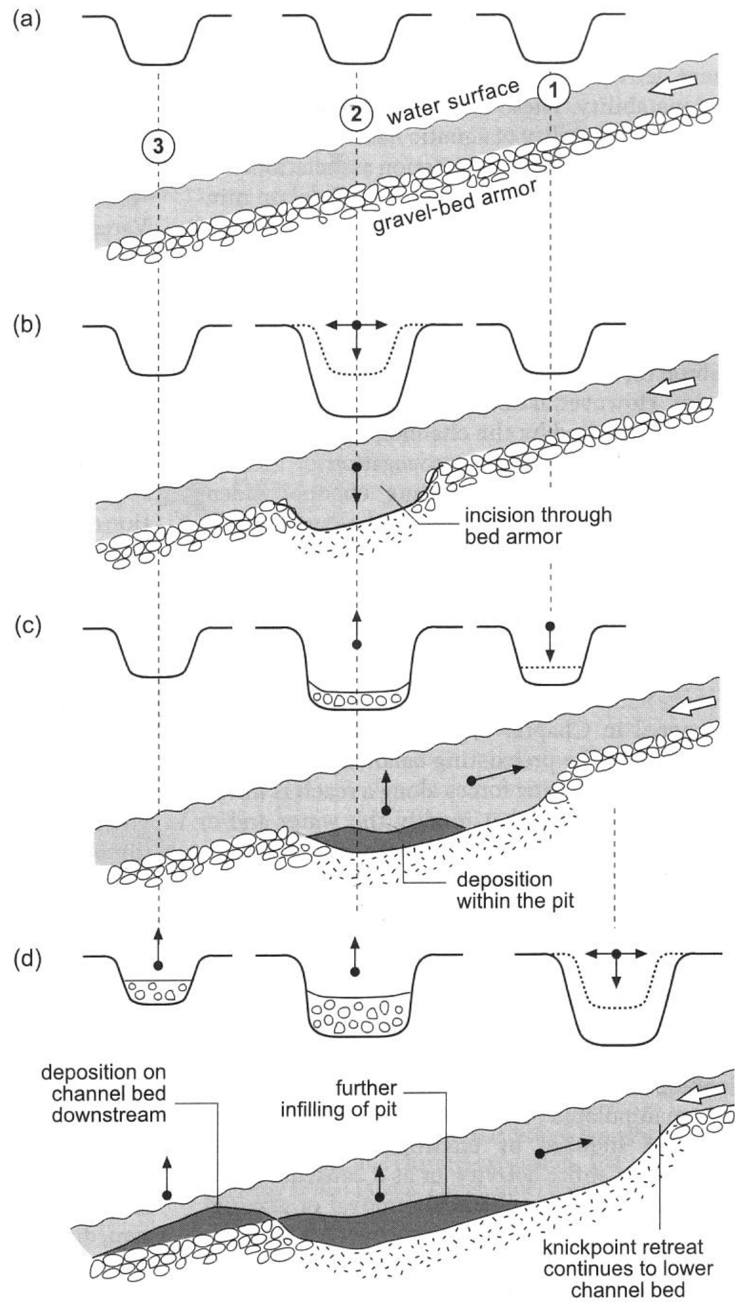


Figure 2-11. Impacts of instream gravel extraction (From Brierley and Fryirs 2005).

Gravel extraction both decreases and increases the channel bed slope. Typical responses include lowering of the stream bed, local increase in slope and flow velocity upon entering the pit and adjustments to channel geometry. The increase in slope at the beginning of the pit causes bed erosion (degradation) adding an additional sediment load downstream (Figure 2-11b). Extraction of gravel causes a pit in the river bed and breaks armour layer. Once bed armour is destroyed, enhanced bed scour may generate a head-cut in the over-steepened reaches and hungry water erodes the bed downstream (Kondolf, 1997). Within the pit, sediment is initially trapped, interrupting the transport through the reach. Downstream, the river maintains the capacity to transport sediment but the sediment load into the reach has been decreased.

The increase in slope at the beginning of the pit causes degradation to occur upstream (Figure 2-11c). Hungry water erodes the downstream end of the pit, as incision expands both upstream and downstream. Sediments are released from the bed upstream of the pit due to the degradation of the channel from the upstream progression of the head-cut and associated channel expansion (Figure 2-11d). The sediment may continue to deposit downstream of where the gravel extraction occurred (Brierely and Fryis 2005).

As explained above, sediment extraction from a river channel promotes channel deposition within the pit caused by the extraction and causes erosion upstream of the extraction, causing the release of more sediment from the channel bed to be deposited downstream. Channel degradation causes an increase in the bed grain size and increases armouring. This decreases the amount of spawning habitat for Kokanee. Degradation also can cause a decrease in the number of riffles and pools within the channel, further simplifying the habitat. Where possible, gravel extraction should be avoided due to these effects, however once gravel extraction has begun enhanced deposition will occur. In such a case, gravel extraction may be necessary for flood control if the entire reach is not reengineered to route the sediment downstream.

2.5. Sediment extraction in Mission Creek

Sediment has been extracted from the Mission Creek channel near KLO Bridge to maintain channel capacity for many years. Since 1967, an estimated 93,690 m^3 of gravel has been removed from Mission Creek near KLO Bridge (Table 2-1). The reach downstream of KLO Bridge has had a sedimentation problem for many years. Recently, sediment was extracted from downstream of KLO Bridge in 1990, 1997 and 2006. This represents a major extraction of sediment approximately every eight years. During these three gravel extraction events, 74 500 m^3 of gravel was extracted (Ray Jubb pers com.).

A large amount of gravel (16 590 m^3) was extracted from Mission Creek downstream of the KLO Bridge in 1981. Gravel bars were also removed from Hollywood Road in 1981 but the amount is unknown. Gravel was also extracted from Mission Creek in 1967, however the amount of gravel extracted is not known.

2.5.1 Methods

The gravel extraction records provide us with a rare opportunity to investigate the amount of sedimentation. We first must make a few assumptions. First, we assume that the channel is regraded to the same level following each sediment extraction. Second, each sediment extraction occurred over the same area of the channel bed.

First, the area of the bed where the gravel extraction occurred must be measured. Two variables must be known: the width and the length of the channel where the gravel was extracted. The length of channel where the gravel extraction occurred in 2006 was provided by Ray Jubb (pers com. 2009). The length and the width were measured using Google Earth (2009). The length of channel where gravel was extracted was 2164 m, extending 870 m upstream and 1 294 m downstream of KLO Bridge. The average channel width was 28.3 m. Therefore the total area of sediment extraction was 61 190 m^2.

Table 2-1. Gravel extraction dates and volumes for Mission Creek.

Date	*Distance (m)*	*Volume removed (m^3)*	*What*	*Where*	*Additional comments*
67		??	Gravel removal bed regraded	KLO Bridge??	Approx. 500 000 spent removing gravel, constructing dykes and placing riprap
9-Jun-81	730		Repair section of Dyke	Directly upstream of KLO Bridge	
Aug-81			Gravel bar removal	Hollywood road	
Aug-81	910	16590	Gravel removal bed regraded	U/S KLO Bridge	11240 removed from site + 5350 side cast in channel
Aug-81	300		Gravel removal bed regraded	D/S KLO Bridge	
Sep-85		2600	Scalping of gravel bars	KLO Bridge	
Sep-85			Scalping of two gravel bars	Lakeshore	
Aug-86		??	Scalping of gravel bars	KLO Bridge	
1990		18650	Gravel removal	KLO Bridge	
1997		45300	Gravel removal	KLO Bridge	
2006		10550	Gravel removal	KLO Bridge	
Total		93690			

To calculate an average sedimentation, we divide the volume of sediment by the area that the sediment was extracted from. The total sedimentation rate since 1967 is 1.53 m. That is, since 1967 the channel bed would have risen 1.53 m if the gravel was not extracted from the bed. To obtain an average sediment deposition rate per year we must assume that the same amount of sediment is transported each year. Clearly this assumption is violated during large or small flow events; however the determination of an average rate is valuable.

2.5.2 Temporal sedimentation patterns in Mission Creek

The Mission Creek channel section downstream of KLO Bridge has experienced a total of 1.53 m of sedimentation since 1967. This is a significant amount of sediment deposited within a relatively short section of channel. If the gravel was not extracted the bed level would be 1.53 m higher in this location than it is currently (Figure 2-12). This would significantly decrease the flood capacity of the channel. This sedimentation would also decrease the height of KLO Bridge. The largest amount of sedimentation occurred between 1990 and 1997. This sedimentation was due to the large flood occurring in 1997. This was the largest flood since 1969.

Sedimentation rates have varied through time. Overall, there is a general increase in sedimentation between 1967 and 2006. The period between 1990 and 1997 experienced the largest deposition rate. This is due to the large 1997 flood that transported a great deal of sediment into the sedimentation section.

As discussed in a previous section, the extraction of gravel accelerates further gravel deposition. However, once the initial extraction occurs, a "pit" or low slope area is set up on the channel bed that encourages sedimentation.

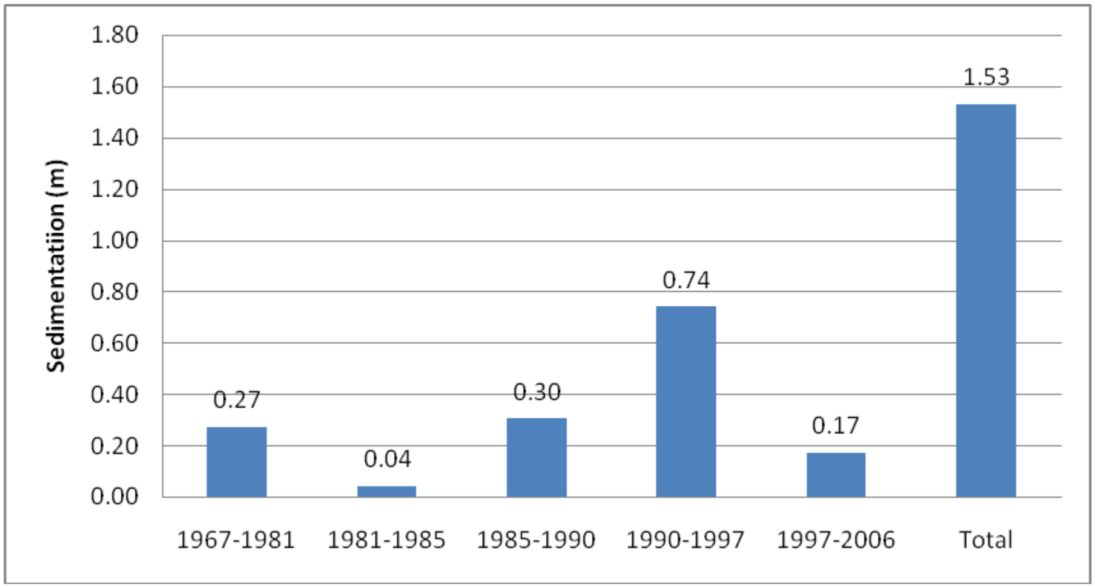


Figure 2-12. Amount of vertical sedimentation based on amount of sediment extracted. Value represents amount of sedimentation occurring from the previous extraction.

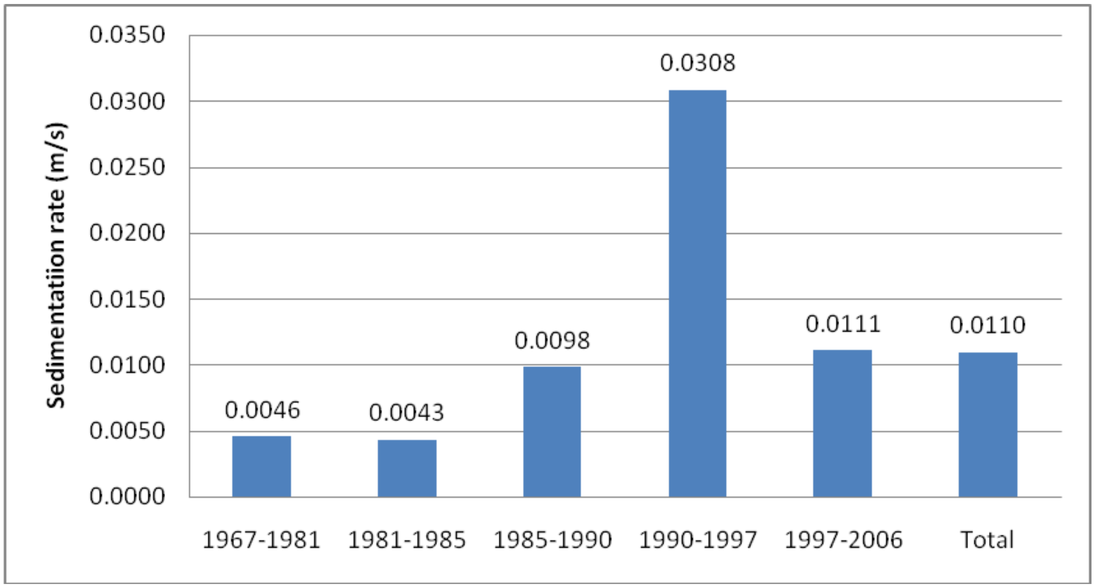


Figure 2-13. Annual average sedimentation rates for Mission Creek near KLO Bridge since 1967.

2.5.3 Effects of gravel extraction on Mission Creek

In 2005, a study of how the useable channel width for fish habitat in Mission Creek changed with stream flow was initiated (Epp 2008). As discussed above, a high flow event in 2006 deposited a significant amount of sediment downstream of the KLO Bridge. An analysis of the useable channel width at Gordon Drive for fish habitat showed a significant increase in the amount of habitat for spawning Kokanee following the flow event (Epp 2008).

In 2007, following the sediment extraction, the cross-sections were reanalyzed. The results showed that the sediment extraction resulted in altered and reduced usable fish habitat widths for both Kokanee spawning and Rainbow trout par rearing (Epp 2008). The change was due to an increase in gradient which increased the velocities and reduced the wetted width and depth. In addition, grain size increased in some locations due to the dredging, further reducing Kokanee spawning habitat.

A follow-up study conducted in 2008 showed that the useable width increased from 2007 to 2008 based on depth and velocity (Epp 2009). However, the grain size appears coarser at most transects such that Kokanee use within the transects decreased (Epp 2009).

A cross-section located 75 m upstream of the dredging was set up as a control. However, the author noted that "the stream gradient appeared to have increased as the channel adjusted to the downstream dredging" (Epp 2008). In 2008, the author noted that "the channel at this transect was apparently down-cutting to adjust to the deeper channel conditions resulting from dredging downstream" (Epp 2009). This resulted in high velocities and more than 90% of the cells dominated by cobbles and stone sized substrates, an increase of approximately 40%. The degradation necessitated the use of another cross-section further upstream as a control. This cross-section has also experienced an increase in the bed grain size from 2007 to 2008, consistent with degradation of the channel bed due to the sediment extraction.

Upstream degradation is precisely what is predicted to occur following gravel extraction (see Section 2.4). The coarsening of the bed grain size occurs as finer particles are transported downstream, leaving the larger particles that are harder to transport. Bed degradation appears to be a significant problem upstream of the KLO Bridge. The sediment eroded from the bed during the degradation will enhance sediment deposition downstream of the KLO Bridge.

3. Hydrological analysis of the frequency of sediment transport/deposition flow events

Sediment is eroded, transported and deposited during high flows. Sedimentation occurs when the amount of sediment being transported into and out of a reach is out of balance, with more sediment coming in than leaving. The greatest imbalance often occurs at the highest flows. Higher flows are associated with sedimentation events at KLO Bridge. Therefore, an analysis of the historical hydrological record was conducted to determine the length and magnitude of high flow events that cause sedimentation at KLO Bridge. Two factors are important: (1) the length of the high flow and (2) the magnitude of the high flow.

3.1. Methods

Data was provided by Water Survey of Canada (Hydat 2006). Two Water Survey of Canada stations were used in the analysis. The first station has an area of 622 km^2, is located on Mission Creek near Rutland (08NM016, 49°51'8" N, 119°20'14" W) and was operated between 1919 and 1946. The second station has an area of 811 km^2, is located on Mission Creek near east Kelowna (08NM116, 49°52'44" N, 119°24'47" W) and was operated between 1949 and 2006. The two stations are not directly comparable due to a change in location. For a given region there is a well established relationship between the drainage basin area and the discharge, where discharge increases with drainage basin area. To account for the difference in discharge between the two stations, the discharge from station 08NM016 were multiplied by the difference in drainage basin area between two sites (1.3039). This procedure allows the discharge record to be extended by 30 years.

The maximum annual daily discharges were used to determine the magnitude of annual high flows. The maximum daily discharge is directly related to the maximum energy level within the channel for a given year. A portion of this energy is used for sediment transport. Maximum annual daily discharges were compared to the mean annual flood (Qaf). The mean annual flood is a good estimation of the bankfull discharge or the discharge that would fill the channel to the top of the banks. The bankfull discharge is the channel forming discharge in alluvial channels. Mean annual flood was determined using the average of the maximum annual daily discharge from 1937 to 2006. Maximum annual daily discharges were higher before 1937 and were therefore excluded. The change in the hydrological regime is most likely associated with the building of reservoirs in the headwaters. The mean annual flood was determined to be 52.1 m^3/s. Maximum annual instantaneous discharge can also be used to determine flow magnitudes however the records for this parameter were significantly shorter than for the maximum annual daily discharge. The same value for Qaf was determined by Gaboury and Slaney (2003). A flood frequency analysis was conducted using the maximum annual daily discharge values from 1949 to 2006. This time period was chosen because it is after the change in the hydrological regime.

The duration of a flood event represents the time that energy can be expended on the bed for sediment transport. The longer the event is the greater the amount of sediment that can be transported per event. Daily discharges were used to calculate the number of days per year that exceeded the mean annual flood.

An additional factor is the volume of water discharged during a flow event. It is a measure of both the magnitude and duration of the flood. The event volume was determined by summing the daily discharge greater than the mean annual flood per year and then multiplying it by the number of seconds that the flood occurred. This value represents the total volume of water discharged during high flow events during a year.

3.2. Results

The maximum daily discharges for Mission Creek show great variability, from the smallest value of 29.8 to the greatest value of 140.8 (Figure 3-1). Here the mean annual flood plus one standard deviation is defined as a large flow. Since 1937 there have been 11 large flows (greater than the mean annual flood plus one standard deviation), which represents a large flow every 6.3 years on average. Recent large magnitude flows occurred in 1990, 2006, and 1997, in increasing order.

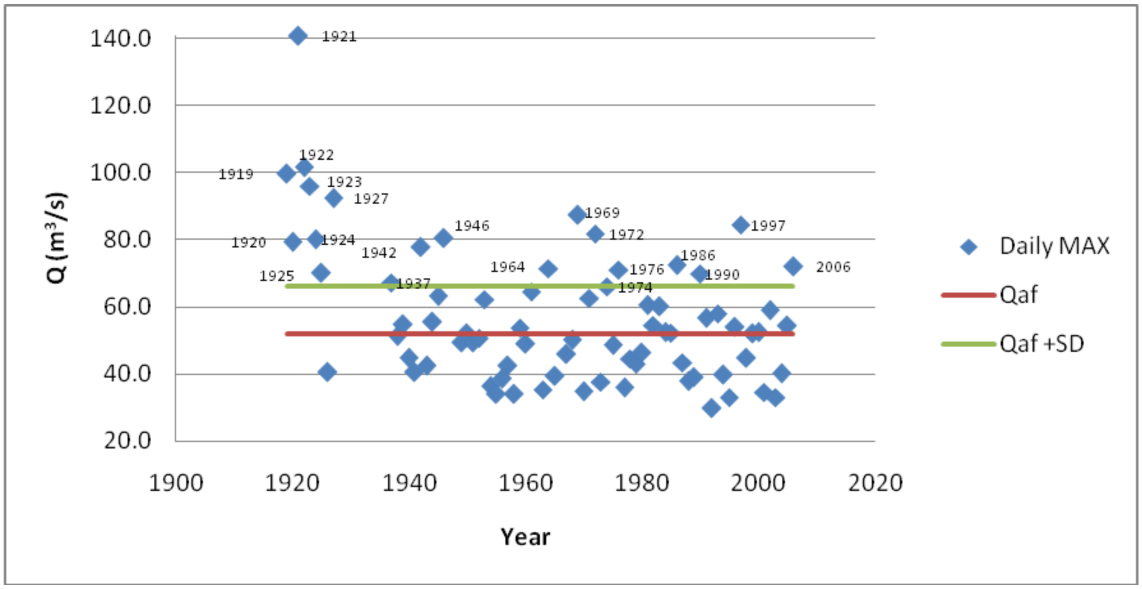


Figure 3-1. Maximum annual daily discharge for the years 1919 to 2006 for Mission Creek. The mean annual flood (Qaf) and the mean annual flood plus one standard deviation (Qaf +SD) are plotted for comparison.

A flood frequency analysis was conducted on the maximum daily discharge data from 1949 to 2006 using a Gumbel Extreamal type 1 distribution (Figure 3-2). This analysis shows that the 1986, 1990, 1997 and 2006 floods had return periods of 13, 11, 36, and 12 years, respectively. The analysis shows that the flows with a return interval of 2, 10, 50 and 100 years have magnitudes of 48, 69, 88, and 96 m^3/s, respectively. These values were slightly larger when discharge values from before 1949 were included.

The maximum instantaneous discharge series displays a similar pattern for the years 1969 to 2006 (Figure 3-3). The maximum annual instantaneous discharge represents the largest discharge reading for a given year. The maximum annual daily discharge represents an average of all the readings taken during the day of the largest flow and therefore is a lower value. The mean annual flood based on the maximum instantaneous discharge (Qafi) is also a larger value, in this case 62.6 m^3/s. In the 37 years of record, the maximum instantaneous discharge exceeded the mean annual flood plus one standard deviation five times, for an average exceedence rate of once every 7.4 years.

The number of days per year that exceeded the mean annual flood was variable through time, ranging from 0 to 18 days (Figure 3-4). Flows of long duration with high magnitudes can transport the greatest sediment. The years where the number of days flow exceeded the mean annual flow by greater than four days are labelled. Recent long duration flows occurred in 2006, 1997 and 1990, in increasing order. Sediment was extracted from the bed of the creek near KLO Bridge following each of these events.

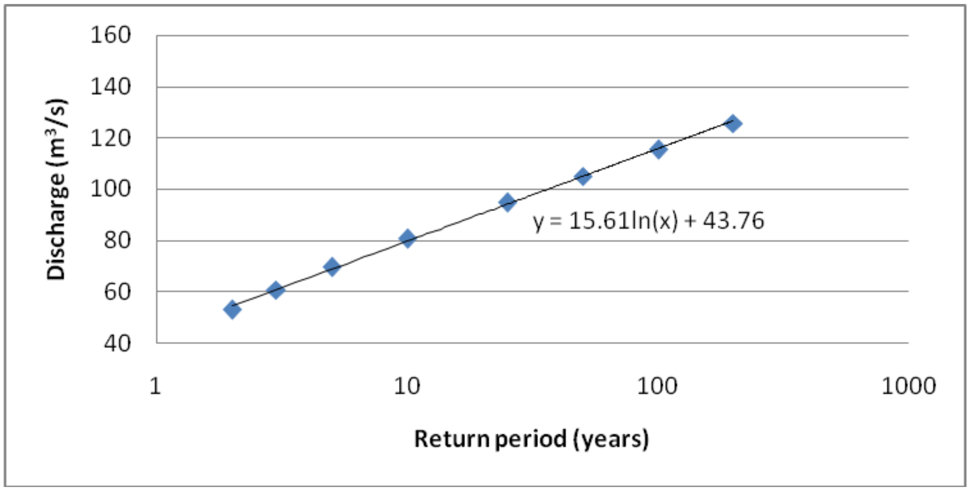


Figure 3-2. Flood frequency analysis for Mission Creek using a Gumbel Extreamal type 1 distribution for the years 1949 to 2006.

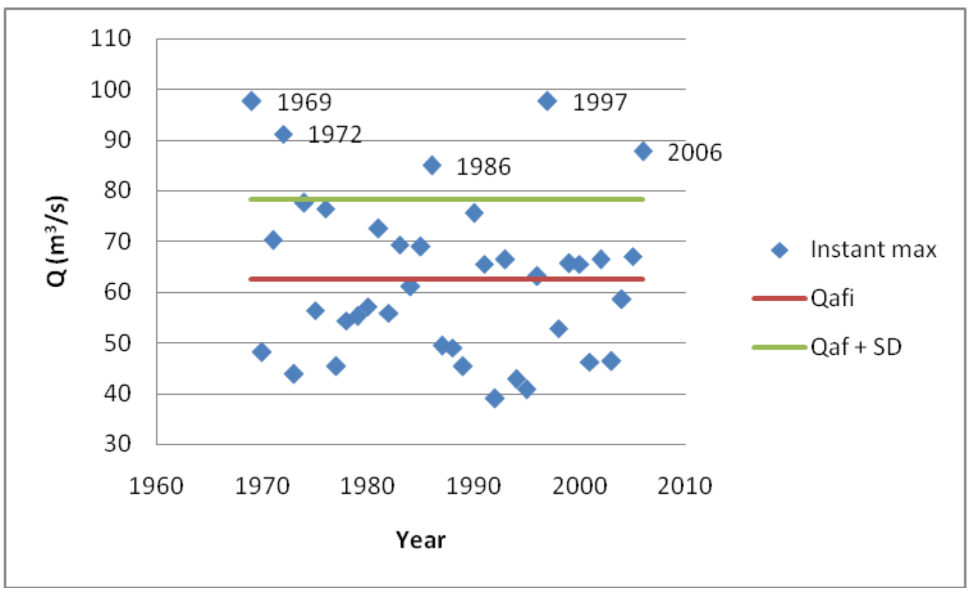


Figure 3-3. Maximum annual instantaneous discharge for the years 1969 to 2006 for Mission Creek. Note the Qafi is the average of the annual maximum instantaneous discharge values.

It is interesting to note that the largest magnitude floods do not necessarily have the longest duration. For example, in 1997 the flood lasted for 12 days, three days shorter than in 1990 (15 days) but the 1997 event had a larger magnitude (84.5) compared to (69.9 m^3/s) in 1990. The flood of 2006 was relatively short (five days) and had a lower magnitude (72 m^3/s). These three most recent high flow events caused sedimentation downstream of the KLO Bridge.

Since 1937, the largest flood occurred in 1972. It had a magnitude of 81.8 m^3/s and lasted for 16 days. Large floods also occurred in 1986, 1976, 1974, 1969, 1964, 1946, 1942 and 1937. The magnitudes and durations of the large magnitude floods are displayed in Table 3-1.

Before 1937, the floods displayed high magnitudes of shorter duration. This means that the flood hydrographs are more peaked and shorter than after 1937. This is precisely what is expected following the construction of reservoirs. The water stored behind reservoirs attenuates the hydrograph by decreasing the peak discharge and extending the flood length. The largest flood was recorded in 1921. With a magnitude of 140.8 m^3/s and lasting 18 days it must have caused substantial flooding.

Table 3-1 Magnitude and duration of the large floods on Mission Creek.

Year	*Max daily annual discharge (m^3/s)*	*Number of days/yr above Qaf*
1921	140.8	18
1922	101.6	7
1919	99.7	8
1923	96.0	5
1927	92.3	9
1969	87.5	10
1997	84.5	12
1972	81.8	16
1946	80.5	15
1924	80.1	8
1920	79.4	10
1942	77.8	8
1986	72.5	7
2006	72.0	5
1964	71.4	3
1976	71.1	1
1925	70.1	7
1990	69.9	15
1937	67.2	2
1974	66.0	10
1961	64.6	1
1945	63.1	9
1971	62.6	1
1953	62.3	1
1981	60.6	4
1983	60.2	4
2002	59	4

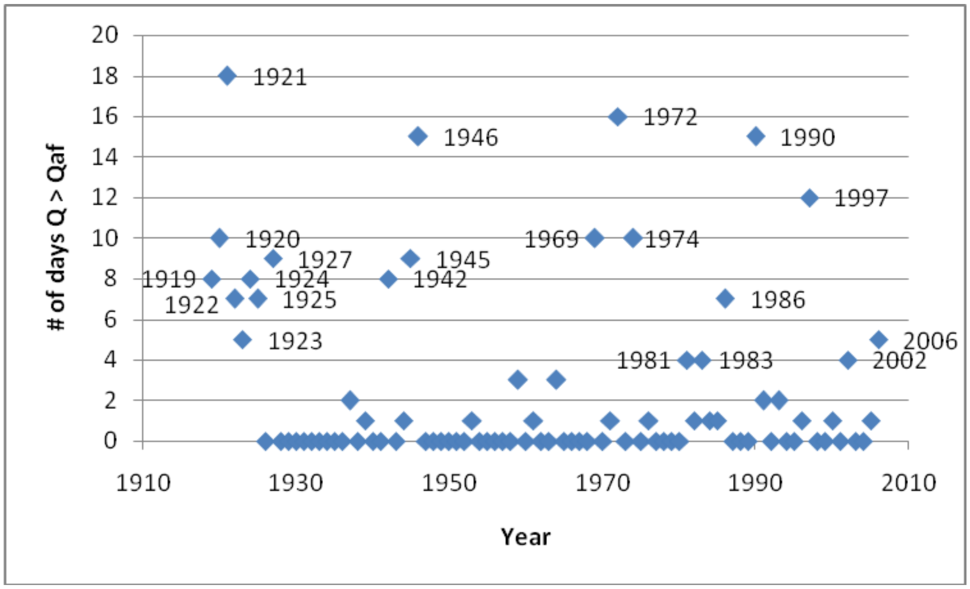


Figure 3-4. Number of days per year that exceed the mean annual flood discharge. The average number of days per year in exceedence is included for comparison.

The total volume of discharge per event (Figure 3-5) follows the same pattern as the maximum annual daily discharge and the number of days that exceed the mean annual flood, with 1990, 1997 and 2006 displaying larger than average values.

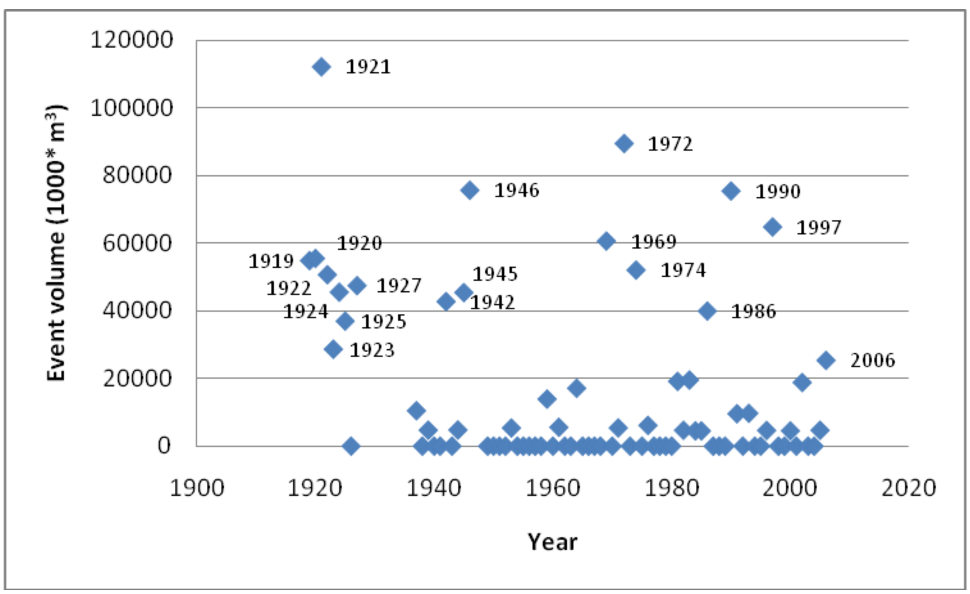
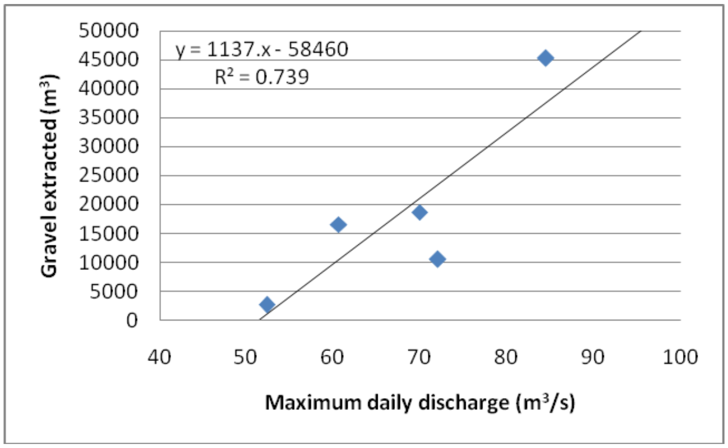


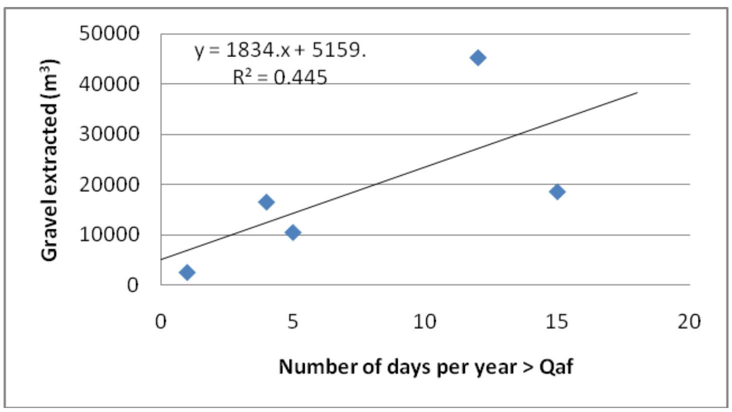
Figure 3-5. Total volume of water during discharge events greater than the mean annual flood per year.

3.3. Relationship between discharge and sediment deposition in Mission Creek

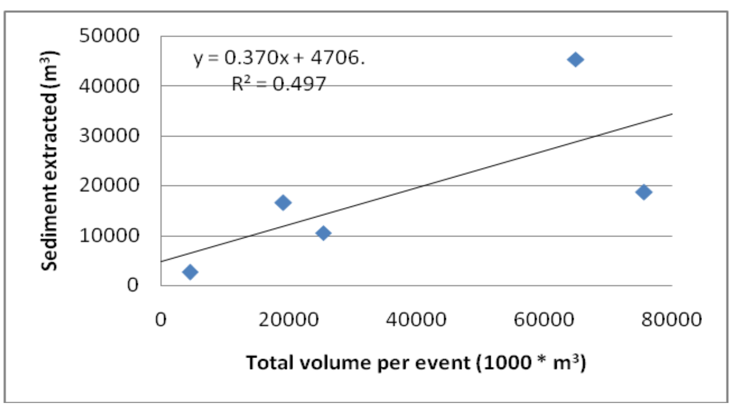
The relationship between the three hydrological parameters and the amount of sediment extracted following the events of 1981, 1985, 1990, 1997, 2006 are shown in Figure 3-6. The maximum daily discharge provided the best fit (R^2=0.739) between the gravel extracted and a hydrological variable (Figure 3-6A).



(A)



(B)



(C)

Figure 3-6. Relationship between the gravel extracted (representing the sedimentation) and the (A) maximum daily discharge, (B) number of days per year greater than the mean annual flood (Qaf), and (C) the total volume of water per high flow event.

4. Analysis of the long profile and downstream grain size patterns of Mission Creek

This section investigates the long profile shape and downstream grain size patterns of Mission Creek. The long profile begins where the channel exits from Gallagher's Canyon and ends near the channel mouth at Okanagan Lake. The long profile displays the change in slope downstream, and the location of riffles and pools. Channel slope is a primary control on the energy within the channel available to transport sediment. Abrupt changes in slope can be related to nick points that cause degradation. These nick points can migrate upstream, damaging habitat. The grain size patterns relate to amount of armouring of large particles on the bed and the energy within the channel to transport the sediment. Grain size is also a primary control on spawning habitat.

4.1. Methods

Several different methods were used to analyse sedimentation on Mission Creek. The primary analysis investigated the shape of the river long profile because changes in the slope of the river are seen in the long profile. Generally, sedimentation will occur where the long profile flattens out. The downstream pattern of grain size is also an important indicator of sedimentation. Generally, very coarse bed grain size locally indicates vertical erosion of the bed (called degradation) and fine bed grain size locally indicates sedimentation (called aggradation). Since sedimentation is related to the sediment grain size and energy within the channel, several channel energy and grain size characteristics were investigated.

4.1.1 Long profile

A river long profile is a plot of a river bed's elevation against the downstream distance. River long profiles are extremely useful in the analysis of a river. The structure of the long profile displays where the slope is steeper and shallower. The location and size and number of riffles and pools can also be seen on long profiles. Long profiles may be determined using Digital Elevation Models (DEM) in the office but they often lack the required detail. Detailed long profiles can only be collected in the field. This is a very labour intensive and time consuming process but the data are invaluable. During the summer of 2007 a long profile of Mission Creek was begun. The data collection was completed in 2008. In 2007, 1007 elevation points were collected over approximately 10 km and approximately 574 elevation points collected over approximately 3.5 km in 2008.

The elevations of the thalweg (the deepest point in a river cross-section) were surveyed in the field using a laser level. Downstream distances were measured with a hip-chain. Bankfull water levels were also surveyed in the field using the highest elevation of leaves and grass deposited by the previous springs flows.

Bankfull channel widths (w) were measured in the field at riffles and were supplemented with measurements from the map of the Mission Creek. Bankfull water surface and bed slopes were determined using linear regressions of bed elevations (thalweg at riffles) and downstream distance. Average bankfull depth (d) was determined by dividing the bankfull width by the bankfull cross-sectional area (A). Bankfull width-to-depth ratios were determined using average bankfull width and depth for each reach.

4.2. Sediment grain size

The grain size on the bed of Mission Creek was measured at 62 locations from Gallagher's Canyon downstream to just upstream of the channel mouth. The grain size distribution of the surface of the bed was determined at the upstream ends of riffles. Where no riffles were present the grain size was determined approximately every 250 m. The grain size was determined using a standard pebble count technique where the B-axis or intermediate axes of 100 randomly chosen clasts were measured on each riffle. For each location the percent boulder, cobble, gravel and sand were determined. The 84th (D_{84}), 50th (D_{50}), and 16th (D_{16}) percentile were also determined.

4.2.1 Reach energy variables

To determine the energy and sediment characteristics for a river channel, the channel must be divided into a number of sections and the average values used for analysis. Mission Creek was divided into 18 reaches from the exit from Gallagher's Canyon and the Mouth. Each reach was 750 m long on average. For each channel reach, several variables were determined, including the average width, depth, width-depth ratio, bed slope, grain size (D_{84}, D_{50}, D_{16}), bankfull shear stress, Froude number, average velocity, bankfull specific stream and mobility ratio.

4.2.2 Hydraulic characteristics

The hydraulic energy within each channel was estimated in three ways: the slope of the bed, the specific stream power, and the shear stress. The specific stream power (ω)

$$\omega = \gamma Q_{af} S/w$$

where γ is the specific weight of water, Q_{af} is the bankfull discharge within a reach, S is the slope of the channel bed and w is the average bankfull channel width. The specific stream power is the rate of energy supply at the channel bed for overcoming friction and transporting sediment per unit area of the bed (Knighton 1998). Shear stress (τ_o)

$$\tau_o = \gamma RS$$

where, R is the hydraulic radius (area / wetted perimeter), and S is the reach energy slope. Shear stress represents the downstream force that flowing water exerts on the bed (Knighton 1998).

The mobility of the bed was estimated using a mobility ratio ($Mr = \tau_o / \tau_c$) where τ_c is the critical shear stress

$$\tau_c = 0.06\ (\rho_s - \rho)\ g\ D_{50}$$

where ρ_s is the density of sediment and ρ is the density of water. The critical shear stress can be approximated by D_{50} in mm (Lapointe et al. 2000). Mobility ratio divides the bankfull shear stress by average median grain size; high values indicate greater bed mobility than low values.

Average velocities (U) were estimated by dividing the annual flood by the bankfull cross-sectional area (Q_{af} / A). The Froude number

$$Fr = U/\ (dg)^{0.5}$$

where g is the gravitational constant is a measure of the type of flow within the channel. Super critical flow occurs where Froude numbers are above one, critical flows occur where Froude numbers equal one and subcritical flow occurs where Froude numbers are below one.

There are several sources of error within this analysis. First, the bankfull water depth was determined in the field by vegetation debris left during the last high water event. Although a reliable indicator of the bankfull height, the height could be too high or too low. The velocities and Froude numbers rely on the bankfull cross-sectional area. If the bankfull height is incorrect these velocity and Froude number will also be in error. Shear stress and mobility ratio are also sensitive to bankfull depth.

4.3. Results

This section presents the long profile, bed grain size patterns, and reach analysis of Mission Creek. First, the long profile structure is investigated. Significant breaks in slope as well as high slope and low slope regions of the profile are identified. The trends in grain size downstream are then analysed.

4.3.1 Long profile patterns

The long profile of Mission Creek is concave downstream, with the bed slope decreasing downstream (Figure 4-1). This is a very typical pattern for river long profiles. Significant breaks in slope occur at 1080 m, 7420 m, 6040 m and 8890 m. Breaks in slope may be natural or as a result of river management practices. They may represent nick points and an unstable channel bed configuration.

The first break in slope occurs at 1080 m downstream within the natural section of Mission Creek. It is related to a change in channel pattern from multiple channel to single channel downstream and therefore is probably not a significant problem.

The second break in slope occurs just downstream of where the dyking begins. Although no obvious structure occurs in this location to explain the change in slope it is probably associated with an erosional zone that begins upstream where the channel enters the channelized section and turns towards the lake. This break in slope may be a nick point, may migrate upstream into the natural section and could become a significant problem.

The third break in slope occurs at 7420 m, near the Mindy Tran Bridge and is associated with the irrigation take off and the engineered demonstration riffle (Dill 2002). Since this section is engineered with larger boulders, it is unlikely that further erosion upstream will occur. However, it is possible that downstream degradation could occur and therefore the bed elevations downstream of the demonstration riffle should be monitored.

The fourth break in slope at 8890 m occurs at the beginning of the location where gravel extraction occurred in 2006. Upstream the slope is steeper than downstream. This is a main cause of the sediment deposition in this location. The bed elevation of the upstream portion of this section should be monitored for degradation. This could represent a nick point that could migrate upstream, further damaging fish habitat.

Interestingly, between the 7420 m where the engineered riffle is located and 8890 m where the gravel extraction area begins, the channel is very flat with no riffles or pools. This may be due to repeated extraction of the gravel downstream causing increased slopes and degradation upstream. Downstream of the sedimentation zone the river grades down to the lake.

4.4. Grain size patterns

Mission Creek displays a complicated pattern of grain size varying downstream (Figure 4-2). Overall, the grain size of the Mission Creek bed displays a downstream fining trend, with the median values decreasing from 125 mm to 50 mm at the mouth. A downstream fining is typical for rivers with a concave profile. However, there are a number of undulations in grain size superimposed upon this trend with grain size increasing and then decreasing abruptly. The grain size decreases abruptly downstream where the creek exits from Gallagher's Canyon and then stabilizes at approximately 100 mm D_{50} within the natural section.

The percentage of each grain size class displays a similar pattern (Figure 4-3). The percentage of cobbles and boulders decrease downstream while the percentage of sand increases. The percentage of gravel increases slightly until about 4000 m but then increases abruptly towards the mouth. This change in the rate of increase in the amount of gravel approximately coincides with the end of the natural section of Mission Creek.

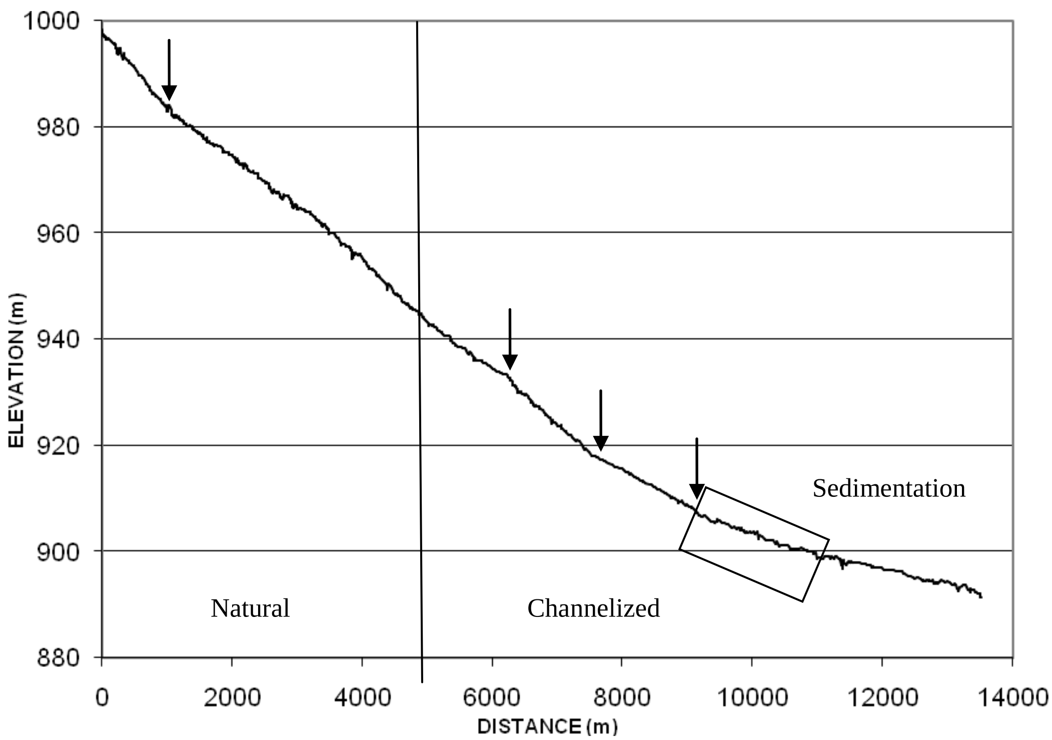


Figure 4-1. Long profile of Mission Creek from the exit from Gallagher's Canyon to the mouth. The arrows indicate breaks in the slope of the channel. The box represents the location of sedimentation near KLO Bridge. The channelized section is downstream of the vertical dividing line.

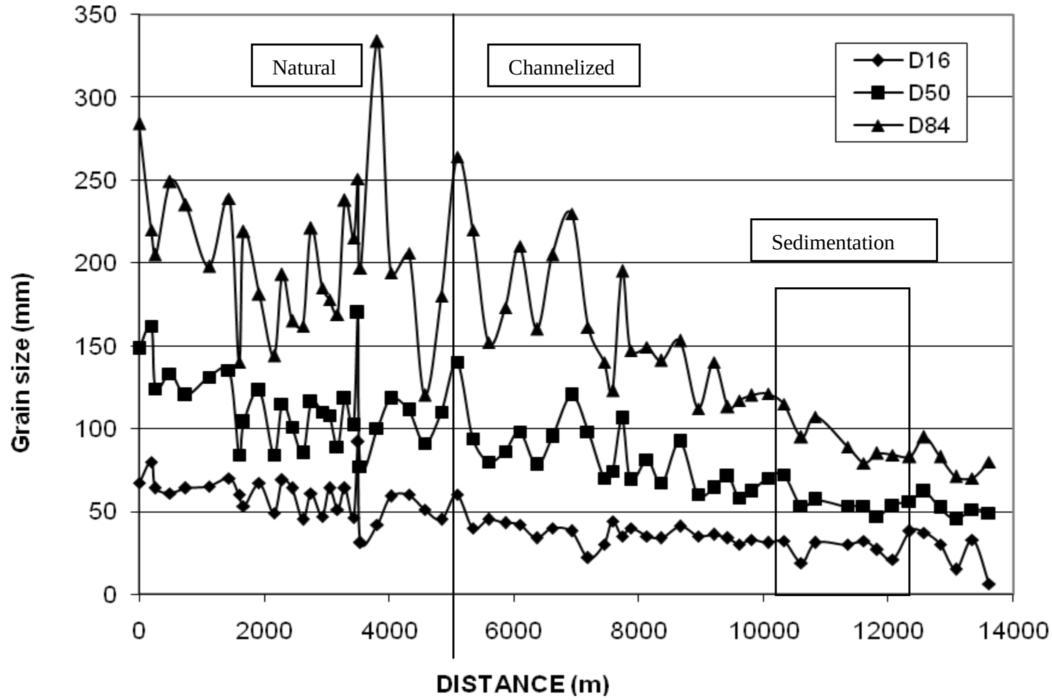


Figure 4-2. Downstream trends in grain size for Mission Creek.

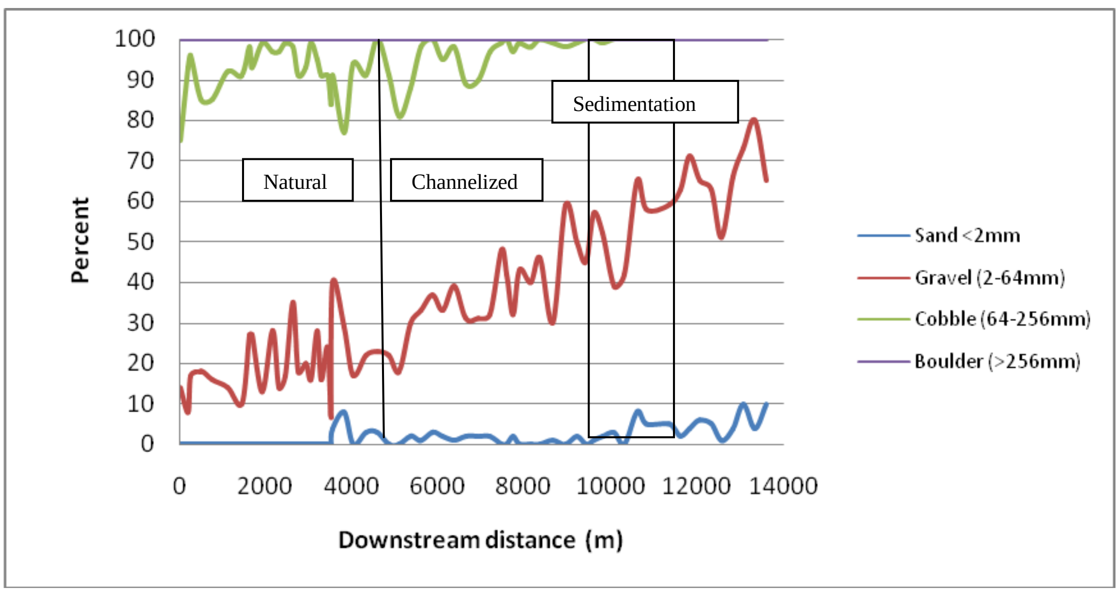


Figure 4-3. Downstream trends in cumulative percentages of sand, gravel, cobble and boulder for Mission Creek. The percentage of each grain size class is cumulative and represented by the space between the lines.

4.4.1 Reach scale analysis

This section presents the analysis of the Mission Creek reaches (Figure 4-4). A summary of reaches 1 through 18 is found in Appendix A. Reaches were defined by changes in slope on the long profile so that the conditions within a reach were homogeneous. This section will discuss the overall downstream trends in the variables, and compare the natural section (reaches 1-5) the steep channelized section (reaches 6-

13), the sedimentation section (reaches 14-15) and the lower slope downstream section near the mouth (reaches 16-18) (Figure 5-4, Table 5-1). Note that the sedimentation section and the downstream section are confined by dykes and dykes also exist in the natural section, particularly in reach 5.

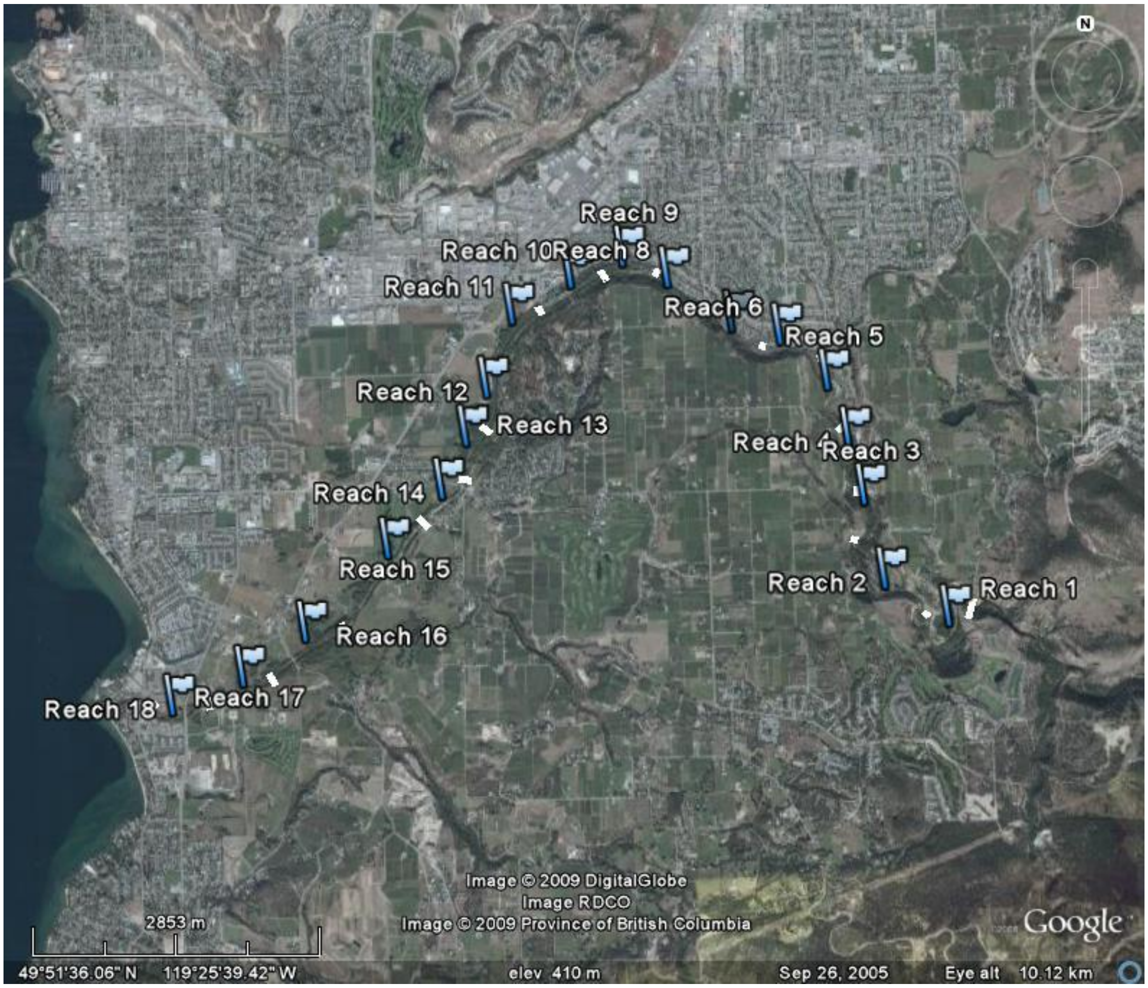


Figure 4-4. Location of 18 reaches on Mission Creek.

Table 4-1. Average section values. Reach 18 was not included in the downstream calculation.

Section	Slope (m/m)	D16 (mm)	D50 (mm)	D84 (mm)	Avg. width (m)	Avg. R	Avg. depth (m)	Avg. Velocity (m/s)	Shear stress (Pa)	Mobility Ratio	Width/Depth	Specific stream power (w/m^2)	Fr
Natural	0.011	60	115	212	31.6	0.8	0.8	2.4	78	0.68	42	173	0.88
Channelized	0.009	40	88	166	22.7	0.9	0.9	2.8	72	0.82	27	189	0.98
Sedimentation	0.004	30	61	110	27.1	1.0	1.0	2.2	37	0.60	28	73	0.71
Downstream	0.003	28	53	83	22.9	1.0	1.0	2.3	24	0.45	23	55	0.76

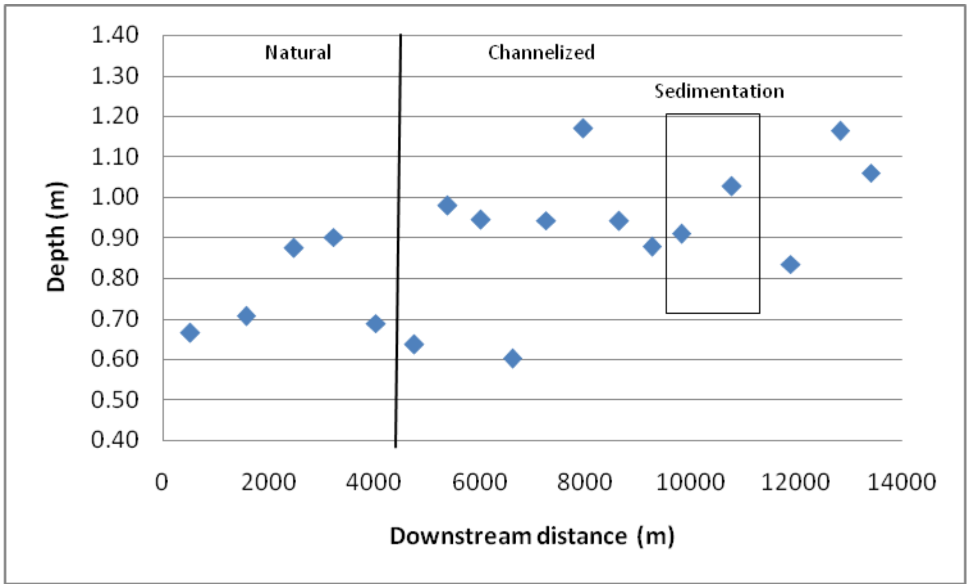
4.4.1.1. Natural section (reaches 1-5)

Reaches 1 through 5 are natural, without significant river engineering. These natural reaches display a wandering gravel bed river pattern with sections containing large gravel bars and sections containing a single channel. The natural reaches are confined by a narrow valley that is only 2.3 times the channel width on average. Zones of sedimentation occur where the valley widens to 4.2 the channel width. This allows space for channels to split around large bars that form.

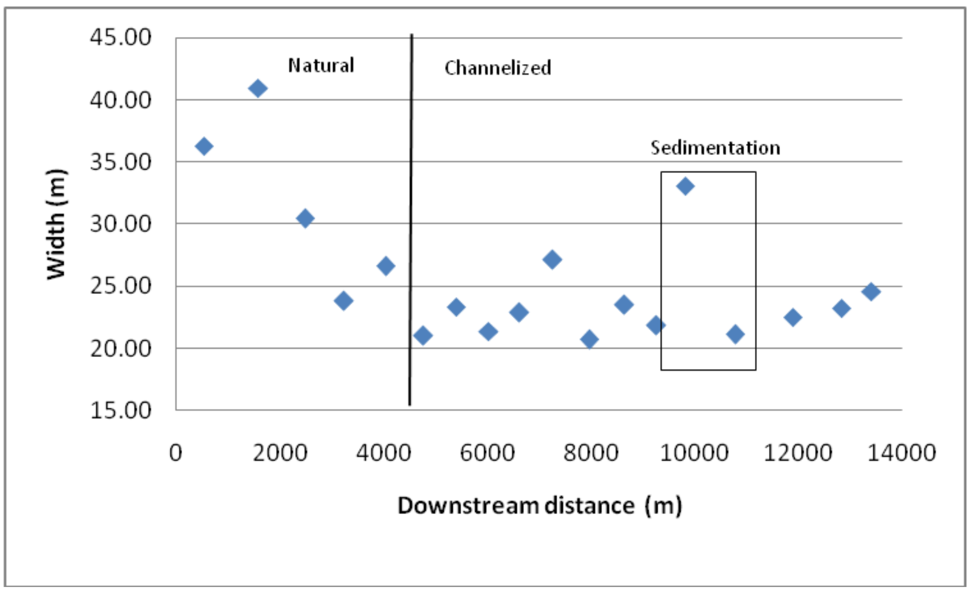
The natural section channels are wide and shallow on average, with the highest width and the highest width-to-depth ratio of all the sections (Table 5-1). The depth generally increased through this section (Figure 4-5A) while the width decreased (Figure 4-5B). These trends in width and depth caused the width-to-depth ratio to decrease through the section (Figure 4-6A). The hydraulic radius displayed the same pattern as channel depth (Figure 4-6B). The average velocities and Froude numbers increase from reaches 2 to 6 following an initial decrease from reach 1 (Figure 4-7A and B).

The grain size decreased through the first three reaches within this section and then increased (Figure 4-8A). The channel slope was highest as Mission Creek exits the confinement of Gallagher's Canyon and stabilizes in reaches 2 to 4 and increases in reach 5 (Figure 4-8B). Shear stress values decrease following reach 1 but increase following reach 2 and decrease slightly at the end of the section (Figure 4-9A). Following an initial decrease, specific stream power steadily increases through the natural section and into the next channelized section (Figure 4-9B). The specific stream power during the 1997 flood reached values as high as 350 W/m^2 (Figure 4-10A). The mobility ratio displays an interesting pattern of decreasing from reach 1 to reach 2 then increasing in reach 3 followed by a steady decrease to reach 6 (Figure 4-10B).

The natural section is the furthest from the channel mouth and displays the greatest slope, D_{16}, D_{50}, D_{84}, shear stress and width depth ratio values of all the sections (Table 4-1). The highest energy and grain size values were seen in reach 1 where it exits from Gallagher's Canyon. The slope and grain size decrease away from the exit from the Canyon. This affects the stream power and shear stress values. The wandering pattern is clearly represented in the reach scale variables. The gravel bars deposited within the channel have caused the channel to be wide and shallow.

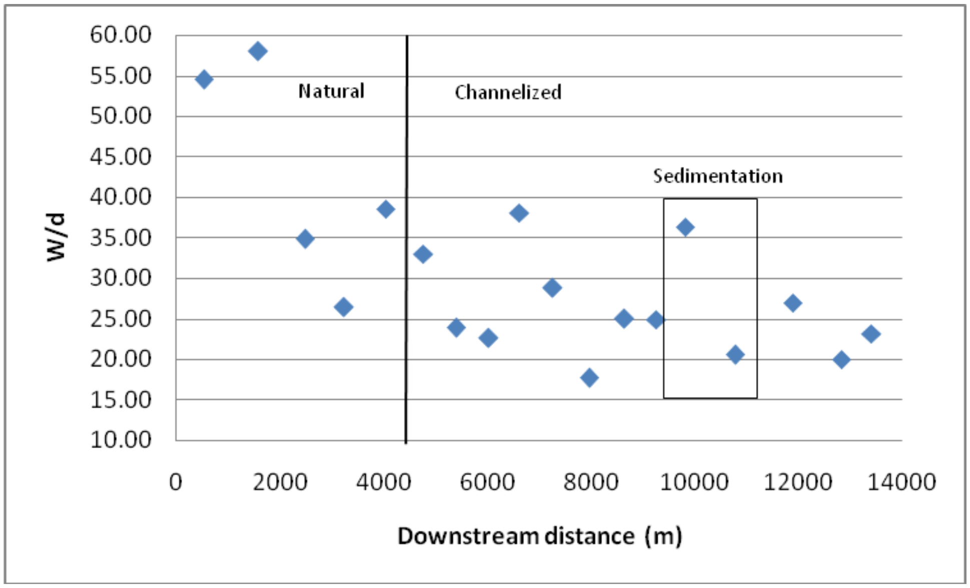


A.

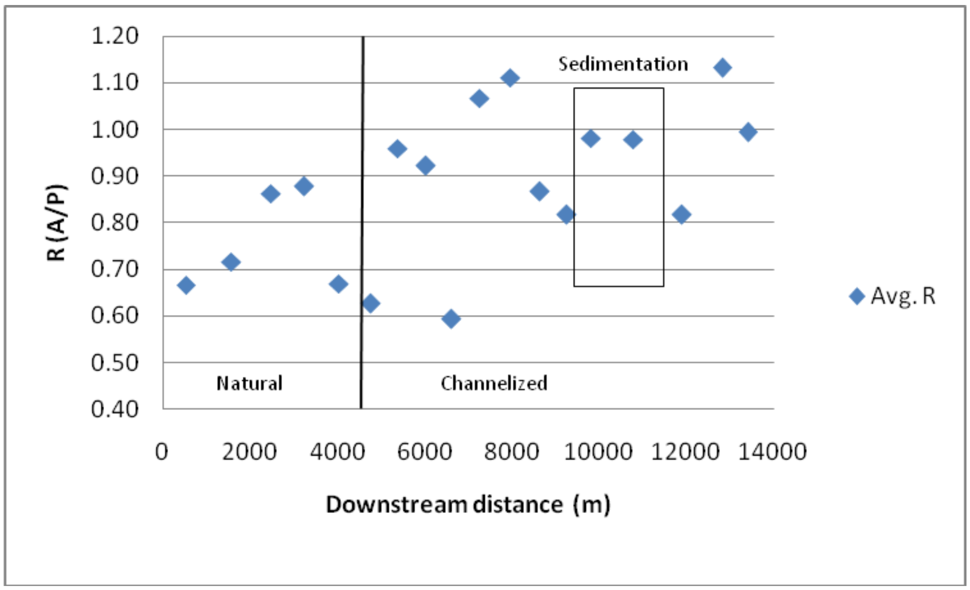


B.

Figure 4-5. (A) Bankfull channel depth for Mission Creek reaches. (B) Bankfull width for Mission Creek reaches.

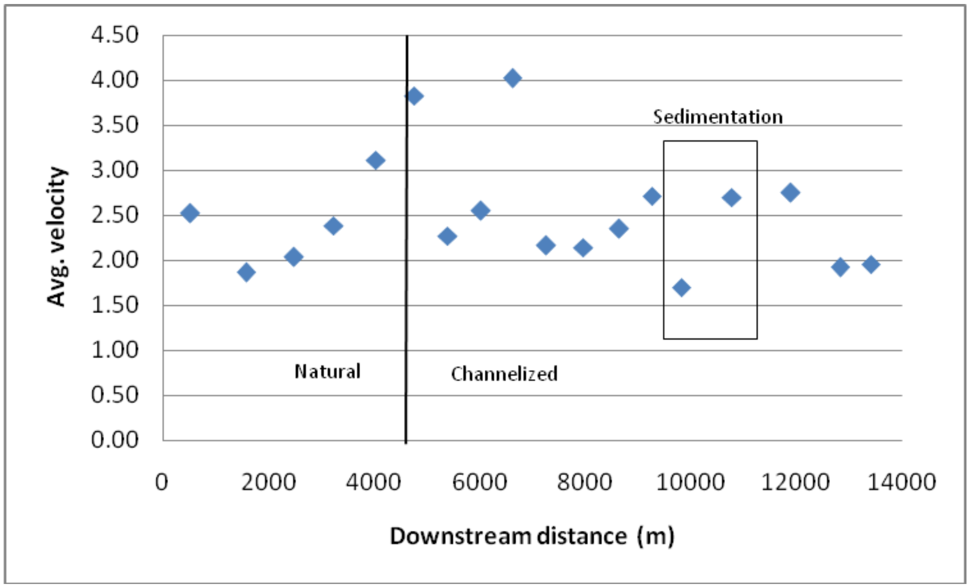


A.

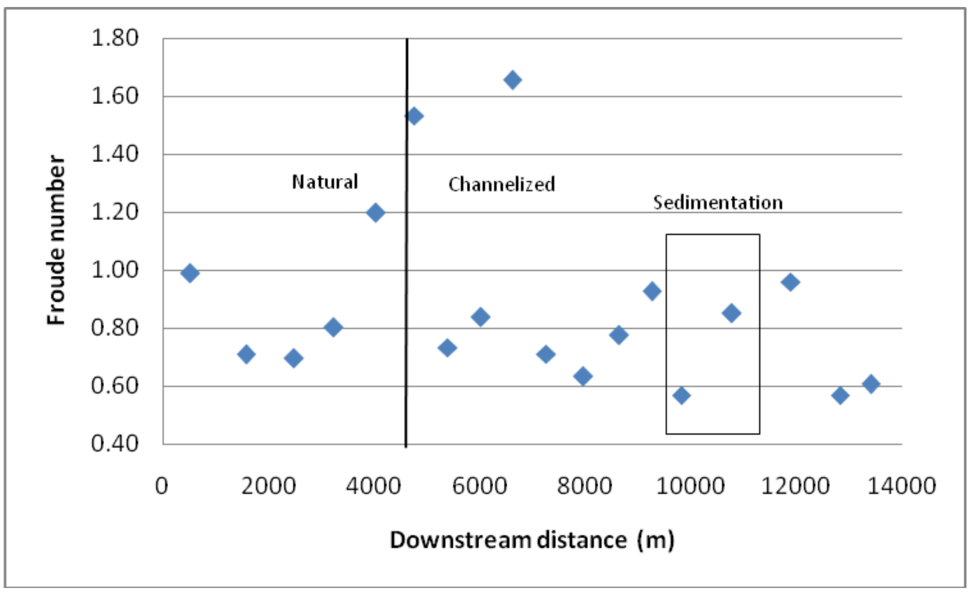


B.

Figure 4-6. (A) Bankfull width-to-depth ratio for Mission Creek reaches. (B) Bankfull hydraulic radius for Mission Creek reaches.

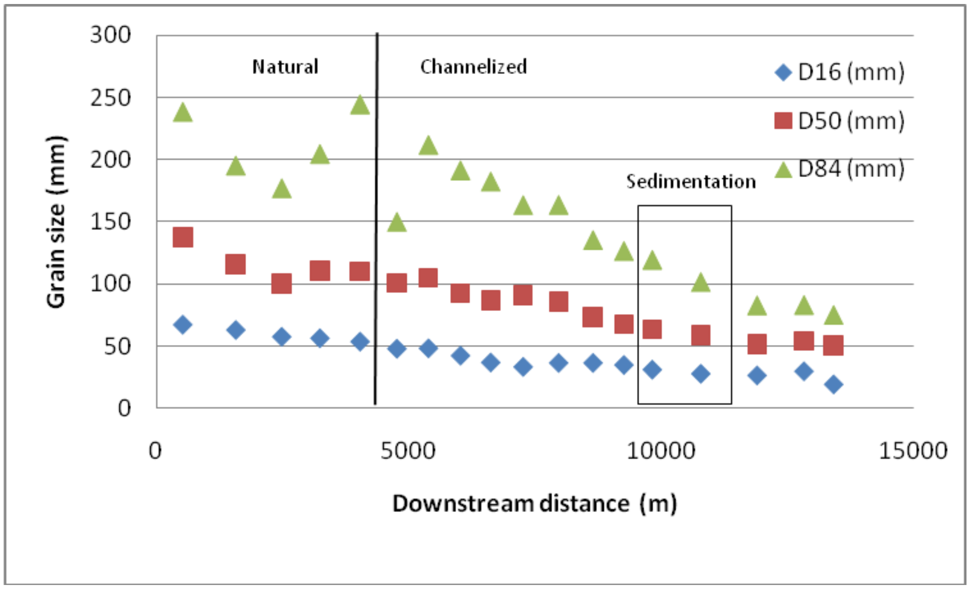


A.

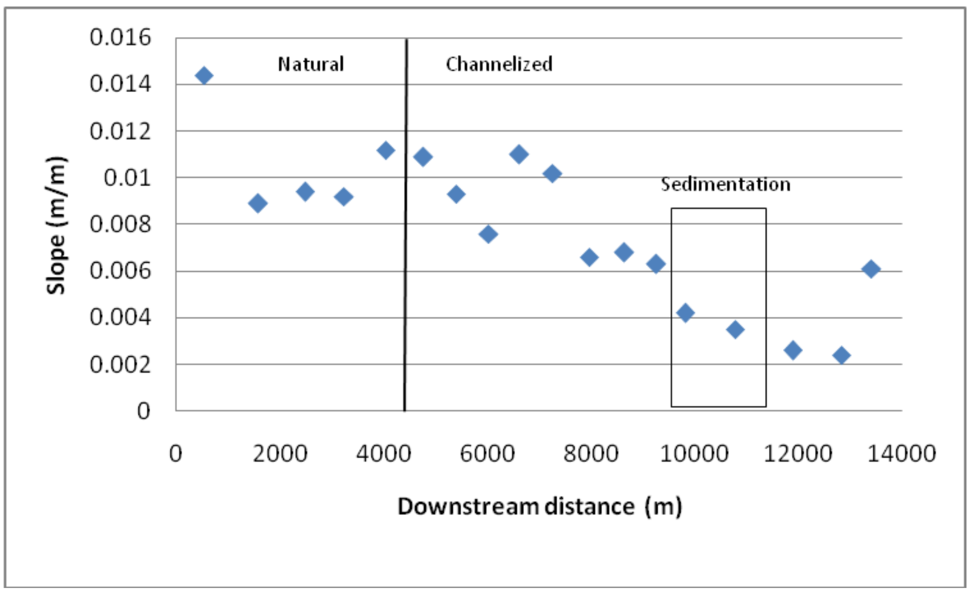


B.

Figure 4-7. (A) Bankfull average velocity for Mission Creek reaches. (B) Bankfull Froude number for Mission Creek reaches.

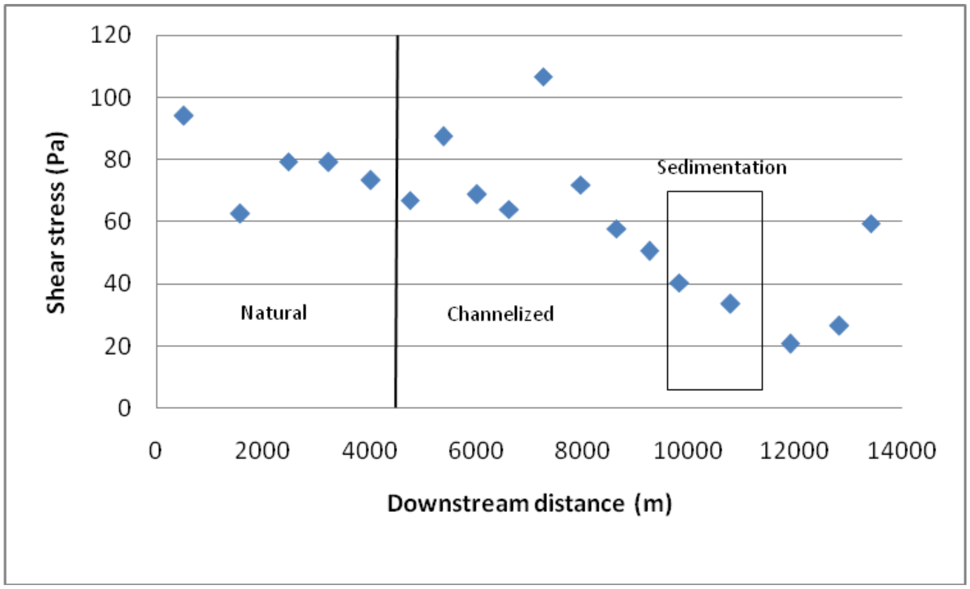


A.

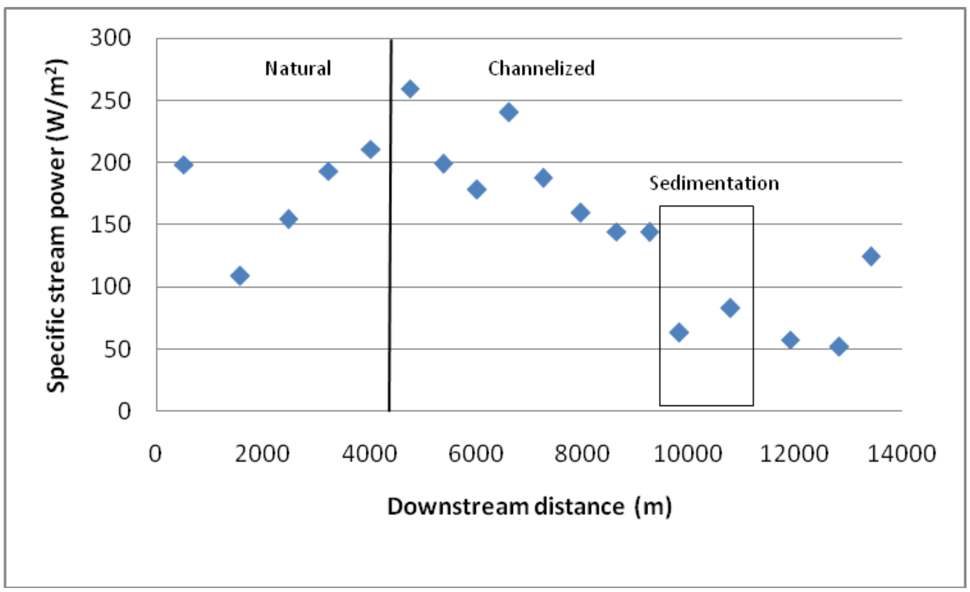


B.

Figure 4-8. (A) Grain size patterns for Mission Creek reaches. (B) Channel bed slope for Mission Creek reaches.

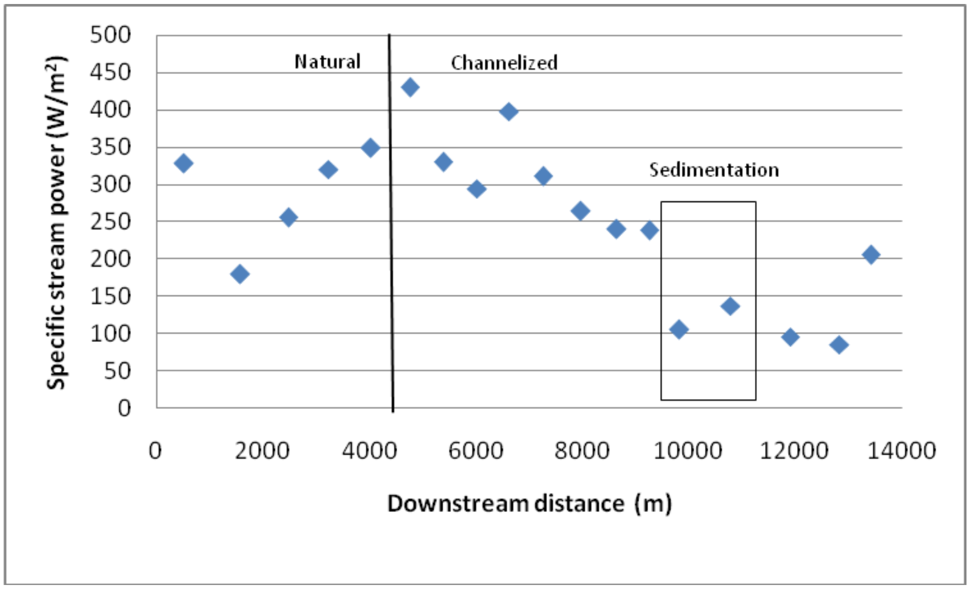


A.

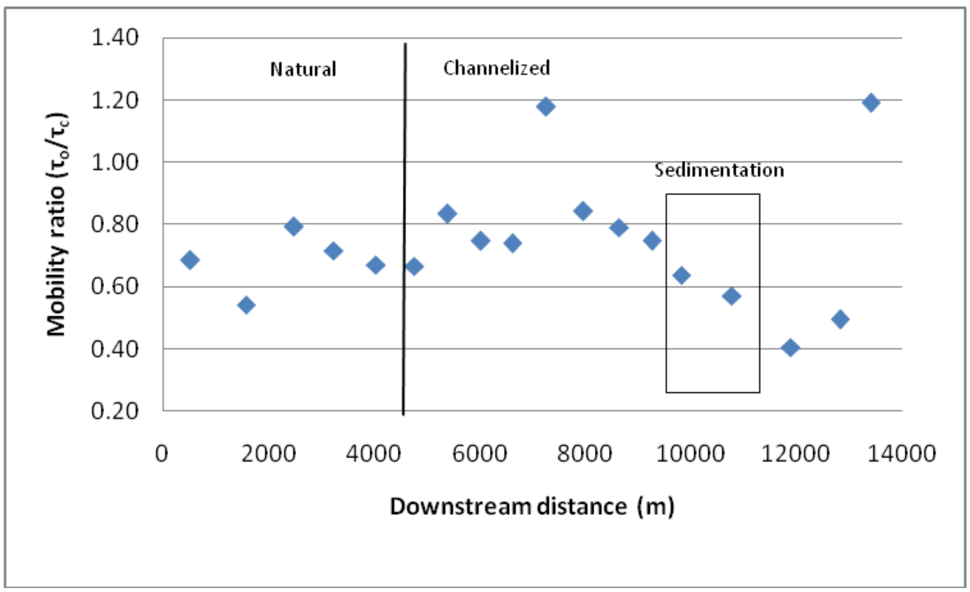


B.

Figure 4-9. (A) Bankfull shear stress for Mission Creek reaches. (B) Bankfull specific stream power for Mission Creek reaches.



A.



B.

Figure 4-10. Specific stream power values for the 1997 flood (A). Mobility ratio for Mission Creek reaches (B).

4.4.1.2. Channelized section (reaches 6-13)

The channelized section begins at reach 6. At this location the channel turns at nearly 45 degrees towards Okanagan Lake. This section contains the engineered riffle in reach 9 and includes Mission Creek near the Eco Centre. The channel is narrow and steep through this section. Only one bar composed of cobbles and gravel has formed within this section in reach 10 at the foot bridge near the Eco Centre. The channel is quite straight through this section having only one large gradual curve in reach 11.

Within the channelized section, channels are narrow and deep on average, with the lowest width and a moderate width-to-depth ratio (Table 5-1). The depth values were variable but generally increased through this section, with the exceptions of reaches 6 and 9 (Figure 4-5A). Channel width values remained relatively constant down the section, with the exception of reach 10 that was significantly wider (Figure 4-5B). These trends in width and depth caused a variable pattern in width-to-depth ratio throughout the section (Figure 4-6A). The hydraulic radius also displayed a variable pattern downstream with reaches 6 and 9 displaying low values, reaches 7, 8, 12 and 13 displaying moderate values, and reaches 10 and 11 displaying high values (Figure 4-6B). The average velocities and Froude numbers generally decreased significantly from reaches 6 to 7 but then increased from 7 to 9, decreased from 9 to 10 and then increased from 10 to 13 (Figure 4-7A and B).

The grain size generally decreased throughout the channelized section, with a slight decrease in reach 9 (Figure 4-8A). Also, the D_{50} was slightly lower in reach 6 but the D_{84} was significantly lower. The channel slope was highest at reach 6 where Mission Creek enters the channelized section (Figure 4-8B). The slope then decreased to reach 8, increased significantly at reach 9 and then decreased to reach 13. The shear stress values increased from reach 6 to 7 then decreased to reach 9. Reach 10 displays the highest shear stress values determined on Mission Creek. Downstream of reach 10 the values decrease (Figure 4-9A). Stream power decreases from reaches 6 to 8 then increase abruptly at reach 9 (Figure 4-9B). Following reach 9 there is a steady decrease in stream power. The specific stream power during the 1997 flood reached values as high as 430 W/m^2 within reach 6 and 398 in reach 9 W/m^2 (Figure 4-10A). The mobility ratio mirrors the pattern in shear stress with reach 10 displaying the highest sediment mobility within Mission Creek (Figure 4-10B).

The channelized section is characterized by a narrow and deep channel with the second highest slope and intermediate grain size (Table 4-1). These characteristics cause the highest velocities, highest specific stream power and high shear stress. Even with the large D_{50} values, the sediment is the most mobile within this section, displaying the highest section average mobility ratio.

Generally, the channelized reach may be erosional (degradational) with high slope, high shear stress and high specific stream power. This causes high sediment mobility. Sections 6 and 9 are particularly narrow causing the highest velocity and Froude numbers on Mission Creek. These characteristics are also driven by the high slope values seen in these reaches. Reach 10 also displays a high slope value as well as a high shear stress and mobility ratio.

Reach 6 represents a potential significant problem. It is the location of recent in-channel engineering work. It appears this work may have decreased the channel width and caused degradation in this location. The upper portion of this reach is currently a point of a break in slope that may migrate upstream through time. If this occurs it could cause degradation of the bed upstream into the natural section. If degradation occurs it will release sediment from the bed. This sediment will travel downstream, exacerbating the sedimentation problem in reaches 14 and 15. Degradation within the natural section will also decrease the habitat value of the natural section. If the 1997 flood of 84.5 m^3/s occurred, the stream power values would reach 430 W/m^2 within this reach (Figure 4-10A). Floodplain stripping has been shown to occur at values of 300 W/m^2 (Lapointe et al. 1997).

Reach 9 is another potential significant problem. It is the location of the Newbury Riffle constructed in 1995. There is also a take off for an agricultural canal within the reach. There are a number of very large boulders just downstream of the canal take off.

Large boulders were also used to build the Newbury Riffle. This section is so energetic that the huge boulders that were used to build the Newbury Riffle have moved downstream. The demonstration riffle was constructed in August of 2000, before the flood in 2006. During this flood the reach experienced specific stream power values of 339 W/m^2. This is well above the 300 W/m^2 needed to cause floodplain stripping (Lapointe et al. 1997). If the riffle was constructed prior to the 1997 flood, it would have experienced specific stream power values of 398 W/m^2 $^($Figure 4-10A).

Reach 10 displayed the highest shear stress and mobility ratio values. There is a large bar located within this reach. It is the only large bar within the channelized section. The channel is also wider in this reach, probably due to the presence of the large bar. However, the bar may have formed because the channel was constructed wider in that location.

4.4.1.3. Sedimentation section (reaches 14-15)

Sedimentation occurs in reaches 14 and 15, downstream of KLO Bridge where historical sedimentation and gravel extraction has occurred. Gravel has been extracted from this reach for a number of decades. Within the sedimentation section, channels are wider and deep on average, with the highest width after the natural section and a moderate width-to-depth ratio (Table 5-1). The sections' average slope, grain size, mobility ratio, specific stream power, shear stress and mobility ratio display the second lowest values.

The depth values are moderate but increase from reach 14 to 15 (Figure 4-5A). Channel width and width-to-depth ratio decrease from section 14 to 15 (Figure 4-5B; Figure 4-6A), while the hydraulic radius remained nearly constant near 1 (Figure 4-6B). The average velocities and Froude numbers also increased from reach 14 to 15 (Figure 4-7A and B) along with the grain size (Figure 4-8A). The channel slope followed the same trend (Figure 4-8B) as did shear stress (Figure 4-9A). Stream power increased from reach 14 to 15 but decreased significantly between reach 13 to 14 (Figure 4-9B). The specific stream power during the 1997 flood values dropped significantly between reach 13 and 14, from 239 to 105 W/m^2 (Figure 4-10A). This huge drop in specific stream power (134 W/m^2) between these two reaches is the cause of the sediment deposition in reach 14 during high flows. The mobility ratio mirrors the pattern in shear stress (Figure 4-10B).

The sedimentation section is characterized by a wide and relatively deep channel with the second lowest slope, grain size, shear stress, stream power and sediment mobility values (Table 4-1). These characteristics cause the lowest velocities and Froude numbers and the second lowest mobility ratio.

Generally, the channelized reach is a depositional (aggradational) with low slope, shear stress and specific stream power. This causes low sediment mobility and deposition. The deposition occurs in this location because of an abrupt decrease in specific stream power between the channelized section and the sedimentation section (Figure 4-9B). The lowest stream power occurs in reach 14 due to the increase in channel width in this location. The downstream decreasing trend in shear stress and mobility ratio are relatively constant from reach 11 to reach 15.

4.4.1.4. Downstream section (reaches 16-18)

The downstream section is closest to Okanagan Lake (reaches 16-18), downstream from the sedimentation section. This section includes the area of proposed channel restoration at the Benvoulin Woods near Corsorso. The section average channel slope, grain size, width and width-to-depth ratio, shear stress, specific stream power, and mobility ratio are lowest in this section (Table 4-1). Several gravel bars are located within this section at reach 18. This section is where the river channel grades to the delta, where the channel mouth enters Okanagan Lake.

The depth values are highest in sections 17 and 18 while channel width steadily increases from reach 15 (Figure 4-5AB). The width-to-depth ratio is quite low but is highest in reach 16 then decreases in reach 17 and increases again in reach 18 where in-channel bars are present (Figure 4-6A). The hydraulic radius follows the same pattern as channel depth (Figure 4-6B). The average velocities and Froude decrease from reach 16 to the lowest values within Mission Creek with the exception of reach 14 (Figure 4-7A and B). Grain size values decrease through this section and are the lowest values seen on the creek (Figure 4-8A).

The channel slope decreased from reach 14 to 17 but increases in section 18 (Figure 4-8B). The increase in reach 18 is probably related to the interaction of the river channel and the lake at the delta mouth. Shear stress values are lowest in reach 16 then increase slightly through reach 17 (Figure 4-9A). Stream power values decrease from reach 15 and are the lowest in reaches 16 and 17 (Figure 4-9B). The assumptions of steady and uniform flow are violated near the mouth of a river; therefore shear stress and specific stream power for reach 18 are not discussed. The specific stream power during the 1997 flood reached values as high as 430 W/m^2 within the downstream section were below 100 W/m^2 (Figure 4-10A). Sediment mobility is lowest in reach 16 and 17 (Figure 4-10B).

The sedimentation section is characterized by a narrow and relatively deep channel with the lowest slope and grain size, (Table 4-1), consistent with the sections location near the mouth of the river. These characteristics cause the lowest shear stress, stream power and sediment mobility values.

Generally, the downstream reach could be a depositional (aggradational) zone with low slope, shear stress and specific stream power. As is expected at the mouth of a river it has the lowest sediment mobility of any section. However, because a significant amount of sediment has been extracted upstream, a significant amount of sediment has not been allowed to enter this section and cause sedimentation. It is clear that sedimentation could occur within this section if gravel is not extracted from upstream. The channels within the downstream section also display a low width-to-depth ratio. The channel has probably adjusted to the new sediment regime by decreasing the width-to-depth ratio. Increasing the width-to-depth ratio increases the hydraulic efficiency of the channel by decreasing the wetted portion of the channel.

4.4.2 River pattern analysis

River pattern provides rivers another degree of freedom to alter their hydraulic conditions and sediment transport patterns. A number of channel river patterns have been identified. Leopold and Wolman (1957) described four river pattern types: meandering, braided, anastomosed, and straight. Meandering rivers are well studied, have single sinuous channels, migrate through lateral accretion, and have slopes much lower than braided (Leopold and Wolman 1957). Straight channels are rare, occurring mainly in delta distributaries. Leopold and Wolman (1957), and Lane (1957) recognized a relationship between slope, bankfull discharge, and channel pattern (Figure 4-11). Braided rivers plot above meandering rivers with similar sediment grain size on a scatter plot of slope and bankfull discharge. Wandering was added later as a transitional river type between meandering and braiding (Church 1983, Burge 2005). Wandering rivers have single channel sections connecting wide, multiple channel sections and were found to plot between braided and meandering (Desloges and Church 1989, Burge 2005). Several other analyses have been conducted to differentiate braided, wandering and meandering rivers.

In 1938, the Mission Creek channel was wide and displayed numerous bars within the channel. Several variables can be used to investigate whether Mission Creek is close to the transition between meandering and braiding. For this analysis four methods were used: slope versus discharge, width-to-depth ratio versus specific stream power, median grain size versus potential specific stream power and slope/Froude number versus the depth-to-width ratio.

The simplest method compares the mean annual flood to the bed slope (Leopold and Wolman 1957). Braided rivers plot with a higher slope for a given discharge. The mean annual flood for Mission Creek is 52.1 m^3/s for all reaches because no major tributaries enter the creek downstream of Gallagher's Canyon. Figure 4-11 shows that all but two of the reaches (16 and 17) plot above the lower limit for wandering rivers on the slope discharge plot. The natural reaches plot well within the braided range. Reaches within the channelized section also plot within the braided range with reaches 6, 7, 9 and 10 plotting the highest and overlapping with the natural sections of Mission Creek. Reaches within the downstream section plot below the lower limit of wandering. The sedimentation reaches plot right at the lower limit of wandering.

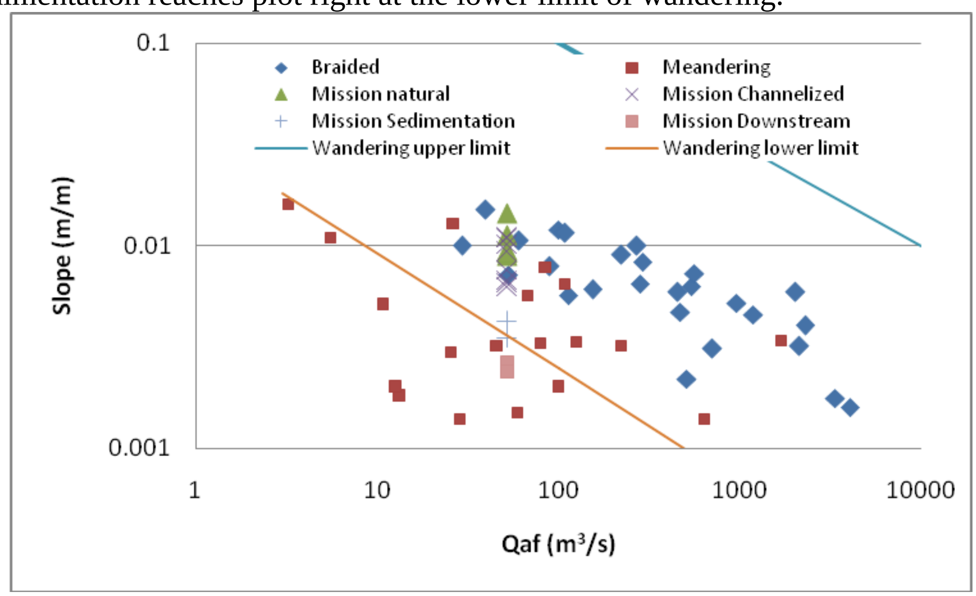


Figure 4-11. Slope versus discharge for Mission Creek (after Leopold and Wolman 1957, upper wandering limit from Desloges and Church 1989 and lower wandering limit from Burge 2005). Additional data for braided and meandering reaches is from van den Berg (1995).

A second analysis of the tendency of the Mission Creek channel to be braided compares the width-to-depth ratio to the specific stream power (Burge 2005). The analysis again clearly shows that the natural reaches and many of the channelized reaches are within the transition zone between braiding and meandering. Specifically, reaches 6 and 9 are within the braided zone and reaches 8 and 10 are well within the transition zone. The sedimentation section reaches are well within the meandering zone and the downstream reaches are in the middle of the meandering zone.

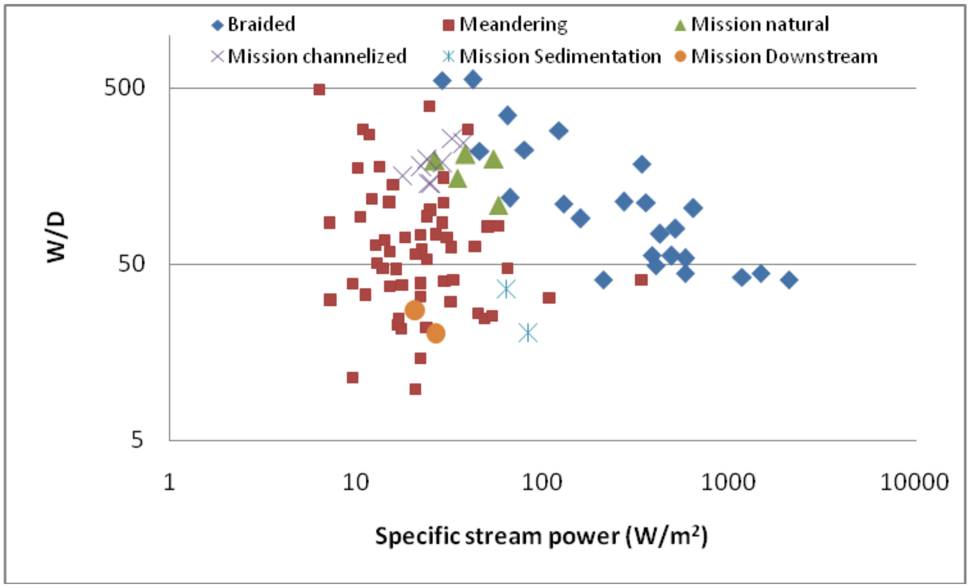


Figure 4-12. Width-to-depth ratio versus specific stream power for Mission Creek (after Burge 2005). Additional data for braided and meandering reaches is from van den Berg (1995).

An interesting analysis of the braided transition was conducted by van den Berg (1995). His analysis compensates for the fact that meandering rivers are sinuous and therefore have lower slopes than straighter braided rivers, even if they occur on the same valley slope. His analysis also includes grain size within the analysis. Grain size is important because smaller grain sizes are more easily transported than larger grain sizes. Again, the analysis shows that the Mission Creek channels are within the braided range. In this analysis all the reaches plot above the discrimination line between braided and meandering identified by van den Berg (1995). The natural reaches and the channelized reaches 9, 6, 7 and 8 plot well into the braided range. The sedimentation reaches plot closer to the transition with the downstream reaches plotting almost on the line.

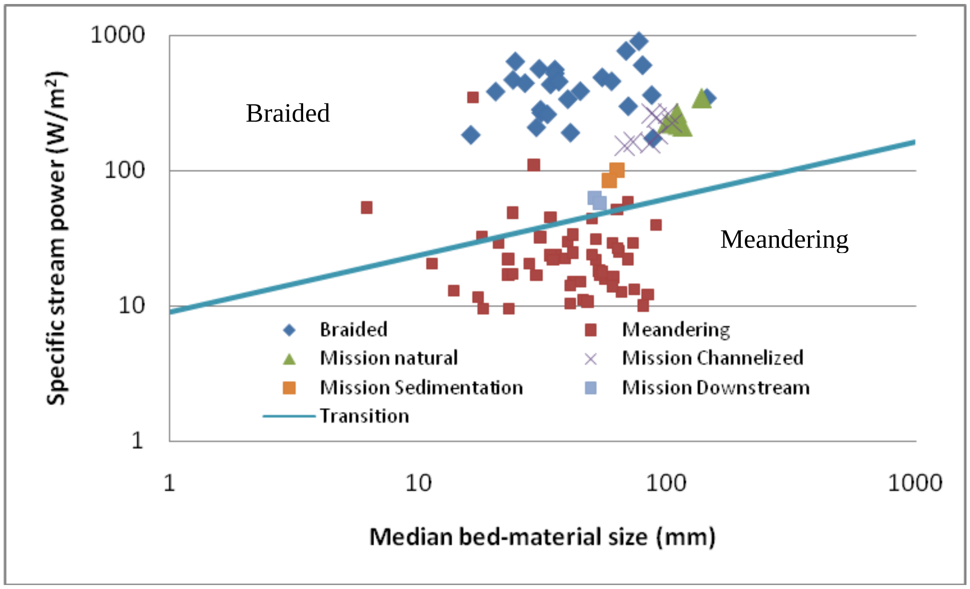


Figure 4-13. Median grain size versus potential specific stream power (after van den Berg 1995). Additional data for braided and meandering reaches is from van den Berg (1995).

The final analysis to investigate whether the conditions within the Mission Creek channel are near those of braided rivers is from Parker (1976). This analysis plots the slope divided by the Froude number versus the ratio of the bankfull channel depth to the width. This analysis shows all Mission Creek reaches plotting within the meandering zone, with the natural sections close to the meandering to braiding transition. Note that there are a number of braided rivers that also plot below the transition line suggested by Parker (1976). In this analysis several of the channelized reaches plot close to the natural reaches and braided rivers of van den Berg (1995), including reaches 10, 9, 6 and 7. Interestingly, one of the sedimentation reaches, reach 14, also plots close to the natural reaches of Mission Creek. The other sedimentation reach and the two downstream reaches plot well into the meandering zone.

The previous four analyses show that the natural Mission Creek reaches are transitional between braiding and meandering. The analyses also show that many of the channelized reaches are also transitional between braiding and meandering. Reaches 6, and 9 consistently plot within or near the braided zone, while reaches 10 and 7 were within or near the braided zone in all but one of the analyses. These reaches are near or above the transition to braiding because of their high bed slopes. This result is explained by the trend in bed slope. The slope is highest in reach 6 and then decreases through reach 7 to reach 8. The bed slope rises again in reach 9 and decreases through reach 10.

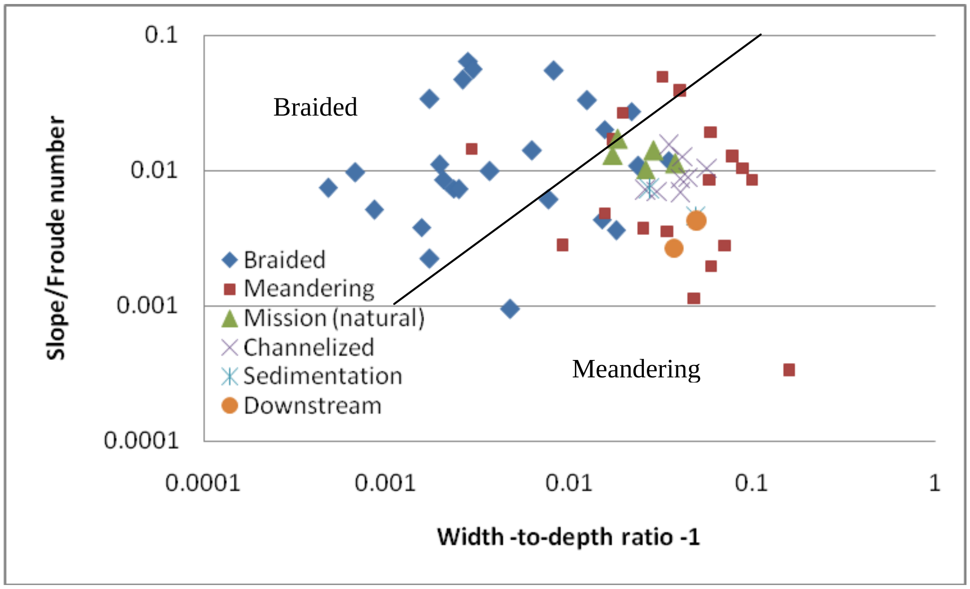


Figure 4-14. Slope divided by the Froude number versus the depth to width ratio (after Parker 1976). Additional data for braided and meandering reaches is from van den Berg (1995).

If these reaches were not confined and narrowed by dykes, they would most likely obtain a multiple channel braided or wandering pattern with in-channel bars storing sediment within the channel. Generally, these patterns with multiple channels provide heterogeneous habitat, including patches with gravel small enough for Kokanee to spawn. Side channels provide refuge from high velocities during high flows. If the channelized sections of Mission Creek were designed to cause deposition within the channel, sediment would be stored for longer times within the channel. This should slow the deposition of sediment downstream of KLO Bridge.

4.5. Comparison with Gaboury and Slaney (2003)

Gaboury and Slaney (2003) determined several channel variables based on cross-sectional data provided by the BC Ministry of Sustainable Resource Management. They found bankfull channel width averaged 31 m for the channel between KLO Bridge and Okanagan Lake (sedimentation and downstream sections of this study). This value is slightly larger than the 27.1 and 22.9 m widths determined from this study. For the same section the channel bed slope was 0.002, slightly lower than the 0.004 and 0.003 values for the two downstream most sections.

Gaboury and Slaney (2003) also noted that the channel width was near the value expected based on the empirical formula $W = 4.5\ Q^{0.5}$ however it should be noted that that this equation is most likely based on single channel meandering rivers. In addition, the data that the formula was based upon probably included sand rivers but Mission Creek has a gravel and cobble bed. In 1938, the natural Mission Creek channel downstream of KLO Bridge was significantly wider than the estimate. Using data from van den Berg (1995) and excluding any sand bedded rivers and splitting the data into meandering and braided rivers changed the formulas. For the braided rivers the new formula ($W = 3.99\ Q^{0.68}$) provided an estimate of 58 m for the channel width (Figure 4-15). For gravel bedded meandering rivers the new formula ($W = 4.14\ Q^{0.46}$) provided a new channel width of 25 m. This analysis was conducted to show that the appropriate equation needs to be used for valid comparison of the estimation of channel characteristics. The results can vary widely depending on the data on which the relationship was determined. An equation derived from local rives should be employed for channel design.

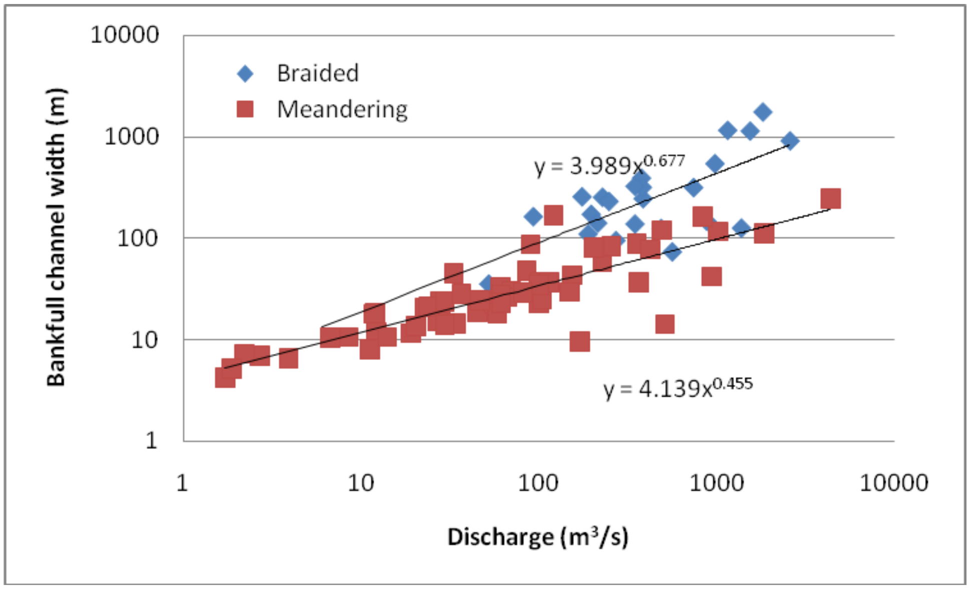


Figure 4-15. Empirical relationship between bankfull discharge and channel width. The analysis is for braided and meandering rivers and excludes sand bedded rivers. The data is from van den Berg (1995).

Gaboury and Slaney (2003) found the channel length has decreased from 29.9 to 10.8 km between East Kelowna Bridge crossing and Okanagan Lake between 1938 and 2003. However, the Mission Creek channel is not very sinuous in the 1938 photo and occupies almost the exact location today as in 1938. They also report that the channel gradient has increased due to the decrease in length from 0.002 to 0.006 m/m. This study found higher channel gradients currently (0.01 to 0.006 m/m).

5. Sedimentation mitigation strategies for Mission Creek

Sedimentation in Mission Creek is due to excess bedload being deposited below KLO Bridge. A majority of the literature on sediment mitigation concentrates on fine suspended load sediment, which may also be a problem in the lower reaches of Mission Creek but is not a focus of this study. Bedload mitigation strategies appear to rely on altering the channel characteristics, such as slope, width and depth to alter sediment transport. In this way the driving forces (specific stream power or shear stress) are manipulated to transport just the right amount of sediment through the reach. This type of channel design only works if the whole river system is analysed because the sedimentation could be transferred downstream or upstream. Another solution to a sedimentation problem is to extract the sediment through gravel mining. A final solution is to decrease the amount of sediment entering the channel.

A review of literature on mitigation of sedimentation problems on river systems found that there are three main strategies:

1. decrease the amount of sediment entering the channel
2. design a channel to carry the amount of sediment supplied to it
3. extract extra sediment from the stream channel

These three strategies will be investigated below.

5.1. Decrease sediment entering the channel

The background level of sediment input from the drainage basin may be high causing sedimentation within the channel. High sediment loads due to land use change such as urbanization, forest practices, and land use change to agricultural lands (Brierley and Fryirs 2005). Sedimentation can be mitigated by decreasing the amount of sediment supplied from upstream. Sediment often enters the channel through landslides from the valley wall connected to the river channel or erosion of the valley walls by the river channel. These processes are active in Mission Creek (Anonymous 2002). A 1998 study of the Mission Creek watershed determined the landslide hazard rating along the mainstem of Mission Creek was high (Anonymous 1998). The study also determined that landslides connected to the mainstem of the creek are the single most significant channel defining event that has occurred within the watershed. The landslide hazard rating for the remainder of the watershed and sub-basins was considered low based upon the limited number of landslides that were identified away from the channels.

A terrain stability study of the Mission Creek watershed completed in 2000 found that 97% of the 95 active and inactive landslides identified were naturally occurring (Anonymous 2000). Approximately 75% of the landslides noted were in unlogged portions of the basin. A majority of these disturbances were debris slides and a combination of debris slides and erosion events.

A historical analysis of landslide and erosion events showed mass wasting activity decreased following 1939 with many sites becoming revegetated (Anonymous 2000). Some events were active through the analysis period (1939 – 1996). Smaller landslides and erosion events (<1 500 m^3) constituted the majority of the events (65%), but 60% of the sediment was derived from three large events (>15 000m^3). The terrain stability study concluded that future landslides and erosion events are expected (Anonymous 2000). They estimated a high likelihood of reactivation of the landslide and erosion events within this area. The majority of the landslides in the study area are naturally occurring and may reactivate again in the future. Remediation of the mass wasting sites was not recommended (Anonymous 2000).

Remediation of some erosion sites within the Mission Creek basin has occurred. A total of 37 high priority erosion sites were identified in a road assessment completed in 1996 (Anonymous 1998). In 1997, 13 of the high priority sites were deactivated along with approximately 60 km of roads. Two of the high priority sites not deactivated in 1997 were reassessed in 1998 and were no longer considered to be a high priority. The remaining 22 high priority sites identified in the 1996 road assessment report had not been deactivated or repaired and the current priority as of 1998 was not known (Anonymous 1998).

There may be locally significant inputs of sediment from valley walls that could be remediated. Remediation of these sites could be conducted in a coordinated effort during the restoration of Mission Creek. One such site occurs in reach 5 (Figure 5-1A) and two additional sites occur within reach 6 (Figure 5-1BC). It should be noted that these sites are not the cause of the sedimentation downstream. However, decreasing the amount of sediment input should decrease the sedimentation a proportional amount. Note that decreasing the input of sediment could exacerbate vertical down-cutting if it is occurring. Recall that down-cutting occurs when the sediment discharge in is less than the sediment discharge out of a reach. Decreasing the sediment discharge in further in a degrading reach will cause increased down-cutting.

A.

B.

C.

Figure 5-1. Erosion sites in Mission Creek. (A) Erosion site in reach 5. (B and C) Erosion sites occurring in reach 6.

Sediment can also be released to the channel from the channel bed through degradation or down-cutting. Three reaches within Mission Creek have the potential to release sediment from the channel bed through down-cutting, reaches 6, 9 and 13.

Reach 6 is a location of in-channel engineering work (Jubb pers com. 2009). Bars were also excavated from the Hollywood Road area in 1981. This work may have decreased the channel width and caused degradation at this location. The upper portion of this reach is currently a point of a break in slope. This break in slope has the potential to migrate upstream through time. If this occurs it could cause degradation of the bed upstream into the natural section. This will release eroded sediment from the bed downstream, exacerbating the sedimentation problem downstream.

The demonstration riffle (Dill 2002) occurs within Reach 9. It also occurs at a break in slope in the long profile. The channel is well below the dyke level downstream of the demonstration riffle (Figure 5-2). There is potential for degradation and release of sediment from this reach, however the presence of the demonstration riffle mitigates much of the potential for degradation.

Figure 5-2. Mission Creek channel looking upstream at the demonstration riffle.

Reach 13 is located directly upstream of the sedimentation section. It also occurs at a break in slope in the long profile. Gravel extraction has caused the channel bed in this section to become steeper (Figure 5-3). There is potential for degradation and release of sediment from this reach.

Figure 5-3. Mission Creek channel looking upstream in reach 13.

5.2. Channel design

The second sediment mitigation strategy is to design a channel so that the sediment transport rate remains constant down the channel with the intention that the amount of sediment supplied to a section of channel is balanced by the amount of sediment transported from the channel section. The main advantage of this method is that if a solution can be found, the sedimentation problem will be fixed. The design is most challenging when the project reach is unstable due to straightening, channelization, changing hydrologic or sediment inflow conditions (Shields et al. 2008). The main disadvantage is that the channel may be so far out of equilibrium that a solution cannot be found or that the channel design is incorrect and the channel is severely eroded as occurred in a California river (Kondolf et al. 2001).

This approach requires the engineer to take into consideration upstream and downstream effects of the channel design as to not cause aggradation or degradation upstream or downstream. The restoration channel design adjusts the slope, width, depth and channel roughness so that the channel has just the right amount of energy at the bed to transport the size and amount of sediment supplied to it based on the range of expected discharge values (Shields et al. 2008). A good review of restoration design is found in Shields et al. (2003) and Shields et al. (2008). The design variables are a function of the independent variables of water discharge, sediment inflow and stream bed and stream bank characteristics.

Channel design approaches may be classified as threshold or active bed methods. Threshold methods are most appropriate when bed-material inflow is negligible. Threshold channels are designed so that a selected fraction of the bed material will be at the threshold for motion at the design discharge. Since the Mission Creek channel has considerable sediment transport, the threshold method is inappropriate according to the criteria outline in Shield et al. (2008).

Active bed approaches should be used for channels with beds that are mobilized during all high flow events (Shields et al. 2003). Active bed channels are more sensitive to changes in channel geometry and sediment transport than threshold channels. The active bed design procedure is intended to produce a channel that will transport the sediment supplied to the reach from upstream (Shields et al. 2008). The active bed design is applicable for single-thread streams with mobile beds and not braided channel networks. Detailed hydraulic and sediment transport simulations can aid in determining the channel design (Gaboury and Slaney 2003). The active bed design method uses one-dimensional hydraulics models.

Channel design width can be determined through analogy, hydraulic geometry formulas and analytical methods (Shields et al. 2008). The analogy methods set the design width to the average of the measured widths within a reference reach that is in a state of dynamic equilibrium. Hydraulic geometry equations as discussed in section 4.5 can be used to estimate the design width. The design variables width, depth and slope can be calculated using analytical methods that use computer models using the input variables discharge, sediment inflow and bed material composition. The stable channel design routine in the hydraulic design software SAM (Copland 1994, Thomas et al. 1999, SAM Hydraulic 2005) can be used to determine channel depth and slope for a sediment input rate.

Before a channel restoration design is begun, a sediment budget for Mission Creek should be conducted to aid in the channel design. The stable channel design routine (SAM) could be used.

5.3. Sediment extraction

Shield et al. (2008) note that many urban areas are built on alluvial fans or other aggradational features with channels supplied by steep headwaters. Historically, the downstream reaches maintained equilibrium by periodical avulsions. However, once floodplains are developed such changes are typically prevented, thus exacerbating the channel aggradation. The above statement well describes Mission Creek.

The effects of sediment extraction on river processes are discussed in section 2.4. As described above, there are a number of negative consequences of sediment extraction. The act of extracting sediment actually increases sedimentation where the sediment was extracted and increases the release of sediment from the channel bed through down-cutting for deposition downstream.

An additional problem with sediment extraction is that it is expensive, requiring periodic excavation and hauling of sediment. The quantities of sediment deposited in Mission Creek downstream of the KLO Bridge are substantial and the cost to maintain a sedimentation trap is considerable (see section 7.4).

Sediment extraction is however an effective way to maintain flow capacity within a channel. It may therefore be used as an interim measure to protect sections downstream from sedimentation before the sediment erosion and transfer problem from upstream can be solved through channel design.

Where sediment extraction is conducted, the channel should be returned to the preextraction condition wherever possible. A meandering thalweg and small bars should be constructed to mimic the previous condition. Sediment extraction may still result in decreased habitat but perhaps less than if the bed is left in a random morphology or with constructed sub-channels. Epp (2009) concluded that future dredging could be done with less impact to usable habitat width if more natural channel configurations and gradients were maintained. A dredged channel that more closely reflected natural conditions and gradients could naturalize more quickly.

6. Evaluation of the restoration plan for Mission Creek

This section provides an evaluation of the restoration plan outlined in the Mission Creek Habitat Restoration Feasibility Study (Gaboury and Slaney 2003) and the Mission Creek Habitat Restoration Study (Gaboury et al. 2004) based on the analyses of the Mission Creek long profile, sediment patterns, sedimentation patterns, and channel characteristics. This section will not discuss the acquisition of plots of land for the restoration.

It is clear that the restoration of meanders and riffle-pool sequences is a successful method of restoring fish habitat in channelized streams (Newbury and Gaboury 1994; Newbury et al. 1997). Locally, the Okanagan River is planned to be restored by setting back the dykes and remeandering the channel (Bull et al. 2000). I agree that complete removal of dykes, although preferable for the geomorphic recovery of Mission Creek, would compromise the flood protection of the City of Kelowna (Gaboury and Slaney 2003). I also agree that re-setting the dykes back on one or both sides of the channel will improve the geomorphic functioning of the channel. One would reasonably expect that an increase in channel width to 40-50 m from 30-40 m would result in bar formation, better pool and riffle definition, substrate sorting to improve spawning gravels and the creation of forested islands (Gaboury and Slaney 2003). A greater setback of the dykes of 20 to 200 m will result in greater restoration of the natural morphology of the channel, including riffle-pool restoration, well sorted substrates, braided channels with numerous islands and ecological interfaces of pool and riparian zones and large areas of usable fish habitat (preferred depths velocities, and substrates and cover) (Gaboury and Slaney 2003). Floodplains would recover within the dykes benefiting nutrient cycling and natural hydrological linkages between the floodplain and the channel. Finally, set back dykes provide better flood protection than narrow dykes because of the increased flood capacity (larger flood channel area). In addition, dyke maintenance should decrease because of the decrease in velocities within the stream that cause erosion and damage to the dykes themselves (Gaboury and Slaney 2003). The condition of the Mission Creek dykes have raised concern for many years (McMullen 1988, Bergman 1995)

An additional advantage of creating a floodplain is that the floodplain stores sediment. Without a floodplain upstream sediment sources that would naturally be stored in the floodplain or channel are routed to downstream lower gradient reaches where the sediment accumulates (Gaboury and Slaney 2003). The aggraded sediments then need to be removed from the channel to prevent the bed and water table from being higher than the surrounding residential and agricultural lands (Gaboury and Slaney 2003). Gaboury and Slaney (2003) identify three channel segments for restoration (Table 6-1).

Table 6-1. Proposed treatments for three channel segments from Gaboury and Slaney (2003).

Channel segment	*Restoration treatment*
Gordon road and Regional Park	Setback dykes
KLO road and Regional Park	Meandering channel with riffle-pool sequences
Regional park to East Kelowna Bridge	Riffle structures, sediment traps and re-define meandering channel

Gaboury et al. (2004) outline restoration plans for the Benvoulin woods meander channel and a sediment trap near Hollywood road. The plan for the Benvoulin woods is to (1) set back the dykes, (2) lower the elevation of the existing dykes and stream bank to create a floodplain that is regularly flooded, (3) construct a meandering channel with riffles and pools using rock riffles, and (4) establish vegetation on the reconstructed banks and floodplain. Because the channel energy is low within this section of channel the possibility of large scale failure of the reconstruction is low. As discussed in previous sections, there is a potential problem for sedimentation within the channel here. The sedimentation problem could be exacerbated by decreasing the slope further due to the increase in channel length from the remeandering.

The second main recommendation of Gaboury et al. (2004) is to construct sediment traps within Mission Creek using rock riffles near Hollywood Road. This location was chosen in part because the channel is incised below the floodplain and therefore there is little flooding hazard in this reach. These traps are expected to hold 5 000 m^3 of sediment. This is only half of the volume of sediment extracted downstream of the KLO Bridge in 2006. The proposed sediment traps would be constructed within reach 6. This reach displays some of the highest energy levels within Mission Creek. This reach has a high potential for degradation which is why the channel is incised in this location. It is unlikely that sediment will deposit within this section without significant head loss from engineering works to decrease the local slope. In addition, sediment will likely continue to deposit downstream of KLO Bridge because of the processes discussed in section 2-4. If sedimentation downstream of the KLO Bridge is to be minimized, this section of channel will need to be reengineered to carry the amount of sediment supplied to it. If present conditions remain, sedimentation will continue downstream of the KLO Bridge.

If it is shown that sediment traps need to be constructed, they should be built where sedimentation is currently occurring. In this way the channel design works with the river to utilize its tendencies and not fight against them.

Because the Mission Creek channel upstream of the KLO Bridge was a wandering or braided river prior to 1938, it may be inappropriate to “restore” the channel to a meandering pattern. Also, the present channel conditions are within the braided range (Figure 4-11, Figure 4-12, Figure 4-13 and Figure 4-14). As described by Kondolf et al.

(2001), modifying a channel to the wrong river pattern can have spectacular and disastrous results. In Coastal California a river was "restored" from a braided river to a meandering river in 1996. The following year, a flood had rearranged the channel to a braided channel. The sediment supply from upstream must be carefully considered before a channel design is decided upon.

A sediment budget should be completed before riffles are constructed within Mission Creek. In some sections, such as the sedimentation section, sediment might overwhelm constructed riffles. In other areas, such as section 6, riffles may be undercut and damaged by high flows. The sediment budget will ultimately aid in the channel design.

Downstream of KLO Bridge the Mission Creek probably was meandering. Evidence of meandering is seen in the floodplain seen in the 1938 orthomap. Therefore, it is appropriate to "restore" the channel to a more sinuous path within the set back dykes.

7. Recommendations

The analyses contained in this report yielded a number of recommendations for the mitigation of sedimentation on Mission Creek. These recommendations are based on processes occurring in three main areas working downstream: the channelization section, the sedimentation section, and the downstream section.

The setting back of dykes to form a floodplain within the new dyke location to improve the geomorphic and ecological functioning of the river is sound. Land should be purchased where possible to allow for the setback of the dykes.

It is important to know where and how much degradation has occurred to understand how much of the sedimentation downstream of the KLO Bridge is due to down-cutting of the channel itself. Therefore a sediment budget for Mission Creek should be calculated using appropriate software such as SAM Design Package for Channels as recommended by Gaboury and Slaney (2003).

Shear stresses on the bed should be evaluated using a hydraulic model such as HEC-RAS to further investigate the potential to mitigate the sediment erosion and deposition within Mission Creek, particularly in the channelized and sedimentation sections.

Once the sediment budget of the channel has been determined, the appropriate channel design methodology should be used. If the channel is shown to have an active bed, channels should be designed using the active bed method (Shields et al. 2006). If possible a channel should be designed to transfer the sediment supplied to it so that aggradation or degradation do not occur.

7.1. Channelization section recommendations

Determine whether degradation is occurring in reach 6. If degradation is occurring, reengineer the channel to stop the degradation. Most importantly the channel degradation cannot be allowed to progress upstream into the natural section. Possible solutions are to place a rock riffle constructed of very large boulders across the bed of the creek to limit further degradation and hold the nick-point in place.

Determine whether degradation is occurring in reach 9 downstream of the demonstration riffle. This section has high slope and energy values and may be degrading. If it is degrading, the down-cutting could to be halted through the addition of rock riffles downstream of the demonstration riffle to control channel gradient.

Determine the extent of degradation in reach 13, upstream of KLO Bridge. This section has high slope and energy values and may be degrading. If it is degrading, the down-cutting could to be halted through the addition of rock riffles.

There are two options for the restoration of the Mission Creek channelized section. In both options the dykes are set back as far as possible to allow for a functioning floodplain within the channelized section.

The first option is to create a meandering channel as Gaboury and Slaney (2003) recommends. The meandering channel could be held in place by large rip-rap and will be designed so that channel degradation will not occur. However, this option does not adequately deal with the excess sediment that is deposited in the sedimentation section. Nor does it return the channel to its prechannelized condition with multiple channels and mid-channel bars. Sediment traps can be built upstream in the channelization section and excavated periodically to decrease sedimentation downstream as described by Gaboury and Slaney (2003) but this option works against the rivers natural tendencies in this section. The improper location of a sediment trap could enhance bed degradation downstream.

The second option is to allow the channel to attain its natural channel pattern. As shown in the river pattern analysis, Mission Creek will likely attain a wandering channel pattern similar to the natural section upstream. If this occurs, the channel will contain vegetated islands, back channels and a wider channel. This will greatly increase the habitat value of this section as patches with small size gravels will be provided for Kokanee spawning and back channels will be formed for rearing and refuge from high velocities.

The channel between where Mission Creek exits its valley and the KLO Bridge could be widened to 60 m, approximately the channel width in 1938. The channel bed area in the wider channel would increase from 103 000 to 304 000 m^2. If the 93 690 m^3 of sediment deposited downstream of KLO Bridge since 1967 were spread out over the larger channel the bed would have only risen 0.31m. However, degradation has also occurred within the channelized reach since 1967. It is unknown where and how much degradation has occurred. But, it is probable that the bed level increase would be offset by a decrease in the amount of degradation.

7.2. Sedimentation section recommendations

Currently, excessive sedimentation is occurring downstream of the KLO Bridge. The deposition of sediment decreases the channel flood capacity and the capacity for water to flow under the KLO Bridge. The sedimentation section has been used to collect and extract sediment for more than 30 years. This should continue in the short term to maintain channel capacity for high flows and to protect restoration works that are planned to be constructed within the downstream section from being overwhelmed by sediment. If the overall channel design for Mission Creek cannot accommodate the amount of sediment supplied to the channel, this section can be used as a sediment trap. The advantages of using this location as a sediment trap are that it already traps sediment, is already disturbed by excavation and has easy access to a main road.

One problem with gravel extraction is that it disturbs a long length of river channel. If this section is to be used as a long term sediment trap, one option is to enhance the sedimentation in the sedimentation section. Deposition of gravel could be enhanced downstream of the KLO Bridge so that sedimentation and gravel exaction disturbance is minimized. Sedimentation is already enhanced in this location by its low slope; however channel widening would further enhance deposition. This would mean setting back the dykes to increase the channel width. This would also increase the channel capacity and decrease flooding risk. Sediment could then be extracted from the channel bed when the channel capacity was compromised. The cost of the extraction is found in section 7.3.

The channel upstream of the KLO Bridge should be graded so that sediment does not accumulate directly under the bridge. Sediment transport rates need to be maintained through the sections upstream and just downstream of the bridge. The engineering could include rock riffles to control local grade and stop the potential for upstream degradation.

Sediment input to Mission Creek should be decreased to reduce the volume of sedimentation downstream of KLO Bridge. Degradation of the river channel may have been a significant contribution to the sedimentation. As recommended above, three sections were identified as having the potential for degradation. If these reaches are down-cutting, they are releasing sediment downstream for sedimentation. Reengineering the channel to stop degradation within the channelized section will therefore decrease deposition within the sedimentation reach.

7.3. Downstream section

Within the downstream section land should be purchased to set back the dykes. A channel should be designed to carry the sediment supplied to it from upstream if possible using the active bed method (Shields et al. 2008) if the channel bed is active. According to Shields et al. (2008) the approach to channel design outlined in Gaboury and Slaney (2003) is appropriate if the channel is found to be a threshold channel with little sediment movement. Restoration of the riffle-pool sequence could provide enhanced deposition of spawning gravels for Kokanee and holding areas for adult fish as well as rearing areas for Rainbow juveniles (Gaboury and Slaney 2003).

7.4. Cost estimates for operation & maintenance including frequency of attention to repair, cleaning, etc., after installation

Cost of gravel extraction was provided by Stan Parker at Ansell Construction Ltd (250-769-4293). An additional quote from A. G. Appel Enterprises Ltd, 1145 Gordon Drive, Kelowna, B.C. was \$2 per m^3 to excavate the sediment and \$5.88 to haul the sediment off site. This is slightly lower than the \$8-10 per m^3 quoted from Ansell Construction Ltd. The cost estimates are based on the sediment volume extracted following the 2006 flood (Table 7-1). The cost of gravel extraction ranges from \$78 800 to \$100 00 for the excavator, and to haul the gravel away from the site. Costs could be recovered through selling the sediment to a gravel pit. The estimated value of the gravel is \$20 000. This lowers the cost to \$58 800 to \$80 000. Based on the historical analysis, the sediment would need to be excavated every 8 years on average. Therefore the cost per year for the maintenance of the sedimentation section is \$7 500 - 10 000 / year on average.

Table 7-1. Cost of sediment extraction from sedimentation section.

	Volume	**Distance downstream**	**Width of channel**	**Area of extraction**	**Depth of extraction**	**Rate**	**Cost**	**Time**
Sediment extracted from bed	10 000 m^3	1, 000 m	30 m	30 000 m^2	0.33m	7.88-10 $/$m^3$	$78 800 – $100,000	3 to 4 weeks
Sediment sold to gravel pit	10 000 m^3					2 $/$m^3$	- 20 000	
Total estimated cost							**$58 800– $80 000**	

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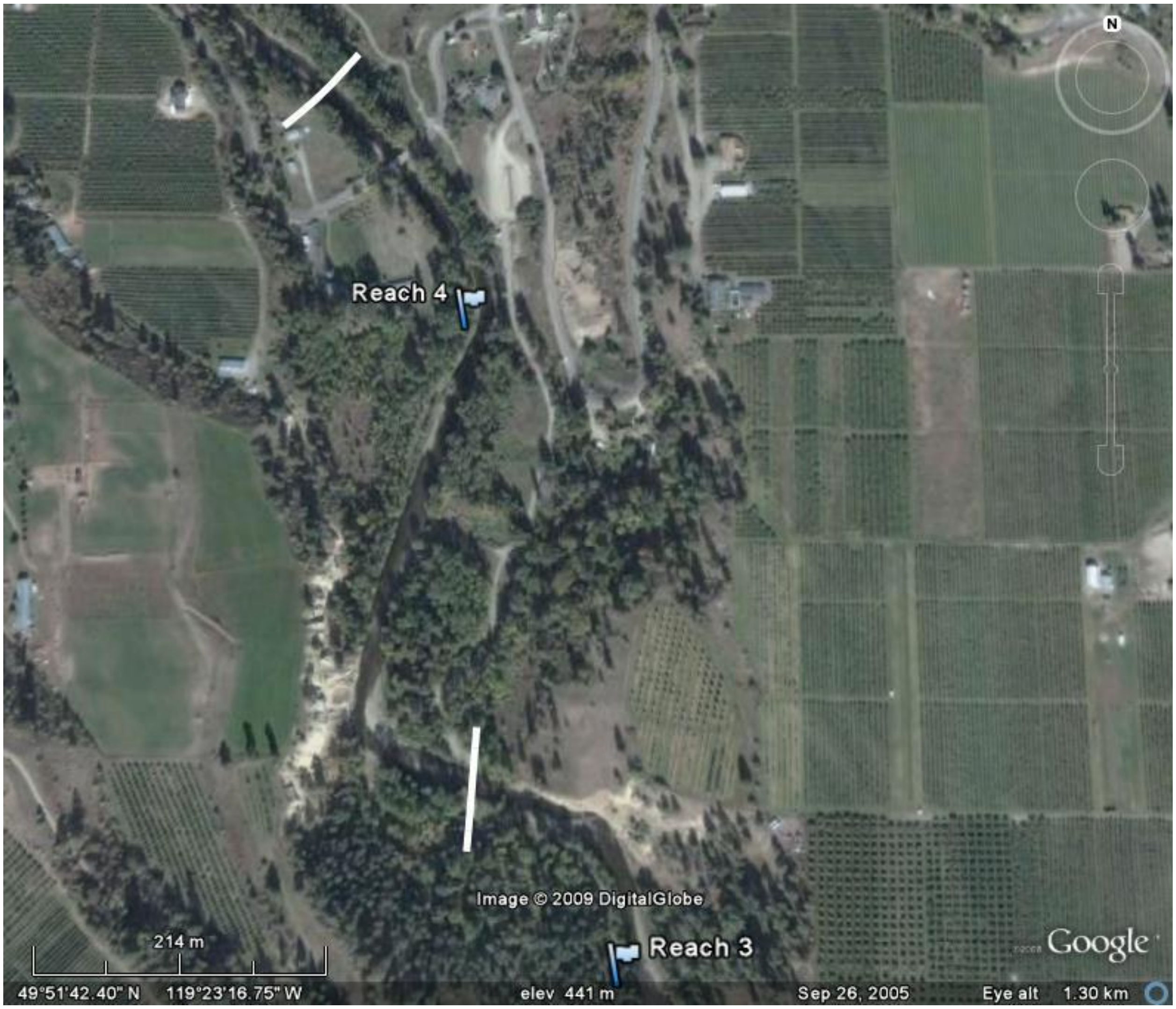
9. Appendix 1 – Reach characteristics

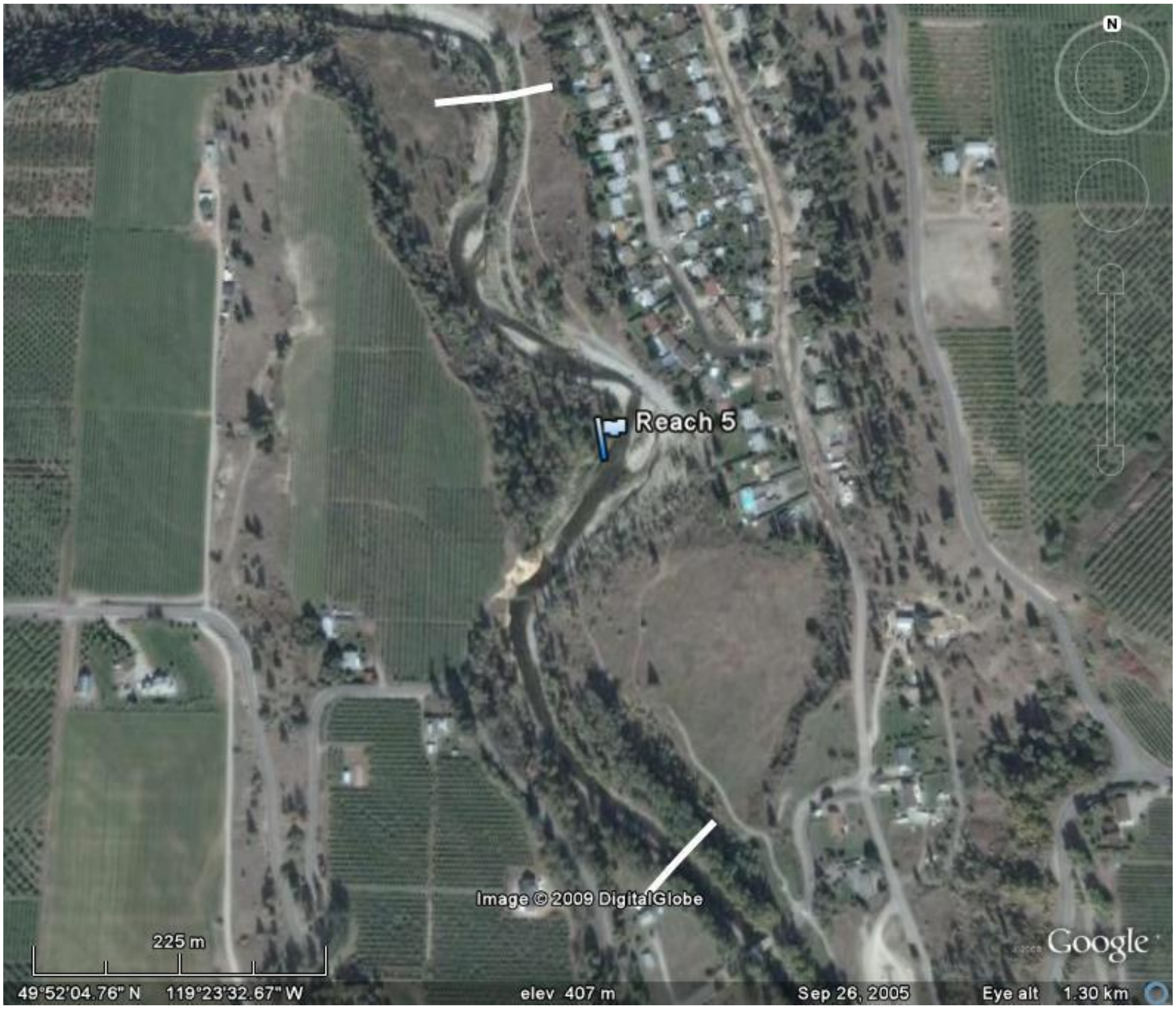
Reach #	**1**	*Length (m)*	1044.7
Start (m)	0	*End (m)*	1044.7
Reach type	Wandering	*Avg. width (m)*	36.3
Slope (m/m)	0.0144	*Avg. depth (m)*	0.67
D16 (mm)	67	*Width/Depth*	54.5
D50 (mm)	137	*Avg. R*	0.67
D84 (mm)	239	*Avg. Velocity (m/s)*	2.52
Avg. % Sand (<2mm)	0	*Shear stress (Pa)*	94.2
Avg. % Gravel (2-62mm)	15	*Mobility Ratio*	0.69
Avg % Cobbles (64-128 mm)	72	*Specific stream power (W/m^2)*	198
Avg. % Boulders (>128mm)	13	*Avg. Fr*	0.99

Reach #	**2**	*Length (m)*	1055.1
Start (m)	1044.7	*End (m)*	2099.8
Reach type	Wandering	*Avg. width (m)*	41.0
Slope (m/m)	0.0089	*Avg. depth (m)*	0.71
D16 (mm)	63	*Width/Depth*	58.0
D50 (mm)	115	*Avg. R*	0.72
D84 (mm)	195	*Avg. Velocity (m/s)*	1.86
Avg. % Sand (<2mm)	0	*Shear stress (Pa)*	62.5
Avg. % Gravel (2-62mm)	18	*Mobility Ratio*	0.54
Avg % Cobbles (64-128 mm)	76	*Specific stream power (W/m^2)*	109
Avg. % Boulders (>128mm)	5	*Avg. Fr*	0.71

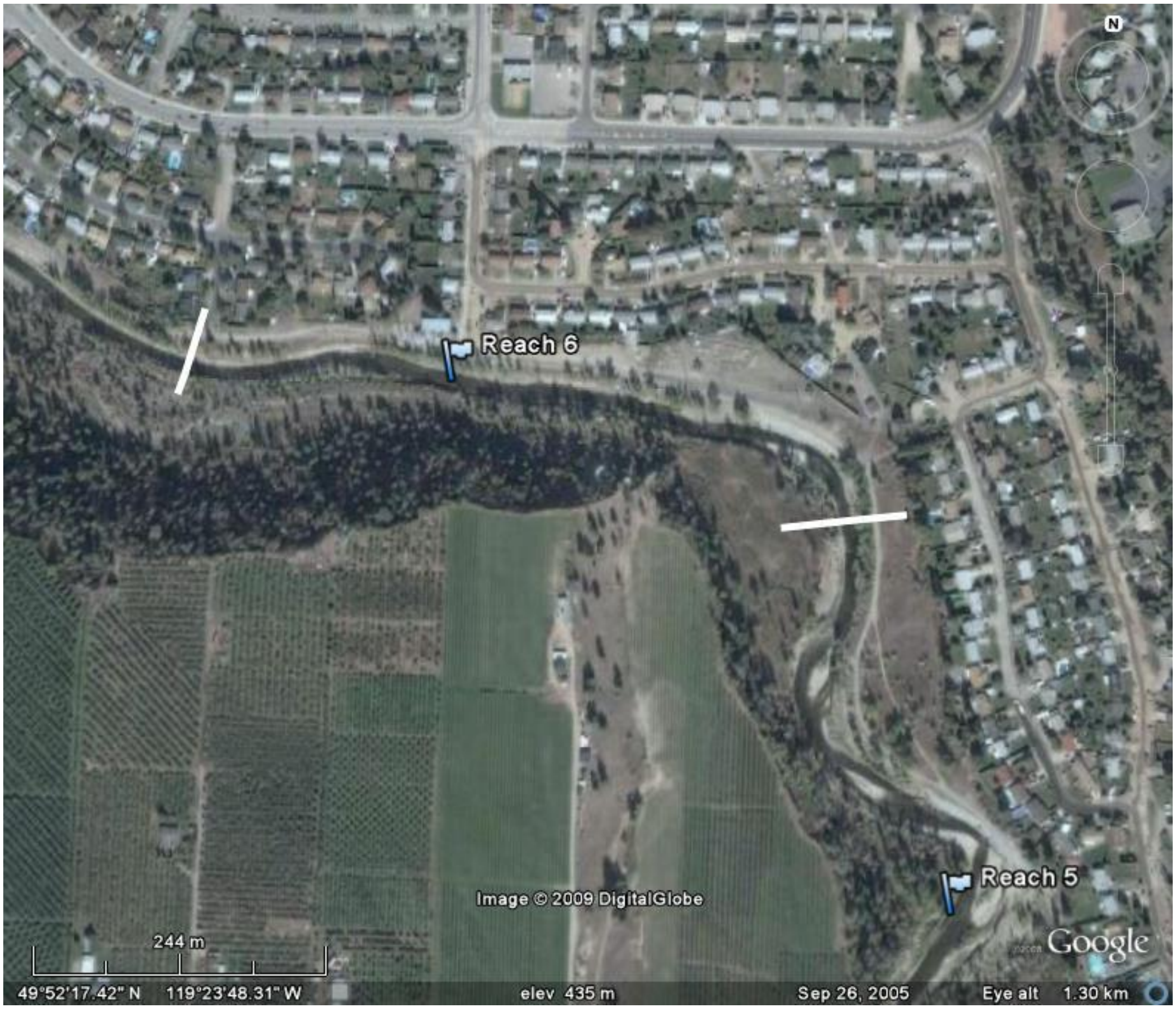
Reach #	**3**	*Length (m)*	764.6
Start (m)	2099.8	*End (m)*	2864.4
Reach type	Wandering	*Avg. width (m)*	30.5
Slope (m/m)	0.0094	*Avg. depth (m)*	0.87
D16 (mm)	58	*Width/Depth*	34.8
D50 (mm)	100	*Avg. R*	0.86
D84 (mm)	177	*Avg. Velocity (m/s)*	2.03
Avg. % Sand (<2mm)	0	*Shear stress (Pa)*	79.4
Avg. % Gravel (2-62mm)	22	*Mobility Ratio*	0.79
Avg % Cobbles (64-128 mm)	74	*Specific stream power (W/m^2)*	154
Avg. % Boulders (>128mm)	4	*Avg. Fr*	0.69



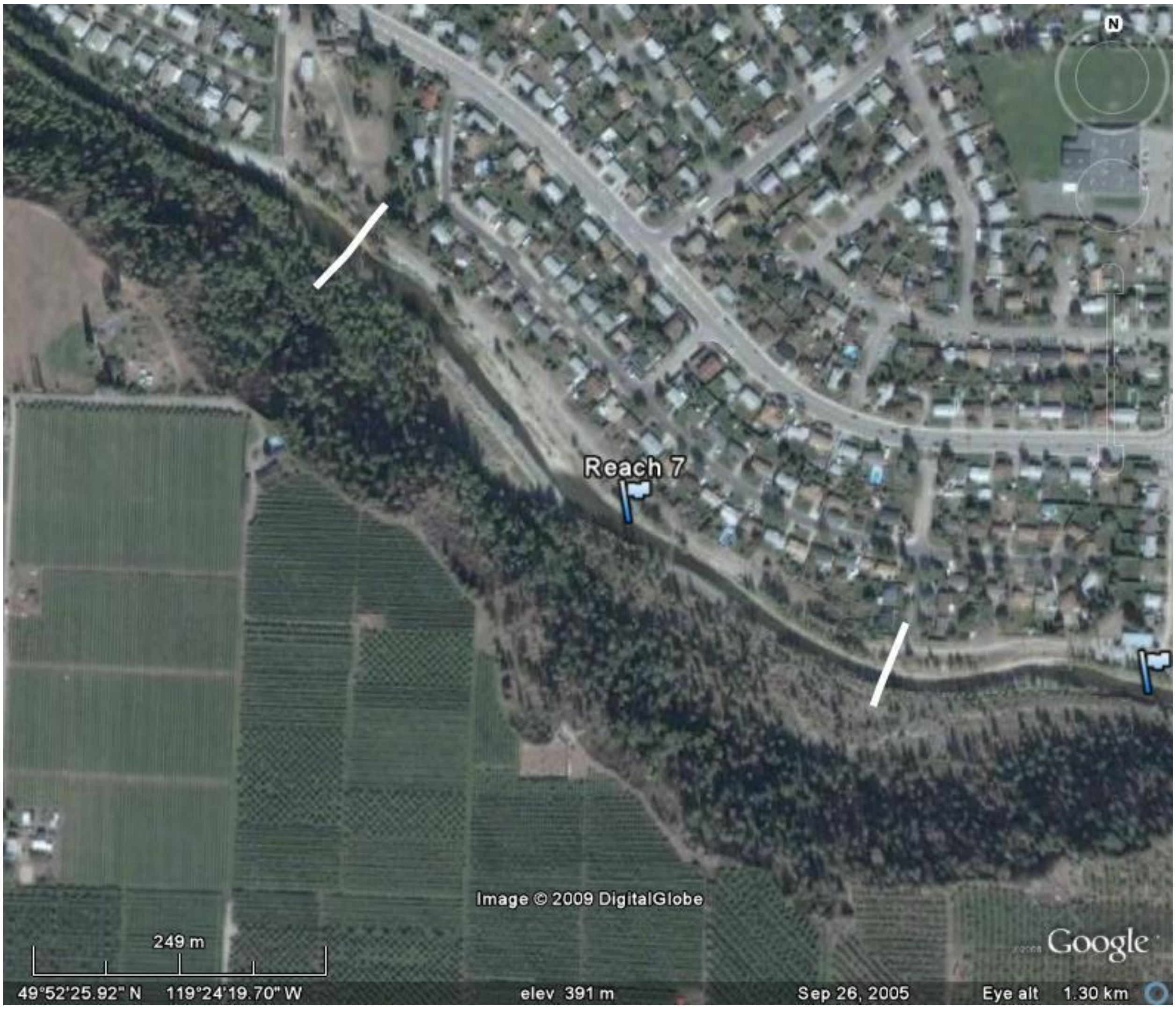
Reach #	**4**	*Length (m)*	744.4
Start (m)	2864.4	*End (m)*	3608.8
Reach type	Wandering	*Avg. width (m)*	23.8
Slope (m/m)	0.0092	*Avg. depth (m)*	0.90
D16 (mm)	56	*Width/Depth*	26.4
D50 (mm)	111	*Avg. R*	0.88
D84 (mm)	205	*Avg. Velocity (m/s)*	2.39
Avg. % Sand (<2mm)	1	*Shear stress (Pa)*	79.2
Avg. % Gravel (2-62mm)	21	*Mobility Ratio*	0.72
Avg % Cobbles (64-128 mm)	70	*Specific stream power (W/m^2)*	193
Avg. % Boulders (>128mm)	8	*Avg. Fr*	0.80



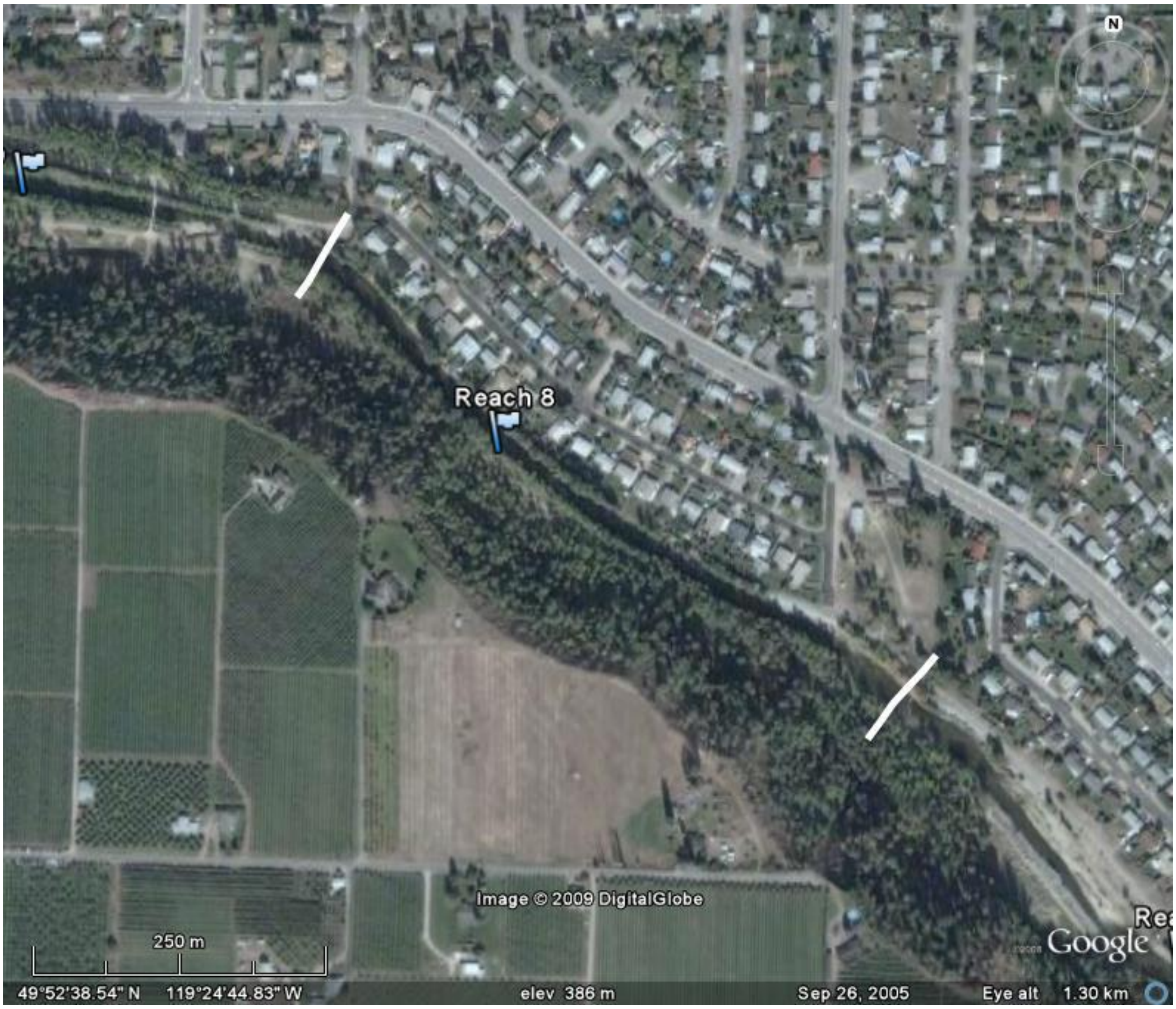
Reach #	**5**	*Length (m)*	845.5
Start (m)	3608.8	*End (m)*	4454.3
Reach type	Wandering	*Avg. width (m)*	26.6
Slope (m/m)	0.0112	*Avg. depth (m)*	0.69
D16 (mm)	54	*Width/Depth*	38.6
D50 (mm)	110	*Avg. R*	0.67
D84 (mm)	245	*Avg. Velocity (m/s)*	3.11
Avg. % Sand (<2mm)	4	*Shear stress (Pa)*	73.5
Avg. % Gravel (2-62mm)	19	*Mobility Ratio*	0.67
Avg % Cobbles (64-128 mm)	65	*Specific stream power (W/m^2)*	211
Avg. % Boulders (>128mm)	13	*Avg. Fr*	1.20



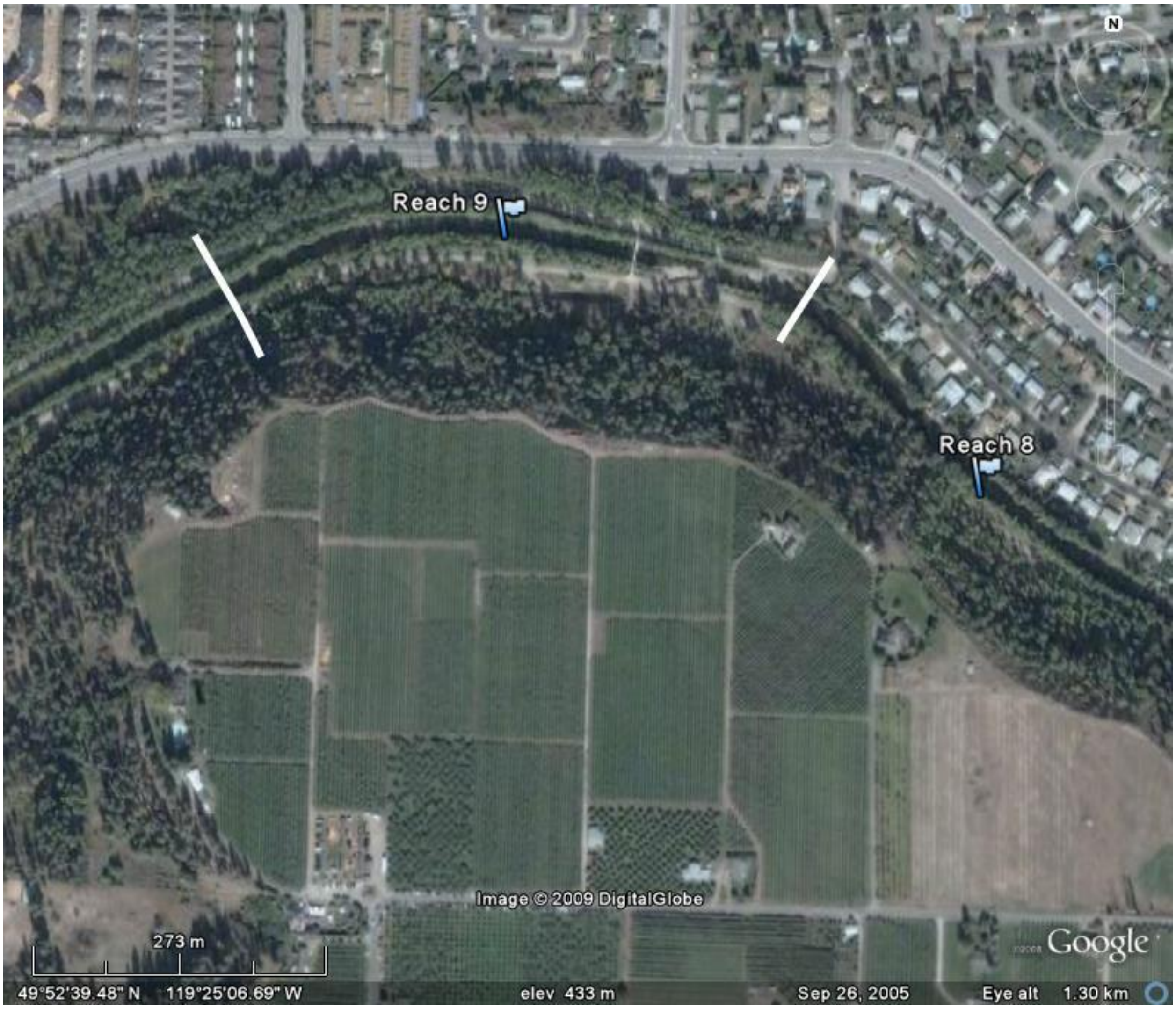
Reach #	**6**	*Length (m)*	615.6
Start (m)	4454.3	*End (m)*	5069.9
Reach type	Channelized	*Avg. width (m)*	21.0
Slope (m/m)	0.0109	*Avg. depth (m)*	0.64
D16 (mm)	48	*Width/Depth*	33.0
D50 (mm)	101	*Avg. R*	0.63
D84 (mm)	150	*Avg. Velocity (m/s)*	3.83
Avg. % Sand (<2mm)	2	*Shear stress (Pa)*	66.9
Avg. % Gravel (2-62mm)	21	*Mobility Ratio*	0.67
Avg % Cobbles (64-128 mm)	73	*Specific stream power (W/m^2)*	259
Avg. % Boulders (>128mm)	5	*Avg. Fr*	1.53



Reach #	**7**	*Length (m)*	633.9
Start (m)	5069.9	*End (m)*	5703.8
Reach type	Channelized	*Avg. width (m)*	23.4
Slope (m/m)	0.0093	*Avg. depth (m)*	0.98
D16 (mm)	48	*Width/Depth*	23.8
D50 (mm)	105	*Avg. R*	0.96
D84 (mm)	212	*Avg. Velocity (m/s)*	2.27
Avg. % Sand (<2mm)	1	*Shear stress (Pa)*	87.4
Avg. % Gravel (2-62mm)	26	*Mobility Ratio*	0.84
Avg % Cobbles (64-128 mm)	62	*Specific stream power (W/m^2)*	199
Avg. % Boulders (>128mm)	11	*Avg. Fr*	0.73

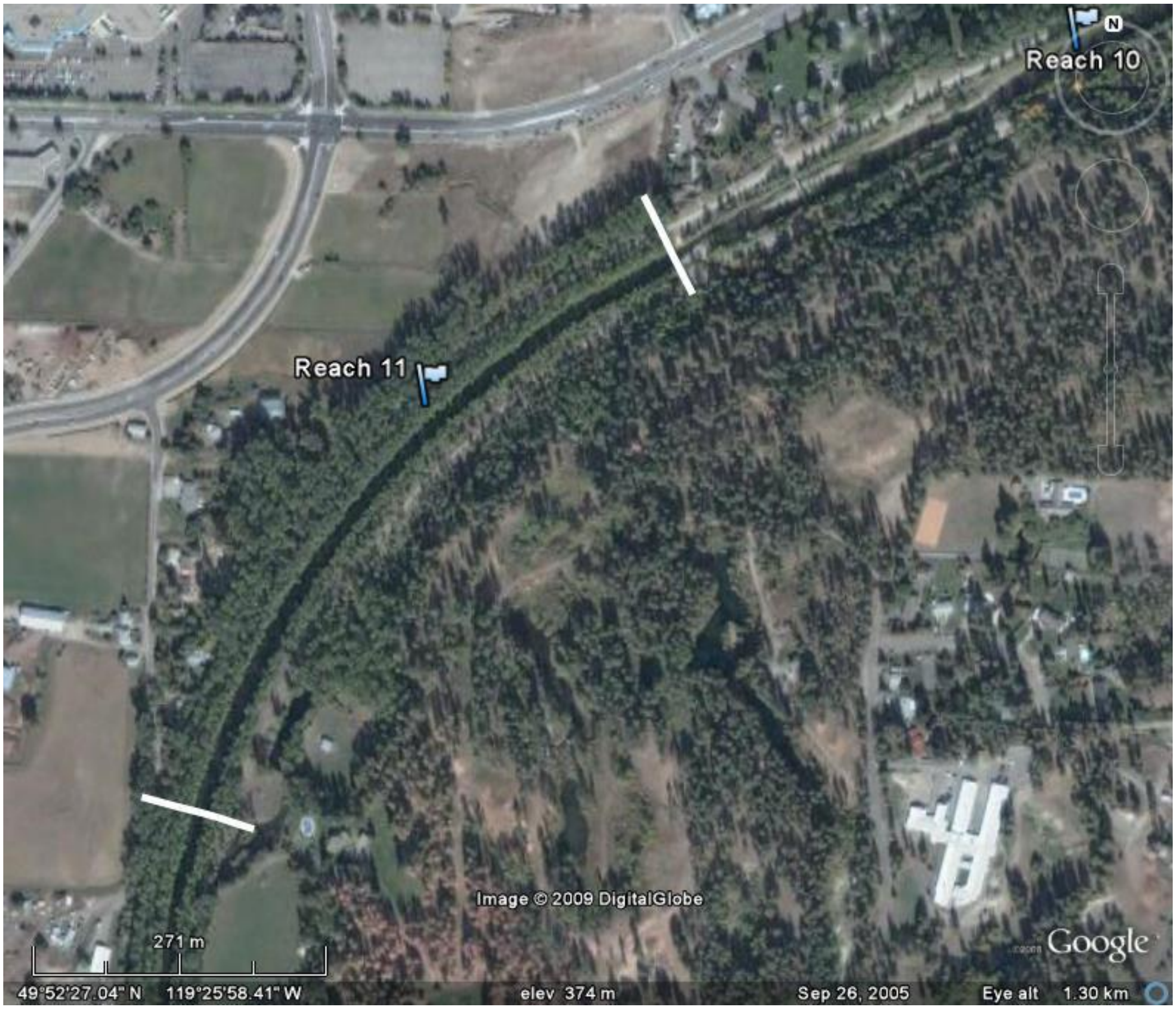


Reach #	**8**	*Length (m)*	634.7
Start (m)	5703.8	*End (m)*	6338.5
Reach type	Channelized	*Avg. width (m)*	21.4
Slope (m/m)	0.0076	*Avg. depth (m)*	0.94
D16 (mm)	43	*Width/Depth*	22.6
D50 (mm)	92	*Avg. R*	0.92
D84 (mm)	192	*Avg. Velocity (m/s)*	2.55
Avg. % Sand (<2mm)	3	*Shear stress (Pa)*	68.7
Avg. % Gravel (2-62mm)	33	*Mobility Ratio*	0.75
Avg % Cobbles (64-128 mm)	63	*Specific stream power (W/m^2)*	178
Avg. % Boulders (>128mm)	3	*Avg. Fr*	0.84



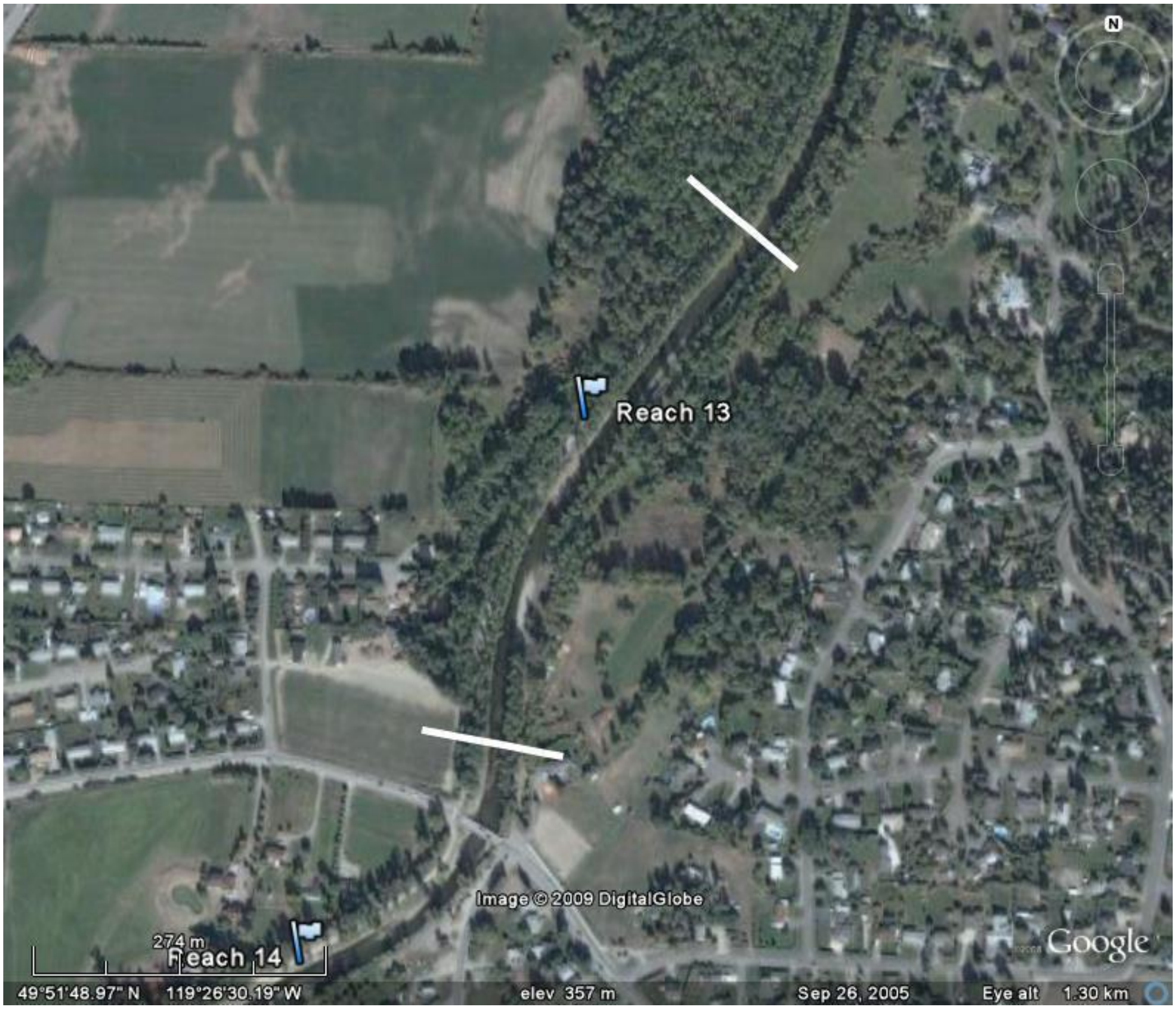
Reach #	**9**	*Length (m)*	562.5
Start (m)	6338.5	*End (m)*	6901
Reach type	Channelized/engineered riffle	*Avg. width (m)*	22.9
Slope (m/m)	0.011	*Avg. depth (m)*	0.60
D16 (mm)	37	*Width/Depth*	38.1
D50 (mm)	87	*Avg. R*	0.59
D84 (mm)	183	*Avg. Velocity (m/s)*	4.02
Avg. % Sand (<2mm)	2	*Shear stress (Pa)*	64.0
Avg. % Gravel (2-62mm)	34	*Mobility Ratio*	0.74
Avg % Cobbles (64-128 mm)	59	*Specific stream power (W/m^2)*	240
Avg. % Boulders (>128mm)	7	*Avg. Fr*	1.66

Reach #	**10**	*Length (m)*	723.1
Start (m)	6901	*End (m)*	7624.1
Reach type	Channelized	*Avg. width (m)*	27.1
Slope (m/m)	0.0102	*Avg. depth (m)*	0.94
D16 (mm)	34	*Width/Depth*	28.8
D50 (mm)	91	*Avg. R*	1.07
D84 (mm)	164	*Avg. Velocity (m/s)*	2.16
Avg. % Sand (<2mm)	1	*Shear stress (Pa)*	106.7
Avg. % Gravel (2-62mm)	37	*Mobility Ratio*	1.18
Avg % Cobbles (64-128 mm)	58	*Specific stream power (W/m^2)*	188
Avg. % Boulders (>128mm)	4	*Avg. Fr*	0.71

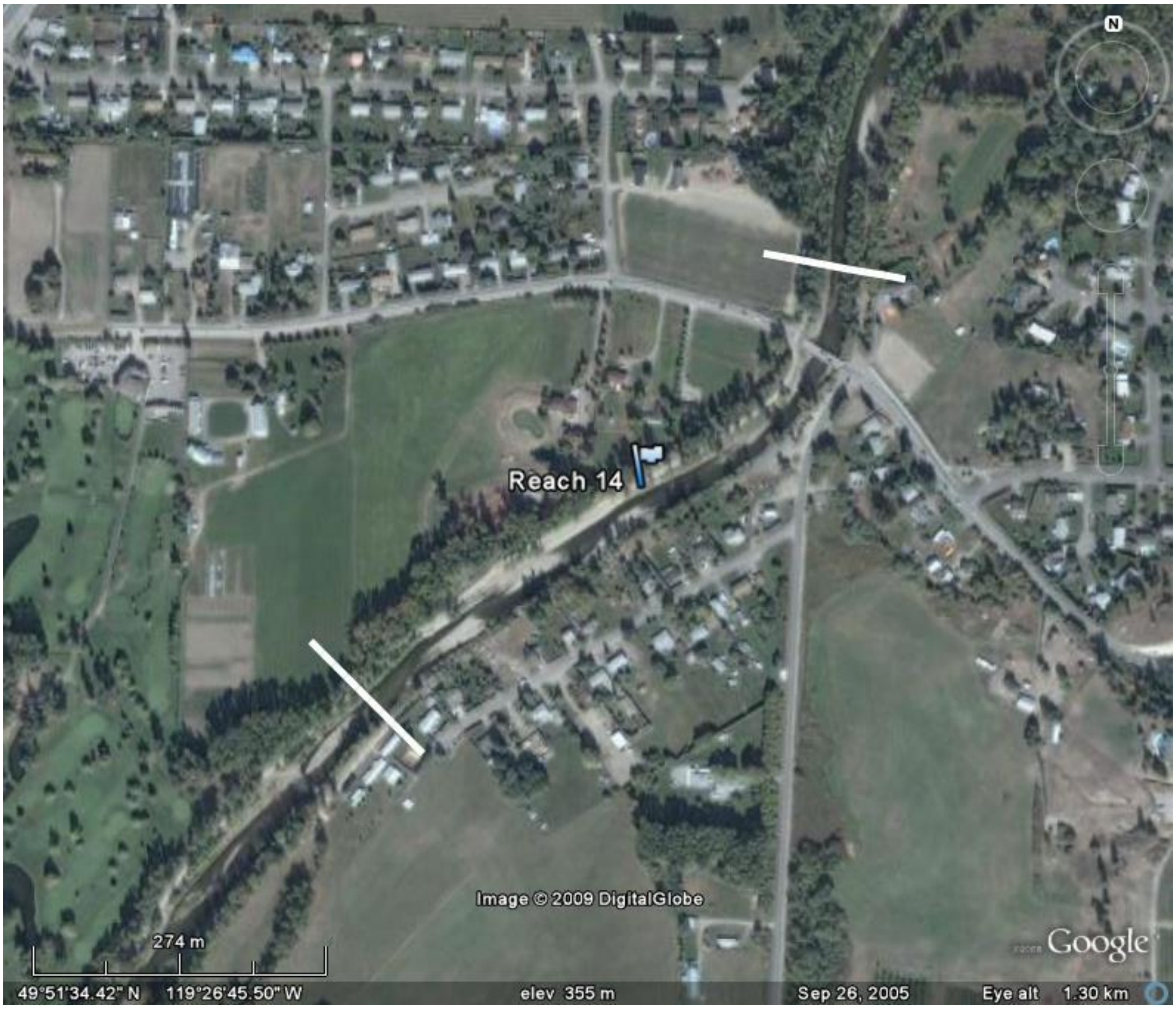


Reach #	**11**	*Length (m)*	680.4
Start (m)	7624.1	*End (m)*	8304.5
Reach type	Channelized	*Avg. width (m)*	20.7
Slope (m/m)	0.0066	*Avg. depth (m)*	1.17
D16 (mm)	37	*Width/Depth*	17.7
D50 (mm)	85	*Avg. R*	1.11
D84 (mm)	164	*Avg. Velocity (m/s)*	2.14
Avg. % Sand (<2mm)	1	*Shear stress (Pa)*	71.9
Avg. % Gravel (2-62mm)	38	*Mobility Ratio*	0.84
Avg. % Cobbles (64-128 mm)	60	*Specific stream power (W/m^2)*	160
Avg. % Boulders (>128mm)	2	*Avg. Fr*	0.63

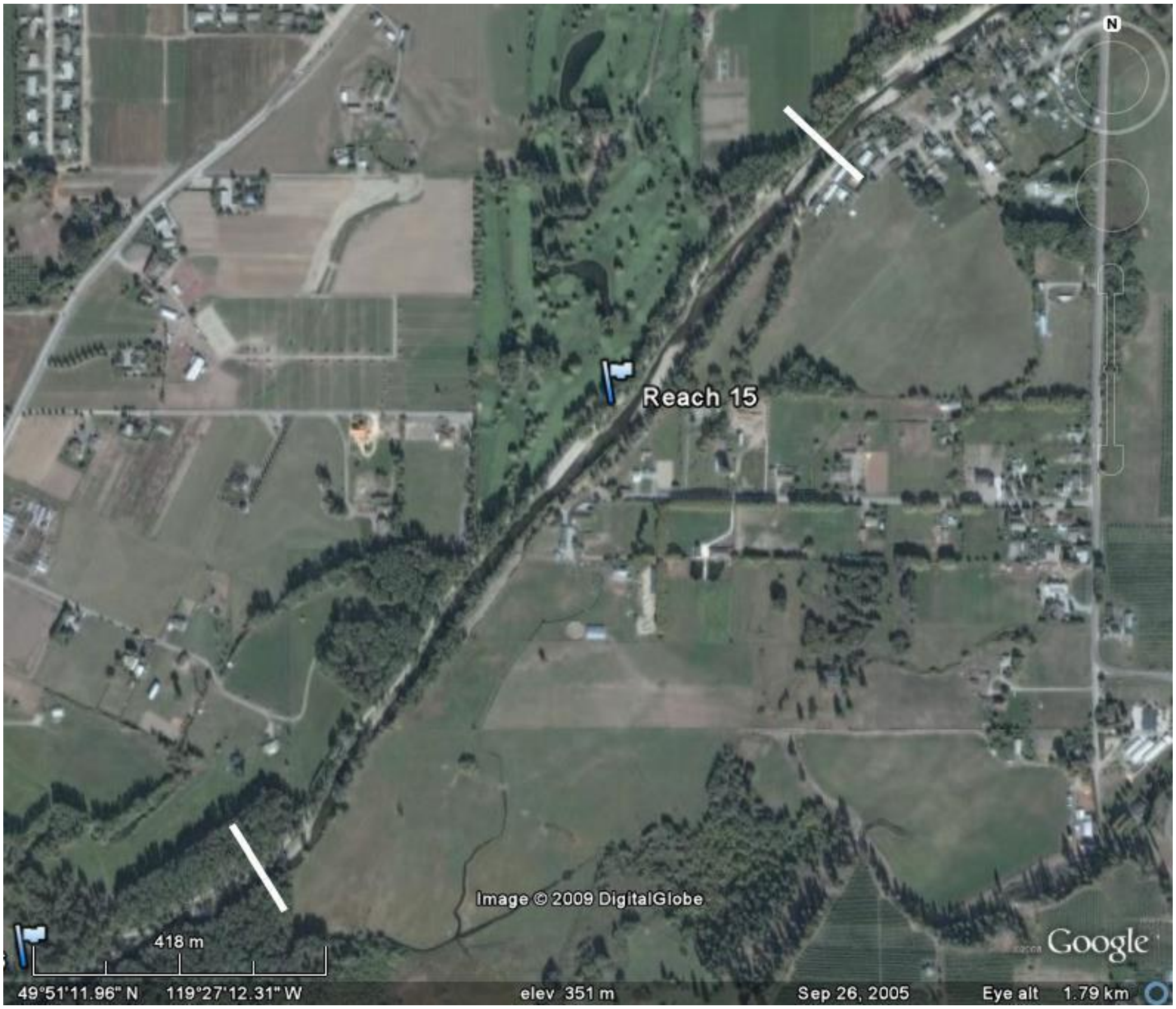
Reach #	**12**	*Length (m)*	681.9
Start (m)	8304.5	*End (m)*	8986.4
Reach type	Channelized	*Avg. width (m)*	23.5
Slope (m/m)	0.0068	*Avg. depth (m)*	0.94
D16 (mm)	37	*Width/Depth*	25.0
D50 (mm)	73	*Avg. R*	0.87
D84 (mm)	135	*Avg. Velocity (m/s)*	2.35
Avg. % Sand (<2mm)	0	*Shear stress (Pa)*	57.7
Avg. % Gravel (2-62mm)	45	*Mobility Ratio*	0.79
Avg. % Cobbles (64-128 mm)	54	*Specific stream power (W/m^2)*	145
Avg. % Boulders (>128mm)	1	*Avg. Fr*	0.77



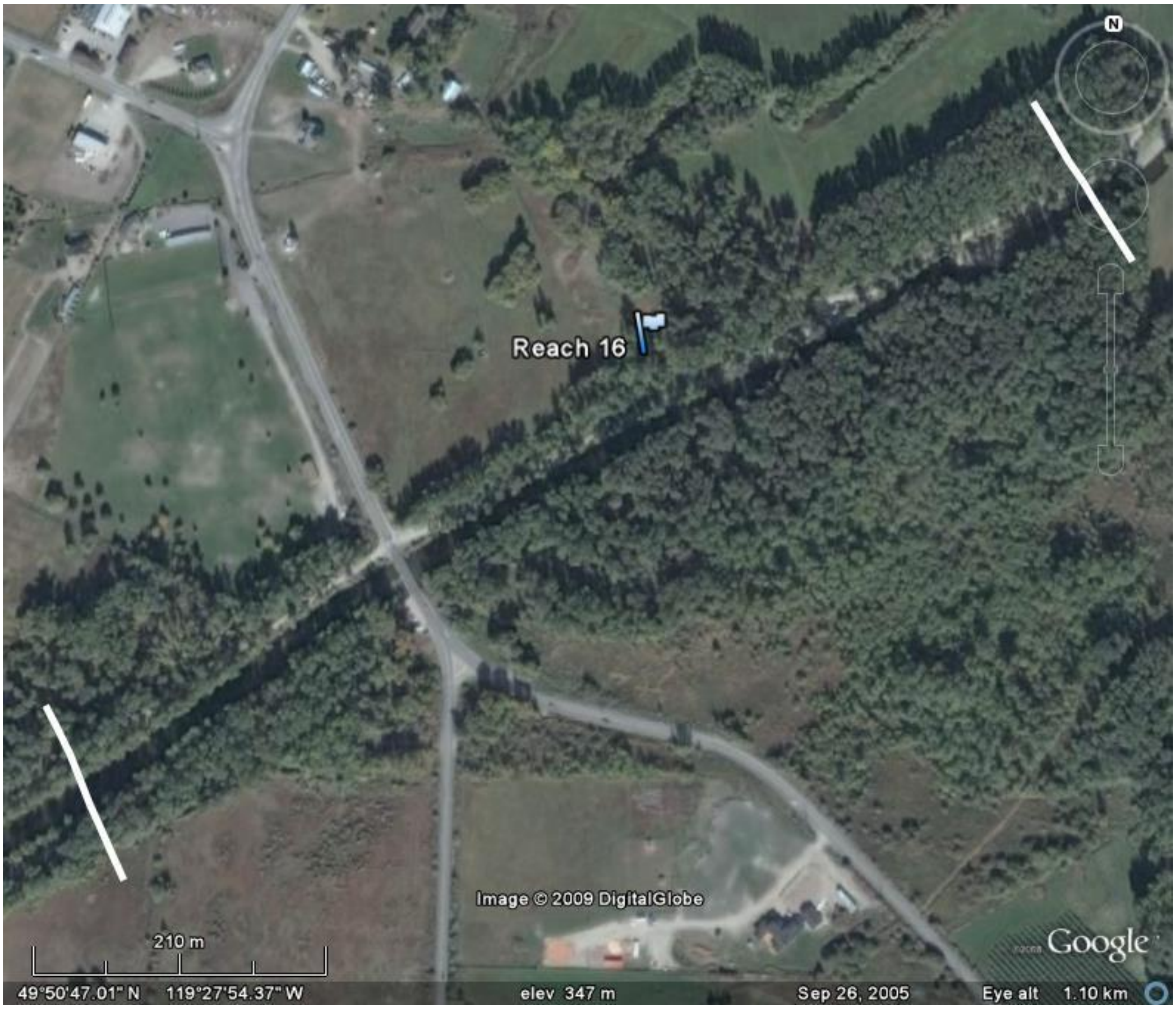
Reach #	**13**	Length (m)	540.3
Start (m)	8986.4	End (m)	9526.7
Reach type	Channelized	Avg. width (m)	21.9
Slope (m/m)	0.0063	Avg. depth (m)	0.88
D16 (mm)	35	Width/Depth	24.9
D50 (mm)	68	Avg. R	0.82
D84 (mm)	127	Avg. Velocity (m/s)	2.72
Avg. % Sand (<2mm)	1	Shear stress (Pa)	50.5
Avg. % Gravel (2-62mm)	47	Mobility Ratio	0.75
Avg. % Cobbles (64-128 mm)	52	Specific stream power (W/m^2)	144
Avg. % Boulders (>128mm)	1	Avg. Fr	0.93



Reach #	**14**	*Length (m)*	583.5
Start (m)	9526.7	*End (m)*	10110.2
Reach type	Channelized/depositional	*Avg. width (m)*	33.1
Slope (m/m)	0.0042	*Avg. depth (m)*	0.91
D16 (mm)	31	*Width/Depth*	36.4
D50 (mm)	63	*Avg. R*	0.98
D84 (mm)	119	*Avg. Velocity (m/s)*	1.70
Avg. % Sand (<2mm)	2	*Shear stress (Pa)*	40.4
Avg. % Gravel (2-62mm)	47	*Mobility Ratio*	0.64
Avg. % Cobbles (64-128 mm)	50	*Specific stream power (W/m^2)*	63
Avg. % Boulders (>128mm)	0	*Avg. Fr*	0.57

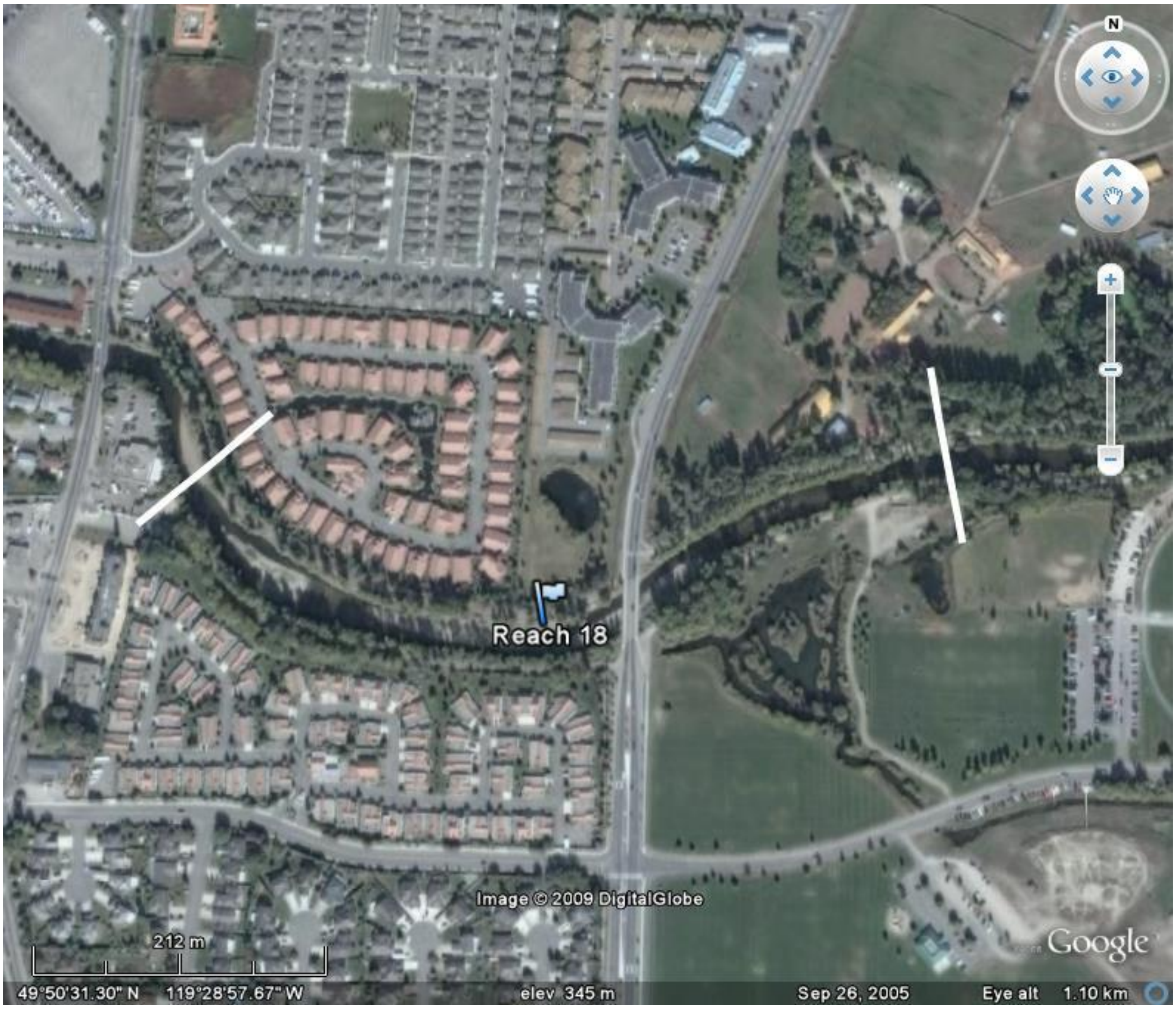


Reach #	**15**	*Length (m)*	1338
Start (m)	10110.2	*End (m)*	11448.2
Reach type	Channelized/depositional	*Avg. width (m)*	21.1
Slope (m/m)	0.0035	*Avg. depth (m)*	1.03
D16 (mm)	28	*Width/Depth*	20.6
D50 (mm)	59	*Avg. R*	0.98
D84 (mm)	102	*Avg. Velocity (m/s)*	2.70
Avg. % Sand (<2mm)	5	*Shear stress (Pa)*	33.6
Avg. % Gravel (2-62mm)	52	*Mobility Ratio*	0.57
Avg. % Cobbles (64-128 mm)	44	*Specific stream power (W/m^2)*	83
Avg. % Boulders (>128mm)	0	*Avg. Fr*	0.85

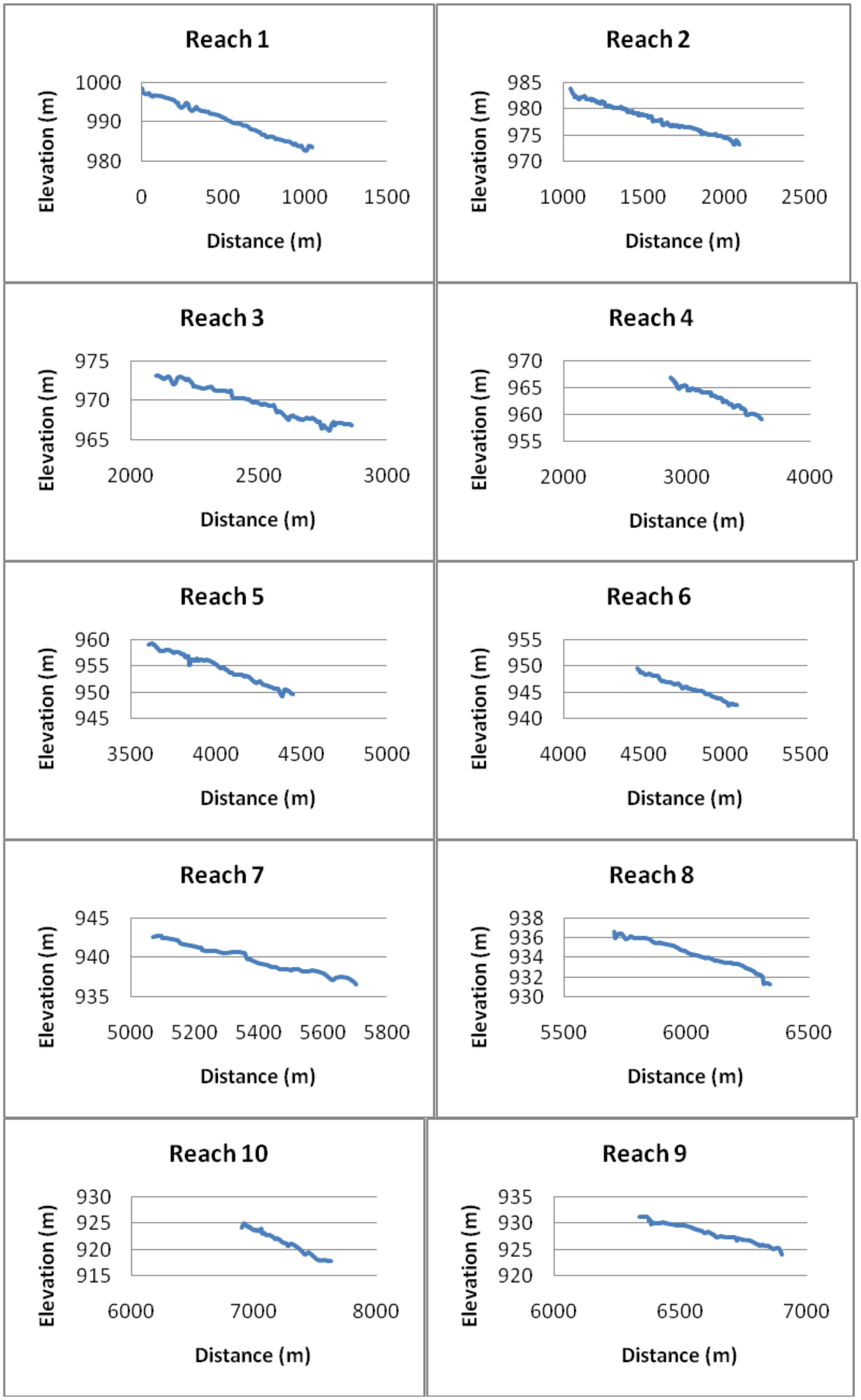


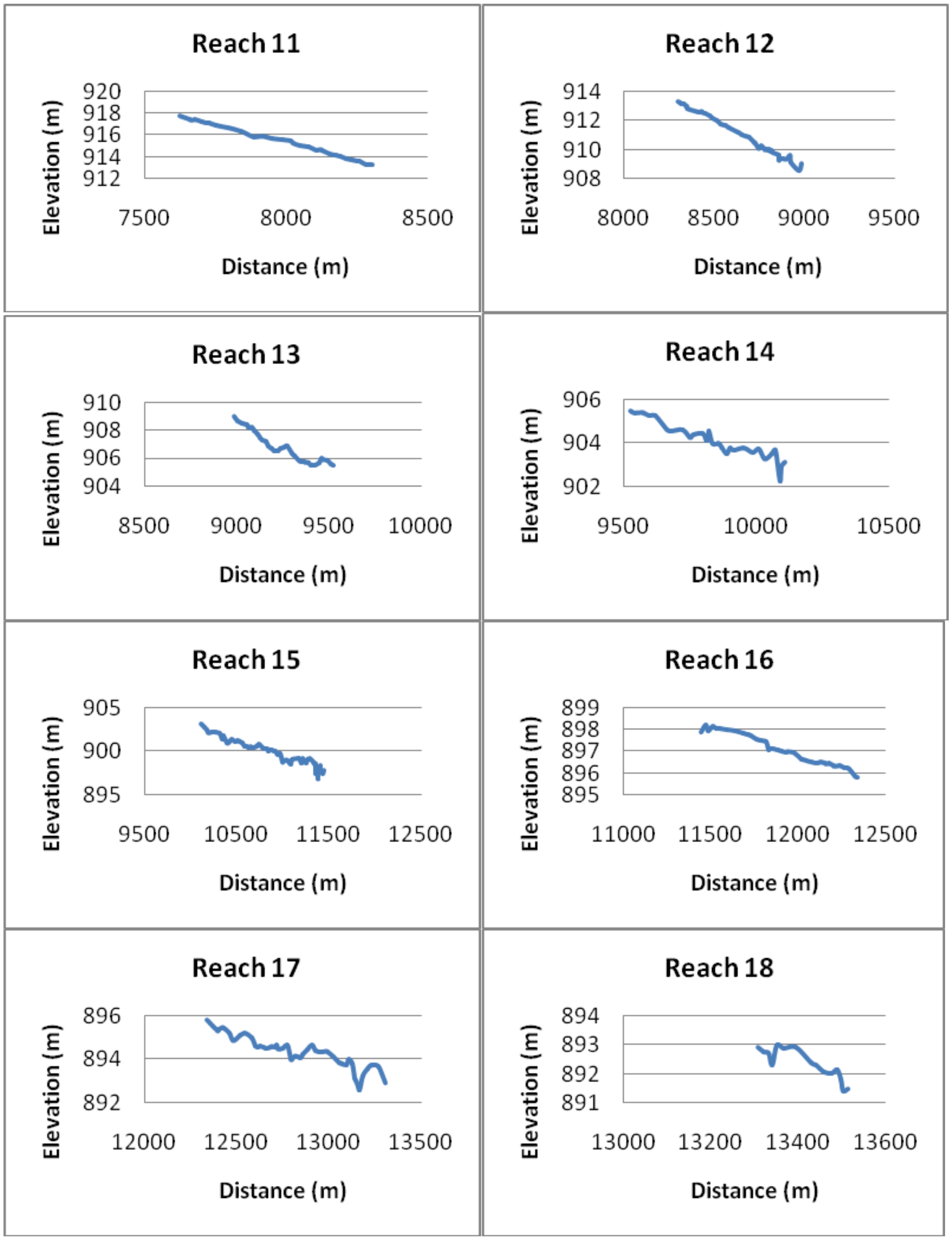
Reach #	**16**	*Length (m)*	890.9
Start (m)	11448.2	*End (m)*	12339.1
Reach type	Channelized	*Avg. width (m)*	22.5
Slope (m/m)	0.0026	*Avg. depth (m)*	0.83
D16 (mm)	27	*Width/Depth*	27.0
D50 (mm)	51	*Avg. R*	0.82
D84 (mm)	83	*Avg. Velocity (m/s)*	2.75
Avg. % Sand (<2mm)	4	*Shear stress (Pa)*	20.8
Avg. % Gravel (2-62mm)	62	*Mobility Ratio*	0.41
Avg. % Cobbles (64-128 mm)	34	*Specific stream power (W/m^2)*	58
Avg. % Boulders (>128mm)	0	*Avg. Fr*	0.96

Reach #	***17***	*Length (m)*	968.7
Start (m)	12339.1	*End (m)*	13307.8
Reach type	Channelized	*Avg. width (m)*	23.2
Slope (m/m)	0.0024	*Avg. depth (m)*	1.16
D16 (mm)	30	*Width/Depth*	20.0
D50 (mm)	54	*Avg. R*	1.13
D84 (mm)	83	*Avg. Velocity (m/s)*	1.92
Avg. % Sand (<2mm)	5	*Shear stress (Pa)*	26.6
Avg. % Gravel (2-62mm)	58	*Mobility Ratio*	0.50
Avg. % Cobbles (64-128 mm)	37	*Specific stream power (W/m^2)*	52
Avg. % Boulders (>128mm)	0	*Avg. Fr*	0.57



Reach #	**18**	*Length (m)*	207
Start (m)	13307.8	*End (m)*	13514.8
Reach type	Channelized	*Avg. width (m)*	24.6
Slope (m/m)	0.0061	*Avg. depth (m)*	1.06
D16 (mm)	20	*Width/Depth*	23.2
D50 (mm)	50	*Avg. R*	0.99
D84 (mm)	75	*Avg. Velocity (m/s)*	1.96
Avg. % Sand (<2mm)	7	*Shear stress (Pa)*	59.5
Avg. % Gravel (2-62mm)	66	*Mobility Ratio*	1.19
Avg. % Cobbles (64-128 mm)	28	*Specific stream power (W/m^2)*	124
Avg. % Boulders (>128mm)	0	*Avg. Fr*	0.61


Reach 1
Elevation (m)
1000
990
980
0
500
1000
1500
Distance (m)
Reach 2
Elevation (m)
985
980
975
970
1000
1500
2000
2500
Distance (m)
Reach 3
Elevation (m)
975
970
965
2000
2500
3000
Distance (m)
Reach 4
Elevation (m)
970
965
960
955
2000
3000
4000
Distance (m)
Reach 5
Elevation (m)
960
955
950
945
3500
4000
4500
5000
Distance (m)
Reach 6
Elevation (m)
955
950
945
940
4000
4500
5000
5500
Distance (m)
Reach 7
Elevation (m)
945
940
935
5000
5200
5400
5600
5800
Distance (m)
Reach 8
Elevation (m)
938
936
934
932
930
5500
6000
6500
Distance (m)
Reach 10
Elevation (m)
930
925
920
915
6000
7000
8000
Distance (m)
Reach 9
Elevation (m)
935
930
925
920
6000
6500
7000
Distance (m)


Reach 11
Elevation (m)
920
918
916
914
912
7500
8000
8500
Distance (m)
Reach 12
Elevation (m)
914
912
910
908
8000
8500
9000
9500
Distance (m)
Reach 13
Elevation (m)
910
908
906
904
8500
9000
9500
10000
Distance (m)
Reach 14
Elevation (m)
906
904
902
9500
10000
10500
Distance (m)
Reach 15
Elevation (m)
905
900
895
9500
10500
11500
12500
Distance (m)
Reach 16
Elevation (m)
899
898
897
896
895
11000
11500
12000
12500
Distance (m)
Reach 17
Elevation (m)
896
894
892
12000
12500
13000
13500
Distance (m)
Reach 18
Elevation (m)
894
893
892
891
13000
13200
13400
13600
Distance (m)