Impact of a hydropeaking dam on the Kananaskis River

Changes in geomorphology, riparian ecology, and physical habitat

by

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Abstract

The Pocaterra dam on the Kananaskis River provides a unique opportunity to assess dam induced changes in channel morphology because it has caused reduction in the magnitude of high flows and creation of daily peaking flows with no associated alteration in sediment supply. We assessed reach scale morphological change of the Kananaskis as a result of the hydropeaking flow regime considering change in geometry, planform, vegetation, and pool characteristics and distribution. Pre and post-dam channel conditions were assessed through historical photos, field measurements, remote sensing techniques and modeling. The channel just downstream of the dam widened, the middle six sites show no statistical change, and the most downstream three sites showed statistically significant narrowing. Further changes included a shift towards fewer active channels, abandonment of back channels, increase in density of riparian vegetation, and low diversity of successional stages within the riparian forests. A rational regime model reasonably predicted width adjustment and shift in number of active channels. We also found depth distributions to differ from statistical distributions in the most upstream sites with a higher proportion of low depths while the most downstream site matched the statistical distributions. Pool characteristics were associated with local attributes with large pools formed near large wood and back channels and numerous smaller free forming pools. The hydropeaking signal appears to drive channel change in the upper reaches where the models did not correspond to observed channel characteristics while the reduction in peak flows appears to drive channel morphology in the more downstream reaches. The interactions of the hydropeaking flows with winter ice dynamics also appear to control channel change in this system and contribute to the unique morphology. Channel change is likely associated with decrease in the

quality and quantity of suitable fish habitat and thus may have driven declines in fish diversity along this river. Despite the complexity of this system, these modeling and remote sensing methods simply and accurately characterize changes on the Kananaskis and thus provide a useful and rapid method to assess morphological change in a disturbed system.

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Glossary

MDD Maximum daily discharge

PHABSIM Physical habitat simulation

UBCRM University of British Columbia Regime Model

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Chapter 1

Introduction

As the understanding of fluvial systems develops, changes in river dynamics resulting from anthropogenic influences have become increasingly evident. Though alteration of rivers occurs through land use changes, channelization, mining, and industrialization, the most direct impact on the function of rivers is that of dams. It is estimated that over $^2/_3$ of the water globally exported to the oceans through rivers and streams is at some point intercepted by a dam [Jansson et al., 2000]. As interest in the effects of dams has grown steadily over the past three decades, a wide array of landscape responses have been documented [Petts and Gurnell, 2005].

The great diversity in river response to flow regulation stems from the variability associated with river dynamics [Brandt, 2000]. There is a wide range in the physical structures, operating policies, and function of dams. These unique dam characteristics are an added complexity to the already spatially and temporally variable hydrology. Additionally, site specific sediment supply, bed and bank material, valley geometry, and assemblages of riparian vegetation can limit the transferability of studies from one region to another. However, aquatic and terrestrial species are threatened by dam-induced changes to these river ecosystems. Though the assessment of hydrological, geomorphological, and ecological alterations by dams is by no means simple, this influence on river dynamics must be considered to maintain the integrity of these systems.

The study presented herein focuses on morphological changes associated with the flow regulation of the Kananaskis River. We attempt to document and quantify geomorphic change, model this change to determine the contributing factors, and consider the ways that these changes are modulated by riparian vegetation dynamics. We further consider the biologic implications of the observed change by assessing the modern distributions of depths within the channel and spatial arrangement of pools which are an important characteristic of aquatic habitat. An understanding both the large scale geomorphic change and localized distributions of high depths provides insights into the ways that flow regulation may have impacted the ecology of the Kananaskis River.

1.1 Background Information

Dams impact rivers by altering their capacity to carry sediment and the amount of sediment which is available for transport. These alterations translate into effects on the physical and biological aspects of the system. Generally, Petts [1987] classified the effects to include changes in:

1. Sediment load, discharge, plankton, and other water quality issues downstream from the dam
2. Channel morphology, bed material and macrophyte assemblages and distributions
3. Fish and faunal distributions

An understanding of the suite of changes which dams cause on the landscape requires consideration of each of these classes of changes and the linkages between.

1.1.1 Hydrological Changes

The most explicit change in rivers by damming is the direct regulation of flow causing alteration of the natural hydrological regime. Flow alteration is dictated by the specific function of the dam, which can include hydroelectric power generation, water storage, or flood control [Graf, 1999]. Depending on the dam function, manipulation of flow regime causes changes in the timing, magnitude, and frequency of flows [Ligon et al., 1995, Graf, 1999, 2001, Magilligan and Nislow, 2001, Magilligan et al., 2003, Magilligan and Nislow, 2005]. Flow alteration can occur at a daily or seasonal scale. At a basic level, regulation of flow results in changes in instantaneous flow which form the daily flow patterns. As a dramatic example of daily change, hydropeaking flow regimes are associated with rapid fluctuations between low and high stages in order to generate hydroelectric power [Cushman, 1985]. These ramping flows can cause bankfull flows on a daily scale, whereas in unregulated systems a bankfull flow may occur every 1 to 2 years [Knighton, 1998].

Changes in the seasonality of low and high flows can have profound impacts on channel morphology and biota adapted to seasonal cues associated with a specific flow regime [Richter et al., 1996, Rood and Mahoney, 1990]. This change in timing often manifests as a complete reversal of flow to better suit the intended dam functions. In reservoirs, flow is impounded during months of excess and redistributed to meet power or irrigation needs during historically low flow months. In rivers in arid climates like the Rio Grande or Colorado River seasonal changes can occur due impoundment during the winter months with higher flow release during the summer to supplement crop irrigation [Everitt, 1993, Ohmart et al., 1988]. In many cases natural variability in flow is eliminated and flow remains constant throughout the year. For example, as a result of dam operation, flow in some Southern Albertan rivers which would naturally peak during the summer experiences reduced variability to ensure a steady energy supply to meet demands [Samuelson and Rood, 2004]. The geomorphological and ecological impact of seasonal flow changes can be even more dramatic when combined with other seasonally dependent processes, such as ice dynamics or riparian vegetation [Rood et al., 2005].

Though flows have changed as a result of flow regulation, less transparent is the way which these changes are measured and communicated. In many cases, the change in flow is described through some ratio value, such as the ratio of pre-dam 2-year flood (Q_2) to post-dam 2-year flood for example [Wolman, 1967]. Generally, Wolman [1967] found that a ratio of pre-dam to post dam discharge of 0.9 or greater produces degradational conditions, while a ratio of 0.75 or lower forms an aggradational system. However, typically one single attribute of flow, such as the Q_2, does not represent the only change to flow. This ratio captures only the changes in magnitude of a single high flow and thus neglects changes in the magnitude, frequency, and timing of other biologically and geomorphically relevant flows [Richter et al., 1996]. More commonly, multiple changes to flow occur simultaneously and thus the single ratio value does not capture the entire suite of hydrological changes occurring.

Attempts have been made to rely on statistical analysis to determine the extent to which hydrology has been altered by dam operations [Richter et al., 1996, Magilligan and Nislow, 2001, 2005]. Thirty-two parameters including the magnitude, duration, timing, and rate of change of high, intermediate, and low flows were considered in an Inter-annual Hydrologic Alterations (IHA) analysis. This method has revealed overall changes in flow, such as decrease in 1-day to 7-day high flows or increase in 1-day to 90-day low flows across the dams in the United States [Magilligan and Nislow, 2005]. The IHA analysis allows the determination of the flow attributes which have changed, yet debate exists as to the flow parameters which are most biologically and geomorphologically important. Ultimately, the most relevant flow parameter depends upon the characteristics of the system of interest, including ecological and geoclimatic setting.

1.1.2 Sediment load changes

Changes in the river's ability to convey sediment downstream is another factor unique to each regulated system. The type of dam and nature of the flow alteration control changes to sediment-transport capacity relative to sediment supply. Sediment-transport capacity refers to the maximum amount of sediment a particular flow can carry such that higher flows are capable of transporting more sediment [Celik and Rodi, 1991]. Due to the nonlinear relationship between sediment transport and discharge, changes in flow by dams often translate to a reduction in the total amount of sediment the river is capable of transporting. However, in many cases the sediment supply is also altered by the dam and thus dams can cause change in both the river's ability to transport sediment and the amount of sediment available for transport.

Dams which occur in association with a reservoir often have the greatest impact on the landscape. In the United States, reservoirs over 1.2 x 109 m^3 account for only 3% of the number of dam structures, yet hold over 63% of the water currently in reservoir storage [Graf, 1999]. This prevents downstream conveyance of upstream derived sediment by causing the sediment to settle within the low energy reservoir environment [Grant et al., 2003, Petts and Gurnell, 2005]. Similarly, the dam structure physically prevents sediment from passing through. Impoundment can significantly affect a rivers ability to evacuate sediment because in many systems up to 75% of the sediment load originates in the headwater catchment above the dam [Petts and Gurnell, 2005]. Recent studies indicate that 25-30% of the global sediment flux is intercepted by registered reservoirs [Vorosmarty et al., 2003]. The trapping of sediment within a reservoir combined with the altered sediment-transport capacity can influence amount of sediment evacuated and ultimately result in a wide variety of channel responses.

1.1.3 Channel adjustment

Channel adjustment as a result of dam construction has long been recognized and as early as the mid 1970s degradation rates were cited ranging from 30 to 500 mm/year [Petts, 1984]. However, a wide range of geomorphic responses have been documented [Brandt, 2000, Williams and Wolman, 1984, Graf, 1999, Petts and Gurnell, 2005]. At the grain scale, a coarsening of the bed and imbrication may occur[Ligon et al., 1995, James and Deverall, 1987, Petts, 1988]. Larger scale erosion patterns could also develop in some systems such that bars are eliminated or the channel is widened just downstream of the dam, as was observed in the Green River Basin [Merritt and Cooper, 2000]. An entire shift in the morphology of disturbed channel can also occur [Brandt, 2000, Petts and Gurnell, 2005]. In the case of the Green River, braiding developed further downstream due to the high sediment supply provided from eroded upstream banks [Merritt and Cooper, 2000, Petts and Gurnell, 2005]. In other cases, such as the Mckenzie River, systems favor a single dominant channel by abandonment of backchannels due to reduced flows [Brandt, 2000, Petts and Gurnell, 2005, Church, 1995, Ligon et al., 1995]. Geomorphic changes in a river following damming are ultimately dictated by the nature of the hydrological alteration.

The characterization of channel adjustment following dam construction reflects the Lane [1955] relation:

$$QS \propto Q_b D \tag{1.1}$$

Sediment Supply \ Flow	-	=	+
-	Mild erosion	Erosion	Erosion
=	Mild deposition	Variable	Variable
+	Deposition	Deposition	Rare

Figure 1.1: Dams impact a river system through changes in the sediment load and discharge regime. The flow axis represents the change from pre dam conditions, while the sediment load axis refers to the sediment supply relative to transporting capacity at a given flow [adapted from Brandt [2000]].

where formative discharge (Q) and slope (S) depend upon load of bed material transported (Q_b), and calibre of sediment (D). This relation implies that channel adjustment to altered flow regime can occur through changes in load, grain size, or slope. Further studies which use a dimensionless stream power in the Lane [1955] relation suggest that adjustments may also occur through adjustment of flow depth and the state of the bed [Eaton and Church, 2011]. However, ultimately dams can impact the discharge and upstream derived sediment supply independently, it is useful to consider the possible combinations of impacts which may be inflicted on the river following dam construction (Figure 1.1).

Patterns of erosion and deposition emerge along the downstream gradient. Where reservoirs are present, the region just downstream of the dam is characterized by erosion of the bed and banks because material entrained is not longer replaced with upstream derived sediment [Williams and Wolman, 1984]. Though degradation rates change through time, the maximum degradation is said to occur between the dam and 69 channel widths downstream [Wolman, 1967]. This can manifest as an increase in cross sectional area if flows are capable to entrain bed and bank material [Brandt, 2000]. If flows are not sufficiently high to mobilize all grain sizes, smaller grains will preferentially be transported causing winnowing of fines and armoring of the bed [Williams and Wolman, 1984].

Though degradation is typically observed below the dam, aggradation is also a commonly cited response to flow regulation further downstream. The bed and bank material eroded just below the dam is transported downstream and eventually deposited. Most widely reported is sedimentation at the confluence with unregulated tributaries [Brandt, 2000]. This can cause reduction of cross sectional area, shift towards single rather than multithread channels, formation of fans and bars at tributary confluences, and filling of back channels [Petts and Gurnell, 2005, Church, 1995, Sherrard and Erskine, 1991, Sear, 1995].

Adjustment of channel form occurs due to these erosional and depositional process in response to changes in the hydrologic regime. Changes in channel form remain difficult to predict due to the complex set of controlling factors, including history of the system, properties of the dam, and exogenous influences [Brandt, 2000, Grant et al., 2003]. These influences include features of the drainage system which are outside of the channel, such as anthropogenic influences or riparian vegetation development [Petts and Gurnell, 2005]. The later component is of primary interest in this study because the feedbacks between not only dam altered hydrology and geomorphology but also riparian ecology are increasingly being recognized as essential to our understanding of river response to dams.

1.1.4 Linkages to Riparian Vegetation

Zones of riparian vegetation comprise the interface between the aquatic and terrestrial ecosystem, therefore they provide an important control on the morphology of the system [Trimble, 2004, Simon et al., 2004]. This ecological component impacts multiple processes including the hydrologic cycle and water budgets, soil moisture, resistance to overland flow, and resistance to in-channel flow [Simon et al., 2004]. Additionally, riparian vegetation plays a role in river chemistry primarily through addition of organic carbon to the system. And thus, vegetation within the riparian corridor represents an important controlling factor in the system of river feedbacks.

Though there are a variety of roles which vegetation assumes in fluvial environment, we are focusing on bank stabilization by riparian vegetation. Bank stabilization occurs through the physical adhesion created by the root network. The binding by roots magnifies bank stability by increasing the critical shear stress required to create bank erosion [Tal and Paola, 2007]. The degree of root reinforcement is a function of root growth and density, tensile strength, the strength of bonds between roots and the soil, and the orientation of the root matrix in relation to the direction of stress [Pollen et al., 2004]. The heterogeneity in root structures of different types of riparian vegetation (e.g. grasses, shrubs, and trees) also provides varying levels of bank stability [Trimble, 2004, Simon and Collison, 2002]. Therefore, transitions between habitat types alters bank stability and can impact channel pattern [Merritt and Cooper, 2000, Millar, 2000].

Dam altered hydrology can cause long term changes in the structure and function of riparian ecosystems which may in turn control the balance fluvial erosional and depositional processes. The structure of the riparian forests relies on a flood based disturbance regime and thus the changes induced by dams can impact the successional progression of the environment [Rood et al., 2005, Rood and Mahoney, 1990, 1995, Jansson et al., 2000]. Damming along braided channels result in narrowing and establishment of riparian species along the previously inundated channel bed [Williams and Wolman, 1984]. This further acts to lock the channel in its narrowed position. Decreased lateral migration along meandering rivers within the Great Plains stabilized channels while reducing the presence of pioneer species [Friedman et al., 1998]. This creates a disruption in the distribution of succcesional stages and can act to minimize the heterogeneity within the riparian zone. The alterations in habitat composition can potentially cast impacted ecosystems into an alternate stability domain.

1.1.5 Biological impacts

The primary concern driving the study of the effects of dams has increasingly been focused on the biological shifts which accompany geomorphic and hydrologic change [Sparks, 1995, Ward et al., 1999]. Dams can alter nearly every aspect of river ecosystems including flow, sediment, nutrients, temperature, diurnal and seasonal cycles, channel energy, and food availability [Ligon et al., 1995]. Every trophic level within a river ecosystem is either directly or indirectly altered by flow regulation. Periphyton and other microorganisms can experience stress and decline by reduced organic carbon inputs by changing riparian forests [Petts, 1980]. Diversity of invertebrates may also be impacted by declining food availability and catastrophic drift at high flows [Petts and Greenwood, 1985, Munn and Brusven, 1991, Layzer et al., 2007]. These changes can cascade to higher trophic levels and can cause substantial impacts to river biodiversity [Kingsford, 2000, Bunn and Arthington, 2002, Dudgeon et al., 2006, Valentin et al., 1995].

Though a variety of species are impacted by dams, changes in fish populations and diversity remain the most important topic in ecological dam studies due to their social importance. Indeed there is cause for cause as more than 20% of freshwater fish species are either threatened or endangered as result of anthropogenic influences [Naiman et al., 2002]. Fish can be directly impacted by dams when they are physically prevented from spawning or migrating upstream or by physical harm caused by passage through the dam. More subtly dams indirectly affect fish abundance, biodiversity and health by the changes associated with the altered flow regime. These include: changes in the timing of flows altering seasonal cues, reduced habitat availability by lower flows, altered food sources and nutrient retention behind a dam, changes in water temperature, and physical habitat changes [Bain et al., 1988, Bunn and Arthington, 2002, Power et al., 1996, Pringle et al., 2000]. Such changes have been documented globally and thus are not limited to a single geoclimatic setting [Power et al., 1996, Reyes-Gavilan et al., 1996, Kingsford, 2000, Nilsson et al., 2005].

Studies regarding the biological impacts of dams often neglect to consider the changes in geomorphology focusing on the impacts on biota of changing quality and quantity of water or biological links instead. However, often consideration of the geomorphic changes within a system can provide insight into ecological feedbacks even when the mechanisms are not fully understood [Ligon et al., 1995]. For example, the only hydrological affect by dams on the relatively pristine Mackenzie River in Oregon was removal of overbank flows. However, this drove a shift towards a stable single thread channel where bars suitable for chinook salmon redd placement were eroded. With fewer appropriate redd sites there was greater competition for placement of eggs and thus salmon populations in this river have declined by 50% [Ligon et al., 1995]. Similarly, following dam construction on the Oconee River in in the Southeastern United States, lower densities of fish are supported [Evans, 1994], presumably due to reduction in connectivity between the channel and floodplain. Flows were not reduced, but it is likely that the river became entrenched due trapping of the upstream derived sediment within the reservoir. The floodplain previously provided food, rearing habitat, and refugia when inundated. This isolation of the river from floodplain may be contributing to the lower catch rates of black bass (*Centrarchidae*), catfish (*Ictaluridae*), and suckers (*Catostomidae*) observed at this site [Ligon et al., 1995]. In both of these examples, the changes in fish diversity and abundance relate not specifically to the flow alteration, but to the geomorphological dynamics as a result of this dam. Therefore in many cases, studies focusing on changes in fish dynamics might be better served by considering the geomorphic characteristics of a system in addition to the hydrologic and biologic aspects.

1.2 Research Gaps and Objectives

Despite the long history of scientific interest in the effects of dams, there is still some degree of uncertainty regarding the aspects of the system and the relationships between. The hydrological component of dam alteration represents one of the most easily quantified aspects of modified rivers. Abundant gauges exist and records of historic conditions are often readily available, though they may be discontinuous for older systems. There is still no consensus regarding the flow parameter which is most relevant to channel and ecological change. Though geomorphic data is more sparse than hydrologic data, changes in the geomorphological components of dammed impacted systems have been widely studied. Knowledge of geomorphology continues to expand and despite the complexity associated with each individual river, progress has been made toward predicting channel response to dams. Quantification and prediction of change must include consideration of the nature of sediment supply, bed and bank material, valley properties, and channel shape.

Quantification of vegetation creates one of the largest obstacles in dam research as it remains difficult to characterize present distributions in relation to changes which have occurred. The uncertainties associated with the impacts of river regulation on the landscape create many opportunities for research. A greater understanding of processes, such as sediment transport or banks stabilizing effects is needed. However, because these systems are highly interconnected, studies which seek to link hydrologic, geomorphic, and ecologic processes and the system of feedback between them will increase predictive ability and aid in mitigating the consequences. As the system does not exist as a series of disconnected components, but rather as a network of intrinsically linked processes, interdisciplinary research may prove most valuable to dam research. Therefore this study fits within the framework of existing dam literature by providing a systematic way to assess morphological changes by dams under an interdisciplinary lens.

1.3 Research Overview

The research summarized herein represents the case study of one system which provides the opportunity to separate a portion of the confounding factors associated with dams. As the task of understanding river dynamics in response to dams is complex, case studies represent a way to generalize impacts at a small scale, which can then later become synthesized into larger metanalyses. For the Kananaskis River, Alberta, we addressed flow alteration, large scale geomorphic change, riparian vegetation dynamics, and local patterns of channel geometry that are biologically relevant. Further consideration was given to the ways that these processes are linked and the feedbacks between to better understand changes imposed by a hydroelectric dam.

The Kananaskis River of Southwestern Alberta has experienced significant flow alterations since 1956 and possesses unique characteristics which renders it a useful site for our interdisciplinary considerations. The Kananaskis allows the isolation of sediment supply changes from that of hydrologic changes because a lake present at the reservoir location prior to dam construction. Therefore a sediment trap was always present at this point within the valley and no change in sediment supply has occurred as a result of the dam. Additionally this river experienced a unique hydrologic alteration where flows are ramped from 1 m^3/s to 25 m^3/s in a daily hydro-peaking flow regime. Literature is scare regarding the effects of this type of flow regime though it has the potential to cause significant effects of the morphology and ecology of the river. There is also interest in changes to this river because the reach on which we focus has experiences shifts in fish species dominance with loss of some species entirely [Courtney et al., 1998].

The first section of this study focuses on the large scale geomorphic changes which have occurred in the 40 km below the Pocaterra dam. We use flow data, historic aerial photos, and 3D imaging techniques to addresss how the channel pattern, planform, and riparian vegetation have changed between dam construction and present. Further emphasis is given to the the ways that geomorphic changes manifest along a downstream gradient. The downstream propagation of change was captured with 10 study sites distributed along the length of the channel. We also consider the ways which dam induced morphological changes are suppressed or enhanced by vegetation related bank stability. To assess this, a physically based model was used as a predictive tool to understand the directionality of channel change.

The second section of the study considers biologically relevant channel characteristics within three reaches at a smaller scale. Bathymetry was of primary interest, which was determined using remotely sensed imagery and corresponding empirical depth equations. We assessed the depth distributions as compared to statistical distributions suggested by Lamouroux [1998]. We seek to understand how depth distributions compare to the Lamouroux distributions and how the high depths are spatially arranged within pools. Pools are important to the numerous trout species present within the river and thus may provide partial explanation for changes in fish species observed at this site.

This case study makes an important contribution in research regarding the effects of dams on rivers because this site is unique in terms of type of flow alteration and in its steady sediment supply. A better understanding of the geomorphological changes may provide insight into the causes of decline in some of the fish species present and aid in mitigation of these effects. Finally to address channel change by dams we outline useful techniques which view the river as a series of interconnected parts and consider the changes which have occurred in the context of feedbacks within the system.

Chapter 2

Assessing geomorphological and ecological changes along the Kananaskis River, Alberta

2.1 Introduction

River damming is one of the most direct anthropogenic influences on rivers because it affects the basic function of rivers causing a shift in flow regime and driving inadvertent changes sediment supply. Channel adjustment in response to these imposed flow and sediment regimes often results in negative ecological and societal effects. These negative effects have driven extensive research regarding the hydrological and geomorphological changes which occur as a result of dam use in systems from a range of sizes, geoclimatic settings, and dam types [Brandt, 2000, Williams and Wolman, 1984, Graf, 1999, Petts and Gurnell, 2005]. These comprehensive studies highlight the great diversity of responses associated with different combinations of flow and sediment scenarios.

However despite this extensive scientific attention, the changes to rivers caused by dams continue to have unintended consequences across all trophic levels in riverine ecosystems. Reduced peak flows have been found to disturb riparian forest dynamics, particularly colonization of cottonwood which are adapted to a particular flow regime [Jansson et al., 2000, Merritt and Cooper, 2000, Rood and Mahoney, 1990, 1995, Rood et al., 2003]. Alterations to the density and species composition of riparian forests influences nutrient cycling and thus can alter periphyton and invertebrate assemblages [Poff et al., 1997, Ward and Stanford, 2006]. Changes in flow conditions and bed texture also create unsuitable habitat for benthic invertebrates and fish species or cause stress due to stranding or wash out [Cushman, 1985, Ligon et al., 1995, Petts, 1984, Poff et al., 1997]. The impacts of dams on the structure and function of aquatic and terrestrial river ecosystems systems has increasingly become of concern.

The research presented herein focuses on the impacts of a hydroelectric dam on a system which has experienced ecological changes since dam closure [Courtney et al., 1998]. The overall objective of this study is to characterize the evolution of channel morphology of the Kananaskis River and consider the biological implications of these changes. The Pocaterra Dam along the Kananaskis River provides a unique study area because it influences only the flow regime of the river while sediment supply remains unaffected by the dam. Additionally, it provides the opportunity to observe the impact of a hydropeaking dam on channel morphology and riparian vegetation dynamics. Presently, no study exists which describes the morphological channel adjustment in response to the 1955 dam construction and subsequent flow regulation. Specifically, the questions to be addressed include:

1. How has the Kananaskis River morphologically adjusted to the 1955 damming?

2. What role has the riparian ecology played in channel adjustment?

3. How are these changes manifested along the downstream gradient?

To assess these questions, we analyzed historic aerial imagery, flow data, and field measurements to quantify changes within the Kananaskis River, Alberta from 1958 to present. We use regime theory to analyze the morphological adjustments that have occurred along the Kananaskis River. Under regime theory, self-formed rivers maintain a dynamic equilibrium such that channel geometry remains essentially constant [Millar, 2005]. Rational regime theory is used to predict channel equilibrium conditions through physically based equations which characterize relations between sediment transport, flow resistance, and bank conditions [Eaton et al., 2004]. A river is said to have reached regime when their dimensions remain essentially the same over multiple flood cycles. Based on regime theory, we hypothesize that the reduction in formative discharge which appears to have occurred in the Kananaskis will result in a narrowing of the stream channel [Church, 1995]. We further suggest that the narrowing response may be enhanced by vegetative encroachment further stabilizing the banks and trapping fine sediment. Since the relative magnitude of the effect a dam has on peak flows declines downstream, we also hypothesize that the magnitude of channel adjustment will be greatest just below the dam and decrease in the downstream direction. This research adopts a multidisciplinary approach to better understand feedbacks and linkages between hydrology, geomorphology, and ecology in the context of a dam affected system.

2.2 Study Site

The Kananaskis River is a typical high altitude river which flows northward within the front range of the Canadian Rocky Mountains before meeting the Bow River at Seebe, Alberta. It originates at an elevation of approximately 2720 meters and flows down to 1300 m as it meets the Bow River. The Kananaskis is situated within a U-shaped valley shaped by multiple glaciations [Jackson Jr, 1980]. The valley is formed within weak clastic mesozoic rock with mountain ranges composed of Paleozoic carbonate [Sauchyn et al., 1998]. The Kananaskis flows through glacial eroded valley bottom and is characterized by fine grained vegetated banks and coarse gravel-cobble bed.

Within the valley bottom, the modern Kananaskis is generally comprised of three morphologically distinct regions. The upper 13 km is characterized by an irregular channel pattern whose form relates to tributary inputs.(Figure 2.1). Where tributaries converge with the main stem channel, the alluvial fan deposits push the main channel against the opposite valley wall forming a single thread, relatively deep channel. Reaches immediately upstream of tributaries likely are controlled by a backwater effect from the depositional cone of the alluvial fans. These regions are characterized by an anastamosed network of channels and back channels with low connectivity due to permanently inundated areas and subsurface flow. The high sediment input from the tributaries controls reaches just downstream of the fans

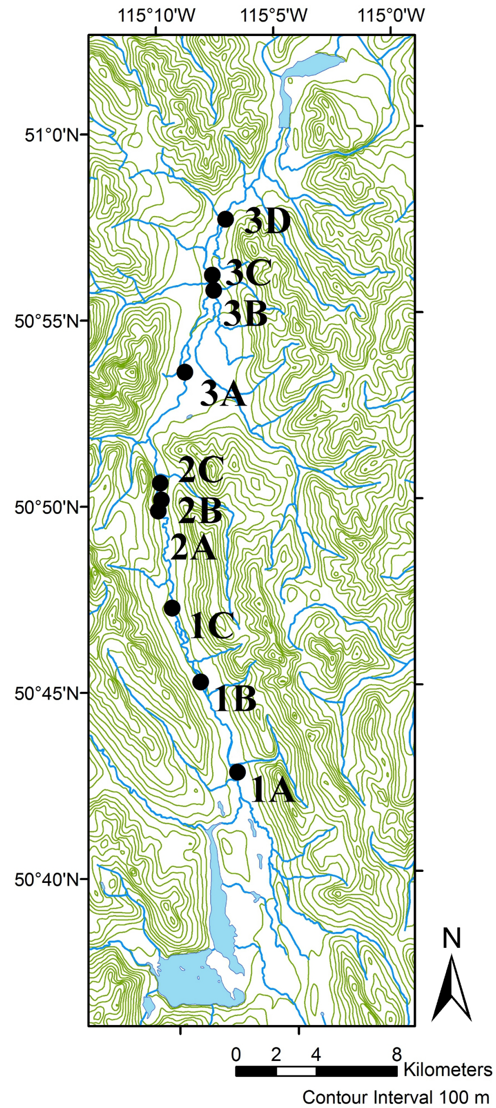

Figure 2.1: The Kananaskis River study reach. Extends from Pocaterra dam in the south flowing northward to Barrier Lake. Black dots indicate study sites.

which are dominated by active bars and high wood load. A shift in channel pattern occurs 14 km downstream of the dam, where the channel becomes single threaded and tortuously meandering for 6 kilometers. Logging did not occur upstream of this region due to the impassibility of log drives through the tight meanders and associated log jams [Johnson and Fryer, 1987]. The remaining length of the river shifts back to an irregular channel form where pattern is controlled by tributary dynamics and anthropogenic disturbance including water diversion from the main channel and bank stabilization.

Though this study is focused on geomorphological adjustments, we are also interested in the impact of vegetation on channel dynamics in this high altitude system. The dominant species located within the riparian forests include Engelmann spruce (*Picea Engelmannii*), lodgepole pine (*Pinus contorta*) and subalpine fir (*Abies lasiocarpa*) with trembling aspen (*Populus tremuloides*) present in the most downstream reaches. Shrubs include birch-leaved spiraea (*Spiraea betulifolia*), buffalo berry (*Shepherdia canadensis*), prickly rose (*Rosa acicularis*), and willows (*Salix* spp.). Commonly, horsetails, mosses, and lichens are the dominant ground cover in wet sites. Logging of spruce and pine occurred in the lower half of the valley from 1886 to 1944 [Johnson and Fryer, 1987]. Studies imply that logging, mining, and water management have not significantly altered the composition of species nor the age distribution within the entire valley, though localized effects of these practices on riparian forests were not considered [Johnson and Fryer, 1987].

Though flow in the Kananaskis historically followed a snow-melt regime, stream flow has been regulated by dams since the turn of the century. Three hydroelectric dams of varying capacity and operating schedule are present along the river. Between the Upper and Lower Kananaskis Lakes, the Interlake dam is among the smallest of the dams operated by Transalta with a capacity of 5 megawatts. It functions primarily as a means to moderate water levels within the two lakes. A short distance downstream from Lower Kananaskis Lake, the Pocaterra dam operates under a hydropeaking flow regime providing pulse power generation throughout the entire year. Barrier Dam is the most downstream structure and operates as a run of the river dam. The study reach extends along the 40 km stretch from Pocaterra dam below Lower Kananaskis Lake to Barrier Lake. We focus on the the channel

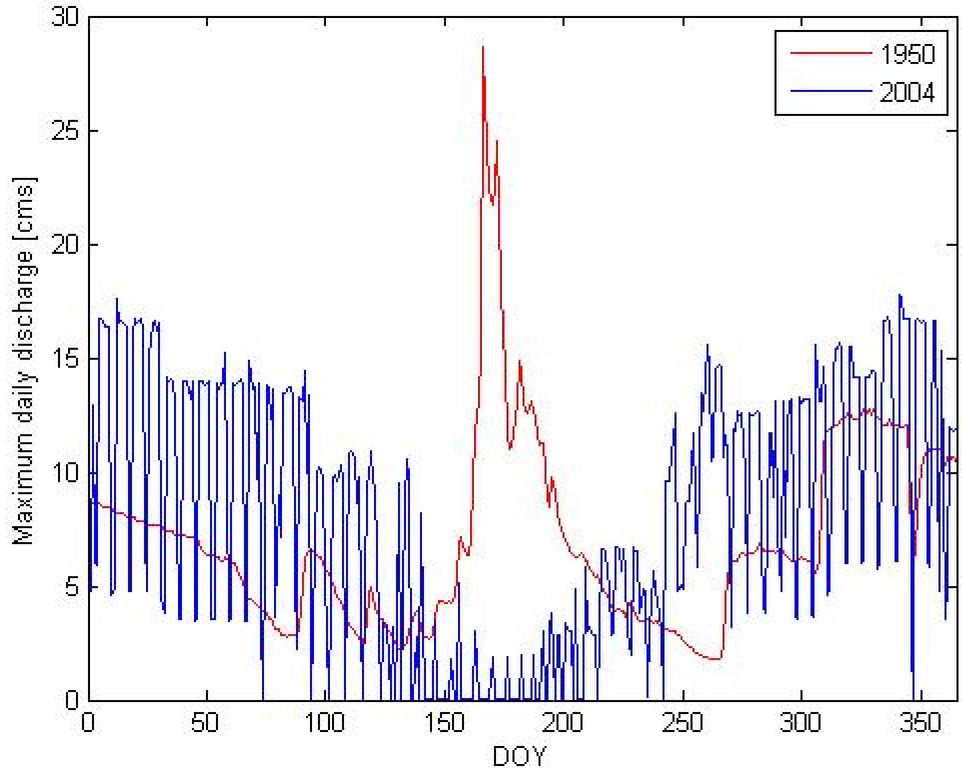

Figure 2.2: Seasonality in flows from a typical pre-dam year, 1950, and post-dam year, 2004. Pre-dam flows (red) reflect snow melt dominated regime with high flows during the early summer. Post-dam flows (blue) experience ramps every weekday, with lower flows during the summer snow melt to raise water level within the reservoir.

adjustment in response to the hydropeaking water release regime associated with the Pocaterra dam. This dam is operated such that the base flow release is approximately 1 m^3/s which is then ramped up to approximately 25 m^3/s up to 12 hours each day to meet energy demands (Figure 2.2). Therefore, the Kananaskis experiences both very low flows and bankfull flows on a near daily basis. This cyclic pulsing is maintained 5 to 7 days a week throughout the entire year.

This system provides a unique opportunity among regulated rivers to isolate the effects of hydrological alteration from that of sediment supply changes. As the

Upper and Lower Kananaskis Lakes were present prior to dam construction, upstream derived sediments were not conveyed downstream. Tributary inputs below the Kananaskis Lakes are the primary sediment source for the study site. Natural Resources Canada identifies 18 tributaries of varying size which contribute sediment and discharge to the main channel [Canada, 2008a,b]. This network of tributaries likely acts to dilute the effects of the dam and thus contribute to a downstream gradient of change.

Ten study sites were distributed along the downstream profile to capture the entire gradient of channel change (Figure 2.1). Study sites with a prefix of 1 are located within the upper morphologic region. Site 1A is situated within backwater effected region of King Creek approximately 3 km downstream of Pocaterra dam. Due to its close proximity to the dam, this site experiences the most rapid stage changes associated with the flood pulse. Site 1B is positioned upstream of Grizzly Creek and thus the surrounding floodplain is characterized by swamp like conditions. Site 1C is located adjacent to two unnamed tributaries in a confined reach of the valley with little space for lateral movement. Sites 2A, 2B, and 2C are located within the tortuously meandering section of the river. Sites with a suffix of 3 are located in the anthropologically influenced downstream region. Site 3A is situated directly upstream from one of the most significant tributaries, Evan Thomas Creek, but the banks at this confluence are stabilized due to its proximity to local infrastructure. Sites 3B and 3C are located within 2 km of each other, though upstream of downstream of the Ribbon Creek confluence respectively. Both sites are characterized by an anastamosed channel dominated by a series of $\approx$ 1 m width backchannels. Site 3D, approximately 37 km downstream from Pocaterra dam, is immediately upstream from Lorette Creek and thus experiences backwater effects. The drainage area at the dam is 151 km^2 while it is 899 km^2 at the most downstream section and thus there is a 748 km^2 net increase in contributing area between the dam and downstream.

2.3 Methods

2.3.1 Quantifying hydrologic changes

The first step in assessing the impact of the dam on channel morphology is to quantify the extent of flow alteration. To address this we place particular emphasis on the channel forming flow, or formative discharge. In this context, this is defined as the flow which mobilizes the most sediment over long periods of time [Andrews, 1980, Benson and Thomas, 1966]. Channel forming flows are often associated with the bankfull flow because the channel is presumed to adjust to the flow just filling the channel cross section [Knighton, 1998]. Of interest for this study is the Maximum daily discharge (MDD) a flow which maintains competence to transport bed and bank sediment and thus contribute to morphological change. Additionally this is the only flow parameter for which a long record is available. Though no records of direct flow release from the Pocaterra dam are available, a long discharge record directly below the dam is accessible from Water Survey of Canada gauge station 05BF003. The pre-dam record of flow extends 30 years prior to dam construction.

To determine the changes to flow, the pre- and post-dam flow records were treated as two distinct populations as they represent separate flow regimes. For the pre-dam period (1932 to 1955) and post-dam period (1986 to 2009), Gumble plots were created for the MDD to determine the flow magnitude which corresponds to a given recurrence interval. Though pre- and post-dam flow record relate to the single point at the gauging station, this data was used to calculate formative discharge at series of points along the downstream profile. To project the flows of a known recurrence interval at points downstream, a power law regional relation between drainage area (A) and discharge (Q) was utilized. Eaton et al. [2002] found that stream flow in snow-melt dominated regimes in British Columbian Rockies are related to contributing area by a power law relation based on their survey of 147 stations in the region. This relation can reasonably applied to the Kananaskis as there are no glaciers present in the drainage basin and it is situated within a similar geoclimatic setting to that for which the study was conducted [Eaton et al., 2002].

This relation follows the function:

$$Q = kA^{0.75} \tag{2.1}$$

The exponent relates to a regional trend determined from Water Survey of Canada stream gauge data for other sites along the Kananaskis River (05BF001, 05BF021, 05BF025). The constant k relates to the discharge produced by a 1 km^2 drainage area. We solved for k using the gauge station drainage area and the discharge estimated from MDD data points on the Gumble plots. The drainage area at each of the study sites was determined from digital elevation models (DEMs) using ArcGIS. With the calculated constant k and known drainage area for each study site, we estimated the discharge associated with each site along the downstream gradient. Our calculated k value is consistent with ranges found for this region which lends support that this is a reasonable estimation of downstream discharge trends [Eaton et al., 2002].

In this semi-arid high altitude system, the flow which dictates channel morphology is not readily apparent and thus multiple flow ranges were calculated. Typically the two year flood Q_2 is commonly associated with channel forming flows [Emmett and Wolman, 2001, Wolman and Leopold, 1957, Wolman and Miller, 1960]. However, for arid regions the more extreme floods may play a more important role in shaping channel morphology. In Central Texas, these large floods are created by short lag times associated with limited vegetation colonization under normally low precipitation conditions[Baker, 1977]. Similarly, the Kananaskis may be controlled by extreme floods resulting from sparse vegetation controlled by the short growing season and cold temperatures. Large floods also appear to cause geomorphic changes in systems such as the Kananaskis with flashy flows, high gradient, and coarse bed [Kochel, 1988].

Therefore, both flow ranges were used in our analysis to determine whether frequent low magnitude or more infrequent higher magnitude flows historically played a greater role in shaping the pre-dam Kananaskis River. For the pre-dam period, we estimated the Q_2 and Q_5. However, the more infrequent, but higher magnitude flows, ranging between Q_5 to Q_{25} may control the channel morphology as is more prominent in arid regions [Baker, 1977]. As such, for each site we calculated the Q_2, Q_5, and Q_{25} for both the pre-dam and post-dam time period using real data points on the Gumble plots. In all cases, Q_2, Q_5, and Q_{25} fell within the range of data and thus there was no extrapolation beyond the dataset range.

2.3.2 Detection of morphologic change

Width change

The extent of morphological change which has occurred since dam closure was assessed through historic aerial photos. Imagery was acquired through Alberta Environment and Sustainable Resources Development. The oldest set of aerial photos which extends over the entire study reach was a 1:15,840 infrared collection acquired in 1958. A 1:30,000 set of 2008 true color photos was used to represent modern conditions. Sets of aerial photos from 1972 and 1996 are also available which provided snapshots of the intervening time period. The 1958 and 2008 aerial photos were georeferenced to 2008 Worldview imagery using ArcGIS. By georeferencing the images to the half meter resolution satellite imagery systematic errors associated with lens distortion of the aerial photos was minimized.

The oldest available photos were acquired 3 years after dam construction, yet we have chosen to use this imagery as a proxy for pre-dam conditions. This study observes large scale morphological changes which require a long period to adjust. Therefore the use of 1958 photos to represent pre-dam conditions was deemed appropriate. Other studies support that morphological adjustment occurs on the scale of decades rather than years [Church, 1995].

Though resolution of the aerial photos is sufficient to map channel planform, 3D visualization of the river provided a greater context regarding the structure of the fluvial landscape. Agisoft PhotoScan software was used to create 3D polygonal models from the 1958 and 2008 sets of imagery. Each model was created from two adjacent stereopair sets. These models were used as visualization tools to set the stage for the observed trends and aid identification of features on the surface which are not readily apparent from the 2D nadir photos, such as channel confinement or tree height.

Quantification of channel changes was based upon measurements from these georeferenced aerial photos. The primary parameter of interest was width because it is the most readily adjustable channel dimension due to the character of the bed and banks. The Kananaskis is comprised of a coarse gravel bed and fine banks with a coarse cohesionless gravel toe. Under shear stress by flow, undercutting and erosion of the fine banks will preferentially occur rather than transport and erosion of the coarse material comprising the bed [Eaton et al., 2004, Eaton and Church, 2007]. Therefore, channel change is most likely to occur in the form of narrowing, widening, or shifts in numbers of channels rather than bed degradation and adjustment. Width also represents a channel morphological parameter which can be assessed from the available historic images of the Kananaskis River. Along the 40 km study reach, 10 sites were chosen for width analysis. For each site, a reach averaged width was determined from 11 measurements spaced approximately one bankfull width apart. Bankfull width was identified from these photos and 3D models primarily through patterns of riparian vegetation and floodplain topographic break.

Planform change

Though width changes are indicative of channel adjustment, we also considered changes in morphology occurring over the period of interest that may not be captured by the width adjustment analysis. To assess these additional changes, the morphology was mapped photogrammetrically at three of the 10 sites for both the 1958 and 2008 photo series. For each of the three morphologically distinct regions of the river, we chose to map one site which is representative of observed changes within that region. Historic flow records at the time of 1958 imagery acquisition is unavailable therefore direct comparison of the channel at a similar stage is not possible. A comparison of the two sets of maps at each of the three sites provides a first approximation of the morphological changes which are not reflected by bank advancement and retreat.

Mapped morphological units included the wetted surface, active exposed bars, inactive vegetated bars, modern floodplain, vegetation stabilized islands, and alluvial fan surfaces. Active bar surfaces (B_a) were identified as any part of the bed which was exposed at the time of image acquisition which had not been colonized by vegetation. Inactive bar surfaces, (B_v) were defined as parts of the bed that were topographically distinct from the floodplain but include early successional vegetation colonization. Alluvial fans (F_a) included the depositional cone at the confluence of tributary with the main stem channel. The floodplain (F_f) was the valley bottom which is typically heavily vegetated and topographically higher than vegetated bars. Islands (F_i) were identified as floodplain surfaces which are detached from the main floodplain surface. Finally the water surface (S_w) was defined as any region inundated at the time of image acquisition.

Vegetation dynamics

As vegetation may modulate the post-dam morphological adjustment, vegetation classes on the river margins were identified at each of the 10 sites. Defined vegetation classes were limited to pioneer grasses and seedlings, shrubs and herbaceous species, and mature trees. The three classifications relate to successional stage which provide qualitative assessment of lateral movement. Identification to lower taxonomic levels was not possible due to the relatively coarse resolution of the 1958 aerial photos. Interpretation of successional stages was based upon the 3D models allowing increased confidence in the classification due to vegetation height distinction.

All observations derived from the recent aerial photography included ground reconnaissance to ensure that width, vegetation, and channel pattern identification relate to the associated ground conditions. Field based measurements were also used to identify other features of the landscape which are relevant to channel metamorphosis. Grain size distribution was analyzed at the 10 field sites using photosieving methods [Dugdale et al., 2010]. Channel gradient and rooting depth of vegetation were measured at the sites. These ground measurements were used as input values in the model described in the following section.

2.3.3 Modeling channel adjustment

The University of British Columbia Regime Model (UBCRM) calibrated to the field site was used to predict the magnitude and directionality of channel change associated with the flow alterations imposed by the Pocaterra dam. This physically based model relates channel morphology to identified governing conditions following regime theory and the optimality criteria [Eaton et al., 2004]. The UBCRM was chosen due to its ability to model channel steady state configuration and due to the modest data inputs, particularly important in the pre-dam scenario for which data is limited. We use the UBCRM to model channel response to flow regulation as it has been shown to model transitions following logging [Millar, 2000]. This rational regime model combines relations of bed material transport, flow resistance, and channel boundary conditions to estimate an equilibrium channel form. The river systems for which it has successfully been applied exhibit similar boundary conditions to the Kananaskis River including vegetation stabilized near-vertical fine grained banks and a non cohesive gravel bed[Eaton and Church, 2007].

This model provides an approximation of changes in channel dimensions and transport capacity which should occur following flow alteration. It allows us to predict equilibrium geometry for the pre-dam and the post-dam scenarios and thus interpret the transition which has occurred. For the purposes of this study we are focused on prediction of pre- and post-dam channel width. Width is the only parameter readily visible and quantifiable from the aerial imagery and thus this output parameter will allow model calibration.

Though the model is a powerful predictive tool, it is underlain by assumptions which limit our ability to quantitatively predict channel adjustment [Eaton et al., 2004]. First, the UBCRM predicts equilibrium channel conditions and we are using it under the assumption that the channel shifts from one equilibrium state toward another. However, the pre-dam Kananaskis channel may not have reached equilibrium given the glacial history of this region. Therefore, we apply the model under an assumed conditional equilibrium and assert that adjustments relating to the glacial legacy are operating on sufficiently long time scales that they are negligible in the context of this study [Eaton and Church, 2009, Brooks, 2003]. Similarly, in the 57 years since dam closure the post-dam channel may not yet be at equilibrium, in which case this study characterizes a transitional state rather than end members.

The second assumption of the UBCRM is that a single discharge associated with an equilibrium sediment transport rate control channel dimensions. Though this limitation is unavoidable, the use of a range of discharges minimize our reliance on a single discharge value. Despite these limitations, the UBCRM acts as a useful postscriptive tool to understand channel change and incorporate components of vegetation enhanced bank stability.

Input parameters to the UBCRM include user specified energy gradient, median particle size (D_{50}), 84th percentile particle size (D_{84}), bank stability index ($\mu\prime$), and formative discharge. Due to uncertainty associated with each of these parameters, a 1000 iteration Monte Carlo simulation was implemented to identify a range of possible channel geometry solutions that reflects the uncertainty associated with the input parameters. For each input parameter, rather than selecting a single value we chose a range of values which reasonably capture the variability associated with each site. Ranges for the input parameters were based upon field measurements and calculations using available data. Then for each of the 1000 iterations, the UBCRM was run with a randomly generated combination of input values from within the identified ranges. The use of a range of input values and repeat random sampling minimizes the dependence of the output on a single user-identified input. The model output includes estimations of geometry related to an idealized trapezoidal channel form for which width is our primary parameter of interest.

Energy gradient was determined from water surface gradient measured both in the field and with GPS coordinates to ensure accuracy. Water surface gradient was measured in the field using an autolevel and stadia rod over a length of approximately 7 bankfull widths. We also measured energy gradient over longer reaches by combining water surface elevations using GPS coordinates with distance along the river measured using GIS. The use of two independent energy gradient measurements allowed greater confidence in this UBCRM input parameter. The calculated water surface slopes were used to represent the energy gradient for both pre- and post-dam scenarios. A single energy gradient value rather than a range was used in the Monte Carlo simulation.

The grain size distribution for both the pre- and post-dam records was also based upon the recent field measurements using photosieving techniques [Dugdale et al., 2010]. For each site D_{50} and D_{84} were calculated for between 10 and 100 samples. Samples included the entire range of grain sizes, from the coarse gravel heads of bars to the finer grained regions. Values for the regime model should relate to the large material transported in the thalweg, and thus the coarsest field measurements were used in the UBCRM. The largest three D_{84} values and corresponding D_{50} values were set as the associated model input ranges. These same ranges were utilized in both pre- and post-dam scenarios under the assumption that the sediment supply has not been altered by the dam.

Adapted from Millar [2005], the bank stability index ($\mu\prime$) was used to represent riparian vegetation dynamics in the UBCRM. It is defined by the ratio between bank erosion threshold and bed erosion threshold. This value has been shown to relate to density of riparian vegetation and thus allows us model the influence of bank vegetation dynamics on channel morphology. In the initial UBCRM pre-dam scenario, we set the $\mu\prime$ to a value of 1, corresponding to banks and bed which are equally erodible. If the modeled width is greater than the observed width then $\mu\prime$ was incrementally increased until modeled widths match observed, effectively calibrating the model to pre-dam conditions. Alternatively, if the predicted width is greater than the observed width then we could conclude either that river morphology is influenced by other mechanisms not included in the UBCRM or that our choice of input parameters did not accurately characterize the system.

Two formative discharge ranges were used in the UBCRM because it is unclear whether the typical 2-year flood or the less frequent higher magnitude floods control channel morphology. Though flow data is sparse for the Kananaskis, there appears to be two distinct populations of flows divided at approximately the 5-year flood (Figure 2.3). Ungauged rivers in this region which have a longer dataset also show two populations of flow (Figure 2.4). The presence of inflection points in the flow data for other sites within the region lend support that the high flows recorded for the Kananaskis do not merely represent outliers but rather potentially important flows driving geomorphic change.

Therefore, model calibration included both ranges. The first formative discharge range for the Monte Carlo simulation included values from Q_2 to Q_5. From the stream gauge data just downstream of the dam Q_2 and Q_5 correspond to 23.5 and 29 m^3/s respectively. These values were then used to estimate formative discharge at each of the sites using the regional power law relation. The second run included a range of Q_5 to Q_{25} for formative discharge which correspond to 29.0 and 46.2 m^3/s respectively. For each pre-dam formative discharge range, we then adjusted $\mu\prime$ to calibrate the model and chose the formative discharge range for which

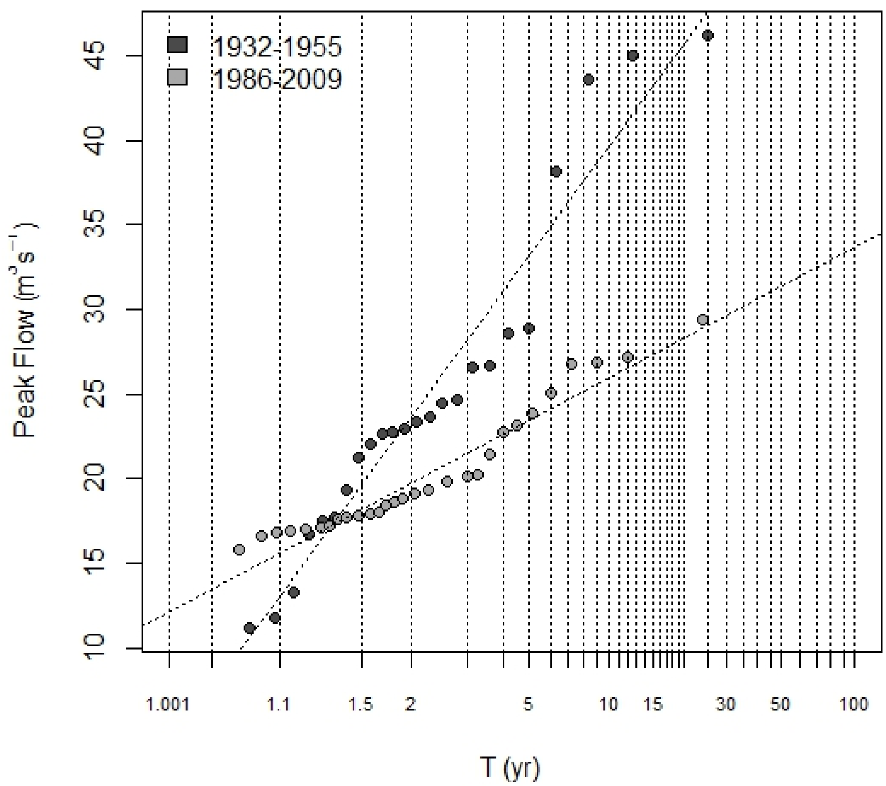

Figure 2.3: Gumble plot of flood frequency distribution of yearly peak flow for pre- and post-dam.

yielded the most reasonable $\mu\prime$ values. We then simulated changes in channel geometry attributed to the dam by using post-dam data for the appropriate formative discharge range. The widths produced from the final simulations relate to the changes in channel geometry which should occur as a result of flow regulation.

The channel characteristics are also dependent upon the number of active threads along the channel. The UBCRM can be used to identify sites which are likely to form multiple active channels as their stable form using the width to depth ratio [Eaton et al., 2010]. We defined a stability threshold for single verses multi-thread channels based on a width to depth ratio of greater than 50. Studies have found

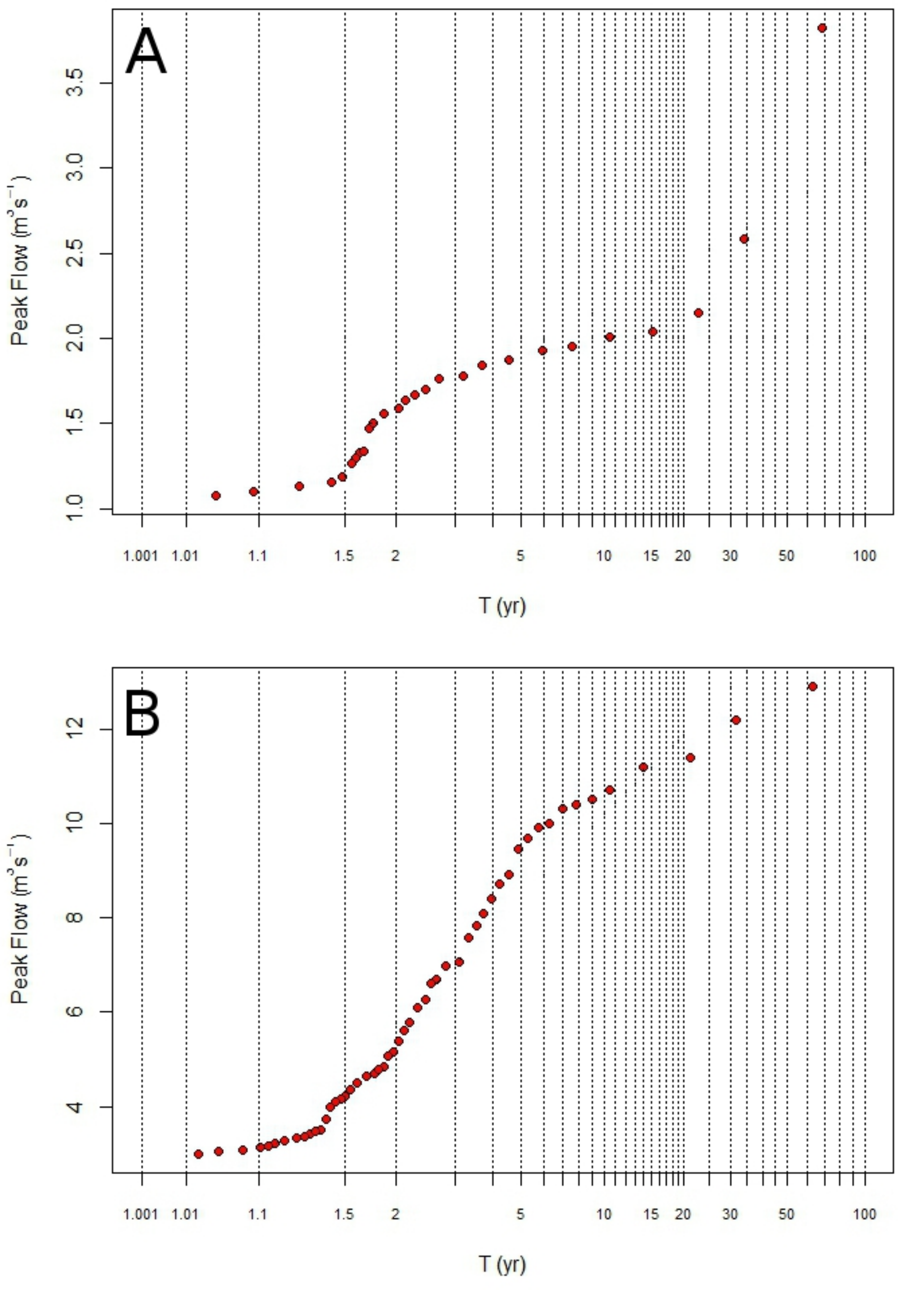

Figure 2.4: Gumble plots of annual peak flows for (A) Castle River near Beaver Mines from 1945-2011 and (B) Highwood River at Aldersyde from 1912-1993 both showing two populations of flow.

that this value represents a threshold at which a single thread is an unstable channel pattern and thus multi-thread channels are more likely to form [Eaton et al., 2010]. In the context of the UBCRM, if the width to depth ratio from the model output was greater than 50 we divided the formative discharge parameter in half and ran the model again, with the resulting width doubled to account for the two equal channels conveying flow. If each branch of the smaller channel had a width to depth ratio which exceeded the stability threshold we divided it again, until a stable number of channels was reached. For the post-dam changes we chose the appropriate $\mu\prime$ and again determined the appropriate number of stable channels. Therefore we can model not only the equilibrium width of the channel but also channel pattern under a given flow regime.

2.4 Results

2.4.1 Quantifying hydrologic alteration

The impact of flow regulation on the Kananaskis has been the creation of a hydropeaking regime and an overall reduction in the maximum annual daily discharge. There was a slight decrease in the median maximum daily discharge (MDD) from 23.5 m^3/s in the pre-dam regime to 19 m^3/s post-regulation (Figure 2.5). Additionally, flow variability has been reduced, with a pre-dam MDD range from 12 to 47 m^3/s and from 18 to 28 m^3/s for post-dam MDD. There has also been a shift in the flow seasonality due to the maintenance of consistent flows throughout the year. Previously, high flows occurred in the spring and early summer freshet and low flows occurred throughout the winter months due to storage as ice and snow within the upper drainage basin. However, under the managed regime peak flows remain essentially constant throughout the entire year to meet energy demands. Therefore, flows during the winter months are much higher than historical values while flows during the summer months are lower than historical values (Figure 2.6).

The dam has effectively removed both the upper and lower end members of the historic flow regime. Prior to flow regulation, there appears to be a natural break in observed MDD and bimodal distribution of flows, those of a recurrence

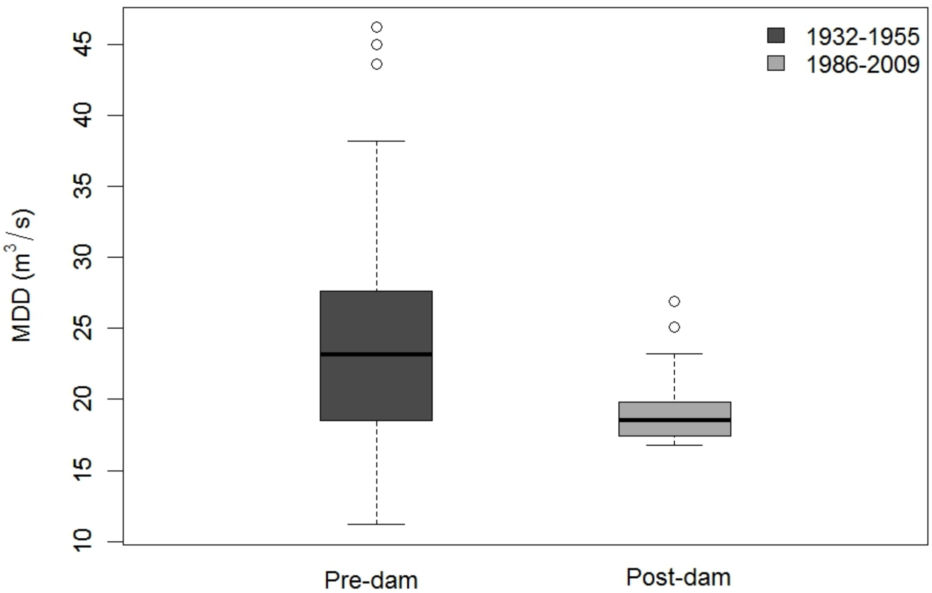

Figure 2.5: Boxplot of maximum daily discharge for pre- and post-dam flow data. Both the magnitude and variability of maximum daily discharge were reduced as a result of Pocaterra dam.

interval less than five and the higher magnitude flows of recurrence interval greater than five (Figure 2.3). The higher magnitude population, occurring in 1932, 1933, 1938, and 1948, represent the most extreme floods on record all greater than 35 m^3/s. Under regulated flow regimes these high flows no longer occur, and the more frequent lower magnitude flows of Q_5 and less have been reduced by 5 m^3/s on average.

2.4.2 Detection of morphologic change

Width Change

Based on the aerial photo analysis, localized width change has occurred along the Kananaskis. Statistically significant width change was detected at four of the ten study sites based on historic aerial photos. Width adjustment was defined as the difference between pre- and post- reach averaged width where a *p* value less than 0.05

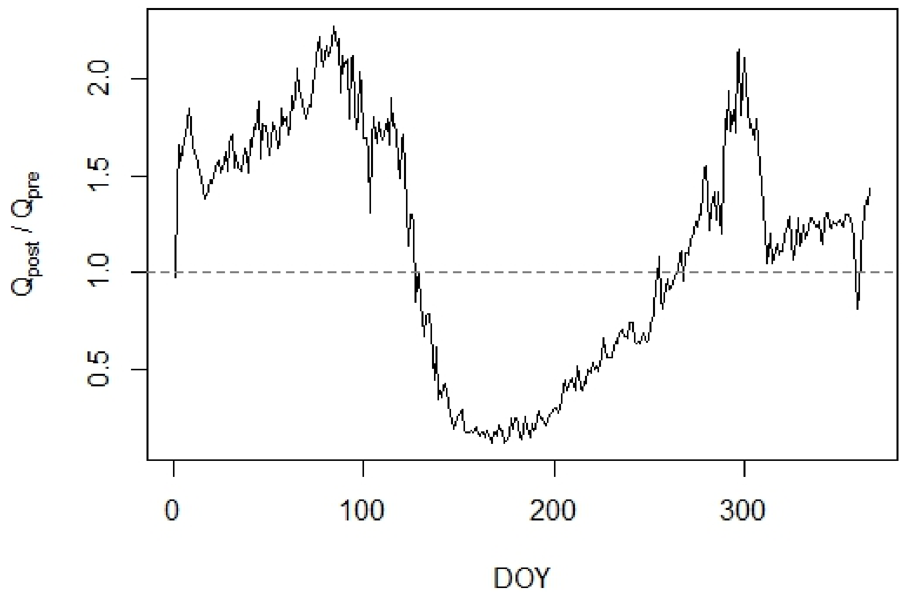

Figure 2.6: Maximum daily discharge for each day of the year (DOY) was used to determine the ratio of post-dam to pre-dam daily discharge. Post-dam flows are substantially higher in the winter and lower in the summer than under the natural flow regime.

in a t-test indicates channel width change. Between 1958 and 2008 channel width adjustment was not unidirectional rather sites experienced widening, narrowing, or no change (Figure 2.7). Located approximately three kilometers downstream of the dam, site 1A experienced a statistically significant 5 m widening. The following six sites (1B-3A), spanning the region 4 to 27 km downstream from the dam did not show a significant difference between the 1958 and 2008 widths. The most downstream three sites 3B, 3C, and 3D exhibited a significant narrowing of 21, 39, and 50 m respectively. Narrowing trends were often associated with decreased number of active channels due to abandonment of back channels.

Though each site represents a single morphological unit, we noted that width

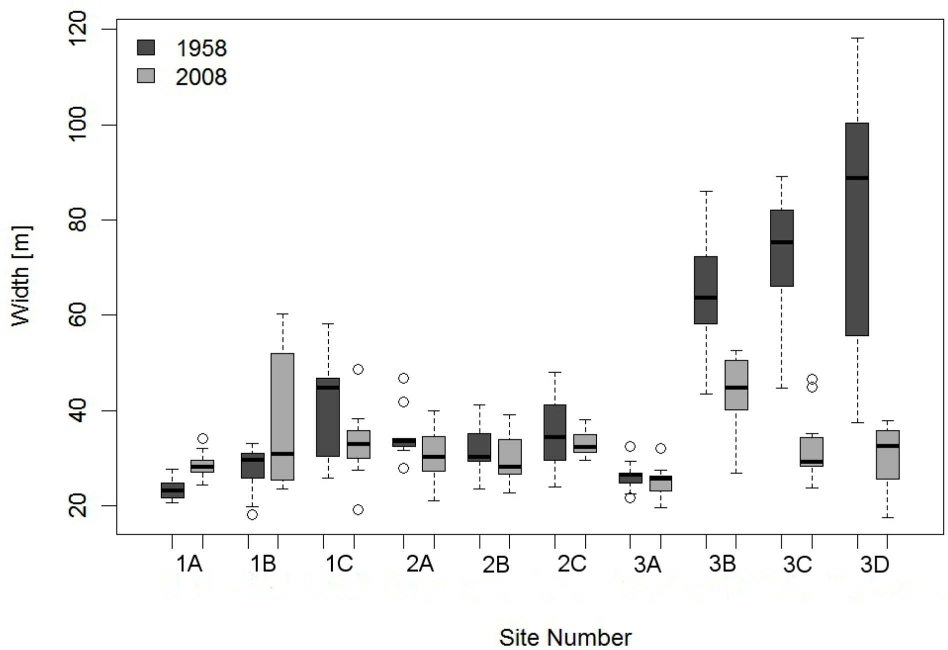

Figure 2.7: Bankfull width based upon 11 measurements per reach from aerial photo measurement. Site numbers correspond to Figure 1 with distance downstream from the dam increasing to the right.

varied substantially within a single site. Single thread reaches like sites 2A, 2B, and 2C show a significantly lower width interquartile range than the multi-thread reaches in the downstream sections. Therefore in addition to changes in width between 1958 and 2008, there were also changes in intrasite variability of width. Sites 1B, 3B, 3C, and 3D each experienced a substantial decrease in width variability over the period of interest while site 1C showed an increase intrasite variability (Figure 2.7). In many cases a decrease in variability was associated with reduction in the number of active channels.

Planform change

Post-dam channel adjustment also occurred through transitions in morphologic units in the channel and riparian corridor. Many of these changes in planform are highlighted by the time series of site 3C (Figure 2.8). There is a decrease in

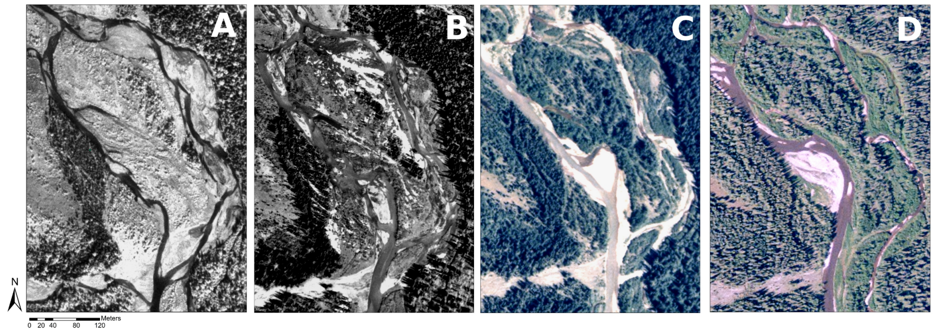

Figure 2.8: Timeseries including 1958 (A), 1972 (B), 1996 (C), and 2008 (D) for site 3B located downstream of the bridge to Kananaskis Village. Images show a shift from multithread channel in 1958 to dominantly single thread channel by 2008 through gradual abandonment of backchannels.

the number of active channels, which throughout the study sites is often associated with the abandonment of back channels in favor of a single dominant thread. At site 3C between 1958 and 1972, flow has shifted predominantly to a single channel, though other channels continue to carry water and presumably sediment at the time of photo acquisition. By 1996, the channel appears to approach a stable form, with a single dominant channel and few back channels active at that time. There are shifts in the positions and number active bars which reflect flow conditions at the time of image acquisition rather than bar dynamics. Throughout the entire study region the system has shifted to favor a single thread, however multiple threads remained prominent features just upstream of tributary inputs and alluvial fans.

We chose 3 sites, 1B, 2B, and 3C to map morphologic units change as they represent the typical responses observed below the dam, in the middle reaches, and in the downstream section respectively. Only the pre-dam (1958) and post-dam (2008) images rather than the intervening images were used because they are georeferenced and thus provide more accurate estimates of surface area. Changes in planform at site 1B are representative of the shifts in channel morphology observed in just downstream of the dam. The width of the active channel including the water surface and unvegetated bars remains unchanged between 1958 and 2008 however the distribution of different surface types has shifted (Figure 2.9). At this site, the channel does not appear to have shifted laterally and thus is locked in essentially

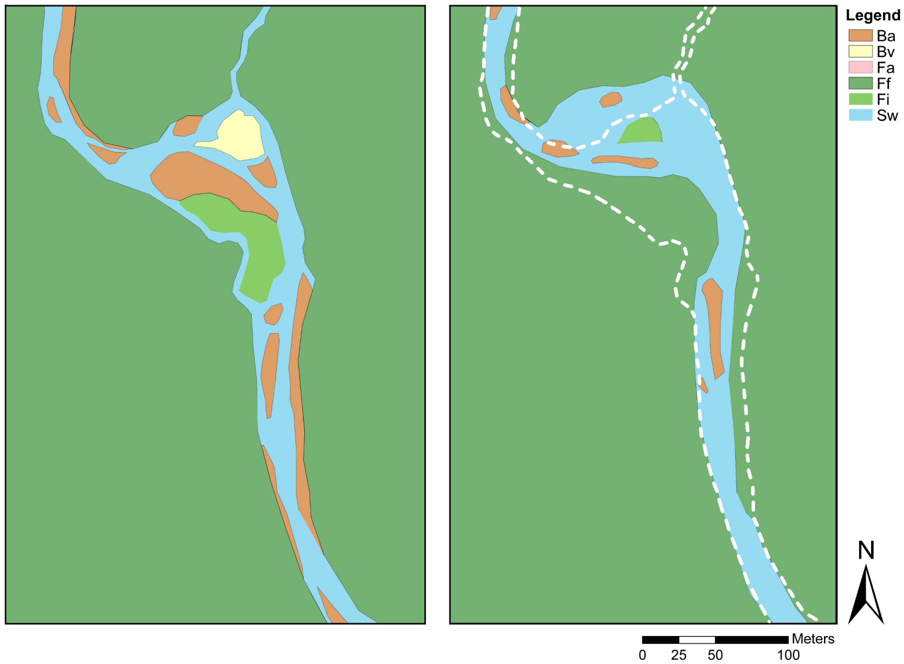

Figure 2.9: Changes in planform occurring at Site 1B, in the upper section of the study site between 1958 (left) and 2008 (right). Surface types include active bars (B_a), inactive bars (B_v), alluvial fan (F_a), floodplain (F_f), island (F_i), and water surface (S_w). 3D imagery and aerial photos were used to identify surface types. On the 2008 map pre-dam channel morphology is indicated by the dotted line.

the same position within the valley bottom. However, the channel has shifted from a multi-thread to single thread pattern with abandonment of small back channels. The 2008 vegetated islands are 18% of their previous extent due to reattachment to the floodplain surface. We also observed complete loss of vegetated bars, in favor of a channel characterized by mature floodplain surface and bare, unvegetated bars. This implies that the structure of the channel adjusted despite the lack of observed width change.

Site 2B exemplifies changes observed in the middle reaches which are situated within the tortuously meandering section of the Kananaskis. Throughout these reaches, overall channel morphology remains similar over the period of interest

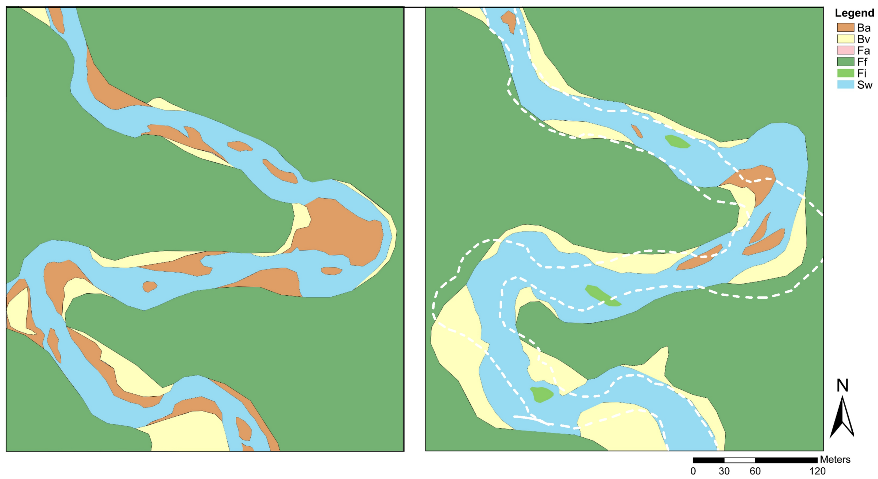

Figure 2.10: Changes in planform occurring at Site 2B, in the middle, meandering section of the study site between 1958 (left) and 2008 (right). On the 2008 map pre-dam morphology is indicated by the dotted line

and little shift occurs in the position of the meander bends indicating relative stability (Figure 2.10). Lateral migration up to 10 meters appears to have occurred, though georeferencing errors may contribute to this apparent change. While the morphology maps appear to show a decrease in active bars, the abundance of active bars in the 1958 imagery is a function of the apparent low water level at the time of image acquisition. Therefore, comparison of active bar surfaces between the two time periods cannot be made without consulting flow data for this time. Important to note however, is the greater than 200% increase in vegetated bar surfaces. In the 1958 imagery vegetated bars are present only on the inside of meander bends, whereas this surface cover dominates bank conditions in the 2008 system.

The morphological changes observed at site 3C are representative of adjustment occurring in the downstream end of the study region. In this reach, flow and sediment conveyance shift from two comparably sized channels to a single dominant thread with smaller channels present (Figure 2.11). Channel migration is most common in the downstream reaches, presumably due to the open floodplain and lack of channel confinement. Here vegetated bars became further stabilized and become part of the modern floodplain with a reduction of nearly 60% in area. The 2008 channel also shows an increase in island surfaces which appear to remain

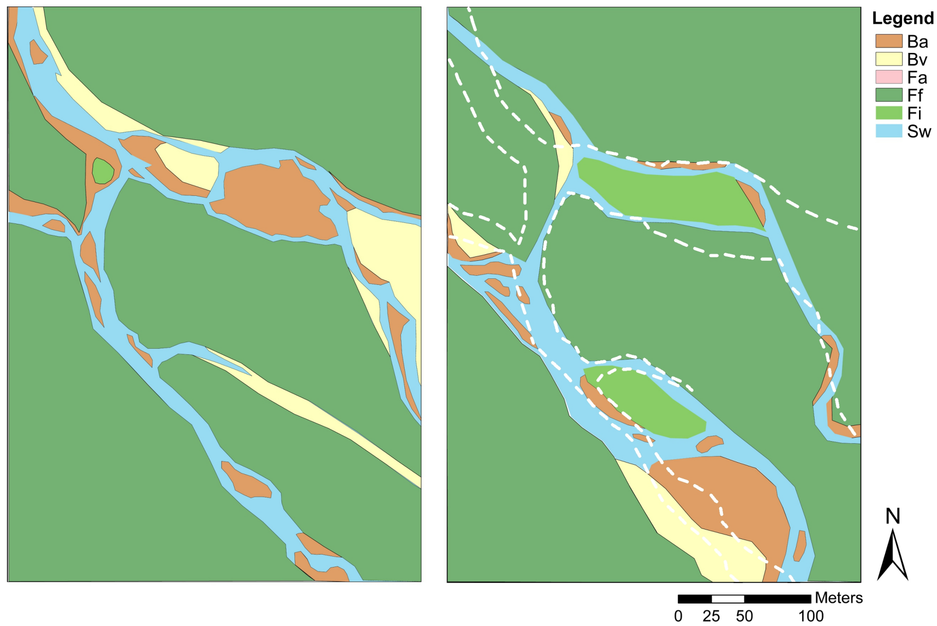

Figure 2.11: Changes in planform occurring at Site 3C, in the lower, most anthropogenically modified section of the study site between 1958 (left) and 2008 (right). One the 2008 map pre-dam morphology is indicated by the dotted line.

above the level of inundation throughout the year. Additionally, the 1958 imagery at this site show that one of the smaller channels in the center of figure 2.11 is partially abandoned and appears to be encroached by vegetation. However it is unclear whether this channel abandonment was initiated with the dam construction or prior to it.

These shifts in planform are important and often overlooked suite of changes occurring in response to dams [Ligon et al., 1995]. As is the case for sites 1B and 2B, no width adjustment was detected which may cause one to conclude that no changes have occurred since dam closure. However, the shifts in geomorphic units show that there has indeed been changes to the form of the channel which may have important ecological implications. The abandonment of backchannels channels which promote a shift toward a single active channel may reduce fish habitat. Additionally, the changes in vegetation classes along the banks could impact re-

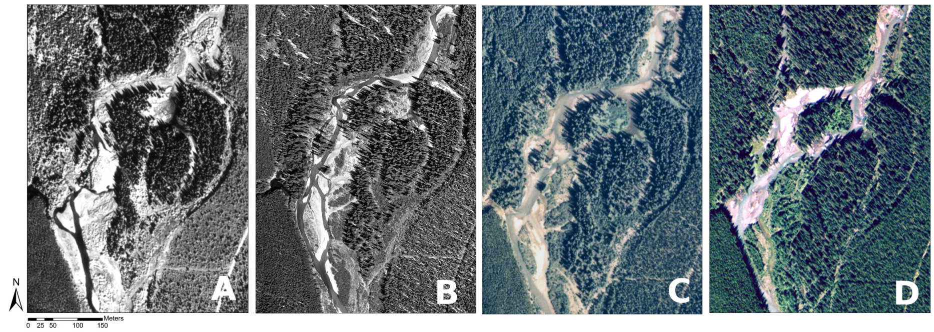

Figure 2.12: Timeseries including 1958 (A), 1972 (B), 1996 (C), and 2008 (D) just downstream of site 1A where channel adjustment is accompanied by encroachment and increase in density of riparian vegetation. Such changes were characteristic throughout the upper region of the study site.

cruitment of woody debris, which also provides instream habitat. These changes to surface cover are therefore an important yet subtle result.

Vegetation change

As the surface cover maps implied, there have by changes in the classes and structure of bank vegetation. The entire study reach was characterized by an increase in density of riparian vegetation and at all sites there was an increased density of trees within riparian forests. In the upper reaches there was a bimodal distribution of 1) mature conifers with minimal understory and 2) grasses, sedges, and shrubs which are early successional species (Figure 2.12). Intermediate successional stages such as deciduous species and saplings were notably absent from the upstream region. This pattern is particularly prominent in the middle reaches located in the meandering section of the river. At these sites the vegetated bars are dominated by sedges, horsetail, and young willows while the mature floodplain species include mature conifers of a single age class.

This bimodal distribution did not manifest as strongly in the downstream sites. The 3 most downstream sites, 3B, 3C, and 3D, were characterized by a more heterogeneous landscape with different successional stages represented. Trembling aspen are present at these sites, as well as a gradient of successional stages within the riparian forests. The downstream reaches were more similar in structure and species distribution to riparian forests along other rivers in neighboring basins in the same geoclimatic and topographic setting, such as the Highwood or Elbow River.

2.4.3 Modeling channel adjustment

The first step in modeling post-dam channel characteristics is to calibrate the model to pre-dam conditions using $\mu\prime$ bank strength index. By running the UBCRM for the pre-dam Q_2 to Q_5 and Q_5 to Q_{25} formative discharge, we identified the most appropriate formative discharge range using values for $\mu\prime$ in the initial model calibration. The Q_5 to Q_{25} are more reasonable given our knowledge of the vegetation densities observed from aerial photos. For many of the sites the Q_2 to Q_5 formative discharge range yielded $\mu\prime$ values for the pre-dam system which were less than one. A $\mu\prime$ of less than one implies that the banks are less erodible than the bed. These values are physically unrealistic due to the presence of vegetation, albeit sparse, along the channel banks.The use of the lower magnitude formative discharge range as the model input parameter under-predicted pre-dam widths. Due to the physical implausible bank conditions associated with the lower discharges, the higher magnitude and lower frequency formative discharge range Q_5 to Q_{25} appeared to more strongly control channel morphology and thus was used in further model scenarios. This is consistent with observations that arid environments may be more strongly controlled by extreme floods rather than the 2-year flood [Baker, 1977]. At the upper regions of the basin this flow range fell between 33.1 and 52.8 m^3/s and between 52.0 to 83.0 m^3/s for the most downstream of the sites (Table B.1).

The model was then calibrated to pre-dam conditions by adjusting the $\mu\prime$ variable. Starting at one, the $\mu\prime$ was incrementally increased until the model predicted width matched observed 1958 width as described by Millar [2005]. This process was repeated for each site yielding 10 unique $\mu\prime$ values. Because $\mu\prime$ varies systematically with vegetation density it provides an estimation of the state of the riparian forests for pre-dam conditions. The $\mu\prime$ values for the 10 sites range between 1.20 and 2.55, corresponding to sparse shrub dominated banks and more densely forested conditions, respectively (Table B.2). The qualitative photo interpretations of pre-dam riparian vegetation is in agreement with the model calibrations such that sites which appear to have more densely vegetated banks also have a higher $\mu\prime$ value in the model calibration.

For the second model simulation, we used the post-dam Q_5 to Q_{25} for the formative discharge input parameter. Model success was based upon the degree of overlap between model predictions and observed widths over a range of two standard deviations from mean of observed channel widths. The widths estimated in the second model simulation for sites 1C, 2A, 2B, 3A, 3B, and 3D fell completely within the acceptable range of the observed widths (Figure 2.13). At these six sites, the UBCRM appeared to reasonably characterize the width associated with the post-dam formative discharge.

Site 3C also satisfied the criteria for model success with 92.3% of model widths falling within the $^+/_-$ two standard deviation range. However, there is a 10 m difference between the mean observed width of 33 m and model mean of 43 m. Therefore, the model estimates were at the upper bounds of the acceptable values. Model results at this site could be improved by increasing the $\mu\prime$, as this site was shown to have increased in riparian vegetation which may promote a more narrowed channel than was predicted by the regime model.

Model results for the remaining three sites did not show as close a match with observed width values. At site 1A, just downstream of the dam, the mean channel width measured was 28 while the model predicted a width on average of 18 m. All of the modeled widths for this site fell below the range of observed values (Figure 2.13). Model results for site 2C also showed widths which were less than observed widths. At this site 49.3% of the modeled widths from the Monte Carlo simulation fell within the 2 standard deviation range of observed values and thus approximately half of the values fell below the range of acceptable values (Figure 2.13). Therefore at these two sites the UBCRM under-predicted channel width.

There was also disparity between modeled and measured widths which resulted from the spread of observed data. For site 1B, all modeled widths fell within the 2 standard deviation range for observed values, though the mean observed width is 37 meters and modeled mean is only 21.3 meters. That this site satisfied our criteria for model success is a function of the wide range of widths measured for this site, rather than a match between observed and predicted widths. Due to the channel

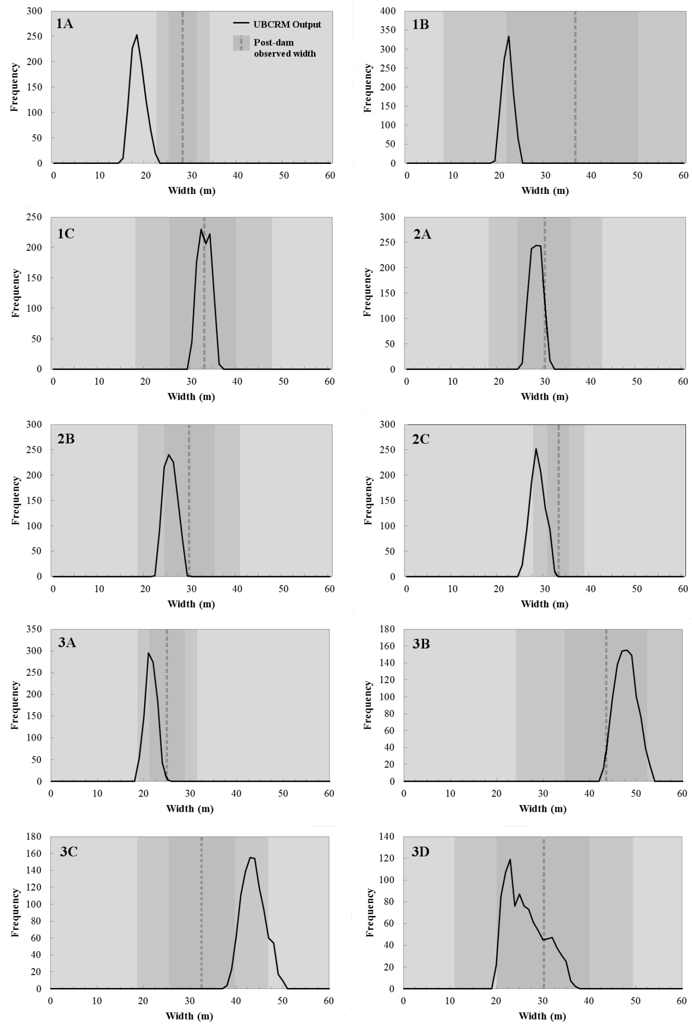

Figure 2.13: Results from UBCRM simulation of post-dam conditions. Dotted lines represent mean of post-dam width measurements with the darker shaded area ranging over +/- one standard devation and lighter shaded area over +/- two standard deviations. The solid line shows results of 1000 iteration UBCRM output using the $\mu\prime$ values calibrated to pre-dam observations.

morphology at this site, a wide range in widths was observed and thus there was a standard deviation of 14.5 meters. Therefore range of acceptable outputs from the model include widths from 8 to 66 meters and all modeled output widths fell within this wide range.

In addition to providing a reasonable estimation of the changes to channel width, the regime model also characterizes the shifts in channel pattern which occurred in the multi-thread reaches. Based on our threshold criteria for number of channels using a width to depth ratio greater than 50, we found that sites 3B, 3C, and 3D were predicted by the UBCRM to be anabranched rather than single channel. The downstream sites 3B and 3C were found by the model to be stable as a network of 3 channels, while site 3D was found to be a stable 4 channel system for pre-dam conditions. This is generally consistent with pre-dam aerial photo observations, though in some cases it is difficult to identify all of the active channels due to imagery resolution. Following the reduction in discharge the model found the most stable channel form for site 3B to be two active channels, and for 3C and 3D to be single channels. This implies that there should be a reduction in channel complexity following flow alteration due to a reduction in anabranching. This reduction is indeed observed for all three sites with fewer active channels present as compared to pre-dam imagery. In the field we observed multiple small backchannels which convey a small portion of flow volume, which may imply that these regions are still in a transitional state towards a new equilibrium form. However, overall the model predictions of shift towards fewer active channels is consistent with the observed trends. The UBCRM is therefore a useful tool in interpreting the equilibrium channel geometry and pattern for both the pre- and post-dam scenarios along the Kananaskis.

2.5 Discussion

Based on the observed and modeled channel widths we cannot reject the hypothesis that river adjustment would follow the regime adjustments predicted by the UBCRM. The model acceptably simulated the observed channel change at 7 of the 10 sites, though results at some of these sites could be improved by incorporating modern bank strength values (Figure 2.13). Of the sites which did follow the modeled adjustments there appears to be downstream trends where the UBCRM tended to under predict bankfull channel width in the upstream reaches. However, our hypothesis was not supported that channel change would follow a single unidirectional narrowing trend which decreases with distance downstream of the dam. Rather responses at each site were variable in that widening, no change in width, and narrowing were found (Figure 2.7). Additionally, the largest channel adjustments between 1958 and 2008 were observed in the most downstream sites contrary to our hypothesis that the greatest channel change would occur just downstream of the dam. The complex response of the system likely relates to multiple factors influencing channel dynamics including changes in hydrology not captured by the formative discharge term, riparian vegetation interactions, and winter ice conditions. Though overall the model preformed well, it is limited by these factors and the basic assumptions associated with the UBCRM.

2.5.1 Hydrology

The disparity between model predictions and results for 4 of the 10 sites may relate to our parameterization of the hydrological forces within the system. Our estimations of formative discharge relate to regional relations using drainage area rather than actual flow data measured for each site. This use of estimated stream flows may limit the models ability to characterize the channel geometry and contribute to the poor model performance at the four sites.

Discrepancies between measured widths and model results at the upstream sites may relate in part to our use of a single formative discharge in the UBCRM. Our choice of a single flow value did not accurately represent the changes in frequency and distribution of flows capable of doing work on the channel. Pre-dam peak flows were higher than regulated peak flows, but occurred comparatively less often. However, under the regulated flow regime bankfull flows occur on a daily basis, though they are lower in magnitude than pre-dam high flows. The UBCRM operates under the assumption that the single flow chosen as the formative discharge is the flow most capable of geomorphic work which typically is the median MMD [Eaton and Church, 2007]. However, this does not account for the duration and frequency of these flows which is an important feature of hydropeaking systems. It may be that these more frequent intermediate flows which control channel change rather than change to the highest flows. It has been shown that intermediate flows drive channel change in the Kemano River following flow alteration [Kellerhals, 1982]. Therefore, because the peak flow in the regulated regime is capable of mobilizing sediment the model does not accurately predict channel adjustment at the upper sites.

While the hydropeaking flow regime complicates our ability to model this system with the UBCRM, it provide explanation for the downstream trends of channel adjustment. The peaking flow regime likely acts as a strong driver of pattern of channel adjustment showing widening at the upstream site, no change in the middle reaches, and channel narrowing in the most downstream sites (Figure 2.7). At the upstream site ramping flows occur most strongly, with flow increasing from 1 m^3/s to 25 m^3/s over an approximately 5 minute interval. This rapid increase in flow depth and associated bank shear promotes bank erosion and scour linked to channel widening. The following 7 sites experience a dampened increase in bank shear as the flood pulse becomes attenuated in the downstream direction. The energy associated with ramping flows appears to be sufficient to prevent narrowing, but to not cause bank erosion. In the downstream 3 reaches, the flood pulse is attenuated such that vegetation is able to colonize bare bar surfaces without experiencing mechanical breakage at the next flood pulse. This vegetation colonization likely promotes further narrowing through stabilization of banks and trapping of fines. This implies that the upstream site responds to the hydropeaking signal while sites further downstream appear to respond to overall reduction in magnitude of flows. This is further supported by our model results where the UBCRM performed better for the sites further downstream.

2.5.2 Ecology

Feedbacks and linkages also occur between the hydropeaking flow regime, vegetation dynamics, and channel adjustment. The daily peaking flow prevents scour and associated vegetation colonization and new tree growth. In the more upstream reaches this is most evident where riparian vegetation is characterized by only mature trees with few age classes or different successional stages present. At this site there has been slight widening and thus vegetation is unable to colonize fresh surfaces. In the middle reaches, there has been little change in channel width and the channel remains essentially locked in position. No colonization space is created due to the lack of lateral channel migration and few successional stages are represented. Any expansion of riparian vegetation is scoured by the subsequent flood pulse. The most downstream reaches have narrowed, due to the more attenuated flood pulse and thus vegetation is able to colonize freshly scoured surfaces. Similarly, freshly colonized surfaces are less likely to undergo mechanical breakage in the following flood pulse because flows are more attenuated.

The implications of the UBCRM results are consistent with observations of vegetation dynamics. With $\mu\prime$ held constant, width in the downstream reaches, particularly site 3C, was predicted to be wider than was actually observed. However, aerial photos show that an increase in riparian vegetation has occurred. It would therefore be more appropriate to use a higher $\mu\prime$ value to correspond to the increased bank strength provided by more dense bank vegetation. The use of an increased bank strength index in the post-dam scenario would cause width predictions to decrease slightly and thus approach the observed value. Through an increase in $\mu\prime$, the model predictions could more closely match observed trends in the downstream sites.

However aerial photos show that all sites exhibited increased bank vegetation and thus all should have a higher vegetation driven bank strength rather than just the downstream sites. Therefore, post-dam $\mu\prime$ should be greater than pre-dam $\mu\prime$ rather than set equal. Consequently the bank strength which we used is the lowest that could possibly be applied and the widths predicted by the model are the maximum possible widths. Yet at many of the upstream sites observed widths which were slightly larger than those predicted by the UBCRM (Figure 2.13). The only way that the model would match these higher widths is through a decrease in $\mu\prime$, which we have already determined is inappropriate given the bank conditions. This implies other factors than those modeled must contribute to the channel behavior.

2.5.3 Ice

Though this study was limited to observations of the system under summer conditions, ice dynamics also appear to be an important control over the river behavior during winter conditions. Flow regulation has changed the hydrology of the system such that flows are much higher in the winter than they had been previously(Figure 2.6). During the winter months, low flows form an ice cover over the river which is either lifted during ramping flows promoting bed mobilization, or reduced the cross sectional area of the channel causing over topping of banks during flood release. Along the entire study reach there was evidence of lifted ice patches within the channel as well as gravel and fine sediment deposition on the floodplain. Additionally, the inundated floodplain regions have been observed to be the result of winter flooding (personal correspondence).

It therefore appears that the hydropeaking flow regime not only causes novel flow conditions in the summer but also unique interactions with ice cover. These interactions with ice conditions could limit the ability of the UBCRM to predicted channel form. The fundamental basis of determining channel geometry with the UBCRM relies the calculation of sediment transport by flow, however if a significant amount of material is transported as a result of winter ice dynamics sediment transport is not accurately represented by the model.

Winter ice conditions also appear to impact the structure of riparian forests. Evidence of mechanical breakage was present at sites across the entire study reach implying that it is not merely summer high flows which prevent colonization along banks. This is particularly evident in the tortuously meandering reaches 2A, 2B, and 2C where ice and log jams are common. There is a sharp distinction between mature forest and early successional grasses, sedges, and willows likely due to the winter ice scour and flooding (Figure 2.10). Because this study was focused on summer flow conditions it is unclear to what extent winter ice dynamics are controlling the unique channel responses on the Kananaskis following dam construction.

2.5.4 Other factors

Other assumptions which accompany the UBCRM also impact our ability to predict channel adjustment. The entire region through which the Kananaskis flows is underlain by a complex glacial history to which the modern fluvial landscape may not be fully adjusted. The pre-dam model scenario was based upon the assumption of conditional equilibrium between flow and flow resistance, however it remains possible that this assumption was violated given the glacial history. Additionally, the widths predicted under the post-dam scenario refer to a new stable channel geometry, while the present system likely represents a transitional stage rather than the fully adjusted response.

2.6 Conclusions

The changes in channel morphology which have occurred from 1958 to present are the result of a complex combination of driving forces. Both long term changes in hydrologic regime like overall reduction in high flows and shifts occurring over a daily time scale manifest in present configuration of channel morphology. The sections of the river just downstream of the dam appear to be most strongly controlled by the hydropeaking signal, while further downstream reaches reflect changes in MDD. This creates a limitation in modeling because it is possible to simulate only changes in the magnitude of flow but not changes in the frequency and duration of flows which are capable of doing geomorphic work. Vegetation also responds to these signals by failing to colonize new surfaces, which in turn affects channel bank strength and ultimately channel width. Changes in vegetation, as a result of natural dynamics and anthropogenic influences, are an important component of landscape evolution and therefore must be considered in predicting channel adjustment. All of these processes are influenced by winter ice conditions which drive vegetation dynamics and play a significant role in sediment transport. Ice plays an important role in shaping channel morphology in high altitude rivers such as this, but further study is needed to determine to what extent river are controlled by winter conditions. Despite these apparent limitations, the UBCRM performed well in predicting post-dam channel width and pattern and also allowed us us to tease out that other factors are contributing to channel geometry other than merely a change in channel forming flow. Changes to other aspects of the ecosystem can be better assessed through understanding of the geomorphic framework which underpins the system.

Chapter 3

Depth distributions and downstream pool spacing

3.1 Introduction

The hydrological and morphological changes which occur as a result of dams have received wide attention due to their impact on both terrestrial and aquatic organisms adapted to the historical regimes [Sparks, 1995, Ward et al., 1999]. Habitat within steams responds quickly to change making these ecosystems particularly sensitive to landscape changes [Power et al., 1988, Ligon et al., 1995, Dudgeon et al., 2006]. Additionally, damage to ecosystems results in a loss of valuable ecosystem services [Baron et al., 2002, Fitzhugh and Richter, 2004]. Changes in flow and sediment can cause changes in the structure of riparian forests [Jansson et al., 2000, Merritt and Cooper, 2000, Magilligan et al., 2003, Rood et al., 2003, Rood and Mahoney, 1990, 1995, Rood et al., 2005], in assemblages of periphyton and invertebrates [Petts, 1980, Petts and Greenwood, 1985], and in populations of aquatic and terrestrial species [Kingsford, 2000]. However, the impact of flow regulation on fish is of particular concern due to their sensitivity to perturbations and their economic importance.

While biotic factors play an essential role in fish survival and reproduction, abiotic factors are directly linked to flow regulation [Bunn and Arthington, 2002]. These abiotic factors are more generally referred to as physical habitat, which include such features are temperature, substrate, depth, distribution of pools and riffles, flow characteristics, vegetation, and other features of the stream [Gorman and Karr, 1978, Milner et al., 1985, Bunn and Arthington, 2002]. Studies show that abundant fish assemblages are associated with with more diverse habitat [Gorman and Karr, 1978, Beisel et al., 1998, Rowe et al., 2009]. Optimal physical habitat characteristics depend upon species, fish life cycle stages, and time of year. Therefore any subtle affect on physical habitat can result in stress on the organisms, impaired reproduction, and mortality [Bunn and Arthington, 2002].

Changes in the physical habitat and corresponding biological linkages contribute to changes in fish assemblages following river damming. High flows and sediment starved waters typical in river reaches just downstream of dams can create higher velocities rendering sites unusable for fish species [Bain et al., 1988]. Rapid flow fluctuations have also been found to cause catastrophic drift of invertebrates which comprise fish food sources [Munn and Brusven, 1991, Layzer et al., 2007]. Additionally, sediment starved waters can mobilize bed sediment promoting armoring of the bed [Poff and Hart, 2002] and decrease appropriate redd sites [Sear, 1993].

Further downstream from the dam where decreased flows are more characteristic habitat changes can also occur. These decreases in flow reduce the usable wetted perimeter or promote channel narrowing, thus reducing available habitat [Bravard et al., 1998, Valentin et al., 1994, 1995]. Low flow can promote deposition of fines between larger clasts preventing flow of oxygen through the substrate and thus deprive eggs the necessary oxygen [Kondolf, 1997, Sear, 1993]. Flow regulation by dams therefore can impact all of the distinct habitats required in fish life cycles and ultimately reduce fish populations and community complexity [Kinsolving and Bain, 1993, Travnichek et al., 1995]. Indeed this has been observed in systems across the world and has been extensively studied to both document the change and reduce consequences of present and future dams [Power et al., 1996, Reyes-Gavilan et al., 1996, Kingsford, 2000, Nilsson et al., 2005].

Due to the complex set of factors impacting fish diversity, this study focuses on the depth component of the physical habitat and the distribution of pools within stream reaches. For many taxa, depth represents an important control on fish size and predation survival [Schlosser, 1982, Gorman, 1987, Harvey, 1991, Harvey and

Stewart, 1991]. Additionally, distributions of depth and velocity are used in Physical habitat simulation (PHABSIM) systems which are a commonly used suite of numerical models in fisheries research [Bovee, 1982]. With these models physical habitat can be quantified in relation to the habitat preferences of a specific fish species or life stage based on a combination of depth and velocity sometimes including substrate and cover [Booker and Dunbar, 2004]. PHABSIM is extensively used to model usable habitat and change to habitat associated with various perturbations [Acreman and Dunbar, 2004]. The arrangement of high depths into pools are also an important aspect of diverse habitat because pools promote variability in depths, velocity, cover, and grain size. Therefore, an understanding of the distribution of depths and pools within the channel allows better understanding the physical characteristics which underpin fish dynamics and allow us to model these changes.

In this study we propose a method of remote sensing techniques to estimate depth distributions and create simple spatial data to understand the arrangement of pools. Depth and pool data is a fundamental characteristic of physical habitat, yet generally requires time and labor intensive fieldwork and surveying. Such data is particularly useful in understanding fish dynamics in channels whose morphology and thus physical habitat has been altered by flow regulation. Therefore, we focus on a case study of the distribution of depths in the Kananaskis River which has been impacted by a hydropeaking dam. Streams such as the Kananaskis which experience rapidly fluctuating flow stage by hydropeaking dams are particularly susceptible to morphological change when the flows maintain competence to mobilize sediment [Cushman, 1985]. Others studies indicate that the minimum flows must be suitable to maintain aquatic organisms and thus we focus on depths at the low flow in the hydrologic regime [Kilgour et al., 2005]. Our primary questions of interest are:

1. How does the distribution of depths within the Kananaskis compare to statistical distributions for streams?

2. How do depth distributions change along a downstream gradient?

3. How are the high depths spatially distributed within morphological features?

We compare the remotely sensed depth data to depth probability distributions based on the Lamouroux model [Lamouroux, 1998]. This model uses a one-parameter density function to characterize the distribution of depths within a channel based on the observation that depth distributions follow an exponential distribution at low stages and tend towards a normal distribution centered about the mean at higher stages [Lamouroux, 1998, Lamouroux et al., 1995]. This model has shown robust performance on a wide range of rivers as it was developed and tested on 30 French and German rivers which exhibited great range of geomorphological and hydrological characteristics with discharges ranging from 0.003 to 1110 m^3/s [Lamouroux, 1998]. These methods were also found to characterize depth distributions in 20 sites in Western Washington ranging in drainage basin size from <180 km^2 to >1500 km^2 [Saraeva and B., 2009]. Because the underlying distributions of depth in the Lamouroux model have been shown to hold across rivers of a variety of scales it can therefore be reasonably applied to the Kananaskis study site [Lamouroux, 1998].

We hypothesize that residuals between observed and modeled depth distributions will have the greatest magnitude in the site closest to the dam because the impact of flow alterations are greatest just downstream of the dam. We also hypothesize that the observed and modeled distributions will match more closely in the sites further downstream corresponding to the attenuation of the flood pulse by tributary inputs. We also expect that high depths will be clustered in pools. By addressing these questions we also may be able to better understand potential ways that flow regulation has impacted fish species.

3.2 Study Site

The Kananaskis River is located within the front range of the Canadian Rocky Mountains flowing within a glacially eroded valley. The sediment supply of this alluvial, gravel bed river is provided primarily by the multiple tributary inputs. The main channel alternates between single thread meandering channel and mulithread anastamosed channel near the backwater influenced regions behind tributaries.

The climate of the Kananaskis is transitional between plains and cordilleran temperature and precipitation. The natural hydrology is characterized by a strong nival cycle, with most precipitation locked in snow in the winter and melting in the late spring continuing into early summer. It originates at a source elevation of 2720 m and thus the river itself experiences sub zero temperatures during the winter months. Therefore, ice dynamics appear to be an important part of this system and evidence of ice impacts was found along the Kananaskis, though to date the influence of ice on channel morphology has not been extensively studied [Morse and Hicks, 2005]. Along other Canadian Rivers, river ice has been found to have a variety of geomorphic impacts including channel widening [Smith, 1979, Martinson, 1980], sediment transport alterations [Prowse, 2001], bedform geometry changes [Ettema, 2002] and damage to riparian vegetation [Uunila, 1997].

Flow regulation has been a feature of the Kananaskis River since the 1930's though it wasn't until 1955 that significant flow alteration occurred with the construction of Pocaterra dam (Figure 3.1). This dam, located at the base of Lower Kananaskis Lake operates on a hydropeaking flow regime, with flows rapidly shifting from 1 m^3/s to 25 m^3/s over the course of a single day (Figure 3.2). This acts to eliminate spring peak flows, increase winter flows, and cause bankfull stage on a daily basis. The peaking flow regime causes the water levels in the floodplain to typically be very high during the growing season compared to pre-regulation. This will have important impacts on the vegetation colonization dynamics. These ramping flows also have potential to affect channel morphology and aquatic species as they are directly linked to instream flow conditions.

Of the ecological changes that have occurred since the 1950's, fish are of primary concern due to their sensitivity to perturbations as well as their importance to angling tourism in this region. As is the case for many regulated rivers, species present within the river have experienced shifts in dominance with loss of some species entirely. Prior to flow regulation and extensive land management, the primary fish within the river included mountain whitefish (*Prosopium williamsoni*), cutthroat trout (*Oncorhynchus clarki*) and bull trout (*Salvelinus confluentus*) [Courtney et al., 1998]. However, by 1965 bull trout, cutthroat trout, and Rainbow trout (*Oncorhynchus mykiss*) were absent from our study reach while mountain whitefish and brown trout (*Salmo trutta*) became the dominant species. Brook trout (*Salvelinus fontinalis*) has also been documented [Nelson, 1965, Courtney et al., 1998]. These changes in fish diversity are attributed to a combination of

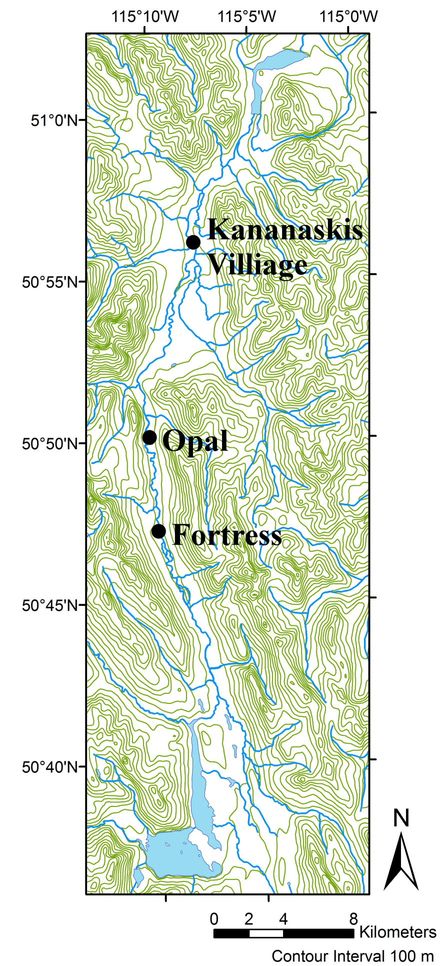

Figure 3.1: Study sites between Upper and Lower Kananaskis Lakes located in the southern edge and Barrier Lake in the north. Flow direction is from south to north.

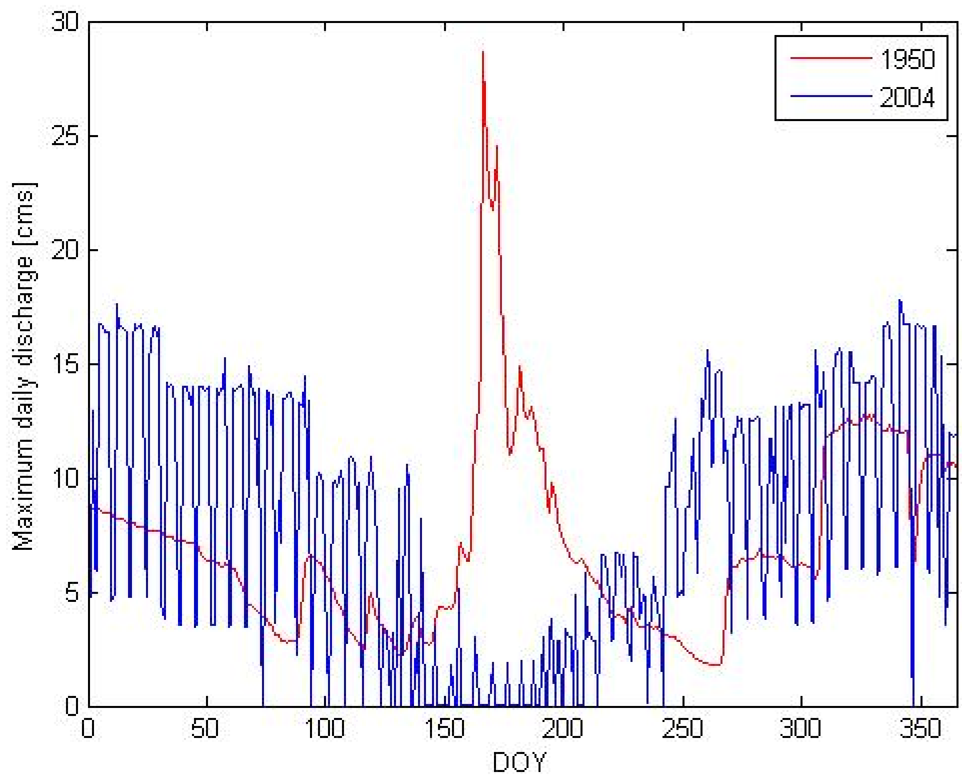

Figure 3.2: Seasonality in flows from a typical pre-dam year, 1950, and post-dam year, 2004. Pre-dam flows (red) reflect snow melt dominated regime with high flows during the early summer. Post-dam flows (blue) experience ramps every weekday, with lower flows during the summer snow melt to raise water level within the reservoir.

factors including stocking, angling, competition, and flow regulation.

The study site is located along the north flowing Kananaksis River between Lower Kananaskis Lake in the south and Barrier Lake in the north. This study focuses on three sites along the Kananaskis in order to capture the downstream gradient of change. The sites were chosen on the criteria that they include a wide range of depths, that each is representative of a morphologically distinct subsection of the river, and that they be accessible. The upper site is located near the Fortress ski resort approximately 12 km downstream of Pocaterra Dam. This morphological subsection is characterized by channel morphology which relates to proximity to tributaries. As this site is located just upstream of a tributary confluence, it is confined between a valley wall and alluvial fan with minimal floodplain development. The middle site is located within the tortuously meandering region of the river approximately 19 km downstream of the dam near the Opal day use area. At this site there are steep cutbanks and large log jams making it a potentially important reach for fish habitat. The lower site is located near Kananaskis Village, 34 km downstream of the dam and just downstream of the tributary confluence with Ribbon Creek. Channel morphology in this subsection of the river is complex and commonly characterized by multiple backchannels less than a meter wide. This site has high sediment input from the tributary confluence and a wide floodplain and thus appears to be laterally active.

3.3 Methods

3.3.1 Field work and surveying

Data collected through extensive fieldwork and surveying at three sites along the Kananaksis River was combined with remotely sensed imagery to allow us to understand the distribution depths at these sites. At each site water depth during low flow was measured to sub-centimeter accuracy using a total station surveyor and reflective prism. The plane of the water surface was identified and bed elevation was measured at 10 cm increments along multiple cross sections of the channel. The highest water depths measured were approximately 1.23 m, above which water velocity rendered continued measurements unsafe. Using the water surface data and bed elevation data we were able to extrapolate the water depth at low flow in the hydropeaking release schedule. This surveying method provided approximately 200 measurements of depth ranging from 0 to 1.23 m along a reach of 20 m.

After fieldwork was conducted, we acquired true color aerial images over the entire 40 km section of river extending from Pocaterra Dam to Barrier Lake. Images were acquired using a Canon EOS 550D optical camera mounted to a helicopter flying 300 to 400 m above the valley bottom. From the fly over, we acquired 2000 images of 2.54 cm resolution with 10% to 70% overlap. Visible ground control points were positioned at each of the three sites allowing us to georeference images and determine the position of depth measurements from field work. River stage at the time of image acquisition was the same as that during field work methods.

3.3.2 Analysis of remotely sensed data

The raw image data required manipulation prior to depth extraction. For each site we selected a reach of river which extended over approximately 11 bankfull widths in length. Using Agisoft Photoscan we created an orthophoto from all images with coverage over the selected reach. By merging a series of images into a single mosaic the impact of lens distortion and differing brightness between successive images was minimized. However, the orthophoto also had a reduced resolution of 16 cm. From the orthophoto binomial masks were created to isolate river pixels from all other pixels. We excluded overhanging trees, large woody debris, shadows, and partially exposed bars from the pixels defined as 'river'.

The ultimate goal of both the field measurements and remote sensing methods was to produce depth maps for each of 3 sites based upon the aerial images. The production of these maps was based upon knowledge of the absorption spectra of pure water. Water has high absorption in the red wavelength and lower absorption in the shorter wavelengths, though each stream will possess a unique absorption spectrum based on the geochemical signature and turbidity [Pope and Fry, 1997]. Due to water's absorption properties, the red wavelength has been shown to correspond to water depth in true color images [Carbonneau et al., 2006, Legleiter et al., 2004, 2009]. High values in the red band have been found to be associated with shallow water and lower red values correspond to deeper water as more of the red wavelength has been absorbed by the deeper column of water.

However, the value of red pixels within sequential images for the same site can show variability due to slight varying shutter speed of the camera and brightness of images so we used a ratio value rather than single band [Legleiter et al., 2009]. Ratio images were produced from the following equation extracted from the true color orthophoto:

$$\frac{\rho_{red}}{\rho_{blue}} \tag{3.1}$$

where ρ_{red} is the red band and ρ_{blue} is the blue band. For each site we produced an image mosaic and a corresponding ratio image.

The ratio image was then georeferenced to depth measurements using the ground control points and a red-blue ratio value was extracted at each location of field measured depth. For each site, an empirical equation was created using the approximately 200 points for field measured depths and extracted red-blue ratio values. A linear trend line was fit to the data in which the red-blue ratio value was log transformed. This trend could be used to estimate water depth for the spatial coverage of each site. First the river pixels were isolated from floodplain and exposed bars using the river mask, then were the input for empirical logarithmic equation producing a map of channel depths.

3.3.3 Modeling

Numerical modeling also provides a way to describe the distribution of depths which might be expected at each site given the water stage under low flow conditions. Lamouroux [1998] found that the distributions of water depths, relative to reach average depth, followed a function characterized by an exponential distribution for low flows and normal distribution centered about the mean during higher flows. Determination of whether the depth distribution at a given flow falls closer to the exponential or normal distribution is a function of a shape factor, t, calculated as:

$$\Delta t = -0.7 * \Delta \ln H \tag{3.2}$$

where H is the reach averaged width, which in this case was calculated from field surveying. Then over a range of relative depths, $\frac{h}{H}$, we could estimate the depth distribution based on the shape factor in the following equation:

$$f\left(x=\frac{h}{H},t\right)=t*exp(-x)+(1-t)*0.951*exp\left[-\left(\frac{x-1}{0.593}\right)^2\right] \quad (3.3)$$

as described in Lamouroux [1998]. Using equations (2) and (3) the depth distribution for low flow was estimated for each site and compared to depths estimated using remote sensing methods.

3.3.4 Pool Distribution

In order to put the depth distributions into a biologically relevant context, we also considered the spatial arrangement of pools. The position of pools at each study reach were mapped to determine the spatial arrangement of high water depths using the depth maps described earlier. In order to systematically identify these features, pools were defined as any region within the channel where water is 25% greater than the average channel depth. This threshold is based upon the Lisle [1987] description of pools using residual depths. A stage independent measure, residual depths are defined as the difference between the bed surface of a pool and that of the adjacent riffles. Using these methods pools are defined as residual depths which are 25% greater than the depth at riffles [Lisle, 1987]. Since our study primarily relies on remotely sensed data rather than field measurements, we used the average water depth instead of depth at riffles. This threshold represented the basis for identification of pool position but the boundaries of the pool were manually mapped. Number of pools, total pool area, and average pool area were also calculated.

3.4 Results

3.4.1 Depth Distributions

Along the Kananaskis water depth was linearly related to the log of the red-blue ratio, though each site exhibited a slightly different relation (Figure 3.3). These differences are a result of subtle changes in turbidity, sun angle, brightness of the image, and other external factors. These relations were as follows:

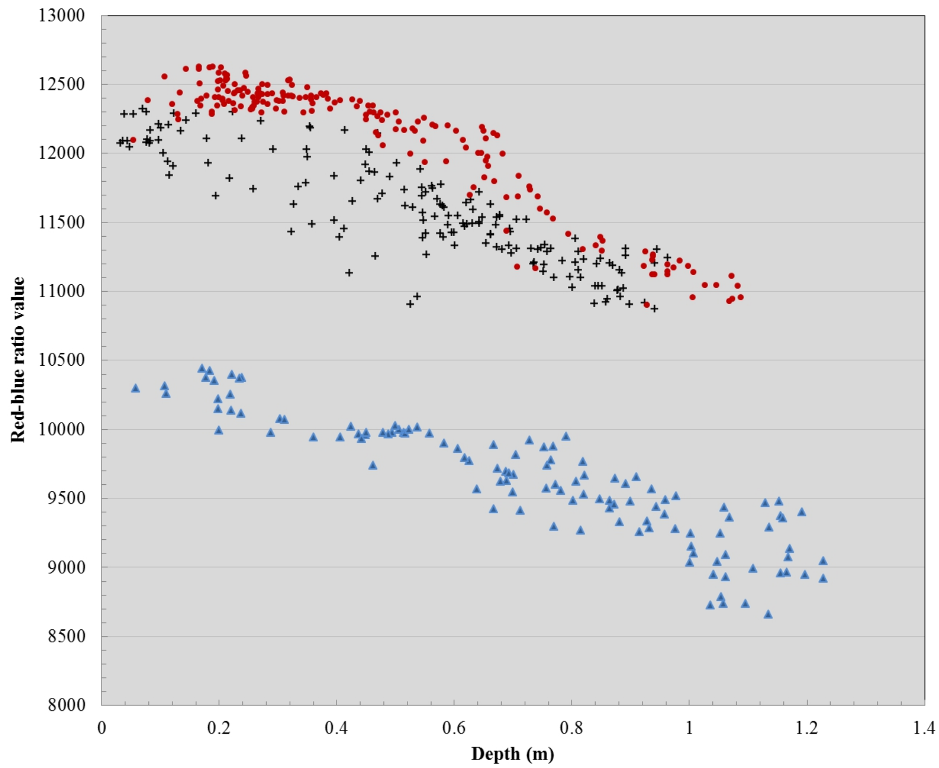

Figure 3.3: Inverse relationship between water depth and red-blue ratio value for the fortress (crosses), opal (trianges), and Kananaskis Village (dots) sites.

where

$$x = \ln\left(\frac{\rho_{red}}{\rho_{red}}\right) \tag{3.4}$$

$$\text{Fortress: } d = 63.795 - 6.76x \tag{3.5}$$

$$\text{Opal: } d = 58.063 - 6.252x \tag{3.6}$$

$$\text{Kananaskis Village: } d = 59.244 - 6.253x \tag{3.7}$$

The relationship between the red-blue ratio value and water depth allowed us

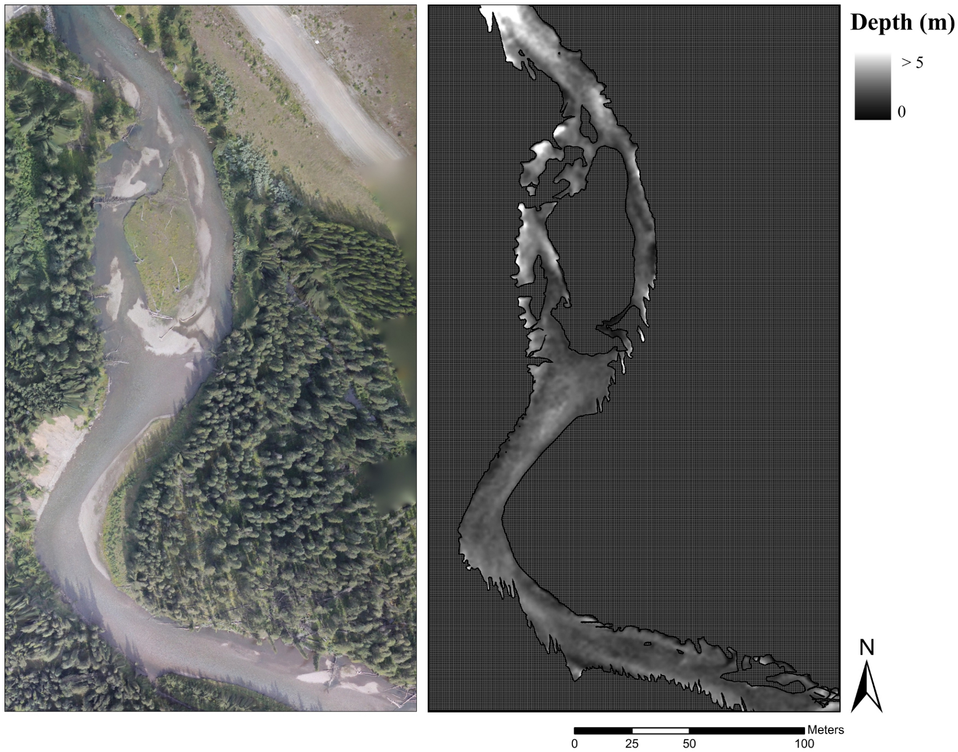

Figure 3.4: True color image and depth map created using empirical equations at Fortress, the most upstream site.

to produce depth maps over a reach 11 bankfull widths in length (Figure 3.4, 3.5, 3.6). This method appears to reasonably characterize water depths and capture the range of depth variability within the channel. The accuracy of depth estimated from the empirical equation decreases with increasing depth because depths greater than 1.23 m fall above the range of measured data used in the algorithm creation. This represents the trade off between data quality and quantity, where the coverage of depth measurements is more complete than field surveying alone, but accuracy is lower.

We assessed depth distributions at the three sites using the remote sensing methods and compared them to the Lamouroux distributions. It is important to note that units are in relative depth, thus a relative depth of 1.00 is equal to the the reach averaged depth. For Fortress this was 0.53 m, for Opal 0.80 m, and for

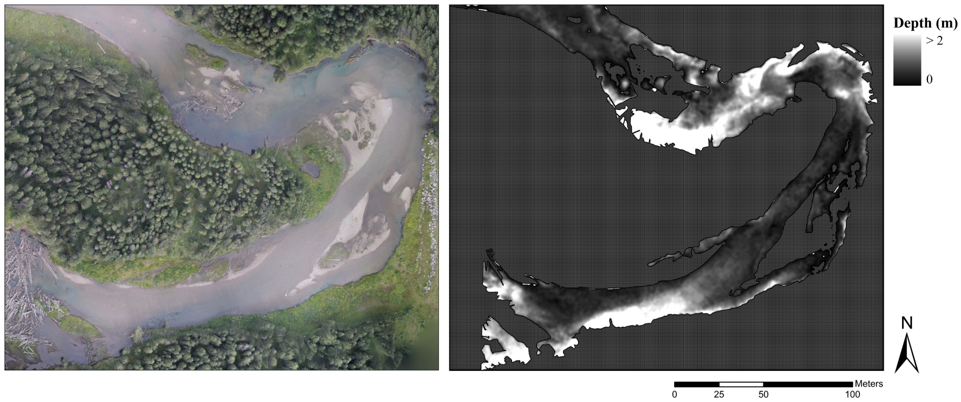

Figure 3.5: True color image and depth map created using empirical equations at Opal, the middle site.

Kananaskis Village 0.48 m. At the most upstream site, Fortress, the greatest proportion of depths fell under the reach averaged depth (Figure 3.7). The peak in the histogram of depths occurred at a relative depth of approximately 0.50 or at one half of the reach averaged depth. However, the Lamouroux model predicted the highest frequency of depths to occur near the reach averaged depth. Therefore, the model predicts a greater proportion of high depths as compared to the observed depth distributions. The predictions and observed values match where depths are near zero and above one meter. However, the distribution of residuals in the relative depth range from 0.15 to 2.00 were $^{+}/_{-}$ 0.6% (Figure 3.7 top panel).

Similar trends were observed in the next site downstream, within the tortuously meandering middle reach though there was a greater frequency of higher depths. At the Opal site, the most commonly occurring depth was less than that predicted by the Lamouroux model with the peak in observed depth distribution falling at a relative depth of approximately 0.70 or 0.56 m and the Lamouroux distribution again peaking near the reach averaged depth. The Lamouroux distribution fell closer to the normal distribution than the exponential distribution as compared to the previous site. The magnitude of residuals was greater at this site, with a range of $^{+}/_{-}$ 1% for relative depth (Figure 3.7 middle panel)

At the most downstream site, located at Kananaskis Village, the remotely sensed depth distribution and Lamouroux model results showed a strong overall match.

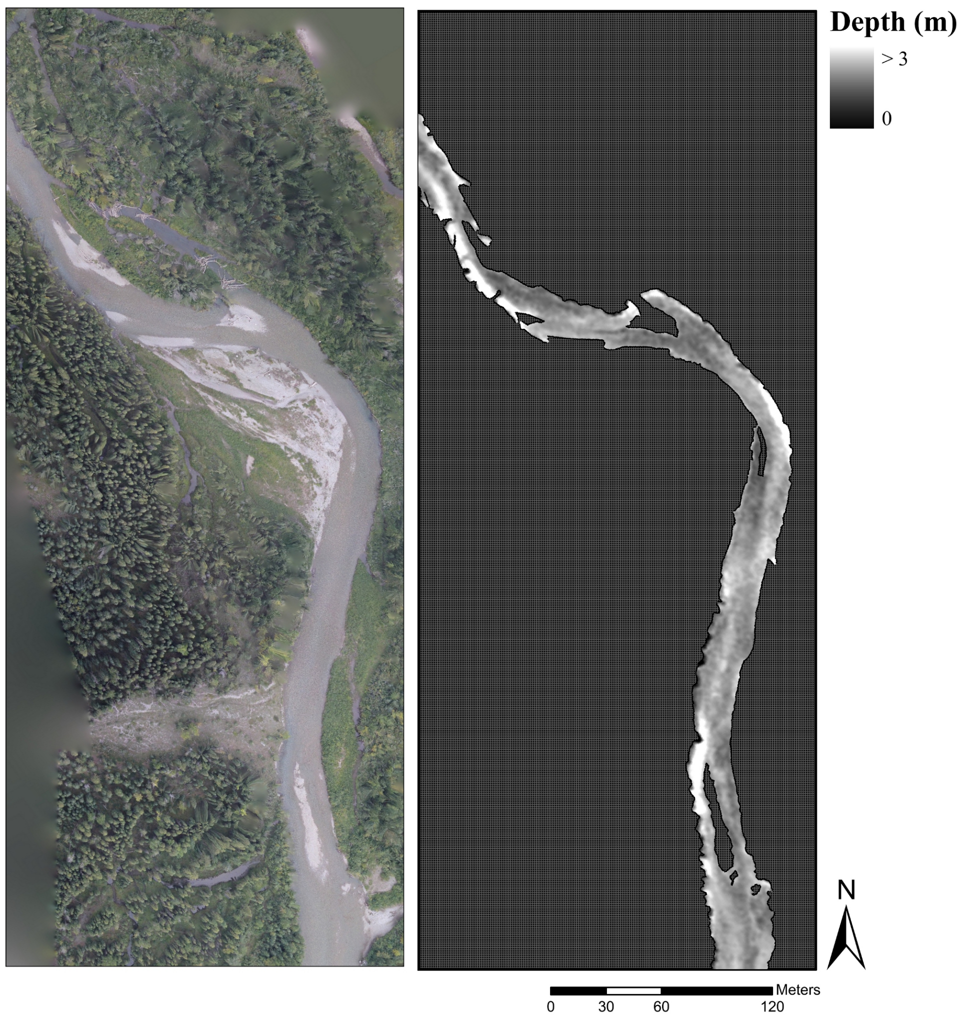

Figure 3.6: True color image and depth map created using empirical equations at Kananaskis Village, the most downstream site.

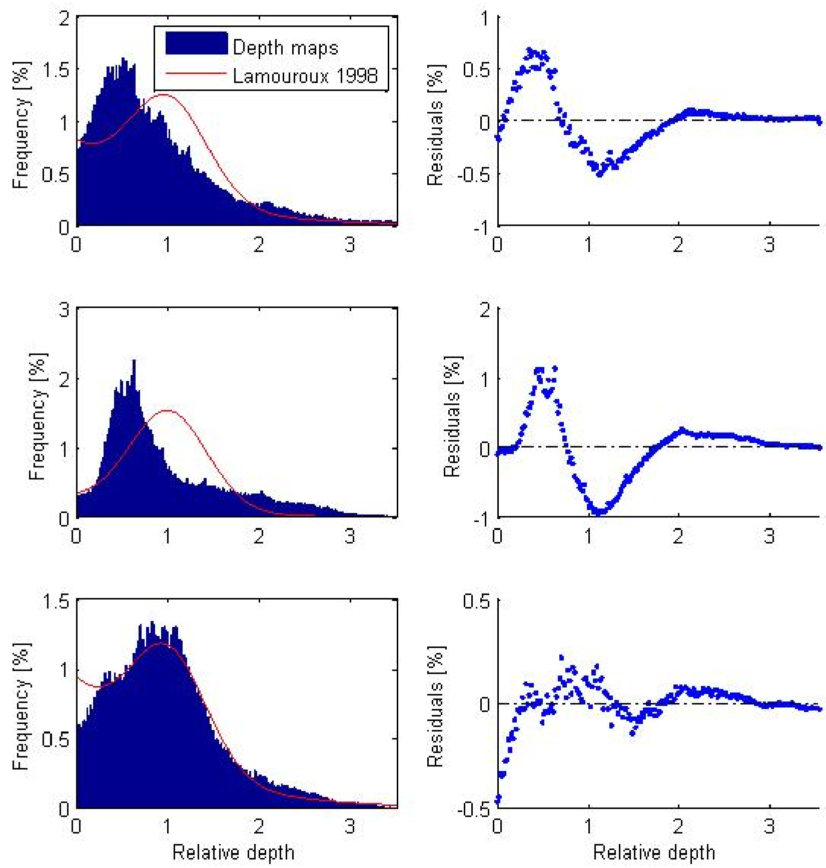

Figure 3.7: On the left, relative depth distributions from empirical depth maps and Lamouroux function using field measured hydraulic width at Fortress (top), Opal (middle), and Kananaskis Village (bottom). On the right are residuals between predictions and observed distributions.

Table 3.1: Pool characteristics.

Site	Reach Length (m)	Total pool area (m^2)	Mean pool area (m^2)	Number of pools
Fortress	890	1137	81	14
Opal	780	5656	435	13
Kananaskis Village	1052	3029	101	30

For relative depths greater than 0.30 or 0.14 m the residuals were typically less than 0.25% and the two distributions peaked at a relative depth of 1.00 (Figure 3.7 bottom panel). However, the model predicted a greater frequency of depths lower than 0.14 m, than was observed on the depth maps. Overall model predictions of the distributions of depths within the channel were best for this site.

3.4.2 Pool Distributions

From the depth maps, we measured total pool area, mean pool area, and number of pools per reach. As might be expected, the spatial distribution of pools appears to be most closely related to channel morphology and orientation within the valley rather than distance downstream of the dam. No clear downstream trends in these metrics occurred and the spatial arrangement and size of pools also appeared to be independent of reach length (Table 3.1).

Numerous pools were present in the fortress site though riffles were a more dominant feature of this reach (Figure 3.8). Of the 14 identified pools, 10 were located near large wood within the channel and comprised 72% of the total area of pools. At this site a deep region was located directly below the bridge which formed in association with stabilization of banks. However, we did not include this region in our analysis of pools. There was some difficulty in identifying pools at this site due to the orientation of the shadows on the water, which confounded identification of water depth at these pixel locations.

The largest pools and greatest area of pools were located along the meanders at the Opal site (Figure 3.9). This was in part due to a exceptional log jam at the southern edge of the reach where large pools have formed both upstream and downstream of the jam. Nine of the 13 identified pools were related to large wood

Figure 3.8: The fortress site was characterized by multiple small pools along the edges of the channel typically near coarse wood within the channel. Pools are depicted with crosshatched shapes overlaid onto the depth maps.

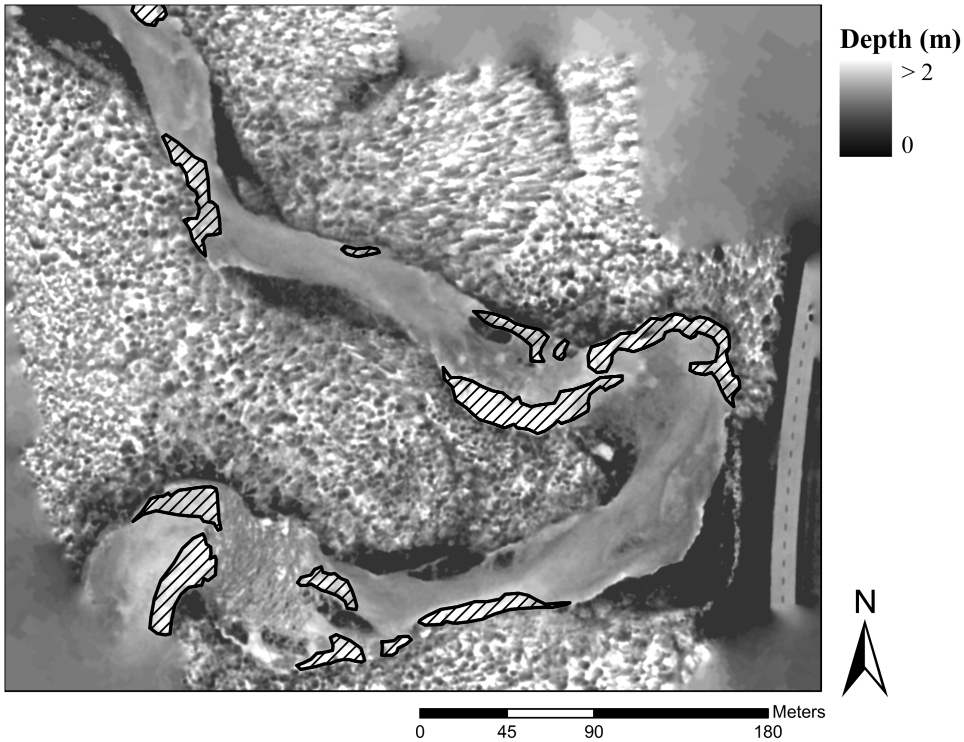

Figure 3.9: The opal site was dominated by large pools near the torturous meanders and log jams.

which accounted for 75% of the total pool area. The remaining large pools also formed near meander bends though the bank stabilization appeared to contribute to this pool formation.

The pools at the Kananaskis Village site were the most abundant, but were small in terms of average pool area and total pool area as compared to the Opal site (Figure 3.10). These pools were typically found on the outside of meander bends, though some woody debris was present. Half of the 30 pools were associated with woody material but accounted for only 36% of the total pool area. This site was also characterized by multiple channels with varying levels of activity and connectivity with the main channel. Unlike the other sites, five of the identified pools were located within back channels. Other back channel pools appeared to be present at this site but were not included in our estimations of pool area because these regions were associated with a different water depth signal and thus did not meet our threshold criteria. Pool presence at this site appears to be more strongly controlled by channel morphology and partial abandonment of channels as compared to the other sites which show dominant pool forming mechanism of wood.

3.5 Discussion

3.5.1 Depth and pool trends

The distribution of depths within each reach provide a basis to interpret possible alterations due to the hydropeaking flow regime and to understand a component of physical habitat within the Kananaskis. The Lamouroux distributions presumably represent the depth distribution for a natural channel and thus the differences between the predicted and observed distributions likely reflect systematic changes to the geomorphology due to regulation. This is further supported by our results that the more upstream sites, Fortress and Opal, show a greater proportion of low depths as compared to model predictions while the further downstream Kananaskis Village site is consistent with the predictions. This implies that distance downstream from the dam is a factor contributing to the depth distributions and thus the high proportion of low depths is the result of the hydropeaking flow regime.

The distribution and arrangement of pools may also relate to the influence of the hydropeaking flow regime. Pool frequency for rivers in this region are typically cited as 5-7 channel widths, with more frequent pools formed when interactions with woody debris and other obstructions occur [Montgomery et al., 1995]. However, in the Kananaskis small pools occurring independently of woody material are much more common. This implies that the formation of small pools may be controlled by other mechanisms.

3.5.2 Controlling factors

Both the trends in depth distribution and those associated with small pool formation may relate to a disequilibrium driven by rapidly fluctuating flows. The high flows capable of transporting large quantities of bed material and low flows transporting less may create the unique distribution of depths as compared to natural streams

Figure 3.10: The most downstream site had many small pools, many of which were associated with back channels.

which would experience comparatively high flows once every year or two.

Additionally the interactions of the rapidly fluctuating flows with ice may also contribute to the observed trends. The high proportion of shallow depths in the more upstream sites may have resulted from ice formation in shallow regions which reduce flow conveyance and support further deposition of sediment [Ettema, 1999]. These could also be the result of ice gouging which pushes sediment along the base of the bank and forms ice ridges thereby creating a high proportion of low depths [Ettema, 1999]. The free-forming pools may be the result of localized scour during high flows near patches of ice during the winter months or by direct ice action[Prowse, 2001].

While the distribution of depths may relate to proximity to the dam, frequency and characteristics of the larger pools are most strongly related to local channel morphology. The most simple channel at the Fortress site had the lowest total area of pools and mean pool size while the tortuously meandering site was characterized by pools an order of magnitude larger. The orientation and formation of pools within the channel morphology was further enhanced by presence of large wood and log jams. At Fortress and Opal the largest pools were associated with scour behind large wood, particularly near meander bends. Further downstream, a lower percentage of the pools was associated with wood while back channel pools were more prominent. Both pools formed by woody material and those occurring within back channels provide important habitat for fish by providing cover and deep water habitat even at low flow.

3.5.3 Implications for fish habitat

The depth distribution has important implications regarding the suitability of this habitat for the fish species present. Of the species currently present, mountain whitefish juveniles and adults and brown trout adults prefer depths greater than 0.90 m while brown trout juveniles prefer depths of 0.53 m [Courtney et al., 1998]. As most of the channel is below this preference during low flow the pools are likely to provide the best habitat. Depths for frys and redds of the species require lower water depths [Courtney et al., 1998]. The high frequency of low depths therefore provide more appropriate habitat for frys. The low flow channel conditions may also be appropriate for overwintering habitat which is commonly cited as depths less than 0.50 m.

However, the rapid fluctuations between the low and high stage may limit the amount of usable habitat within the river. The stage increase can be up to a meter and therefore at the high stage there may be a greater amount of deep habitat. The peak flow creates a large wetted area presumably providing more available sites for fish, however as the flow rapidly transitions to the low stage side channels and some regions of the main channel may become isolated from flow causing stranding. Additionally increases in velocity associated with the higher stage may render some of the deeper areas unsuitable or flush out food sources. The bimodal flow regime may also create two different spatial arrangements of usable habitat, which would require fish to seek different habitat for the low flow and high and could cause drying or flushing of appropriate redd sites. The flow regime may also promote predation within the shallow regions and competition within the deeper regions.

These factors associated with the rapidly fluctuating flows may contribute to the transition in fish species which has occurred since the dam construction. Bull trout and cutthroat trout are species which were historically present but no longer occur. Both species prefer deep slow moving water with bull trout preferring depths greater than 0.30 m and cutthroat trout greater than 0.25 [Baxter and McPhail, 1996, Heggenes et al., 1991]. Therefore, competition would be high for the deep slow moving regions of the channel particularly at low flow and the rapidly fluctuating flow may have increased this competition. Decreased cutthroat trout populations have been observed in BC due to competition with other species [Nelson and Paetz, 1992]. The fluctuating flows may have also stressed organisms reducing their fitness and ability to compete with other species. Bull trout are known to be especially sensitive to environmental disturbance [Baxter and McPhail, 1996]. The changes to the flow regime therefore may have contributed to the decline and loss of these species within the Kananaskis River.

3.6 Conclusions

Channel depth and pool distributions are important components of physical habitat which comprises second order changes associated with dams. With this study we have applied relatively simple techniques to identify deviations from statistical depth distributions and rapidly assess the spatial distribution of high depths within streams. This data is compatible with PHABSIM and could be used to further assess usable habitat within the Kananaskis. In this system, the hydro-peaking flow regime appears to have impacted the distribution of water depths at low flow, promoting a higher proportion of low depths than has been modeled. However, there are numerous pools which provide valuable habitat despite the high frequency of shallow water. As pool abundance and frequency relate to channel morphology we would expect that changes in the channel as a result of the hydropeaking dam have impacted this important habitat for fish. Further study is needed to assess how these distributions and pool frequencies change under peak flow and also incorporate velocity data for both high and low flow. However, assessment of depth and pool frequency represent a valuable component of physical habitat and changes which have occurred therein.

Chapter 4

Discussion and Conclusions

As with most river and streams, the Kananaskis River represents a complex system whose modern morphology is dictated by flow regulation, riparian vegetation dynamics, and ice processes. This research is a valuable contribution to dam literature because few studies have been published regarding the impact of a hydropeaking flow regime on channel morphology. A combination of remote sensing and field techniques allowed us to consider change to nearly 40 km of river in a relatively short time frame. Models provided a useful means to characterize changes in the system but in some cases the impact of a daily peaking flow and interactions with winter ice conditions confounded model results. The techniques used to identify these changes are an efficient way to assess anthropologically influenced river systems.

4.1 General conclusions

Through this study we are able to make some preliminary conclusions regarding the state of the system. The adoption of a hydropeaking flow regime has caused a reduction in peak flows but increase in frequency of bankfull flows (Figure 2.2). This change in flow regime has contributed to a diversity of channel responses including widening just downstream of the dam, narrowing further downstream, and channel simplification along the entire study reach (Figure 2.7). This is consistent with changes observed on other systems where patterns of erosion and deposition vary over space and time [Brandt, 2000, Petts and Gurnell, 2005, Williams and Wolman, 1984]. Further changes have occurred in terrestrial ecology where riparian vegetation is more dense than under pre-dam conditions but with a low diversity of successional stages (Chapter2).

The hydropeaking flow regime may also contribute to the shifts in the distribution of depths within the channel. Reaches just downstream of the dam show a higher frequency of low depths than statistical distributions would imply (Figure 3.7). However, the reach situated further downstream showed a stronger match with the statistical depth distributions. The deeper regions of the channel were clustered into pools whose size and position was dictated primarily by channel morphology (Figure 3.4, 3.5, 3.6). However, numerous large pools were present at all sites in association with log jams, large wood, and back channels while several small free-forming pools were present as well.

4.1.1 Downstream gradient of change

One of the primary objectives of this research was to assess the downstream gradient of change, and in doing so provide a space for time comparison. We hypothesized that effects of the flow regulation would be most pronounced in the sections of the river just downstream of the dam because they experience the strongest flood pulse and thus would experience the greater perturbations driving change. Similarly, we expected the sites further downstream to show more modest channel change by the dampened flood pulse.

Downstream gradients were identified in channel morphology, pool characteristics, and riparian vegetation which support our hypotheses. Moving in the downstream direction width change was characterized by widening followed by a region of no adjustment with narrowing in the most downstream reaches (Figure 2.7). This does not follow our hypothesis that the greatest magnitude of channel change would occur just downstream of the dam. However it does show a clear downstream gradient associated with the flood pulse where erosion dominates the more upstream sections with depositional conditions created further downstream by the high sediment supply from the eroded material and tributary inputs.

Pool characteristics also show some degree of change along the downstream gradient, though more study sites would strengthen this trend. There appears to be a shift from pools formed primarily by large wood to those formed within back channels (Chapter 3). Additionally downstream trends in vegetation occurred where uniformly sized conifers dominate bank vegetation in the upstream reaches while more successional stages and species are present in the more downstream reaches (Chapter 2).

Model performance also depended upon downstream distance from the dam. Closer to the dam, models results did not coincide with observed width and depth rather they predicted a narrower and deeper channel (Figure 2.13, 3.7). However, in the more downstream sites model results were generally in closer agreement with observations. For the UBCRM, this implies that either our input parameters or the model itself did not adequately characterize the system. Additionally in the upstream sites the depth distributions do not match those predicted by the Lamouroux equations indicating that the form of this river differs from many natural streams. Though this does not allow us to provide causation of these channel characteristics, it does imply that width change and depth distributions relate in some way to the strength of the flood pulse.

4.1.2 Interactions with riparian vegetation

There appears to be strong linkages between the hydropeaking flow regime and the riparian vegetation. Overall, we observed an increase in the density of riparian vegetation with minimal new growth as compared to nearby unregulated streams. We attribute this to the high flows which scour bars and banks and prevent colonization of bare sites limiting expansion of vegetation. Therefore in the forested regions of the banks which are not inundated under the peak flows vegetation then has become more dense. The increase in density of vegetation increases the bank strength due to the root cohesion and likely acts to lock the channel in position.

Distance downstream from the dam in part dictates the balance between bank shear stress of the flow and bank strength enhanced by vegetation. Just downstream of the dam at sites 1A and 1B it appears that the erosion by the flood pulse dominates and resulted in widening of the channel. In the middle reaches at sites 1C to 3A the shear stress of the flow appears to be in essential equilibrium with the vegetation related bank stability such that the channel has remained the same width and in approximately the same position. In the furthest downstream sites, 3B to 3D the flood pulse is dampened by tributary inputs and thus the vegetation related bank stability dominates and promotes narrowing of the channel.

4.1.3 Ice dynamics

Channel morphology, depth distributions, and riparian vegetation all appear to be influenced by winter ice dynamics enhanced by the peaking flow regime. Channel morphology is not only the result of daily high flows but also ice related erosion and scour. This occurs by direct ice action and formation of ice at low flows which is lifted and transported along with sediment when the flood pulse moves through the system. These ice interactions may be one of the mechanisms of channel widening just below the dam where the flood pulse is the strongest. However there is evidence of lifted ice patches throughout the entire study reach as well.

Ice may also contribute to formation of small pools due to localized scour and lifted ice patches. The high proportion of shallow depths at low flow is also likely the result of scour and deposition related to ice conditions. Similarly the vegetation along the banks had evidence of mechanical breakage due to ice and tree scars. This is the most prominent in the tortuously meandering reach were it appears that ice jams cause flooding at high flow and form unique vegetation patterns. It is therefore clear that the peaking flow regime not only causes novel summer conditions associated with the daily bankfull flows but also causes unique interactions with ice which impact the morphology of the Kananaksis.

4.1.4 Limitations of study

The study summarized shows relatively simple techniques to assess the influence of flow alterations within a riverine environment. These techniques require minimal fieldwork and calibration for such a large spatial extent. However there are some apparent limitations must be recognized in the context of this study. First, there is a notable absence of pre-dam data for the system including only MDD records and historic aerial photos. Therefore many of the other features of the pre-dam system were speculative, including vegetation species and densities, depth distributions, channel features, grain size, sediment supply, and valley slope.

A further limitation is the use of a single formative discharge to represent an entire regime of flows which is a problem not unique to this study. By using a single flow value we do not accurately characterize the frequency and duration of these flows which are clearly an important factor controlling channel change. This appears to be particularly problematic near the dam where the flood pulse is the strongest. Despite these limitations we were able to reasonably model the system and changes therein and make interpretations about the influences impact and interactions associated with flow regulation in the system.

4.2 Relevance to fish

By understanding the changes in channel morphology, we are better able assess changes in aspects of physical habitat which may in part have driven the shifts in fish species in the Kananaskis. Since dam construction there has been a shift in species from cutthrout trout (*Oncorhynchus clarki*), bull trout (*Salvelinus confluentus*), brook trout (*Salvelinus fontinalis*), and mountain whitefish (*Prosopium williamsoni*) to primarily brown trout (*Salmo trutta*) and mountain whitefish [Nelson, 1965, Courtney et al., 1998]. In this study we focused primarily on pool distribution and characteristics, a defining component of physical habitat. We found a high frequency of shallow regions of the channel at low flow than has been observed for natural channels which has likely been the result of the hydropeaking flow regime. This could limit the amount of available habitat for the fish species present. Additionally the shallow channel may create higher competition for the deeper regions and contribute reduced fitness or mortality.

Presence of deep pools dictate the usable habitat for the fish species. Pool characteristics relate to channel morphology, whereby sinuous and mutlithread channels have a greater propensity for pool formation. Along the Kananaskis, much of the channel has remained essentially in the same position within the valley but has shown channel narrowing and shift toward a single rather that multi-thread pattern. Because pool formation is controlled by channel morphology this shift in channel pattern likely created fewer pools than under pre-dam conditions. Along this line of reasoning, pools may have been reduced due to the abandonment of back channels and presumably reduction in cross sectional area associated with channel narrowing. This would cause a reduction in available fish habitat, particularly for adults and juveniles which require deep, slow moving water. Because no change in width was documented for the many of the sites, the shift towards a single channel is subtle and thus could be overlooked. However, the shift from multi to single thread channel is an important result because it may in part explain declines and loss of the trout species.

Further changes in available pool habitat may occur in association with the riparian vegetation dynamics. Flow regulation has caused essentially the cessation of above bankfull flows, which are required to scour banks and provide fresh colonization surfaces for riparian tree species. And indeed, the upper regions of the river were characterized by mature trees with minimal growth of immature trees and seedlings. We show that woody debris is an especially important mechanism of pool development particularly in these upper regions. While wood is currently present within the river, this interruption of vegetation succession may have already impacted wood recruitment or could do so in the future.

4.3 Future directions

This research examines only a small portion of the biologically relevant consequences of the Pocaterra dam. However, it does provide a solid basis for understanding other driving forces acting on the Kananaskis. Additional studies could elucidate some of the complex linkages within the system. Further consideration should be given to the role of winter ice dynamics in shaping channel morphology, riparian vegetation structure, and physical habitat. Because high flows are such a prominent and disruptive feature of the system, channel velocity and depths should be considered for high flows as well. These further studies would allow us to not only better address the changes in fish populations at this site, but also characterize changes in hydropeaking systems where significant gaps in literature still exist.

Though the effects of dams are more subtle than other anthropogenic influences, they are among the most widespread and have great potential to cause permanent change to the function of river systems. In this study we have proposed means to detect and predict change in large scale morphology and to rapidly assess channel characteristics important to physical habitat. Understanding the changes to physical habitat represents the first step in preserving diversity of river ecosystems. While it is by no means the only factor which dams alter, geomorphic change is perhaps one of the more readily accessible aspects of the system which is quite often overlooked in traditional biological considerations of dams. In the absence of extensive biological surveys, geomorphological studies such as this could better prepare us to make decisions regarding the possible effects of the construction and flow alteration of dams in a feasible time frame.

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Appendix A

Study Sites

Figure A.1: Site 1A 1958 (left) and 2008 (right).

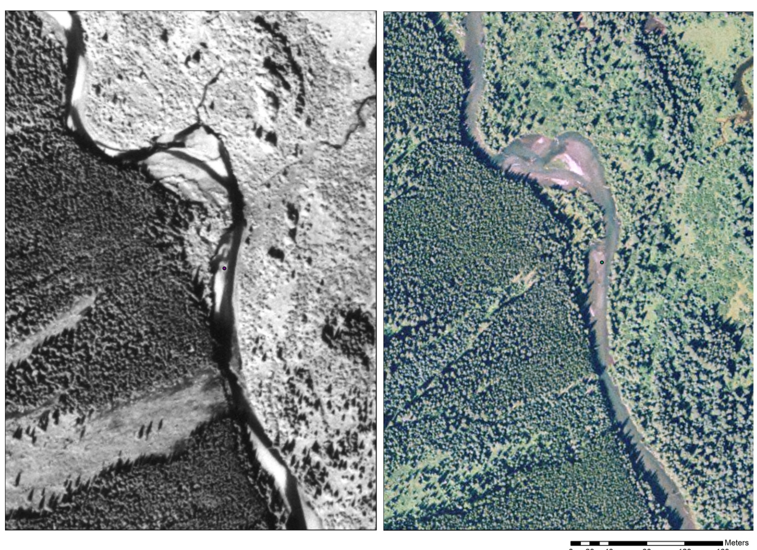

Figure A.2: Site 1B 1958 (left) and 2008 (right).

Figure A.3: Site 1C 1958 (left) and 2008 (right).

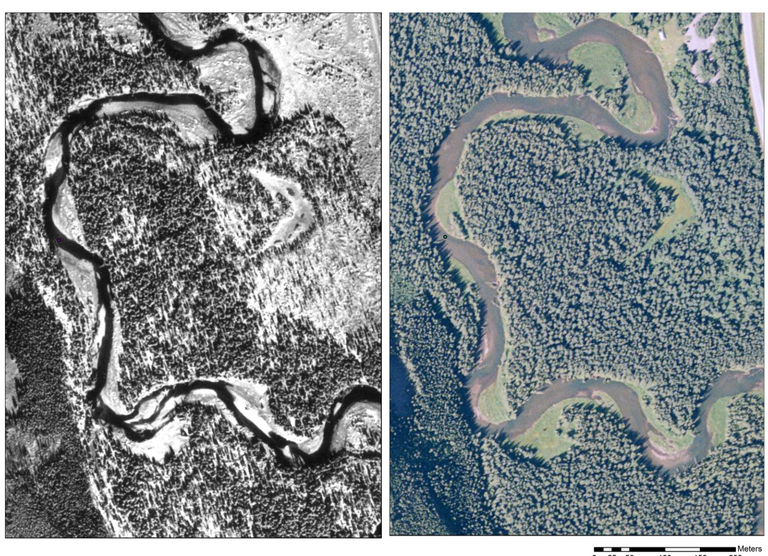

Figure A.4: Site 2A 1958 (left) and 2008 (right).

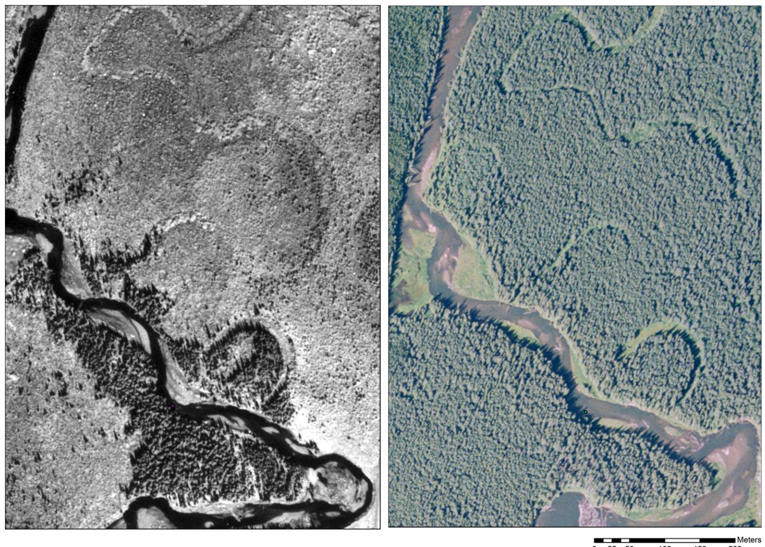

Figure A.5: Site 2B 1958 (left) and 2008 (right).

Figure A.6: Site 2C 1958 (left) and 2008 (right).

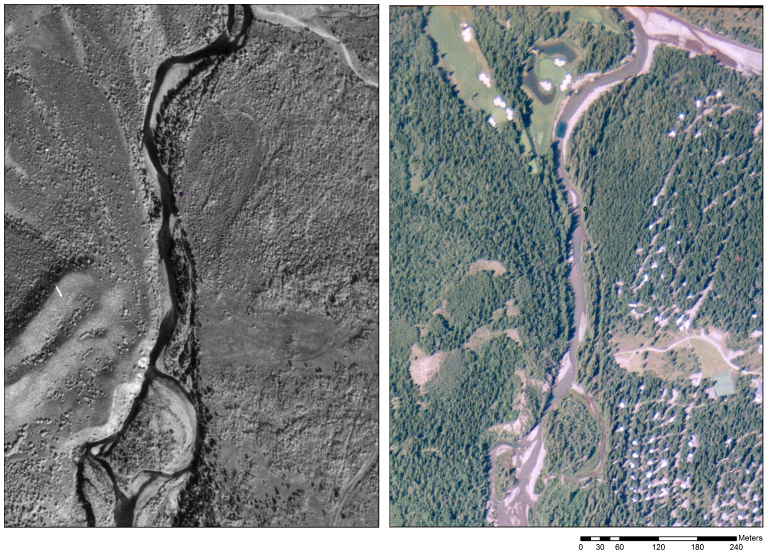

Figure A.7: Site 3A 1958 (left) and 2008 (right).

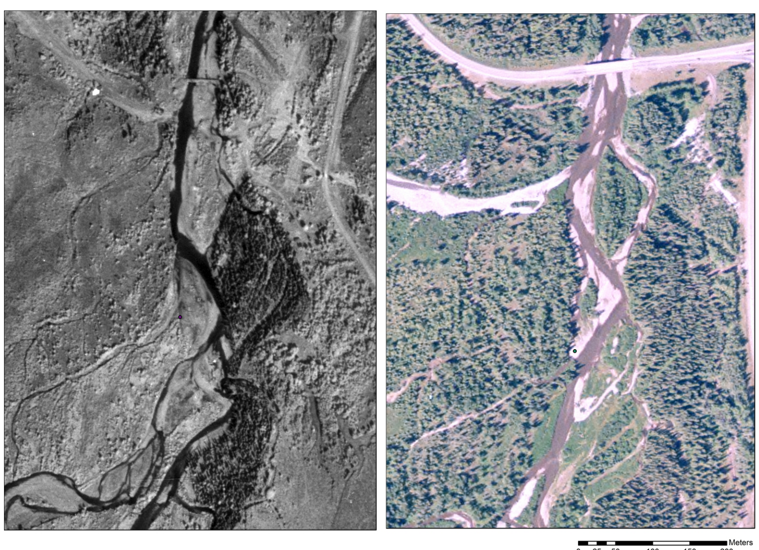

Figure A.8: Site 3B 1958 (left) and 2008 (right).

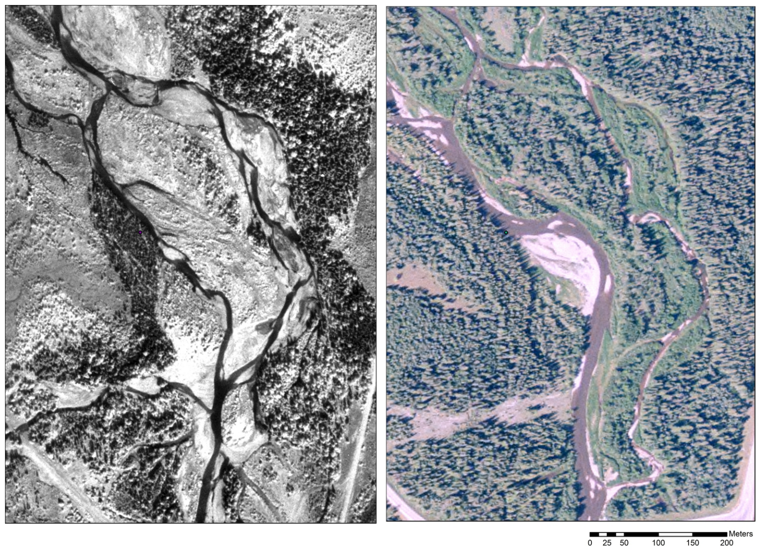

Figure A.9: Site 3C 1958 (left) and 2008 (right).

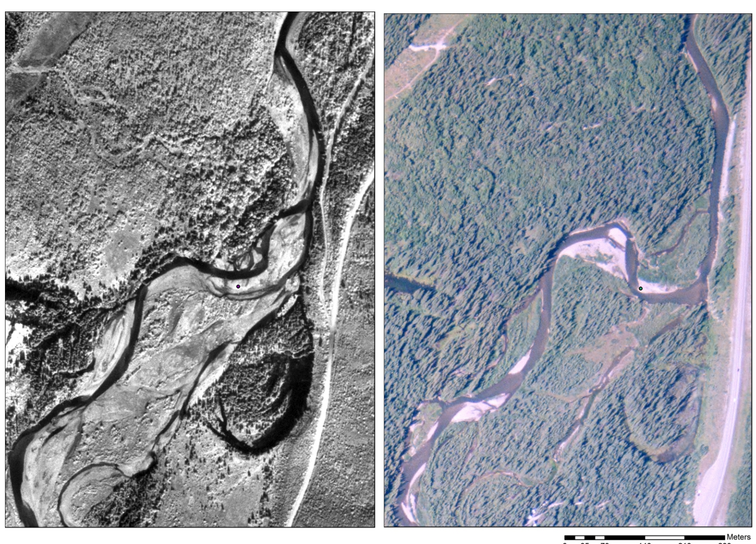

Figure A.10: Site 3D 1958 (left) and 2008 (right).

Appendix B

Regime model inputs

Table B.1: UBCRM discharge range using MDD from 1932 to 1955 and 1986 to 2009.

	Pre			Post		
Site	Q_2 (cms)	Q_5 (cms)	Q_{25} (cms)	Q_2 (cms)	Q_5 (cms)	Q_{25} (cms)
1A	26.8	33.1	52.8	21.7	27.4	33.5
1B	28.7	35.5	56.6	23.3	29.4	36.0
1C	29.6	36.5	58.3	24.0	30.2	37.0
2A	30.5	37.6	60.0	24.7	31.2	38.2
2B	30.6	37.7	60.1	24.8	31.3	38.2
2C	31.9	39.4	62.8	25.8	32.6	39.9
3A	37.7	46.5	74.3	30.5	38.5	47.2
3B	38.9	48.0	76.6	31.5	39.7	48.7
3C	39.0	48.1	76.8	31.6	39.8	48.8
3D	42.2	52.0	83.0	34.1	43.1	52.8

Table B.2: UBCRM input values using $\mu\prime$ calibrated to pre-dam conditions.

Site	Slope	D_{50} (mm)	D_{84} (mm)	$\mu\prime$
1A	0.0027	54.5 - 57.9	88.8 - 123.1	1.3
1B	0.0039	30.7 - 31.8	54.5 - 61.7	2.2
1C	0.0036	26.5 - 29.1	44.7 - 47.6	1.7
2A	0.0025	17.2 - 18.5	31.4 - 34.3	2.15
2B	0.0017	15.8 - 18.1	27.0 - 31.4	2.1
2C	0.0015	13.0 - 14.4	22.3 - 25.5	2.1
3A	0.0066	38.9 - 42.4	85.2 - 105.4	2.55
3B	0.0062	49.3 - 50.8	90.6 - 103.2	1.4
3C	0.0065	30.6 - 42.8	75.8 - 92.8	1.4
3D	0.0037	50.3 - 71.0	98.5 - 198.1	1.2

Appendix C

Study Sites

Figure C.1: Site 1A 3-D imagery from 1958 Near IR imagery.

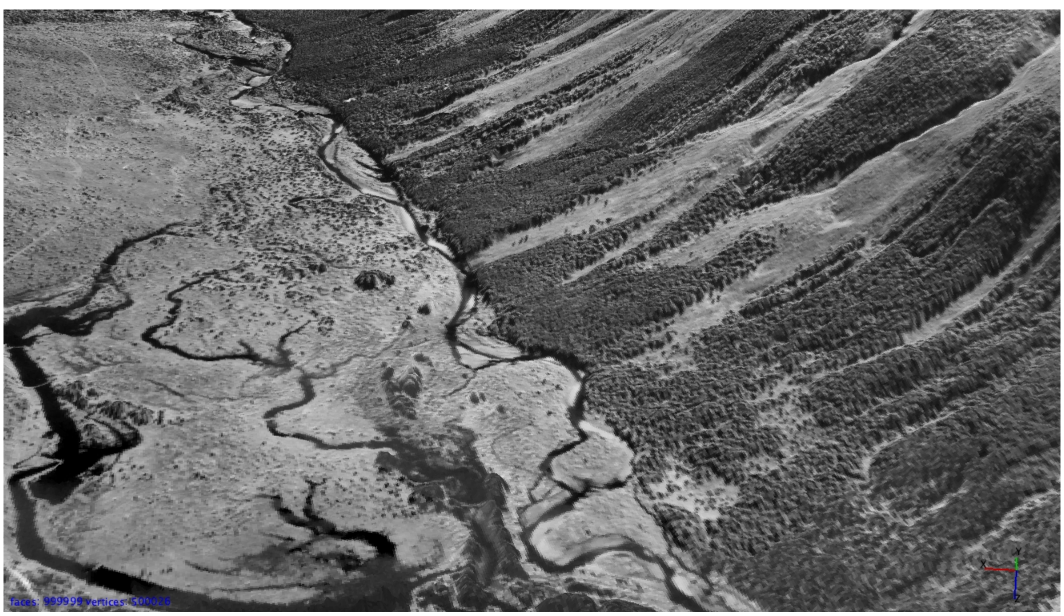

Figure C.2: Site 1B 3-D imagery from 1958 Near IR imagery.

Figure C.3: Site 1C 3-D imagery from 1958 Near IR imagery.

Figure C.4: Site 2A 3-D imagery from 1958 Near IR imagery.

Figure C.5: Site 2B 3-D imagery from 1958 Near IR imagery.

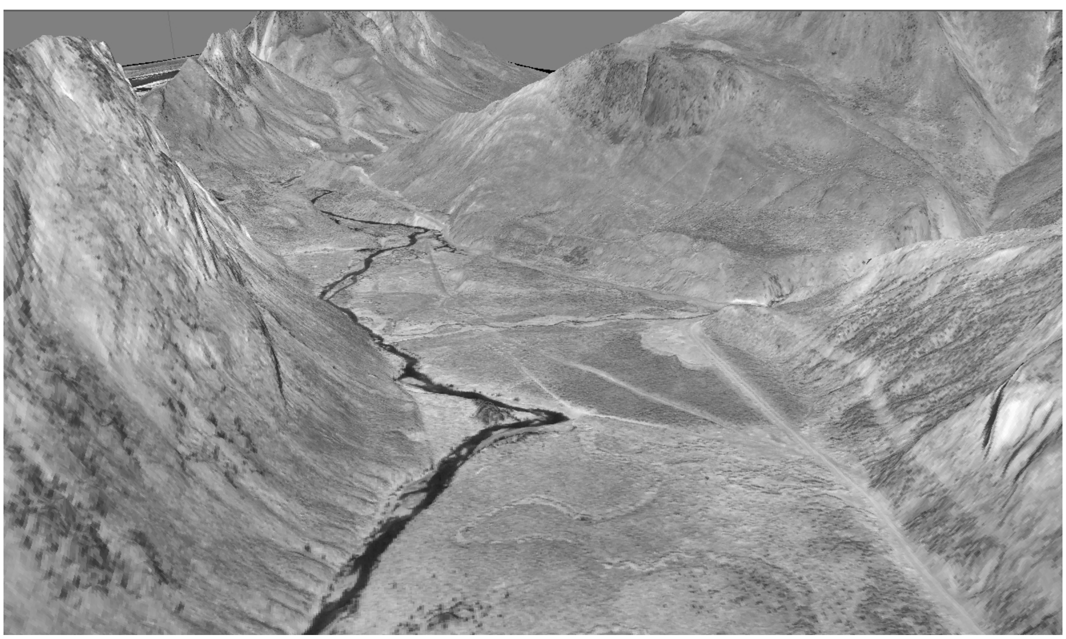

Figure C.6: Site 2C 3-D imagery from 1958 Near IR imagery.

Figure C.7: Site 3A 3-D imagery from 1958 Near IR imagery.

Figure C.8: Site 3B 3-D imagery from 1958 Near IR imagery.

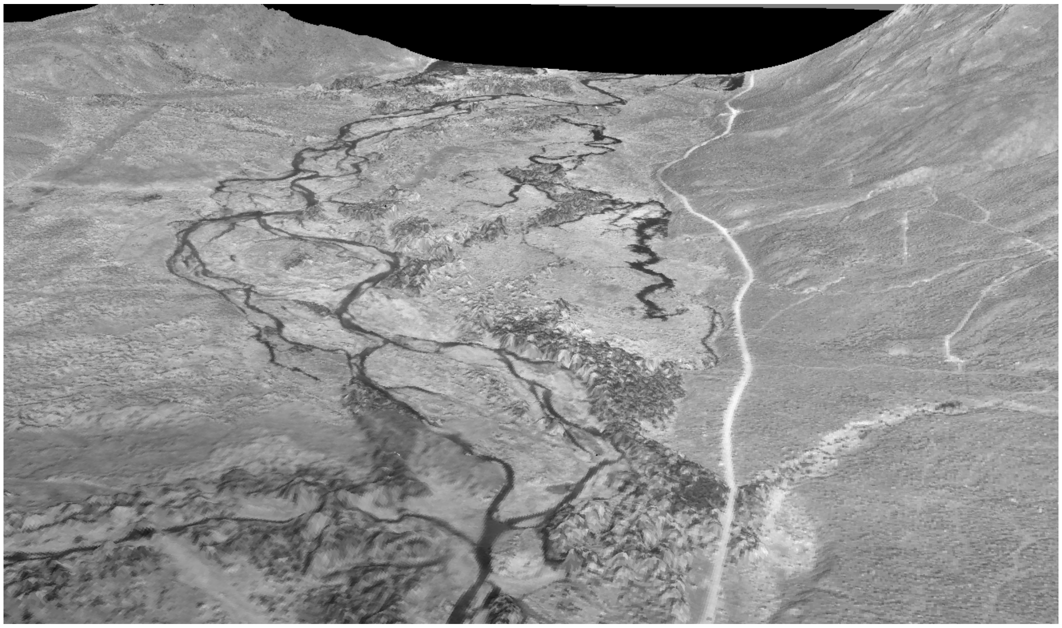

Figure C.9: Site 3C 3-D imagery from 1958 Near IR imagery.

Figure C.10: Site 3D 3-D imagery from 1958 Near IR imagery.