

A century of landscape-level changes in the Bow watershed,  
Alberta, Canada, and implications for flood management

by

Tanya Taggart-Hodge  
BASc, McGill University, 2013

A Thesis Submitted in Partial Fulfillment of the  
Requirements for the Degree of

MASTER OF SCIENCE

in the School of Environmental Studies

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## **Abstract**

This study used a comparison of one hundred and forty-eight historical (1888-1913) and current (2008-2014) oblique photographs from thirty-two stations to identify land cover changes that have occurred in portions of the Bow and Elbow valleys as well as surrounding Kananaskis Country region. Implications of these changes for flooding and flood management were explored. Forest cover was found to have drastically increased over the past century, particularly in the Bow valley, as did areas of direct human development. In the same time period, grasslands increased in the Elbow valley but decreased in the Bow, while regenerating areas decreased uniformly throughout both valleys. An analysis of pre (2008)-and-post (2014) flood conditions demonstrated no change in coniferous forest cover in both valleys over the 6-year period, but uncovered a decline of 20% in the Elbow and 3% in the Bow in the broadleaf/mixedwood category. The Elbow's channel zone was larger in 2014 compared to 2008, whereas the extent of the Bow's channel zone remained constant. However, both the Bow and Elbow's bare exposed bars increased substantially, most likely as a result of the 2013 flood. The major source of water flows that contributed to the 2013 flood event originated in high elevation rock and scree areas, which, unlike floodplains, are elements of the watershed that cannot be manipulated over time. It is now recognized that forest cover should act as a buffer to floods. Nevertheless, the 2013 flood event occurred despite the massive buffering effect of a huge increase in older forest stands across the study area. The final discussion includes recommendations for improving flood management in the area.

## Table of Contents

Supervisory Committee . . . . .	ii
Abstract . . . . .	iii
Table of Contents . . . . .	iv
List of Tables . . . . .	vi
List of Figures . . . . .	vii
Acknowledgments . . . . .	ix
Dedication . . . . .	xi
Chapter One. Introduction 1 . . . . .	1
1.1 Study Objectives . . . . .	1
1.2 Global Context . . . . .	2
1.3 Mountain Legacy Project . . . . .	6
1.4 Overview . . . . .	7
Chapter Two. Study Area and Background . . . . .	8
2.1 Location . . . . .	8
2.2 Vegetation . . . . .	8
2.3 Geology & Geomorphology . . . . .	10
2.4 Climate . . . . .	10
2.5 Flood regime & Flood Record . . . . .	11
2.6 History & Land Use . . . . .	19
2.7 Fire History . . . . .	22
2.8 Water control structures . . . . .	23
2.9 Factors affecting flooding . . . . .	24
2.10 Forests & Floods . . . . .	27
2.11 Conservation, Ecological Restoration & Novel Ecosystem . . . . .	30
Chapter Three. Methodology . . . . .	35
3.1 Introduction . . . . .	35
3.2 Repeat photograph . . . . .	35
3.3 Digitization Process . . . . .	36
3.4 Fieldwork . . . . .	38
3.4.1 Definition of a photographic station and location . . . . .	39
3.4.2 Selection criteria . . . . .	40
3.4.3 Sample selection . . . . .	42
3.4.4 Gridding, locating stations & aligning images . . . . .	42
3.4.5 Field location accessibility . . . . .	45
3.4.6 Weather and haze . . . . .	46
3.4.7 Photographic equipment . . . . .	47
3.4.8 Field notes/metadata . . . . .	47
3.4.9 Safety measures . . . . .	48
3.4.10 Effective crew . . . . .	49

3.5 Image processing .....	52
3.6 Choice of classification system .....	55
3.7 Application of classification system .....	56
3.8 Limitations .....	60
Chapter Four. Results .....	67
4.1 Introduction .....	67
4.2 Aggregation & extent of land cover classes .....	68
4.3 Change in land cover classes .....	70
4.4 What the landscape has become .....	72
4.5 What the landscape was historically. ....	74
4.6 Elbow vs Bow comparison (historic-repeat) .....	76
4.7 Elbow (pre-and post- flood) .....	80
4.8 Bow (pre-and post- flood) .....	82
4.9 Elbow vs Bow fluvial comparison (pre-and -post flood) .....	84
4.10 Summary .....	88
Chapter Five. Discussion .....	90
5.1 Introduction .....	90
5.2 Interpretation of fluvial geomorphological changes .....	91
5.3 Implications for flood management .....	94
5.4 Alberta's Flood Damage Mitigation Strategy .....	96
5.5 Intervention & Restoration: Challenges & Opportunities .....	101
5.6 Questions for Future Research .....	109
5.7 Concluding remarks .....	109
References .....	111
Appendix A – Station Lists .....	123
Appendix B – 2014 Field Crew .....	127
Appendix C – Image Masks .....	128
Appendix D – Transition Matrices .....	189

## List of Tables

Table 3-1	Dataset Summary . . . . .	42
Table 3-2	Classification System . . . . .	57
Table 3-3	Definitions of Classification Categories . . . . .	58-59
Table 4-1	Percentage change in land cover classes over past century . . . . .	71
Table 4-2	Comparison of historic and repeat land cover categories in the Elbow valley between 1895-97 and 2008 . . . . .	77
Table 4-3	Comparison of historic and repeat land cover categories in the Bow valley between 1888-90 and 2008-10 . . . . .	77
Table 4-4	Percent change in land cover classes between 2008 and 2014 images in the Elbow valley . . . . .	80
Table 4-5	Percent change in land cover classes between 2008 and 2014 images in the Bow valley . . . . .	82
Table 5-1	A synthesis of land cover changes and their implications for flood damage mitigation . . . . .	95-96

## List of Figures

Figure 1-1 Disciplines drawn on by this thesis . . . . .	5
Figure 2-1 Study Area . . . . .	9
Figure 2-2 Five stations chosen for calculating climate WNA projections . . . . .	12
Figure 2-3 Hargreaves climatic moisture deficit (mm) for historical and future periods across five stations . . . . .	13
Figure 2-4 Precipitation as snow (mm) between August in previous year and July in current year for historical and future periods across five stations . . . . .	14
Figure 2-5 Spring Precipitation (mm) for historical and future periods across 5 stations . . . . .	15
Figure 2-6 Peak flow for Bow River at Calgary, 1911-1996 plus three historical floods . . . . .	17
Figure 2-7 Highest average daily flow for Bow River at Banff, 1909-1996 . . . . .	17
Figure 2-8 Peak daily flow for Bow River at Banff, 1909-2013 . . . . .	18
Figure 2-9 Alberta 72-hour precipitation patterns, June 19-22, 2013 . . . . .	18
Figure 2-10 Annual maximum daily rainfall (mm) at Kananaskis, 1939-2013 . . . . .	19
Figure 2-11 Progression of dam development in the Upper Bow basin . . . . .	24
Figure 2-12 Decision-making framework for ecosystem intervention . . . . .	34
Figure 3-1 Key milestones for the study . . . . .	35
Figure 3-2 Rapid appraisal at Library and Archives Canada . . . . .	37
Figure 3-3 Examination of glass plates at Library and Archives Canada . . . . .	39
Figure 3-4 Location photo taken at Miller 1928 Station 9 . . . . .	40
Figure 3-5 Landscape grid placed on a mastered image . . . . .	43
Figure 3-6 Tripod placement at Stn. 532 (Chungo) . . . . .	45
Figure 3-7 Fog at Mt. Burns . . . . .	46
Figure 3-8 Storm cell looming on Mt. Chester . . . . .	47
Figure 3-9 Camera levelling and kestrel measurements at Prairie Creek . . . . .	48
Figure 3-10 Tunnel Mt Field Notes, July 2014 ( <i>page 1</i> ) . . . . .	49

Figure 3-11 Tunnel Mt Field Notes, July 2014 ( <i>page 2</i> ) . . . . .	50
Figure 3-12 Steep terrain on Mt. Lady MacDonald . . . . .	51
Figure 3-13 Camera alignment at Bridgland’s 1928 Stn. 477 . . . . .	52
Figure 3-14 Image Labeler mask for The Knob 1895 . . . . .	64
Figure 3-15 Image Labeler mask for The Knob 2008 . . . . .	65
Figure 3-16 Image Labeler mask for The Knob 2014 . . . . .	66
Figure 4-1 Montage of landscape changes seen in study area . . . . .	67
Figure 4-2 Classification categories for synthesized results . . . . .	69
Figure 4-3 Extent of historic and repeat land cover classes . . . . .	70
Figure 4-4 Land cover changes across study area . . . . .	73
Figure 4-5 Historic composition of present-day land cover . . . . .	75
Figure 4-6 Transformations from historic to 2008 land cover classes in the Elbow . . .	78
Figure 4-7 Transformations from historic to 2008-10 land cover classes in the Bow . .	79
Figure 4-8 Transformations between 2008 and 2014 in the Elbow valley . . . . .	81
Figure 4-9 Transformations between 2008 and 2014 in the Bow valley . . . . .	83
Figure 4-10 Pre to post 2013 flood transformation in the Elbow valley . . . . .	85
Figure 4-11 Pre to post 2013 flood transformation in the Bow valley . . . . .	87
Figure 5-1 Challenging land cover classification . . . . .	92
Figure 5-2 Components to Alberta’s Flood Mitigation Strategy . . . . .	98
Figure 5-3 Landscape Evolution Model . . . . .	103
Figure 5-4 Modified Landscape Evolution Model . . . . .	105
Figure 5-5 Lighting of 1918 grassland fire . . . . .	107

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## Dedication

I dedicate this thesis to

Fred Roots, a great mentor and friend

and

Jacki Brocklebank,  
Amber Rancourt,  
Lorraine Gerlitz,  
Dominic Pearce  
and Rob Nelson

who lost their lives as a result of the 2013 flood.

# Chapter 1 – Introduction

## 1.1 Study Objectives

On June 19<sup>th</sup>, 2013 severe flood waters swept across one-quarter of the province of Alberta, Canada costing the province \$6 billion (Boyle & Cunningham, 2013; Environment Canada, 2013; Wake, 2013), affecting 55,000 km<sup>2</sup> of the province and causing the death of five people (Alberta Government, 2014; Calgary Herald, 2014). Calgary, the fourth largest city in Canada, was hit hard, as were dozens of other communities. Thirty-two local governments declared states of emergency, and the Province of Alberta as a whole declared its first ever State of Provincial Emergency (Alberta Government, 2014). It was reported that, “the rate at which the river sped through High River, a town of nearly 13,000, was faster than that over Niagara Falls, submerging over half the town” (Environment Canada, 2013:2). This costly natural disaster resulted in the displacement of 100,000 people – the largest evacuation in Canada over the past 60 years (Environment Canada, 2013; MNP LLP, 2015). The sediment debris caused by overflowing of the Bow River led to a one-week closure of the Trans-Canada highway, and a three-day closure of the Canadian Pacific Railway, effectively paralyzing east-west traffic (Jakob et al., 2014).

These floods were triggered by the convergence of three low pressure weather systems causing 270 mm of rain to fall within the span of 3 days (“Alberta Environment and Sustainable Resource Development Precipitation Map,” 2013; Jakob et al., 2014). In the Canmore area, more than 220mm of rain fell in under 36 hours, nearly half of Canmore’s average annual rainfall (Alberta Government, 2014). In this vein, Jakob (2014) states that, “the 1-day maximum rainfall was 75% greater than the long-term average rain for the month of June” (Jakob, 2014:1). This represents an estimated *rainfall* return period of 235-575 years (Jakob, 2014). As a result, 9.1 million cubic metres of rain fell in the Cougar Creek watershed (tributary of the Bow in Canmore) over three days (Jakob, 2014). The sudden rush of rainfall was compounded by a heavy mountain snowpack and already saturated ground unable to soak up the excess water (Environment Canada, 2013). Already-elevated antecedent moisture conditions

combined with frozen soils and abundant bedrock outcrops contributed to much of the rainfall turning into runoff (Jakob, 2014). The contribution of snow to total runoff has been estimated to be between 12 and 29% in the case of the Cougar Creek catchment (Jakob, 2014). Peak flows were recorded at  $306\text{m}^3/\text{s}$  for the Bow River, representing a 200 to 400-year return period flow on the Bow River (Jakob, 2014). A return-period period of 200 equates to a 0.5%  $[(1/200) * 100]$  probability of it occurring in any one year. This does not mean it will occur every 200 years; it simply means each year it has a 0.5% chance of occurring. In any given 200-year period, a 200-year event may not occur, occur once, twice or even three times. A 200-year flood is 10 times less likely to occur in any given year than a 20-year flood. In the case of the 2013 Alberta flood event, when historical floods were accounted for, the return period dropped from 200 to 400-years to 15-20 years (Jakob, 2014).

In the aftermath of 2013 flood event, politicians, agency staff, scientists, and affected residents inquired into the causes. Specifically, they questioned: (1) what measures could be undertaken to reduce future flood risks and impacts? (2) Was the flood a consequence of a changing climate? (3) Had changes in the landscape amplified or depressed the impact of the flooding, and exactly what were these changes. As a step towards being able to answer these questions, this study undertakes a systematic analysis of land cover changes over the past century in the flood-affected watershed. There are two primary objectives of this study:

1. to measure what land cover changes are evident through a comparative study of oblique images taken between 1888-1895 and 2008-2014 in the study area; and,
2. to explore the implications of these changes for flooding and flood management.

## 1.2 Global Context

The 20<sup>th</sup> century saw a significant shift in which the human-ecosystem relationship moved from nature-dominated to human-dominated (Turner et al., 1990). Globally, this shift was made possible by rising technological capacity and a burgeoning

human population. In conjunction, the past half-century has seen growing efforts to assess ecosystem and landscape-level change such that both ecological and human wellbeing are considered (Hodge 1997). This underlies an important premise of sustainability — a corresponding care and respect for people and ecosystems enabling them to remain healthy both in the present, and for future generations (Hodge, 2011). Nearly three decades ago, the work of the World Commission on Environment and Development led to popularization of the idea of sustainable development (Brundtland, 1987). This strategy pursued solutions that would both promote economic growth and enhance the environment (WCED, 1987). This represented a deviation from dominant economic mechanisms that did not fully internalize ecological and human well-being. The past thirty years have seen a rise in anthropogenic transformation of the earth, leaving very few ecosystems untouched {Ellis:2011im; Ellis:2013ba; Hobbs:2013tb}. People have caused such extensive changes in the earth's climate, geology, hydrology and biology that we have entered a new geological epoch, the Anthropocene (Crutzen, 2002b; 2002a; 2006; Crutzen & Steffen, 2003; Ellis, 2011; 2015; Ellis & Ramankutty, 2008; Ruddiman, Ellis, Kaplan, & Fuller, 2015). Ecological novelty is on the rise worldwide (Hobbs, Higgs & Harris, 2009; Hobbs, Higgs, & Harris, 2014a; Hobbs, Higgs & Hall, 2013; Perring & Ellis, 2013; Standish et al., 2013; Starzomski, 2013). We are now faced with an opportunity to create a desirable Anthropocene, rather than one riddled by destruction and extinction (Ellis 2011; Martin et al., 2014).

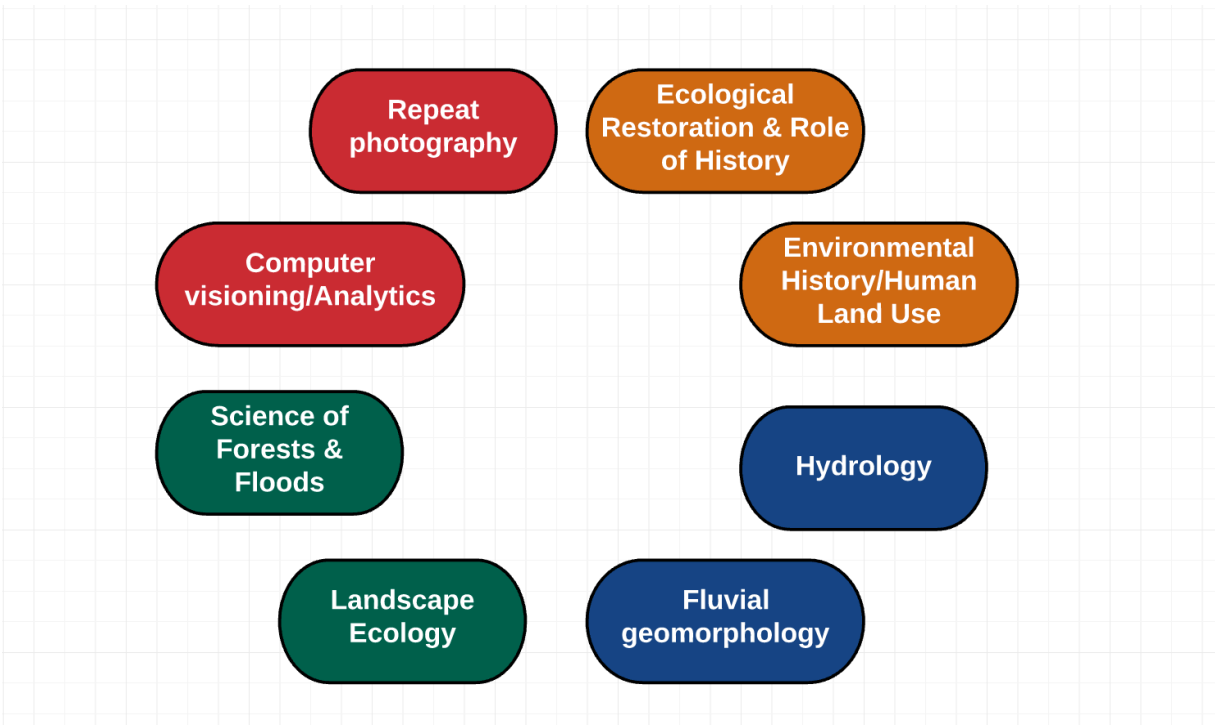
Not only is the world constantly changing, but so is our understanding of it (Adams, 1990). Science is the quest to understand how the natural world works, and is based on the premise that such understanding must be reached through observable physical evidence (E. O. Wilson, 1999). As human beings, we tend to be selective in our recollection of the past, with each generation redefining what is deemed natural (Pauly, 1995). It is clear that we live in a period of rapid transformation where the abiotic and biotic worlds are drastically changing all around us, possibly more so than ever before and as a result of our actions (S. L. Lewis & Maslin, 2015). This human-caused environmental change is continuously affecting biotic communities and influencing abiotic conditions (Perring & Ellis, 2013). Consequently, we are susceptible to falling in a spiral where reference conditions are hard to pinpoint. Demographic and

technological trends have in fact shaped our sources of data, thereby affecting our perceptions through time (Adams, 1990). One can only inquire into the impact of humans on the global environment by in turn inquiring on the impact of the global environment on humans; as was stated by members of the Club of Rome many years ago (D. H. Meadows, Meadows, Randers, & Behrens, 1972), it is a dynamic system with reciprocal components in constant interaction.

These constant interactions are leading to a new “ecological world order” (Hobbs, Higgs, & Hall, 2013d), where human influences are causing systems of abiotic, biotic and social components to take on novel qualities that are in fact very different from those that prevailed historically (Hobbs, Higgs, & Harris, 2014a; Hobbs, Higgs, & Hall, 2013d; Hobbs, Higgs, & Harris, 2009). When this unfolds and active human management ceases, it is termed a novel ecosystem (Hobbs, Higgs, & Hall, 2013a). Not all ecosystems undergoing rapid change are novel; when the change is reversible and ecosystems can be restored to their historic state, they are termed hybrid (Hobbs, Higgs, & Hall, 2013c). Novel ecosystems are not new in themselves; what is new is the pace and extent of environmental changes presently unfolding (S. T. Jackson, 2013). Taking the premise that nothing is static in this world, that change is integral to ecosystems and to human beings, we can conclude that it would be wise to attempt to understand the change that is unfolding, yet humbly recognize that the complexity, spatial and temporal scale, and inter-connected nature of natural systems are such that there will always be uncertainty and unpredictability.

The field of environmental studies is inherently multidisciplinary with its focus being the study of human interactions with the environment. Decision-making around environmental problems represents a challenge because they are complex problems. The main problem that motivates and underlies this thesis is flooding and its risk to people. There is a key distinction between complicated and complex problems. When each part can be understood independently and serves a separate function, such as the mechanics of a car, it represents a complicated system. The whole can be understood through the combined functions of its parts. On the other hand, in a complex system, such as the human body or an ecosystem, the whole is greater than the sum of its parts. Complex systems are riddled with uncertainties and unpredictability. Unlike a

material artifact such as a painting, there is no original condition for an ecosystem; it is dynamic and always changing (Higgs, 2003). Consistent with multidisciplinary studies described above, this study touches on the disciplines identified in Figure 1-1.



**Figure 1-1. Disciplines drawn on by this thesis.** The red components relate to image capture and analysis, the green to ecosystems, the blue rivers, and the orange the human-dimension.

This study grapples with the challenge of understanding ecosystems under conditions of rapid change through a study of land cover transformations over the past 130 years in the Bow and Elbow watersheds of Alberta. This region represents one of the portals into the Canadian Rocky Mountain parks, renowned for their scenic splendour and outstanding landscape features. Through the past century, much has changed in the human-ecosystem relationship in the front ranges of the Canadian Rocky Mountains. This time period is of tremendous significance as it captures the shift from aboriginal land management practices to European colonization into the New World. Today, it is well known that these parks, as well as surrounding provincial lands, are primarily forested – a feature that is often taken for granted. However, forests have not always dominated this landscape. This study is one of the first to specifically

quantify the magnitude of change in land cover types across a portion of the Bow watershed between 1888 and 2009 using historical oblique mountain survey photographs paired with modern repeat photographs. These photographs serve as empirical evidence for the state of the landscape 130 years ago and more recently, in turn shaping the narrative of history for this region.

The choice of time frame and scale are key in undertaking many scientific studies. The time-horizon of 130 years in the present study represents approximately 7 generations. Using this time frame was made possible by the remarkable availability of photo pairs that bracket this period. Such a time horizon is significant in several ways as it: (1) captures the major transitions in land-use and human-presence that have been so formative in the front ranges of the Canadian Rocky Mountains; (2) is long enough to capture the response to human interventions by ecosystems; and (3) provides insights that can strengthen our ability to think and plan in a century-long time frame and therefore be better prepared for the future.

Determining the nature of land cover changes in the Bow watershed is important for numerous reasons. It enables better understanding of physical and ecological processes, as well as how people have and continue to modify the landscape. Thus, it provides insights on ecological change and human ecosystem management. The Canadian Rockies and particularly the Eastern slopes in Alberta hold special importance both to Canadians and to people from around the world because of the region's compelling and awe-inspiring landscapes. We can better appreciate this region when we understand its legacies.

### 1.3 Mountain Legacy Project

This research is associated with the Mountain Legacy Project (MLP), a research program focused on landscape change in the Western Canadian cordillera. Its mandate is to study landscape ecology, ecological restoration and social perspectives on landscape change in the mountains of Western Canada through repeat photography, archival research and field-based studies. Almost every mountain range in British Columbia, Alberta and the Yukon is included in archival collections. Since its inception,

the MLP has benefited from research involvement, funding support or collaborations with Library and Archives Canada, Alberta Parks, Parks Canada, Alberta Agriculture and Forestry, Universities of Victoria, Alberta, Northern British Columbia and Western. In 2016, MLP began collaborating with the Canadian Mountain Studies Initiative at the University of Alberta in order to explore the possibility of serving as one of the grounding pillars for the creation of a Canadian mountain observatory research platform.

The MLP's work is made possible by a collection of systematic and comprehensive high resolution historical survey photographs taken in preparation for the first topographic maps of Canada's western mountains. From 1888 to 1958, Dominion Land and Geological Survey of Canada surveyors used photographs alongside survey measurement to produce hundreds of highly accurate maps (MacLaren, Higgs, & Zezulka-Mailloux, 2005; Trant, Starzomski, & Higgs, 2015). This collection includes more than 120,000 large format photographs stored as negatives on glass plates (Trant et al., 2015). Since the first MLP field season in the late 1990s (Rhemtulla, Hall, Higgs, & Macdonald, 2002), over 6,000 images have been repeated (Trant et al., 2015). These late 19<sup>th</sup> and early 20<sup>th</sup> century photographs, paired with contemporary repeat photographs taken from exactly the same location, provide a significant platform for studying ecological change. Vegetation patterns are especially striking in the paired images, and new segmentation and classification software (Jean et al., 2014) open up the collections to focused studies of landscape change.

The Mountain Legacy Project Editing and Administering Tool (MEAT) was created as a means to organize the MLP data assets and serve as its depository. General information on the MLP, including archival records, can be found at [mountainlegacy.ca](http://mountainlegacy.ca).

## 1.4 Overview

Following this introduction, Chapter 2 provides a description of the study area and a summary of key background literature. Project methodology is described in Chapter 3. Chapter 4 provides an account of the land cover changes that were identified. Lastly, implications for flood management, challenges and opportunities are discussed in Chapter 5.

## Chapter 2 – Study Area and Background

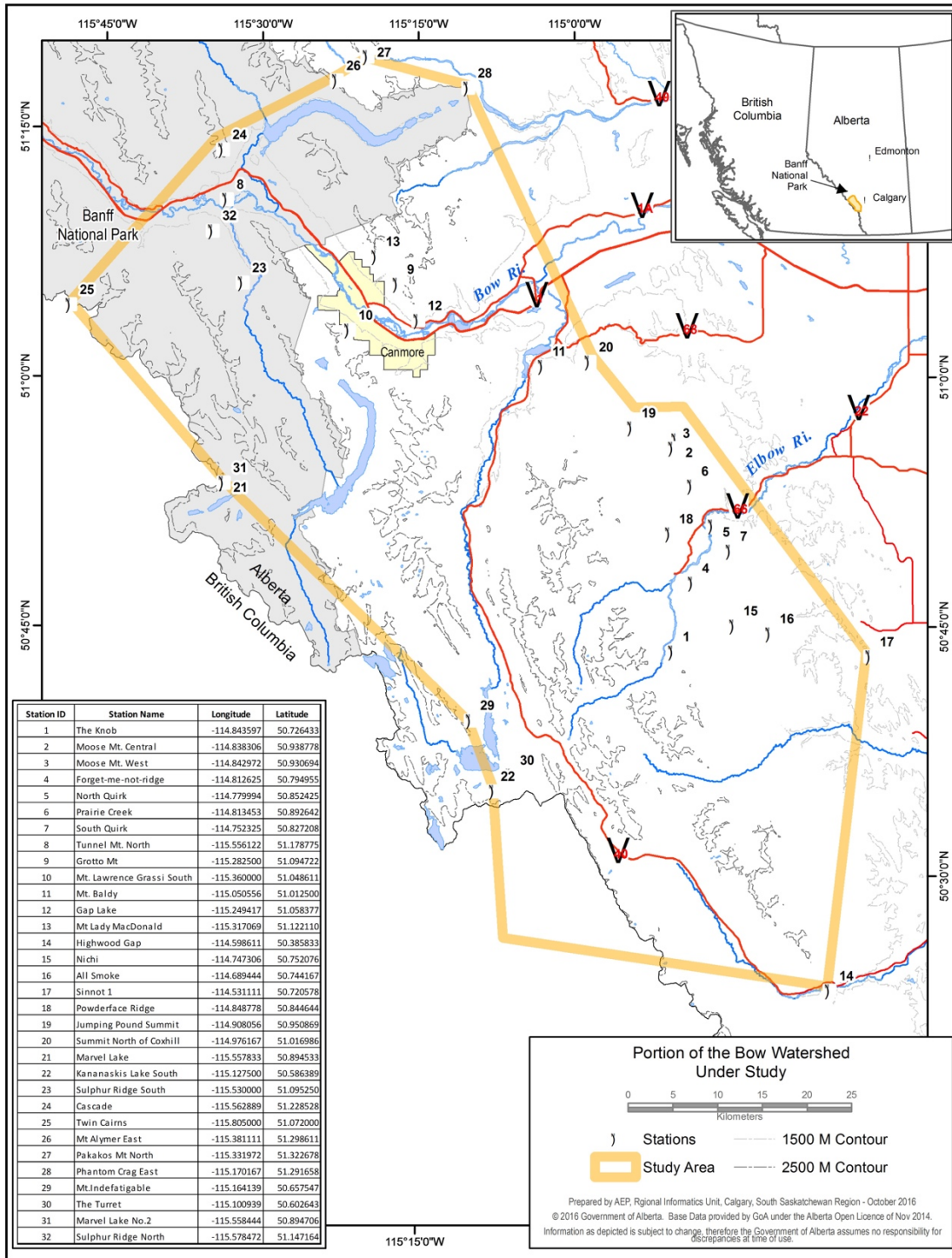
### 2.1 Location

The study area (Figure 2-1) is located in Kananaskis Country, west of Calgary, Alberta in the foothills and front ranges of the Canadian Rocky Mountains. It covers 4,540 square kilometres. The distance between the northern and southernmost stations is 118.30 kilometres, while the eastern and westernmost stations are separated by 101.41 kilometres. Elevation of stations varies from 1,503m to 2,430m above sea level (ASL) across the study area, which encompasses the municipalities of Banff, Canmore, Exshaw and Morley as well as a component of the wildland park system of Kananaskis Country.

### 2.2 Vegetation

The study area is located in the Montane Cordillera ecozone, or the Rocky Mountain natural region of Alberta. It can be further classified as part of the subalpine and montane natural sub-regions (Natural Regions Committee, 2006). The foothills, a landscape of long ridges and rolling hills, represent the transition from high mountain headwaters to prairie conditions.

Tree species such as Engelmann spruce (*Picea engelmannii* Parry.), white spruce (*Picea glauca* Voss.), sub-alpine fir (*Abies lasiocarpa* Nutt.), lodgepole pine (*Pinus contorta* Douglas.) and aspen (*Populus tremuloides* Michx.) are found here (Johnson & Fryer, 1987; Nelson & Byrne, 1966). The major vegetation type is conifer mixedwood (Natural Regions Committee, 2006). Radiocarbon dating has uncovered evidence of the presence of spruce and pine forests in the Bow River drainage as early as 10,000 <sup>14</sup>C years ago (L. E. Jackson Jr, MacDonald, & Wilson, 1982). Prior to 10,100 <sup>14</sup>C years ago, vegetation in the central Canadian Rocky Mountains was sparse and dominated by shrubs and herbaceous plants (Reasoner & Huber, 1999).



**Figure 2-1. Study Area.** Portion of the Bow Watershed Under Study. The portion of the area is demarcated with the yellow contour line. Stations are numbered on the map, and identified in the legend.

A dramatic shift occurred circa 10,100 <sup>14</sup>C years ago when the shrubby vegetation was replaced by a rapidly expanding *Pinus*-dominated forest (Reasoner & Huber, 1999). This open forest was maintained, possibly as a result of fire, between circa 9,000 and 4,160 <sup>14</sup>C years ago. Then, from 4,160 to 900 <sup>14</sup>C years ago, closed *Picea abies* forests dominated (Reasoner & Huber, 1999). There was a significant reduction in arboreal taxa at 900 <sup>14</sup>C years ago in the river basin accompanied by an expansion of valley-floor meadows as a result of an increase in modern alpine tundra and subalpine meadow taxa (Reasoner & Huber, 1999).

## 2.3 Geology & Geomorphology

The majority of Alberta was covered in ice during the last glacial maximum; glacial retreat began in this region around 19,000 years ago (P. U. Clark et al., 2009). The Bow Valley emerged from retreating ice during the Last Wisconsin glaciation, approximately thirteen thousand years ago (Armstrong, Evenden, & Nelles, 2009, Alberta Environment and Parks, 2014). The braided river aggregation of the Bow can be dated between 12,000 and 10,000 years ago (N. Eyles, Eyles, & McCabe, 1988). It is flanked by fluvial terraces cut in gravel fill over 100km from the edge of the Rocky Mountain Front Ranges to beyond Calgary (L. E. Jackson Jr et al., 1982). The underlying bedrock in the region is primarily limestone, shale, young sandstone, and coal (Osborn, Stockmal, & Haspel, 2006, Jakob et al., 2014).

## 2.4 Climate

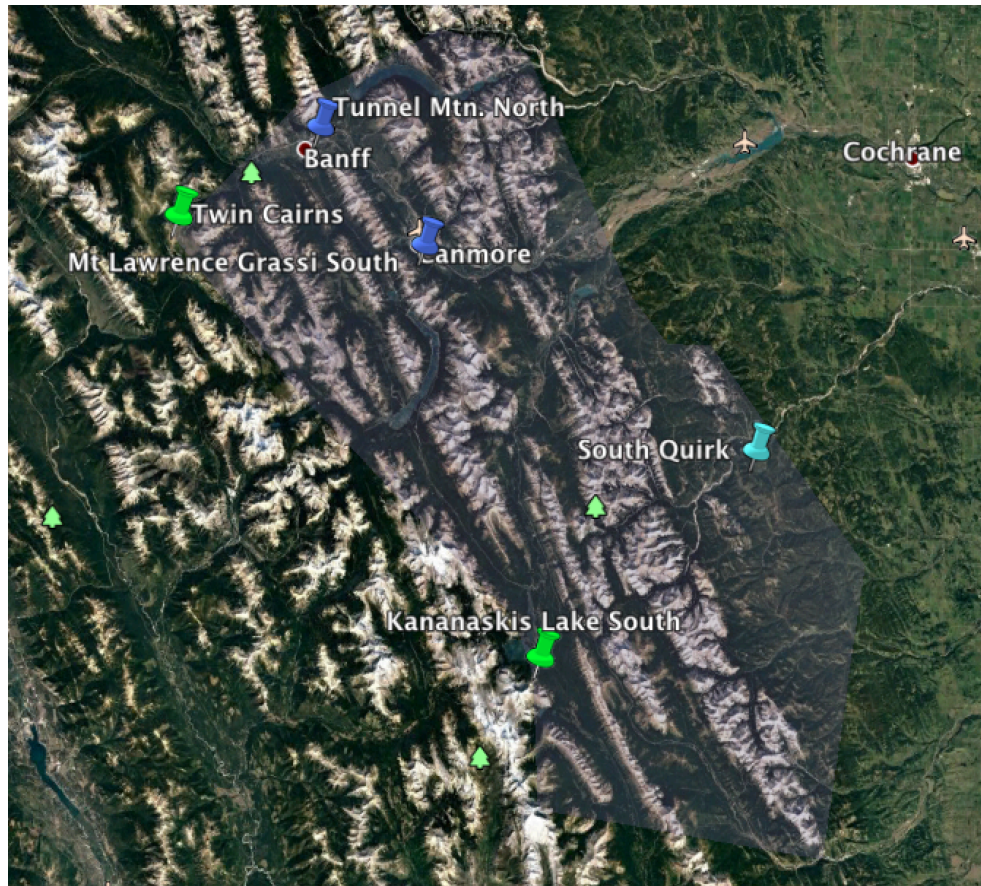
Four air masses — the maritime polar, continental polar, maritime tropical, and continental arctic — interact and influence temperature and precipitation regimes in Alberta (Natural Regions Committee, 2006). A significant portion of snowfall at higher elevation and in the foothills originates from the maritime polar air mass, which comes from the north Pacific (Natural Regions Committee, 2006). In the summer, severe weather tends to occur as a result of maritime tropical air masses from the west or the south (Natural Regions Committee, 2006). This particular air mass is most responsible

for convective storms, severe rainfall, tornadoes, and hailstorms. The weather patterns in the Montane sub-region result in a mean annual temperature of 2.3°C, mean annual precipitation of 589mm and mean number of growing degree days >5°C of 1017.

Climate Western North America Version 4.74 was used as a source of scenario data for projected climate change in the study area. The model used was Climate WNA AR4-cccma-cgcm3-A2. A climate scenario has been defined as, “a projected future climate based on a specific greenhouse gas emissions path for this century, calculated by a specific global climate model (GCM)” (Murdock & Spittlehouse, 2011:11). It is calculated by taking the difference between a projected future and simulated present-day climate (Murdock & Spittlehouse, 2011). For the purpose of this study, such a model serves as a reference when considering climate in the region, and posits how climate change may affect flood risk. The selected climate variables assessed include: (1) climate moisture deficit (mm) (Figure 2-3); (2) precipitation as snow (mm) (Figure 2-4); and (3) spring precipitation (mm) (Figure 2-5). These climate variables were calculated for five key stations across the study area: Tunnel Mt North, Mt. Lawrence Grassi South, South Quirk, Kananaskis Lakes South and Twin Cairns (Figure 2-2).

## 2.5 Flood Regime and Flood Record

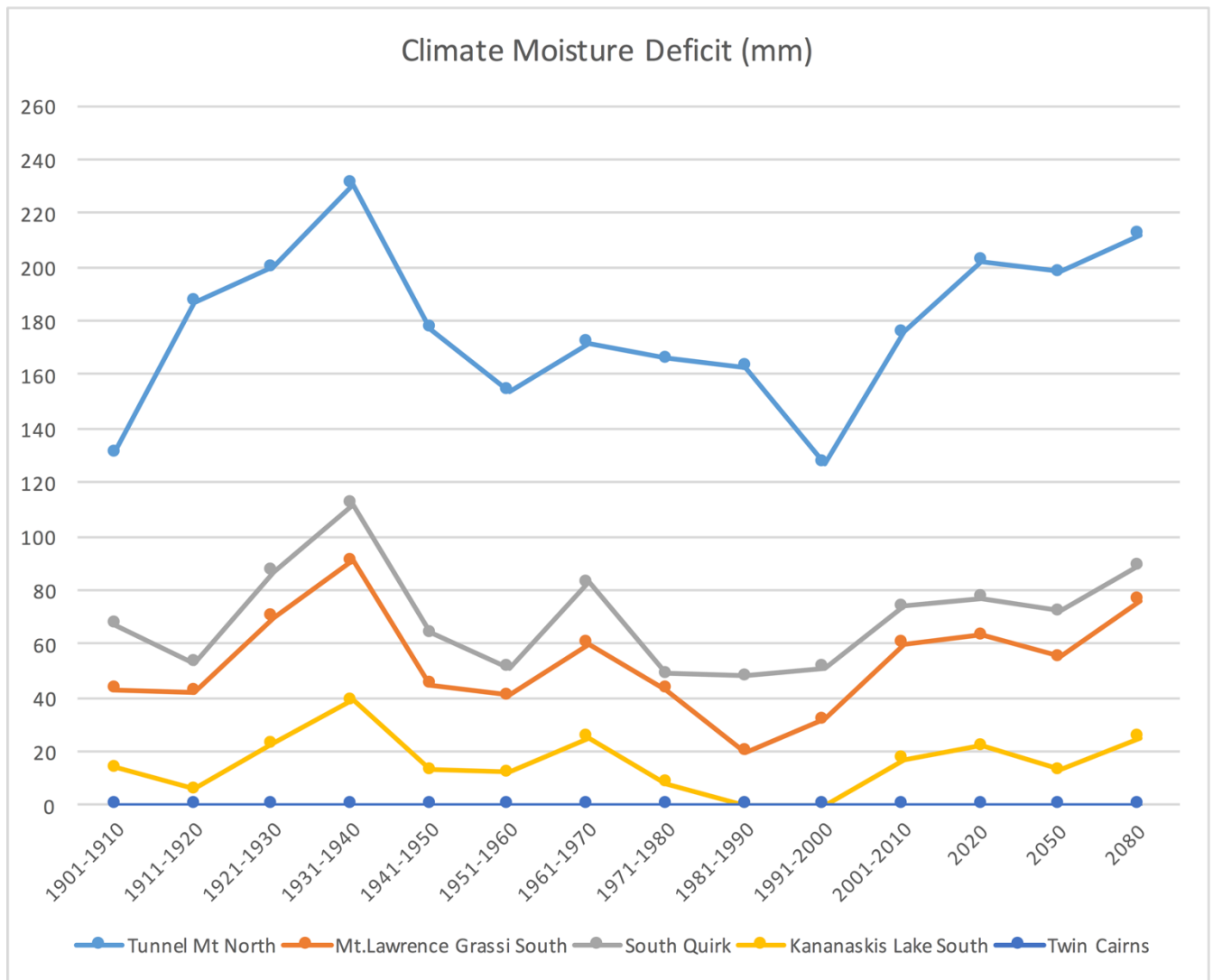
The flood regime of this area is characterized by annual floods, mostly driven by extreme rain events compounded by snowmelt in the late spring or early summer. Flooding occurs as a result of melting at a synoptic scale across the entire river basin at the time of spring peak melt, or a severe rain event on an isothermal snowpack (Rain-on-snow event) (M. Wagner, personal communication, October 14, 2015). As meteorological factors vary each year, the potential for flooding does not remain the same each year; storm input and antecedent moisture conditions are constantly fluctuating, and thus influence flooding potential. A continuous flood record exists from 1911 onwards for the Bow River at Calgary (Neill & Watt, 2001). The three largest known floods preceding the collection of continuous data occurred in 1879, 1897 and 1902 (Neill & Watt, 2001).



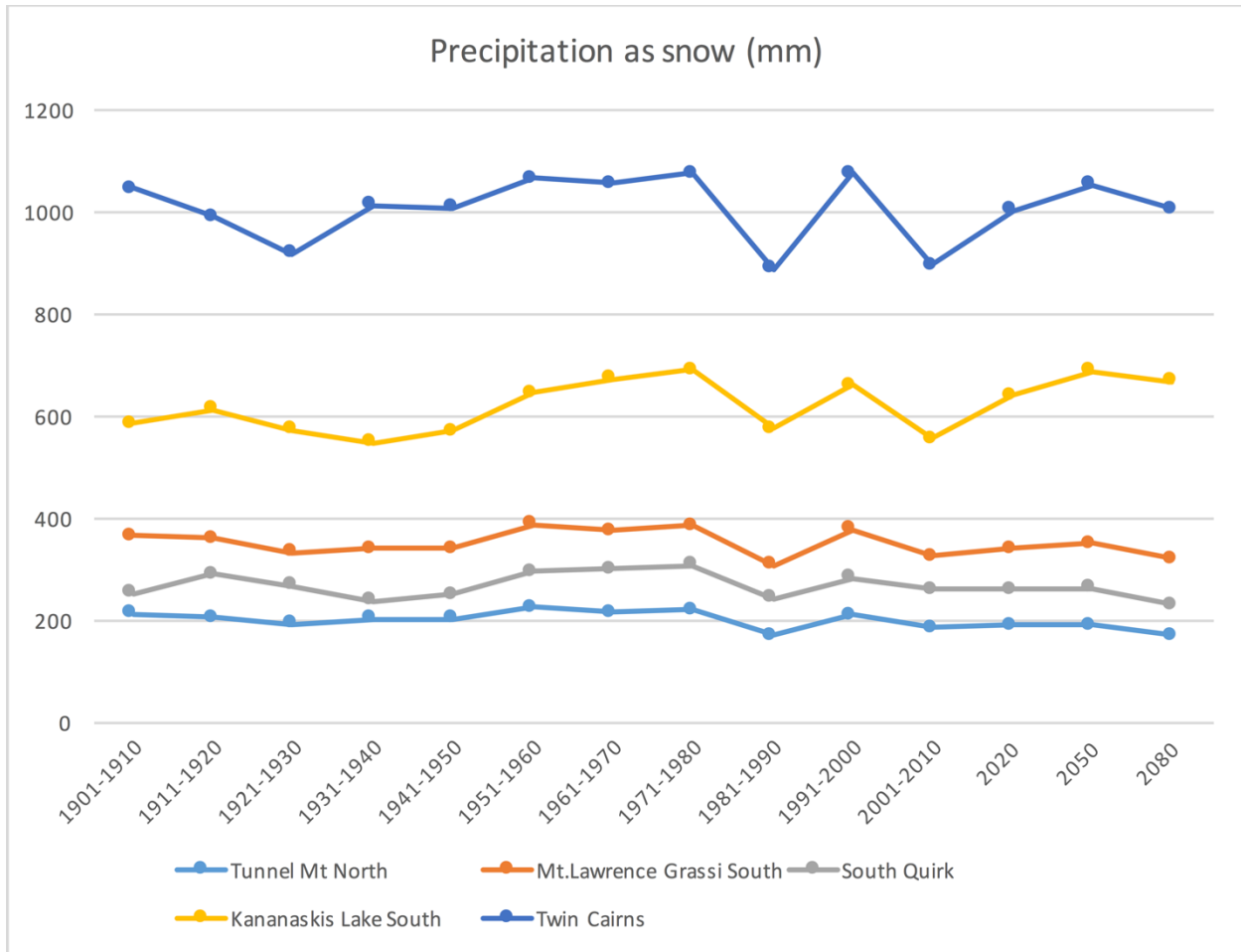
**Figure 2-2. Five stations chosen for calculating climate WNA projections.**

Projections for different climate variables were calculated for Tunnel Mt North, Mt. Lawrence Grassi South, South Quirk, Kananaskis Lakes South and Twin Cairns. These are representative of the spectrum of variability between the northern and southernmost, as well as western and easternmost stations in the study area. Base map data ©2016 Google

Less is known of the 1879 flood event, resulting in a number of studies assigning it the same peak discharge as the 1897 event (Neill & Watt, 2001). Neill et al. (2011) plotted the 118-year flood peaks at Calgary as accurately as possible (1879-1996), where missing values were plotted as zero (Neill & Watt, 2001) (Figure 2-6). The next largest flood occurred in 1932, and after that there were no major floods up to 1996 (Neill & Watt, 2001). To this effect, Neil et al. state that “the nine highest events all occurred before 1934” (Neill & Watt, 2001:31). This aligns with McLennan’s account: five major floods were recorded between 1897 and 1932 for the Bow, the largest of which occurred in 1897, producing a discharge of 99,000 c.f.s. in Calgary (McLennan, 1987).



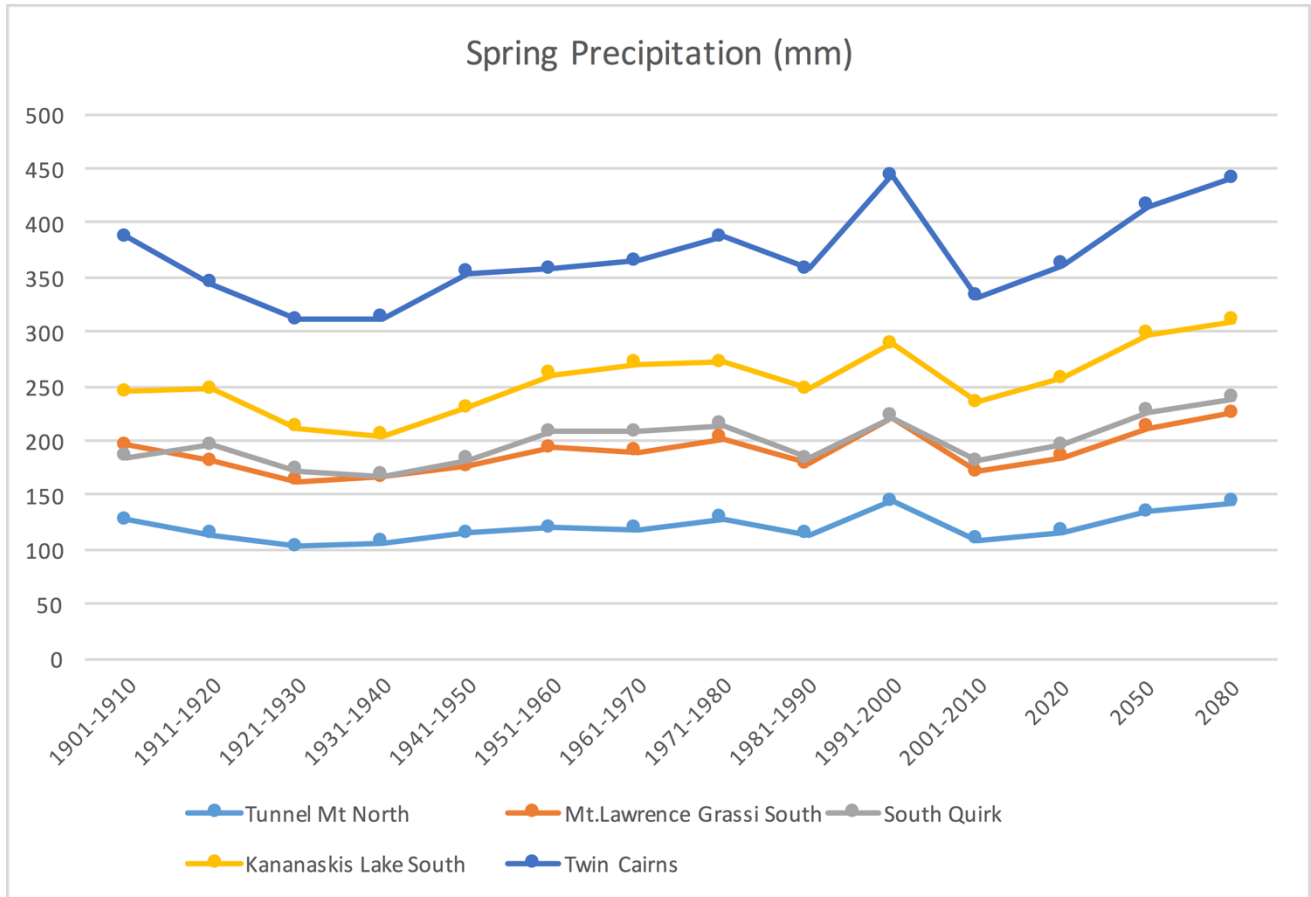
**Figure 2-3. Hargreaves climatic moisture deficit (CMD) in millimetres (mm) for historical and future periods across 5 stations.** The CMD is a dryness index, the higher it is, the hotter it is, leading to the absence of rainfall. The CMD affects potential wildfire and forest productivity. A CMD of zero would indicate there is more precipitation than there is evapotranspiration. A decadal time frame was chosen as a means to see generalized trends while still maintaining historical detail. Twin Cairns, located at the northwest edge of the study area appears to have consistently more precipitation than evapotranspiration, no matter the year. The other four stations have similar patterns from 1901 to 2080, yet Tunnel Mt North, located in Banff and at the northern edge of the study area, has a significantly higher CMD than the others. It certainly points towards a higher risk of wildfire between 1991 and 2080. Source: Climate Western North America model.



**Figure 2-4. Precipitation as snow (mm) between August in previous year and July in current year for historical and future periods across five stations.** This is an indicator of how much snow is falling and thus the state of the annual snowpack. A decadal time frame was chosen as a means to see generalized trends while still maintaining historical detail. Twin Cairns has the highest snowfall, followed by Kananaskis Lake South. The other three stations range between 200 and 400 mm of snow per year and are not projected to change significantly moving into the future. Elevations for the five stations are: Tunnel Mt North 1,672m, Mt. Lawrence Grassi South 2,178m, South Quirk, Kananaskis Lake South and Twin Cairns: 1,989m. Source: Climate Western North America model.

This is a significant amount, considering the mean discharge is 3300 c.f.s., typically rising to 11,000 c.f.s. during heavy spring runoff (McLennan, 1987). Flood risk from winter ice jams has been a problem for the Bow as early as 1896, but was partly mitigated by the construction of the Bearspaw Dam in 1954 (McLennan, 1987). The Banff (2210 km<sup>2</sup>) flood record spanning 87 years (1909-96) painted a very different picture, showing more even distribution of large flood events over the same time period

(Neill & Watt, 2001) (Figure 2-7). The 1923-1962 and 1979-1996 Seebe (5170 km<sup>2</sup>) flood records show a similar trend as the Calgary one, with its six highest floods occurring from 1923-33 (Neill & Watt, 2001).



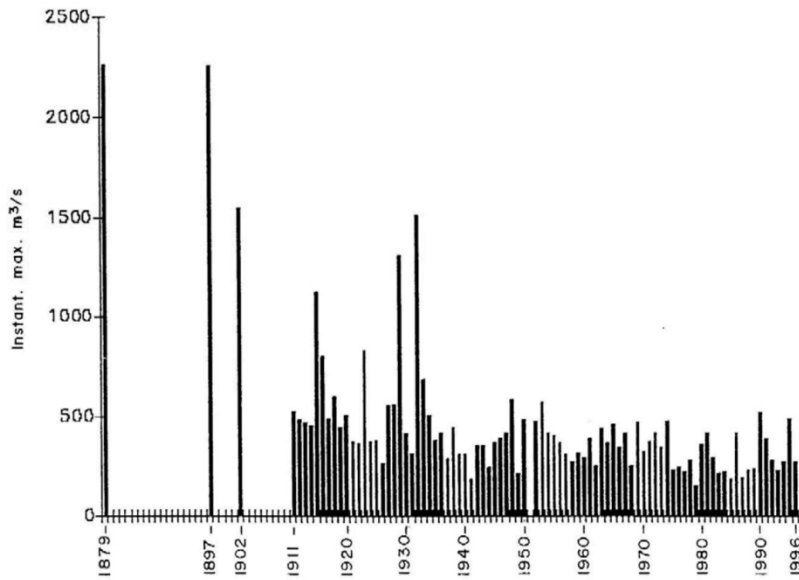
**Figure 2-5. Spring Precipitation (mm) for historical and future periods across five stations.** Spring precipitation is a measure of how much rain is falling in the spring. A decadal time frame was chosen as a means to see generalized trends while still maintaining historical detail. Spring precipitation is projected to increase at all five stations, although more so at Twin Cairns and Kananaskis Lake South than at the other three stations. Source: Climate Western North America model.

Studies assessing flood frequency for the Bow River at Calgary (7860 km<sup>2</sup>) have arrived at substantially different conclusions (Neill & Watt, 2001). Montreal Engineering Co (Momenco) conducted a hydrologic analysis in 1968 for the Bow River; Neill et al. (2001)'s breakdown of Momenco's Calgary Floodplain Study findings follows (Neill & Watt, 2001).

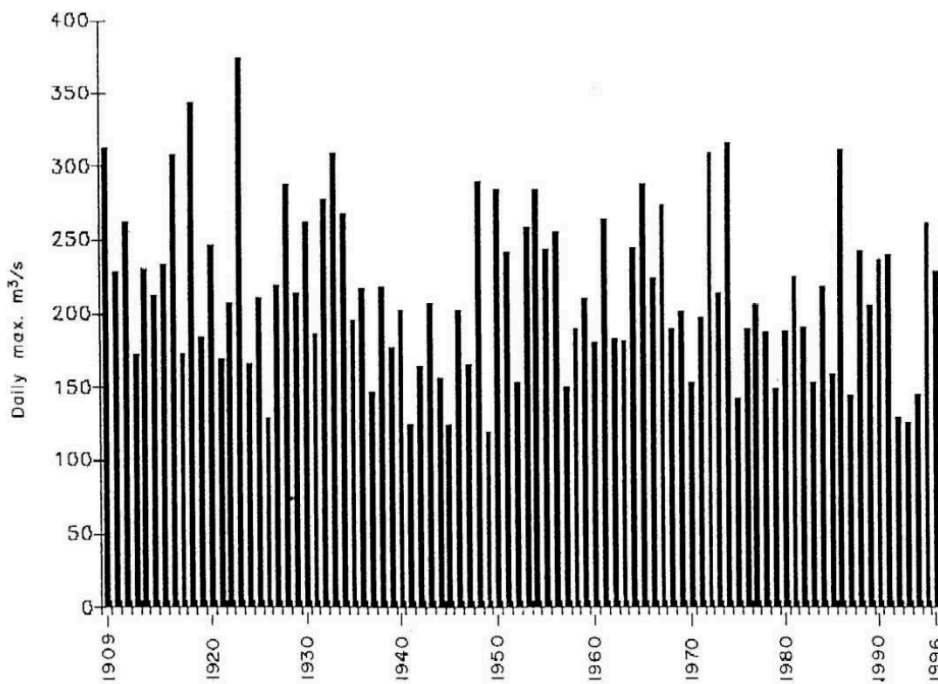
It is very difficult to conclude flood frequencies for the Bow; it has been hypothesized that the difference in flood magnitude before and after 1933 may be due to the absence of cyclonic storms over the Bow River Basin after 1933. The flood of 1902 occurred in the middle of a very wet summer whilst the 1929 and 1932 events both occurred on June 3 as a result of heavy rains in the foothills, west of Calgary.

Momenco's study of the 1971 Bowness flood study concluded that major storms often followed a path critical to the Bow River but since 1932 none have followed this same path. In this report they used a peak flow (instantaneous max) of  $2500 \text{ m}^3/\text{s}$  for a 100-year flood frequency. This study also confirmed the absence of flood-producing rainstorms over the Bow since 1932. The return period for the 1879 and 1897 floods was noted to be seventy years based on  $2265 \text{ m}^3/\text{s}$ . At that time no major changes in forest cover were identified. Alberta Environment's Calgary 1983 Flood Plain Study found the opposite to be true. Neill et al. (2001) note that, "reference is made to extensive forest fires that are said to have burned 60% to 80% of the Eastern Slopes in the late 1800's and early 1900's, and that might partly account for the extreme floods before 1910. In the aforementioned 1983 study, the 100-year return period volume is adjusted to  $1980 \text{ m}^3/\text{s}$ , which was exceeded only by the 1879 and 1897 floods events. A major fire swept through the Bow valley in the early 1880s, while the Elbow valley as well as other portions of the study area were hit by a major fire in 1910 (R. Arthur, personal communication, September 30, 2016). The conclusion is drawn, however, that "because forest influences on runoff come and go, the early and late records should be combined for purposes of frequency analysis" (Neill & Watt, 2001:33).

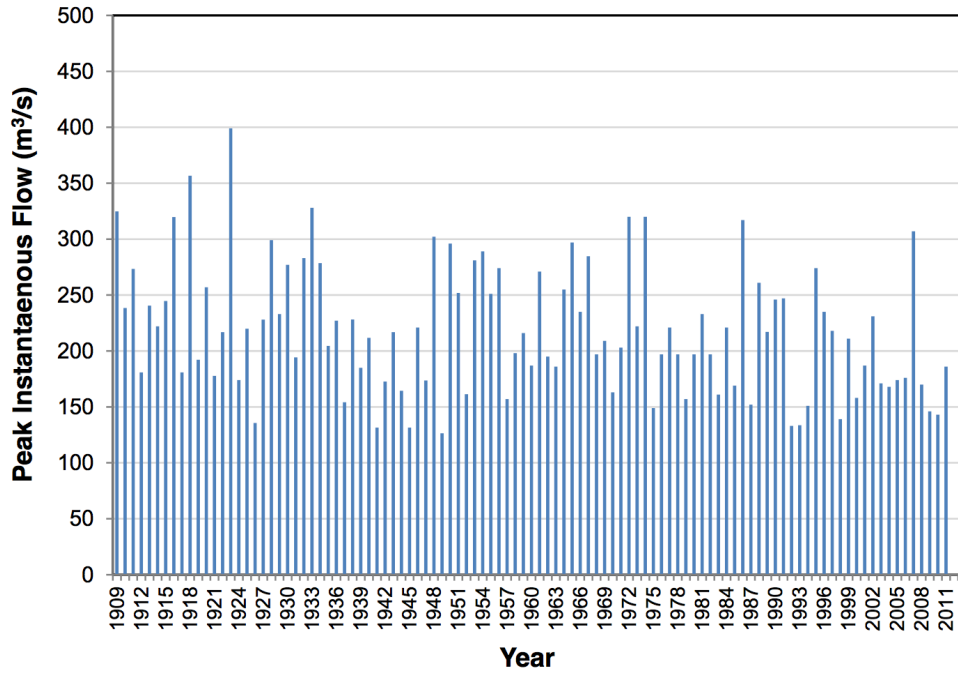
A more recent study undertaken by BGC Engineering following the 2013 floods included a more updated flood record for the Bow River at Banff, located 1.6km north of Tunnel Mountain (Figure 2-8). The torrential rains that occurred in 2013 (Figure 2-9) certainly represent an anomaly when looking back at the daily rainfall record for Meteorological Service of Canada's Kananaskis station (Figure 2-10), which is located 2km northeast of Mt. Baldy.



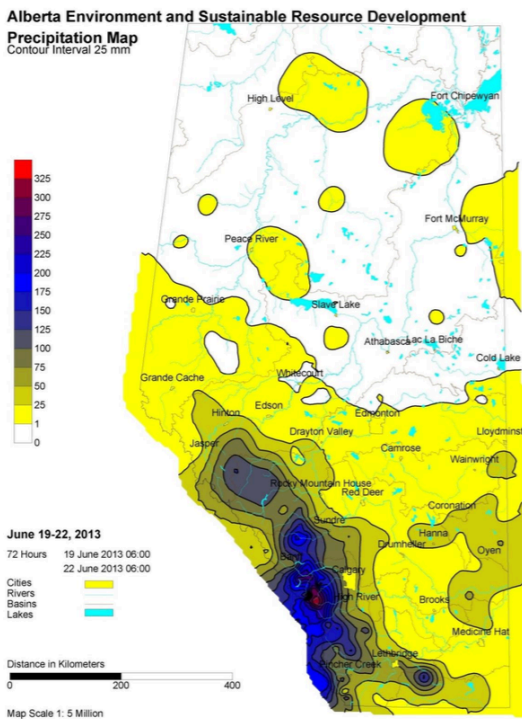
**Figure 2-6. Peak flow for Bow River at Calgary, 1911-1996 plus three historical floods.** Source: Neil et al. 2001.



**Figure 2-7. Highest average daily flow for Bow River at Banff, 1909-1996.** Years are represented on the x-axis, while each column represents the largest daily max in each given year. Source: Neil et al. 2001.

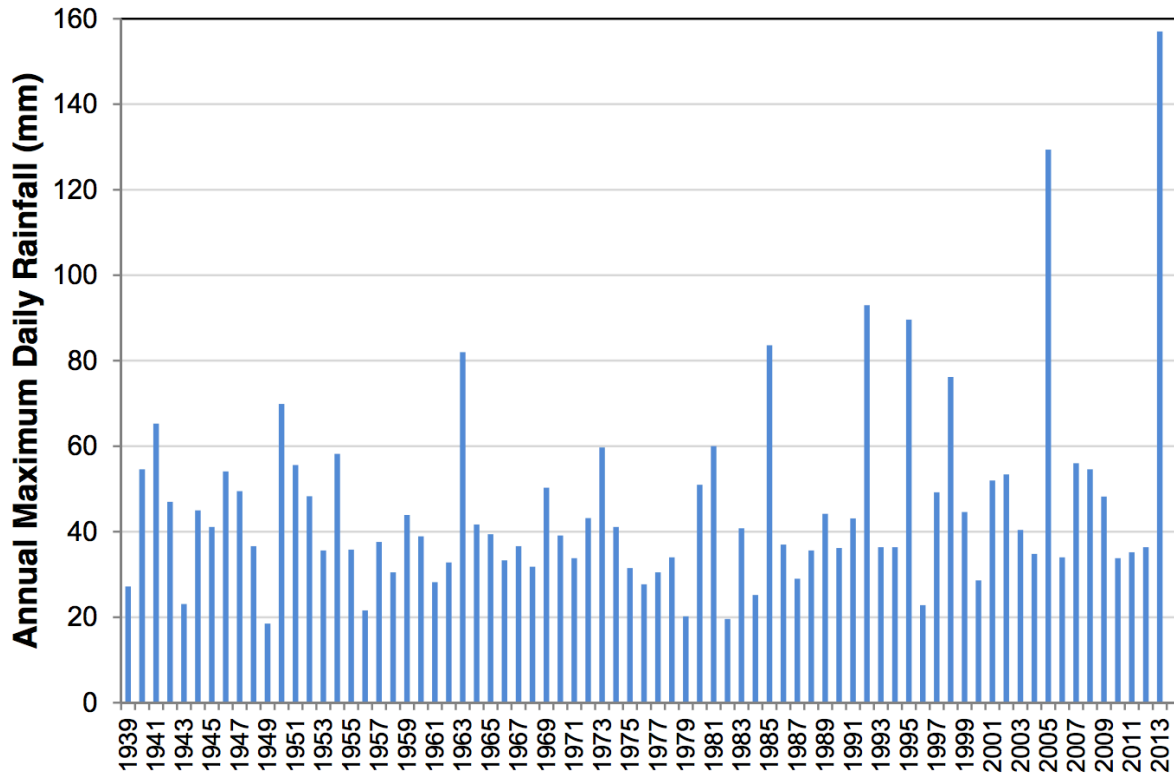


**Figure 2-8. Peak daily flow for Bow River at Banff, 1909-2013.** The peak/instantaneous flow represents the very peak that a flood reaches even just for the shortest measurement interval (15 minutes in some cases). Source: (Jakob, 2014).



**Figure 2-6. AESRD precipitation map for the June 2013 storm event** (<http://www.environment.alberta.ca/forecasting/data/precipmaps/precipmaps.html>).

**Figure 2-9. Alberta 72-hour precipitation patterns, June 19-22, 2013.** Source: (Jakob, 2014)



**Figure 2-10. Annual maximum daily rainfall (mm) at Kananaskis, 1939-2013.** Illustrates how abnormal the torrential rains in 2013 were compared to the norm. Source: (Jakob, 2014).

## 2.6 History and Land Use

Paleo-Indians occupied this area since 10,000 BCE (White, 1985). They migrated to the region for its source of wood for shelter and fire and grasslands to the east populated by bison or buffalo — a primary source of food and clothing (McLennan, 1987). An archeological study of the Vermillion Lakes site in Banff found records of human presence as early as 10,300 before present (Fedje et al., 1995). In fact, evidence has been uncovered that demonstrates an intensive human occupation of the region around present-day Banff between 200 CE - 1,500 CE (Christenson, 1971). This long-established population of aboriginal peoples collapsed around 1750 as a result of the expanding European colonization across the continent (White, 1985). This collapse also coincided with the arrival of the Stoney and Cree peoples in the area

(White, 1985). It was around this time that the pre-European period ended, replaced by the fur-trading period (1775-1850) (Byrne & Scace, 1964).

There were three aboriginal groups present in the area during the fur-trading period: the Blackfoot Nation, the Tsuu T'ina (formerly called the Sarcee) and the Stoney First Nation. The Bow Valley was the domain of the Blackfoot Nation when the first settlers arrived (McLennan, 1987). The Blackfoot are of Algonquin origin and are thought to have moved to southern Alberta from eastern Canada; they are now divided into three nations: the Blood, the Peigan and the Blackfoot (McLennan, 1987). The buffalo (*Bison bison* Linnaeus.) was a staple food with spiritual significance (Brasser, 2009; McLennan, 1987). Prior to 1730, the Blackfoot lived a nomadic and communal life; around 1730, their lifestyle shifted as they acquired horses and guns from other tribes, thereby enabling them to continue dominating the plains throughout the 18<sup>th</sup> century (McLennan, 1987).

In the 17<sup>th</sup> century, the Tsuu T'ina arrived from northern Alberta and came to be integrated with the Blackfoot; however, their population was decimated by smallpox and measles introduced to the native people from European contact, as well as by the extinction of the buffalo, resulting in a population of only 255 in 1877 (McLennan, 1987). Simultaneously, the Stoney First Nation lived in the Eastern Slopes as a result of being pushed westward by the Blackfoot from the central plains (McLennan, 1987). Unlike the Blackfoot, the Stoney did not rely dominantly on one animal for their survival, and had a diverse environment on which to rely; being very knowledgeable of the mountain passes as well as resourceful, they played an important role in guiding early explorers (McLennan, 1987).

Between 1857 and 1861, Irish-born geographer and explorer Captain John Palliser led an expedition in search of a route through the Rockies, organized by the Royal Geographical Society (Brouillette, 1970; Palliser, 1859; Spry, 1968). He gathered a team of specialists including French botanist Eugène Bourgeau, specialist in earth magnetism Thomas Wright Blakiston, naturalist and geologist James Hector and astronomer John William Sullivan (Brouillette, 1970). Together they produced a key historical document of Canadian geography; creating a much more detailed and accurate map of the area, recording a range of characteristics from climate, fauna, and

flora, to geology and natural resources (Brouillette, 1970). This was the first multidisciplinary scientific expedition into Western Canada, with its primary purpose being the assessment of the natural resources potential for the region (Roots, 1998). Furthermore, Roots (1998) explained that, “unusual for expeditions of that time, all of the scientists were sympathetic students of native customs and language” (Roots, 1998:1). This initial expedition provided the building block for the decision in 1880 to make the Bow Valley the westward route for the Canadian Pacific Railroad (CPR) (McLennan, 1987).

The aboriginal peoples living in Kananaskis Country at the time of the Palliser Expedition (1857-60) used Kananaskis Pass as the main travel route as it had the best hunting and pasture for horses within one day’s travel on either side, even though it was the highest of all passes in the region (Roots, 1998). In 1854, James Sinclair led a party of 100 settlers and 250 head of cattle from Red River through north Kananaskis Pass to end in Oregon (Oltmann, 1997). The area now called Kicking Horse Pass which has become the major transportation route for the CPR and the Trans-Canada Highway was seen as a less desirable route by the First Nations as it did not offer game or horse feed (Roots, 1998). By 1884, the coal deposits near present-day Canmore and Anthracite discovered by Hector in Palliser’s expedition had been well investigated and were highly appealing for steam railway technology development (F. Roots, personal communication, September 30, 2016). Others have explained that the reasoning for the choice of Kicking Horse Pass were the problems presented by Kootenay Lake further south and a desire to have the main route to the west be further from the United States, for defense reasons (B. Jamieson, personal communication, September 23, 2016). Today, Kananaskis pass is only used by hikers and does not have a road, whereas Kicking Horse Pass is the primary route.

Explorers, missionaries, fur traders, law enforcers and railway builders were all involved in opening up the Bow Valley, first through exploration in the 18<sup>th</sup> century and later through settlement and development in the 19<sup>th</sup> and 20<sup>th</sup> centuries. When the large portion of land formerly claimed by the Hudson’s Bay Company was sold to the Canadian government in 1870, the populations of aboriginal peoples were in a

downward spiral as a result of “famine, denial of provisions, forced relocation, and antagonistic policy decisions” (Brasser, 2009:1).

Treaty Number Seven was signed in 1877, leading the Blackfoot to give up their land in return for a little bit of money, cattle and agricultural tools from the Canadian Government (McLennan, 1987). They retained the right to hunt buffalo while it lasted, but had to move onto reserves once it went extinct. Disease and starvation hit the nation (as it hit all First Nations at the time), and in 1890, their leader Crowfoot passed away (McLennan, 1987).

The construction of the CPR through the Rockies only began in 1880 as a consequence of the Province of British Columbia threatening to leave the Confederation (“Canadian Pacific Railway,” 2008). The rail route to the Pacific was completed in 1885 (“Canadian Pacific Railway,” 2008). The construction of the CPR opened up development and economic opportunities, shaping the course of history in the subsequent century. The lumbering, ranching, and grain farming industries boomed and in 1894, the city of Calgary was created (McLennan, 1987). Large areas of the Bow watershed were logged and mineral exploration was also underway (White, 1985). That same year (1885), William Pearce initiated the establishment of Banff Hot Spring Reserve (later named Rocky Mountains Park Reserve) (Coschi, Fong, & Finkelstein, 2007). Thus began the park period, which continues today. Economic development through the tourism industry was prioritized, and industry was developed near Canmore and Exshaw, towns excluded from the park system for that reason (Van Kirk, 1969).

## 2.7 Fire History

Fire is a critical process in maintaining numerous plant communities in this region. Cliff White’s research in Banff National Park in 1985 confirmed that, “before the 1880s fires were relatively frequent in low elevation forest stands with mean fire return intervals (average time between fires in a defined area) often ranging from 20 to 40 years” (White, 1985:7). This was very different from higher elevations, where forest fires were much less frequent due to cooler temperatures and higher levels of moisture (White, 1985). Others have documented fire history in the area, including Hawkes

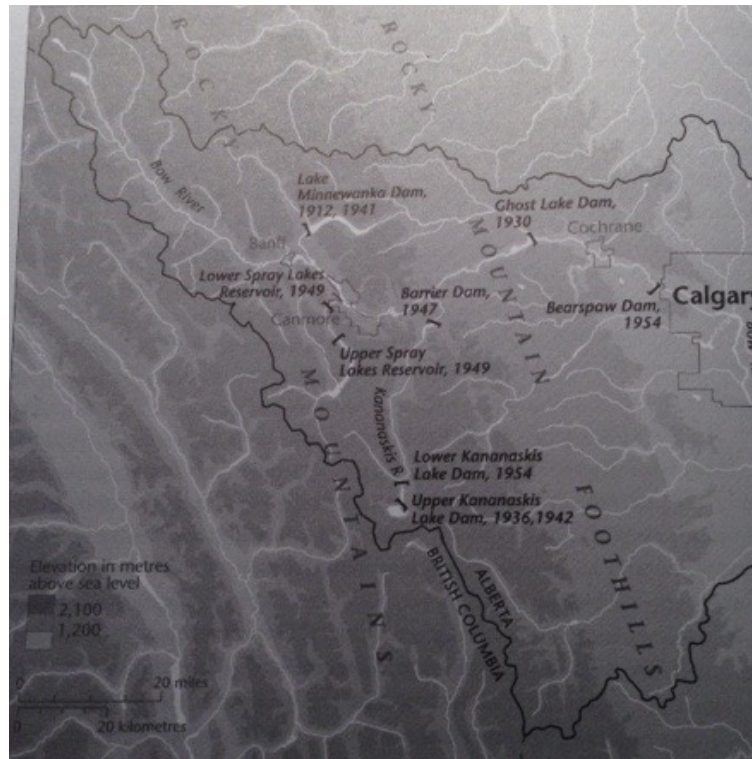
(1979) and White (1984) in Kananaskis and Banff respectively. Some have posited that fires were abnormally widespread between 1880 and 1900 due to sparks from the construction of the railway and other land use practices by early settlers (Byrne, 1968; Byrne & Scace, 1964). Another hypothesis is that droughts were less frequent during that decade, resulting in fewer fires (White, 1985).

However, fire history in the region is much deeper in time. Evidence of char, the conversion of organics into charcoal, have been studied in the area. Reasoner et al. stated that, “fire has been an important disturbance agent in the vicinity of Crowfoot Lake since circa 9000 <sup>14</sup>C years before present (...) periods of high char during the drier earlier Holocene are probably due to frequent low intensity surface fires in the catchment” (Reasoner & Huber, 1999:489). That said, there is undeniable evidence that there was a sharp decrease in fires around 1910, possibly due to the establishment of national parks in the area with a park warden service, associated fire control programs, and change in fire ignition (Van Kirk, 1969; White, 1985).

The little ice age occurred approximately between 1300 and 1850 (Grove, 2004); European colonization coincided with a major shift towards a warmer climate, and thus drier conditions with more fires (B. Jamieson, personal communication, September 23, 2016).

## 2.8 Water control structures

The major tributaries to the Bow include: the Spray, Cascade, Kananaskis, Ghost, Highwood and Elbow rivers as well as the Nose, Fish, West Atwood, and Crowfoot Creeks. Major dams on the Bow are represented in Figure 2-11. The Glenmore Dam, completed in 1932 and located on the Elbow River, holds back the reservoir that serves as the primary source of drinking water for Calgary (McLennan, 1987).



**Figure 2-11. Progression of dam development in the Upper Bow basin.** Source: (Armstrong et al., 2009)

It also enables the control of downstream flow from the Elbow, thereby mitigating flood risk. The Bears paw dam was built in 1954 in response to the need to mitigate winter flooding and ice packing on the Bow River (TransAlta, 2016). Until 1973, the Glenmore dam was the sole source of municipal drinking water for Calgary; after 1973, the two reservoirs began sharing this role (McLennan, 1987). All other river manipulations upstream of Calgary are for power generation, whilst all of those below Calgary are for irrigation (McLennan, 1987). Although the Bears paw dam was originally built for flood mitigation, it produces significant electrical power and also provides municipal water to the city of Calgary (McLennan, 1987).

## 2.9 Factors affecting flooding

A flood is described as, “the overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally

submerged” (IPCC, 2012: 175). There are many types of floods such as “fluvial floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods and glacial outburst floods” (IPCC, 2012:175). Floods typically occur as a result of heavy precipitation over a short period of time, lighter precipitation over a long period of time, snowmelt, ice-jams, the failure of a dam or a local intense storm (IPCC, 2012; Jones, 1997; Viessman & Lewis, 1996). Many conditions affect flood formation, including “geological composition, terrain slope, soil permeability, porosity, crusting and prior wetness, and incident rainfall intensity and duration” (Bradshaw, Sodhi, Peh, & Brook, 2007:2380). Floods can be exacerbated by natural events such as earthquakes, landslides and storm surges (Maidment, 1992). Ultimately there are two hydro-meteorological factors responsible for producing floods: storm input (rainfall intensity, depth, and duration) and antecedent soil conditions (Alila & Green, 2014a; 2014b). Due to the innumerable possible combinations for such factors, it is practically impossible to have a general predictive model for floods (Viessman & Lewis, 1996).

Globally, a warmer climate is posited to increase the risk of floods (IPCC, 2011) (Hirabayashi et al., 2013). This conclusion is based on river routing models which compare river discharge (100-year flood) when global temperatures average at 21 degrees celsius rather than 20 degrees Celsius (Hirabayashi et al., 2013). In these models, flood frequency increased in 42% and decreased in 18% of the land grid cells (Hirabayashi et al., 2013). Areas of highest risk include southeast Asia, Peninsular India, eastern Africa, and the northern half of the Andes (Hirabayashi et al., 2013). The Bow River basin was not explicitly analyzed in Hirabayashi et al’s study (2013), but it was encompassed in a zone where flooding is projected to increase (see Hirabayashi et al., 2013 Figure 2A). Warmer air is correlated with more rain falling during heaviest downpours, in turn leading to flooding (Perera, Sanford, & Cleetus, 2012). This is because warmer air holds more moisture; condensation occurs when warm air meets cooler air (Perera et al., 2012). Drought is a measure of annual precipitation, and is also projected to increase in some areas as a result of climate change (Perera et al., 2012). Climate change is projected to lead to more flooding in some regions because of the increased *intensity* of precipitation events (Perera et al., 2012). This is an important distinction. Finally, climate change is leading to season creep - where spring weather

arrives earlier, causing snowmelt to occur earlier and condensing runoff earlier in the summer (Perera et al., 2012). The increase in flood risk arises from large populations living in the modelled inundation areas. As freshwater and climate are intrinsically linked, a change in one inevitably leads to a change in the other. The relationship between freshwater resources and the changing climate today has serious implications not only for human beings, but for all living species (Bates, Kundzewicz, Wu, & Palutikof, 2008).

River floodplains have attracted human settlement throughout the world for thousands of years as they are near a water supply, offer fertile soil for agriculture, and tend to be flat which is desirable for infrastructure and housing development (DHI, 2011). Floodplains are inherently created by floods – an ongoing process. Millions of people are affected by floods on an annual basis, with ensuing costs in the billions of dollars (DHI, 2011). A recent study found that floods have killed more than 500,000 people and displaced over 650,000,000 people worldwide over the past thirty years (Kocornik-Mina, McDermott, Michaels, & Rauch, 2015).

Warming over the past few decades has resulted in a number of changes to the hydrological cycle which include: “increasing atmospheric water vapour content; changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff” (Bates et al., 2008:3). As a general trend in the 20<sup>th</sup> century, precipitation increased in high northern latitudes, as did the frequency of heavy precipitation events (Bates et al., 2008). This is different from areas 10°S to 30°N where precipitation decreased (Bates et al., 2008). This is compounded by very dry land areas more than doubling around the globe since the 1970s (Bates et al., 2008). Climate change is expected to result in a decrease in streamflows in the South Saskatchewan River basin, which includes the Bow River Sub-basin (Grinder, 2010). The apparent reduction in water storage in mountain glaciers and snow cover is another factor, in turn affecting the quantity and timing of runoff in glacier and snowmelt-fed rivers such as the Bow (Bates et al., 2008). The melting of glaciers and subsequent decline in their contribution to streamflow raises concerns around the sustainability of flows in the late summer and fall (Grinder, 2010).

Climate models project a continued increase in precipitation for high latitudes, as with average river runoff (Bates et al., 2008). This equates to higher risk of flooding and higher risk of droughts; in other words —more frequent extreme events. The decline of water supplies stored in glaciers and mountain snow cover is a serious concern, not only for those relying on the Bow River for their water supply, but also for one-sixth of the world's population, all of whom rely on melt water from major mountain ranges (Bates et al., 2008). These changing extremes resulting in more floods will likely exacerbate water pollution, food insecurity, and unstable water infrastructure (e.g. hydropower, flood defenses, irrigation systems etc.). Climate change is not the only major factor currently affecting freshwater systems. Population growth, land-use changes, urbanization and burgeoning economic activities are also at play. Globally, we require more and more water to sustain our irrigation systems and our growing population. Climate change will only aggravate these existing pressures.

The current state of the Bow watershed was recently assessed by World Wildlife Fund Canada (WWF, 2016). The threats to the watershed were found to be very high due to the overuse of its waters, pollution from agricultural practices and potential for pipeline incidents, leading to a poor score for its overall watershed health. At the same time, water quality was deemed to be fair and fish health good (WWF, 2016). Predicted changes in climate may increase the risks of droughts and flooding (Macgregor, 2015).

Floods inevitably occur, whether it be due to a large storm with heavy precipitation or rapid snowmelt; with climate change, meteorological inputs such as precipitation and temperature are becoming more variable and unpredictable. Combined with population growth leading to increased urbanization and water infrastructure, freshwater systems are becoming more and more stressed. The overarching conclusion is clear; there will be more floods, and in some cases with increased severity in the future, and therefore this elevates the importance of mitigation.

## 2.10 Forests and Floods

One possible mitigating factor to floods is forest cover. Forests act as natural barriers to floods by reducing erosion as a result of the mechanical reinforcement of the

soil by tree roots, the buildup of an organic layer on the forest floor and the reduction of soil pore water pressure caused by forest evaporation (Maidment, 1992). Trees have the capacity to intercept rainfall, evaporate moisture and enable more complete infiltration and absorption of water into the soils; once trees are removed, runoff typically increases (Bradshaw et al., 2007; C. Clark, 1987).

An understanding of the relationship between forest cover and flooding continues to evolve. Many existing studies attempt to uncover the possible effect of deforestation rather than forest infill on the flood regime of a watershed. This has led to post-disturbance (logging) watershed hydrology studies, most of which use chronological pairing (CP) (Beschta, Pyles, Skaugset, & Surfleet, 2000; Caissie, Jolicoeur, Bouchard, & Poncet, 2002; Cheng, 1989; Guillemette, Plamondon, Prévost, & Lévesque, 2005; Harr & McCorison, 1979; Harr, Harper, Krygier, & Hsieh, 1975; Hornbeck, 1973; Lynch, Sopper, & Partridge, 1972; Moore & Scott, 2005; Moore & Wondzell, 2005; Reinhart, Eschner, & Trimble, 1963; Riekerk, 1989; Robinson et al., 2003; Rothacher, 1965; Rothacher & Rothacher, 1973; Stednick, 2008b; 2008a; Swank, Vose, & Elliott, 2001; Thomas & Megahan, 1998; Troendle, Wilcox, Bevenger, & Porth, 2001; Wright, Sendek, Rice, & Thomas, 1990; Ziemer, 1981) – a technique that compares significant changes in stream flow between two watersheds with similar physical, geomorphologic and floristic properties, and which are subject to the same meteorological forcings. Typically, one watershed is maintained as a control while the other undergoes forest harvesting (Brantley, Miniati, Elliott, Laseter, & Vose, 2014). This method has been demonstrated to have important methodological shortcomings that have, until recently, been overlooked in the forest hydrology literature (Alila & Green, 2014a; 2014b; Alila, Kuras, Schnorbus, & Hudson, 2009; Bunnell, Kremsater, & Houde, 2011; Stahli et al., 2011). One of the major problems with the CP technique is that it does not properly control for the combined effects of storm input and antecedent soil moisture conditions on floods, and therefore does not fully isolate the effect of forest harvesting on stream flow. Therefore, CP stems from an uncontrolled experimental design which results in erroneous CP estimations of changes in magnitude of stream flow, usually an under-estimation (Alila et al., 2009; Alila & Green, 2014a; 2014b).

This problem has been overcome recently by pairing pre- and post-harvest flows by equal frequency (as opposed to equal storm input) thereby controlling for both the storm input and antecedent soil moisture conditions – a method referred to as frequency pairing (FP) (Brantley et al., 2014; Green & Alila, 2012a). FP uses a series of annual peak flows in the same watershed over a decade or more and adjusts for hydrologic recovery once trees have been removed to determine how often a flood of a given size recurs; this creates a frequency curve that takes into account both the magnitude and frequency of occurrence (Allen & Ingram, 2002; USDA Forest Service, 2010). Although the FP method is relatively new to forest hydrology studies, it is well-established in the broader field of hydrology, climatology, and engineering (Bonsal, Zhang, Vincent, Hogg, & Hogg, 2001; Booth, 1990; McCuen, 1998). FP analyses have found an increase in peak flows as a result of deforestation in all recurrence intervals, from small to large flows with long recurrence intervals (Alila et al., 2009; USDA Forest Service, 2010). In other words, deforestation consistently leads to more floods, both big and small, and the effect of deforestation affects flood regimes over long periods of time (Green & Alila, 2012a).

CP-based studies have dominated the literature for over a century and the prevalent consensus from such a body of literature is that the forest cover is not affecting events larger than the 2 to 10-year flood events (Bathurst et al., 2011; Beschta et al., 2000; Calder, 2005; Thomas & Megahan, 2001). In contrast, older and more recent studies that have used FP show how forest removal can increase the magnitude across a much wider range of return periods (Birkinshaw, Bathurst, Iroumé, & Palacios, 2011; Brath, Montanari, & Moretti, 2006; Reynard, Prudhomme, & Crooks, 2001; Svoboda, 1991). In all these studies, such increase in absolute terms is larger as the event size increases and the larger the flood the more frequent it becomes with no apparent threshold beyond which forests have no effects, at least not before the 50 and 100-year return period flood events.

There have also been studies that have examined the effects of deforestation from fire rather than harvesting on flood regimes. Some studies found the consequence of fire to be increased runoff as well as an increase in flood frequency (Brown, 1972; Candela & Aronica, 2003; Lavabre, Torres, & Cernesson, 1993; Scott, 1993). This

could be due to the increased hydrophobicity (Soto & Diaz-Fierros 1998) or the reduction in rainfall interception and transpiration as a result of the elimination of vegetation (De Bano 2000, Scott 1993). Not all studies found such results however; Arnica et al. (2002) found a lower peak discharge for post-fire conditions, particularly in larger burnt areas. Yet, when Candela (2003) studied the same watershed a year later using a different methodology and incorporating the antecedent soil moisture conditions, they found an increase in the average runoff following fire. Suffice to say that each river basin is unique in its area, annual rainfall, soil type and land use, and therefore may likely respond differently. Furthermore, the watershed's response is different depending on elapsed time since the fire, with some having found that the effects are greater in the year following a fire than in subsequent years (Scott & Van Wye 1990, Scott 1997, De Bano 2000).

It appears that no experiments using the CP or the FP method have been undertaken in the study area. Nonetheless, alpine areas dominate in these watersheds, with the major source of water flows contributing to flood events coming from high elevation rock and scree. Approximately 60% of the total flow of the Bow river originates in the mountains, which comprise roughly 20% of the drainage basin (Armstrong et al., 2009; Grinder, 2010). The portion of scree and rock represents an element of the watershed that has not changed over time and cannot be manipulated. What has changed is the vegetation cover and anthropogenic development, both of which are measured in detail in this thesis.

## 2.11 Conservation, Restoration & Novel Ecosystems

In many parts of the world today, traditional approaches to preservation, conservation, and restoration are buffeted by rapid changes such as species invasions, climate change, and other environmental and ecological processes. These are the practices that are in play for long-term intervention in my study area. Where damage has occurred, restoration is appropriate. Extensive preservation and conservation actions have already been taken. Yet, the overlapping dynamics of change constitute an emerging ecological novelty.

Global CPR (Conservation, Preservation and Restoration) (Brower, 1994) is inherently challenging in a world where change is simply a reality of life. Gómez-Rompa and Kaus (1992) stated that, “as concerned members of this industrialized civilization, we have recognized that humanity is an integral part of the biosphere, at once the transformer and the self-appointed protector of the world” (Gómez-Pompa & Kaus, 1992: 271). Over the past thirty years, ecological restoration has arisen around the globe in response to the widespread practice of unsustainable activities leading to the damage and degradation of ecosystems. Unlike conservation which, at its roots, is about the rational use of natural resources, or preservation which concerns the maintenance of the planet’s biodiversity (Brower, 1994), the purpose of ecological restoration is to repair and reverse the damaging effects that have been incurred on ecosystems while also improving human well-being (Society for Ecological Restoration International Science & Policy Working Group, 2004).

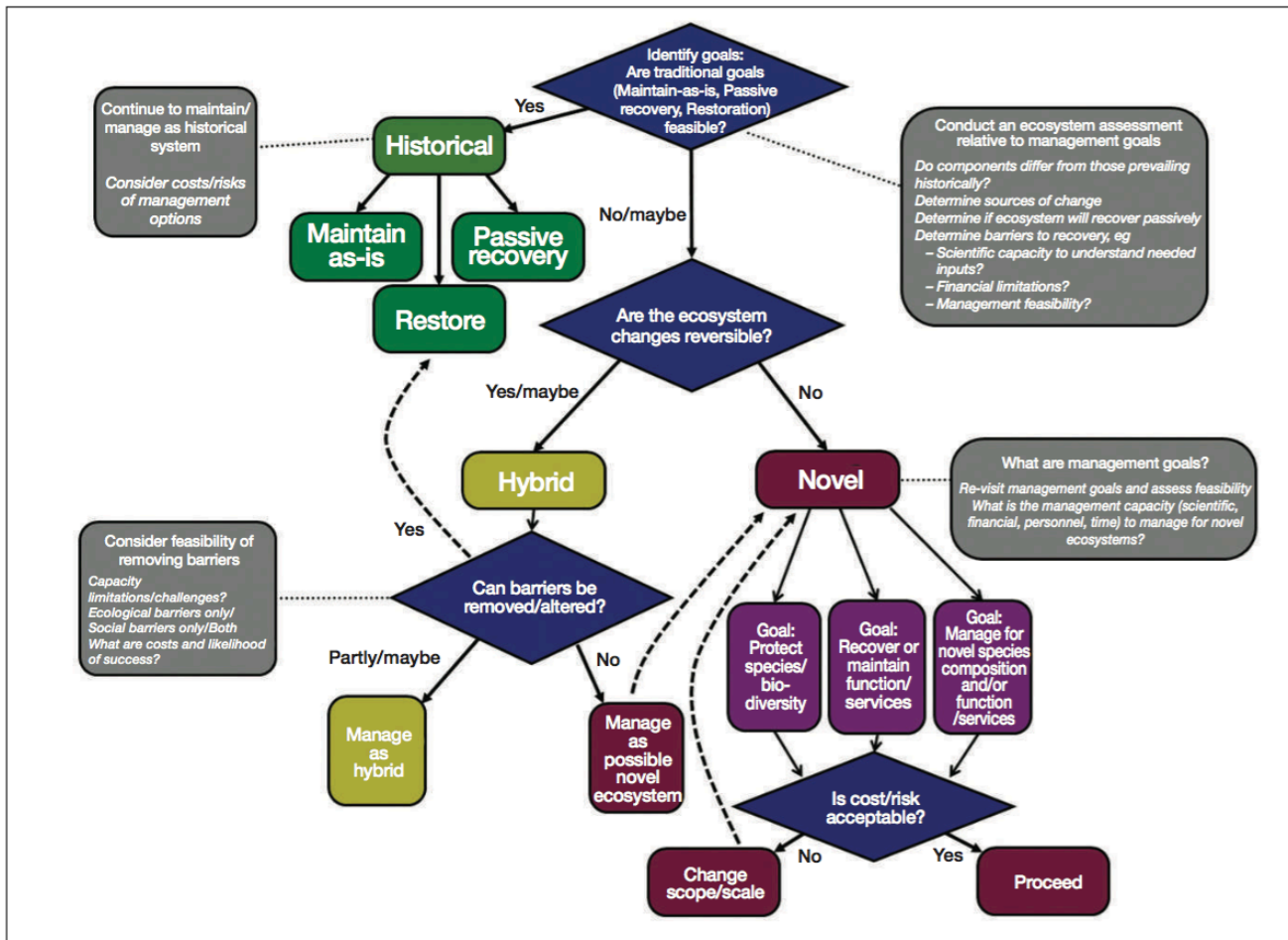
Ecological restoration has traditionally aimed to recover a given ecosystem to its historical trajectory. It is further based on the premise of achieving ecological integrity, that is to say maintaining the condition that is deemed to be characteristic to a given region, both in terms of ecosystem function and composition (Government of Canada, 2000). In the last decade, restoration is increasingly conducted with the understanding that ecosystems are dynamic, and therefore should aim for resilience and self-sustenance (Parks Canada and the Canadian Parks Council, 2008). Restoration design should be multi-dimensional, taking into account the ecological, social, cultural, spiritual and economic context (Parks Canada and the Canadian Parks Council, 2008). Parks Canada and the Canadian Parks Council have suggested three guiding principles for ecological restoration; (1) effective in restoring ecological integrity; (2) efficient in its use of financial resources; and (3) engaging for people and communities (Parks Canada and the Canadian Parks Council, 2008). One thing is clear: ecological restoration helps redress the crisis of biodiversity loss, which has been noted as one of the most critical environmental crises of our time (Rockström, Steffen, Noone, & Persson, 2009). Biodiversity loss has now been internalized as one of nine key planetary boundaries (Steffen et al., 2015), while a new planetary boundary titled “novel entities” has been added.

Novel ecosystems have been defined as, “systems that differ in composition and/or function from present and past systems as a consequence of changing species distributions, environmental alteration through climate and land use change and shifting values about nature and ecosystems” (Hobbs, Higgs, & Hall, 2013b). Novel ecosystems are becoming more and more prominent around the world and have become an important consideration in ecological restoration.

As people have impacted a large proportion of terrestrial and aquatic marine ecosystems, whether directly or indirectly, and as abiotic conditions are shifting rapidly across the globe as a result of climate change, some argue that every ecosystem is novel (Mascaro, Harris, Lach, & Thompson, 2013). For instance, even the most remote ecosystems that have not been directly impacted by human presence are being affected by climate change (Walther et al., 2002). However, this generalization is too broad to be helpful (Mascaro et al., 2013). The key in distinguishing novel ecosystems is in human agency; novel ecosystems are not actively managed. Historical ecosystems can become novel when they are subjected to species invasions, whilst formerly heavily managed sites such as agricultural lands can become novel when they are abandoned (Mascaro et al., 2013). To this effect, Mascaro et al. explain, “humans do not prescribe the abiotic and biotic characteristics of novel ecosystems as they do in agricultural fields, for example. Rather, novel ecosystems are the response of the biosphere to human influence” (Mascaro et al., 2013: 49). Finally, novel ecosystems arise when they pass a certain threshold where restoration to the historical system is no longer possible, distinguishing them from hybrid ecosystems which have elements of novelty but can still be restored to their historical state (Hallett et al., 2013). It has been estimated that at least 36% of the globe is covered today with novel ecosystems (Perring & Ellis, 2013).

The question of what should be the target ecosystem state and trajectory arises (Hulvey et al., 2013, Hobbs, Higgs, & Hall, 2013b). Traditional ecological restoration approaches which sought to remove invasive species as well as any disturbances that led to ecosystem degradation are no longer feasible or necessarily appropriate when managing novel ecosystems, as such systems cannot be restored to pre-disturbance conditions (Hulvey et al., 2013). Restoration to a near historic state may be desirable for intrinsic values, but be in direct competition with the desire to restore for the current

provision of goods and services (Hulvey et al., 2013). It thus becomes of focusing on target species or biodiversity, restoring or maintaining function or service, or managing for new species compositions or functions (Hulvey et al., 2013). Hobbs et al. (2014) have delved into this further by presenting a tool/decision-making flowchart to help managers weigh their options (Figure 2-12) (Hobbs, Higgs, Hall, Bridgewater, et al., 2014b). The discussion in Chapter 4 relates directly to these challenges.

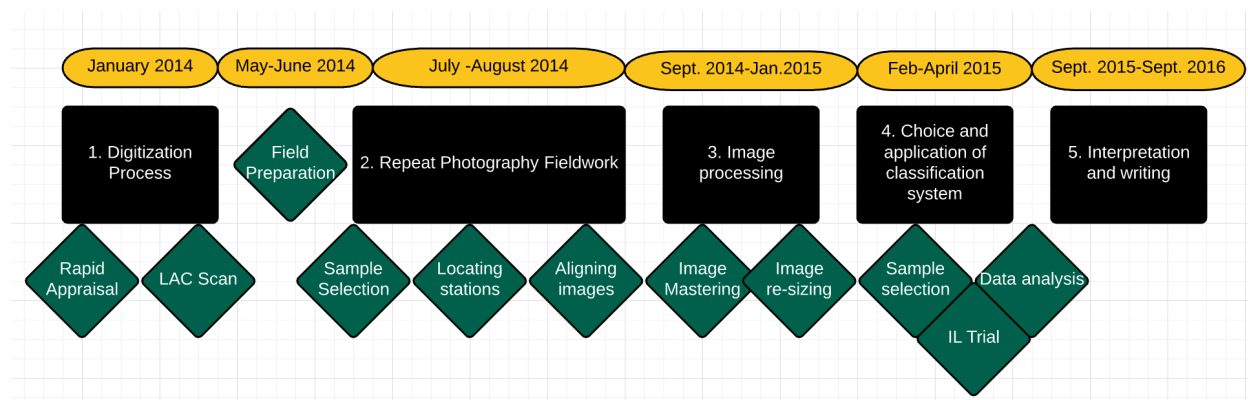


**Figure 2-12.** Decision-making framework for ecosystem intervention. Source: (Hobbs, Higgs, Hall, Bridgewater, et al., 2014b) Presents key questions to consider when embarking on restoration of ecosystems, based on whether the ecosystem is in a historical, hybrid or novel state.

# Chapter 3 – Methodology

## 3.1 Introduction

This chapter begins with a general overview of repeat photography followed by the four key elements that comprise the techniques used to obtain and compare landscape images: (1) digitization process (2) repeat photography fieldwork (3) image processing and (4) choice and application of a classification system. Figure 3-1 shows the key milestones for the study. The chapter concludes with an overview of the limitations of the study.



**Figure 3-1. Key milestones for the study.** The timeframe is depicted in the top row in yellow. The five key elements that comprise the research program are numbered in the four black boxes. The more detailed steps are represented in the green diamonds associated with each element and matching the chronology presented at the top. LAC refers to Library and Archives Canada. IL Trial refers to the Image Labeler trial.

## 3.2 Repeat Photography

Repeat photography is the practice of taking photographs at different points in time from the same physical vantage point. In this study spanning 130 years, repeat photography leads to oblique photo pairs (historic and repeat) or triplets (historic and two repeats). Systematic repeat photography leads to the creation of long-term image datasets that capture change over time (Trant et al., 2015). This allows an exploration of both natural and human-produced impacts on ecosystems and landscapes. For

example, the comparison of image pairs can reveal how climatic variations, land use practices and disturbances can shape landscapes (Webb, 2010). An additional benefit is that photographs communicate changes that are easily understood to diverse audiences. This means the images have significant educational as well as management and research value. Oblique images offer a “human-eye” view of landscapes in contrast to the overhead or aerial image perspective from aerial photography or satellite imagery. In this thesis I focus primarily on the research value of the images to show the extent and significance of ecosystem and landscape change.

Repeat photography was first used as a scientific method in the field of glaciology, when images were used to demonstrate glacial retreat (Webb, 2010). This method continues to be instrumental to glaciology today (Byers, 2007; Schmidt & Nüsser, 2009). Repeat photography has since been used in a wide array of fields, from urban planning to mountain studies (Byers, 2007), environmental studies (Falk, 2014; Hentati-Sundberg & Olsson, 2016; Nyssen et al., 2009; Sanseverino, Whitney, & Higgs, n.d.) and anthropology (Smith, 2007; 2014). Historians and archivists, such as those at Library and Archives Canada (LAC), are familiar with this method to capture change. Archivists have long been interested in acquiring historical photographs due to their cultural and symbolic importance, yet their scientific utility when combined with modern repeats was previously overlooked (Delaney, 2008). This changed through the partnership between MLP and LAC; the glass plate collection of mountain photographs now comprises one of LAC’s most significant collections (Delaney, 2008).

### 3.3 Digitization Process

Prior to conducting fieldwork, historical glass plate photographic negatives held in special facilities at LAC’s Gatineau Preservation Facility (Gatineau, Québec) were identified for digitization. The size of the collections at LAC (>70,000 mountain survey photographic negatives) and the relative difficulty of examining these fragile images make working with them a painstaking process. At present, except for about 10% of the collection, photographic negatives are known only at the survey level and not by individual plates. In January 2014, a team comprising Eric Higgs (School of

Environmental Studies, University of Victoria), Rob Watt (retired, Parks Canada), Rick Arthur (retired, Alberta Agriculture and Forestry), Mary Sanseverino (Computer Science, University of Victoria) and the author travelled to Gatineau, Québec to undertake an assessment of collections pertaining to a number of research and management priorities.



**Figure 3-2. Rapid appraisal at Library and Archives Canada.** (Left to right) Rick Arthur, Rob Watt, Jeanine Rhemtulla and Tanya Taggart-Hodge, January 2014 [Eric Higgs].

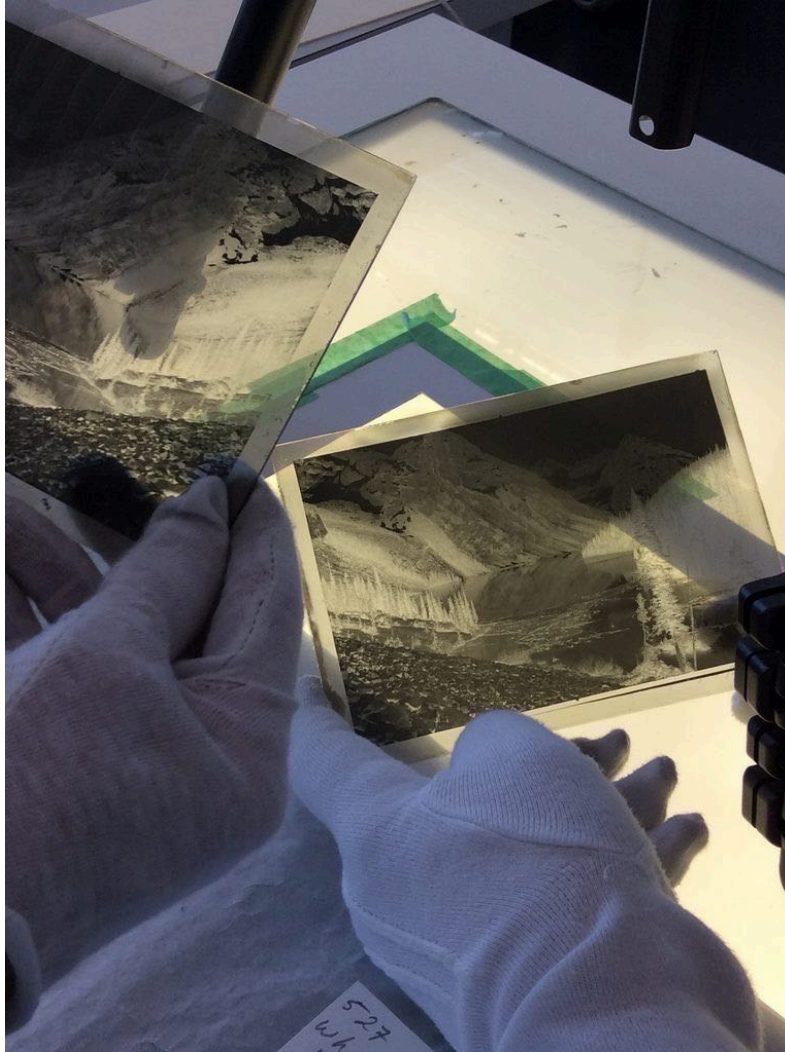
With collaboration from LAC archivists Jill Delaney and Kayley Kimball a rapid appraisal method for assessing a large number of glass plate negatives was developed. Up until the development of the rapid appraisal technique, only high resolution scanning was used; often, images were scanned to gain a sample of where they might be. The objective was to reduce the cost to the sponsor so that images outside of the areas of interest were not scanned. The rapid appraisal technique consists of a group of researchers manually going through survey boxes of glass plates in order to record the

content of each box in excel spreadsheets, photograph the plates on site, and select specific stations or areas of interest for detailed scanning once the photographs have been reviewed and located. This represents a much more cost effective method than ordering an entire box to be scanned without knowing the geographical coverage of its imagery.

In January 2014, over the course of five days, and working with two digital camera systems, we examined and photographed more than 2,000 negatives (Figure 3-2 & 3-3). Following the LAC trip, the copy photographs were sorted by survey, inverted digitally (using Photoshop 5) to produce a positive image, and then located spatially using google earth and expert knowledge (Rob Watt, Rick Arthur & Mary Sanseverino), a process which took several months. Select glass plate negatives were scanned at 1,800 pixels per inch and 16-bit grayscale using Library and Archive Canada's Epson 10000 XL flatbed scanner with sufficient dynamic range to capture most if not all of the image data from the glass plates. This was the starting point for a series of digital transformations: cropping the black border to show only the image; some contrast adjustments to maximize their characteristics for field use, and rotation to "level" the image. The resulting image became a "master" image, and served as the base for all subsequent uses (e.g., applying a grid to the image to make field location easier). The scanned images were saved as .tiff files. Although the specific images scanned as a result of the 2014 LAC trip were not used directly in this study, high resolution historical images previously digitized following this same process were used as the basis for this study.

### 3.4 Fieldwork

In order to acquire third view imagery to complete the existing photo pairs and use the triplet to assess land cover changes following the 2013 flood, repeat photography was conducted in July and August of 2014 in the study area described in Chapter 2, and its key components are described below.



**Figure 3-3. Examination of glass plates at Library and Archives Canada. January 2014**  
[Mary Sanseverino]

### 3.4.1 Definition of a Photographic Station and Location

The promontories (mountain tops, ridges) in the landscape where historical surveyors captured their photographs are referred to as *stations* (e.g. Figure 3-4); within each station there are distinct *locations* based on where the historic survey camera was positioned for the best vantage point, and each location may have several images (Chris Gat, 2013).



**Figure 3-4. Location photo taken in 2014 at Miller 1928 Station 9.** Rick Arthur is captured sitting next to a historical cairn [Vladka Lackova-Gat].

### 3.4.2 Selection Criteria

This study was restricted to those stations located within the study area whose boundaries are contained within the Bow watershed. The Elbow drainage basin is comprised within the Bow watershed. Stations were drawn from surveys conducted by McArthur (1888-90), Wheeler (1895-99; 1913-14) and Dowling (1905), creating a time interval of 93-121 years for the repeat images. The process of selecting 32 stations (totalling 148 images) was undertaken following six criteria: (1) presence of (at least) one image pair that can be mastered; (2) human-eye high elevation view; (3) absence

of objects in the foreground; (4) unique azimuth and coverage; (5) image quality and (6) presence of vegetation. The limitations incurred from my sample are discussed in Section 3.8 of this chapter.

(1) Many stations are tentatively demarcated on the Mountain Legacy Project Editing and Administration Tool (MEAT)'s map, yet they contain only historical images that have not yet been repeated. The first criterion is thus to ensure that selected stations contain appropriate image pairs, including a historical image with its associated repeat. Not only must there be an image pair, but it must also be mastered. Alternate images were included in the analysis only if they were mastered with enough confidence in the precision of the overlay.

(2) The sample was further narrowed by the application of a second selection criterion: human-eye, high-elevation view. Only those image pairs from promontories (higher elevation stations) were selected to be analyzed to ensure the comparison of images with similar perspective distortion.

(3) Only those images which did not contain objects in the foreground (e.g. trees, rocks) were selected as part of the sample. The land cover classification process is based on a net pixel count. Including images with foreground would have skewed the pixel count because objects in the foreground contain many more pixels than those in the background.

(4) Independent image pairs were selected, each with a distinct azimuth, from each station, thereby covering separate parts of the landscape. Each station can have between 1 and 15 image pairs; this is because historical surveyors often completed a full panorama (360 degrees) from each station.

(5) A number of historical images have significant vignetting (reduction in the image's brightness at the periphery compared to the centre) and/or the quality of the image has deteriorated due to flaking, fading or staining. Such images were not selected.

(6) Image pairs which only captured mostly high elevation mountain tops and rock were not favoured as the focus of this study is on forest cover and fluvial changes rather than geological changes.

### 3.4.3 Sample Selection

The application of the selection criteria resulted in a final sample of 148 images (Table 3-1), which have been divided into two categories: fluvial stations and regional stations. First, those stations which overlooked a portion of the Bow and Elbow rivers were selected to study fluvial changes (Table A-1 and A-2). These fluvial stations served as the basis for my field work, as the aim was to conduct a third view for all of these existing photo pairs in order to create an image triplet. These image triplets would provide a before & after view of the river channels following the major 2013 flood event as well as the historical photographs.

Second, additional stations within the boundaries of the study area were selected to complement geographical coverage provided by the fluvial stations, thereby enabling a regional scan of land cover change for this area (Table A-3). In other words, the fluvial stations were concentrated in the Bow and Elbow valleys whereas the rest of the sample consisted of stations located on mountain tops throughout the rest of the study area. All of the repeat images (2008-10) used in this study were taken by other MLP field crews.

### 3.4.4 Gridding, locating stations & aligning images

Each image that was repeated was digitally layered with a grid prior to being printed for the field. This was done in Photoshop CS6 using a landscape grid action. The action file was saved, and then accessed via the actions panel (Figure 3-5).

**Table 3-1.** Dataset Summary

Area	# of images in database	# of images selected once the selection criteria were applied
Bow	54	39
Elbow	72	39
Regional Scan	164	70
Grand Total	290	148



**Figure 3-5. Landscape grid placed on a mastered image.** Gridding is done using Photoshop prior to printing the image and taking it into the field. The grid on the photograph approximates that found on the camera viewfinder, thereby enabling more precise alignment of the repeat.

All images were given a tentative GPS coordinate location in the lab, based on an estimate of its location using google earth. Once the images were gridded and printed, a helicopter was taken to conduct a reconnaissance flight to see whether the hypothesized GPS locations on paper were in fact correct. During these flights, I would sit at the door of the helicopter with the printed, gridded image in hand, and look at the landscape below to verify whether the site below was in fact the site where the image had been taken from. Once it was deemed the correct location, the helicopter would drop the team off and we would proceed to determine the exact location where the image was taken from. MLP teams have always strived to reach sub-metre accuracy when it comes to locating the spot where historical surveyors stood. The principle of parallax, which entails the alignment of objects in the foreground and background, and then moving the camera in three dimensions to match the alignment represented in the historic image, was used to locate the exact spot where the tripod of the historical surveyor was placed (Malde, 1973; Webb, 2010). A printed copy of the historic image with a grid was used to determine the height, camera tilt, and perspective (portrait or

landscape) as accurately as possible (Webb, 2010). The cross hairs are important to a successful repeat image; the grid used on the print-out matches closely the grid on the camera viewfinder, and therefore enables more precise alignment. An azimuth was recorded for each photograph captured.

It was not always possible to place the tripod on the original location because of impeding vegetation, rock falls, erosion, human disturbance or activity, or the presence of a historical cairn placed on the exact spot where the historical tripod would have been placed. In these cases, the tripod is placed as close as possible to the original location in an alternate location, and is noted as such in the field notes (e.g. Figure 3-6). In rare occasions, cairns are partially dismantled and rebuilt after the photography is completed. In some cases, where the entire station is covered in dense vegetation, the images were taken from the open door of a hovering helicopter. This resulted in the image being labelled as an 'alternate' in the database. If the alternate was within a metre accuracy, it could still be mastered.

Eighteen stations were visited as part of this research during the 2014 field season; eight in the Elbow and ten in the Bow. Five of these stations were not included in the analysis as they were lower elevation stations (e.g. taken on the side of a highway or a lake rather than on a mountaintop) and would have skewed the data. A total of 42 pairs were transformed into triplets as a result of this work. An additional 19 stations were selected to achieve the regional scan. A detailed breakdown of all stations visited in 2014 and/or used in this research can be found in Appendix A.

### 3.4.5 Field Location Accessibility

Although it was possible to reach mountain photographic stations on foot—after all, this was how the original photographic surveyors reached the stations—much of MLP's fieldwork is facilitated by helicopter support provided by the province of Alberta's Ministry of Agriculture and Forestry. This support was achieved by incorporating MLP work into the daily priorities of fire suppression and reconnaissance activities. Even with the help of a helicopter, it was not always possible to reach a station due to challenging winds, topographic features, and atmospheric conditions on mountain tops.

In such cases, the crew was dropped off at a nearby saddle or ridge, and hiked to the photographic station.



**Figure 3-6. Tripod placement at Stn. 532 (Chungo).** At times, the tripod must be placed on top of a cairn in order to achieve the perfect alignment; this example illustrates the capture of a repeat of Bridgland’s 1928 image. The station was visited during the 2014 field season, but is not part of the sample used in this study.

### 3.4.6 Weather and Haze

Weather is the most common factor impeding fieldwork, and includes high winds, extreme cold or hot temperatures, cloud formations, and electrical storms. Visibility can be affected by clouds, ground fog, forest fire smoke haze, and variable lighting conditions through the day (high contrast in the middle of the day versus long shadows in early mornings or late afternoons), and season (effective daytime light is limited the farther away from summer solstice) (Figure 3-7). For these reasons, photography takes

place ideally late morning to mid-afternoon as much as possible. As we do not shoot in the rain or fog, there are occasions when we had to return to a station on a different day if the weather did not cooperate. When it was unavoidable, some fieldwork was completed in the later hours of the afternoon, resulting in long shadows in the imagery.



**Figure 3-7. Fog at Mt. Burns.** (Left to right) Nicole Goodman and Vladimira Lackova [Rick Arthur].

The 2014 field season occurred in July and August, as stations were mostly clear of snow. On rare occasions, snow was present at higher elevations, such as Mt. Chester (Figure 3-8). This timing lined up with the historical surveys, which were generally conducted from June through September. In most cases, we are not aware of the exact dates of the historical images.

### 3.4.7 Photographic Equipment

Two cameras were used for the 2014 field season: a Hasselblad H3D-39 (39 megapixel) with a 35mm f/3.5 mm lens, and a Nikon D800E (36.3 megapixel) with a 28 mm f1.8 lens. Cameras were placed on a tripod and carefully levelled (Figure 3-9). The

wide angle lenses are ideal for this type of fieldwork as they provide roughly the same field of view as the historical survey images.



**Figure 3-8. Storm cell looming on Mt. Chester.** (Left to right) Mary Sanseverino and Vladimira Lackova [Tanya Taggart-Hodge].

### 3.4.8 Field Notes/Metadata

Field notes were taken at each station using the MLP template (Figure 3-10 & Figure 3-11). This template includes the date of visit, start and finish time, name of pilot, RW call sign, station and weather narrative, hiking party, field note author(s), keywords, identification numbers for the photo pairs, elevation, and GPS coordinate. A Kestrel weather instrument (Figure 3-9), compass, and GPS were also brought to each station. The Kestrel was used to measure the temperature, wet bulb, wind speed, gust speed, relative humidity and barometric pressure. All of these measurements were noted as complementary metadata for each station, even though they were not explicitly analyzed as part of this study.



**Figure 3-9. Camera levelling and kestrel measurements at Prairie Creek.** (Left to right) Vladimira Lackova and Tanya Taggart-Hodge [Rick Arthur].

### 3.4.9 Safety Measures

Safety is paramount when working in high-risk mountain environments. An extensive wilderness first aid kit including a small tarp and bear spray were carried at all times. We also had extra thermal layers, gloves, hats, sunscreen, water and food. We remained in regular communication with Alberta wildfire control dispatchers through VHF radio communication. A Delorme InReach SE satellite-based emergency communications and beacon device was carried as a backup. For safety reasons, we did not work alone in the field, instead typically working in teams of two or three. The terrain was sometimes treacherous (Figure 3-12), weather unpredictable, and process lengthy, therefore we consistently relied on each other for support. The importance of

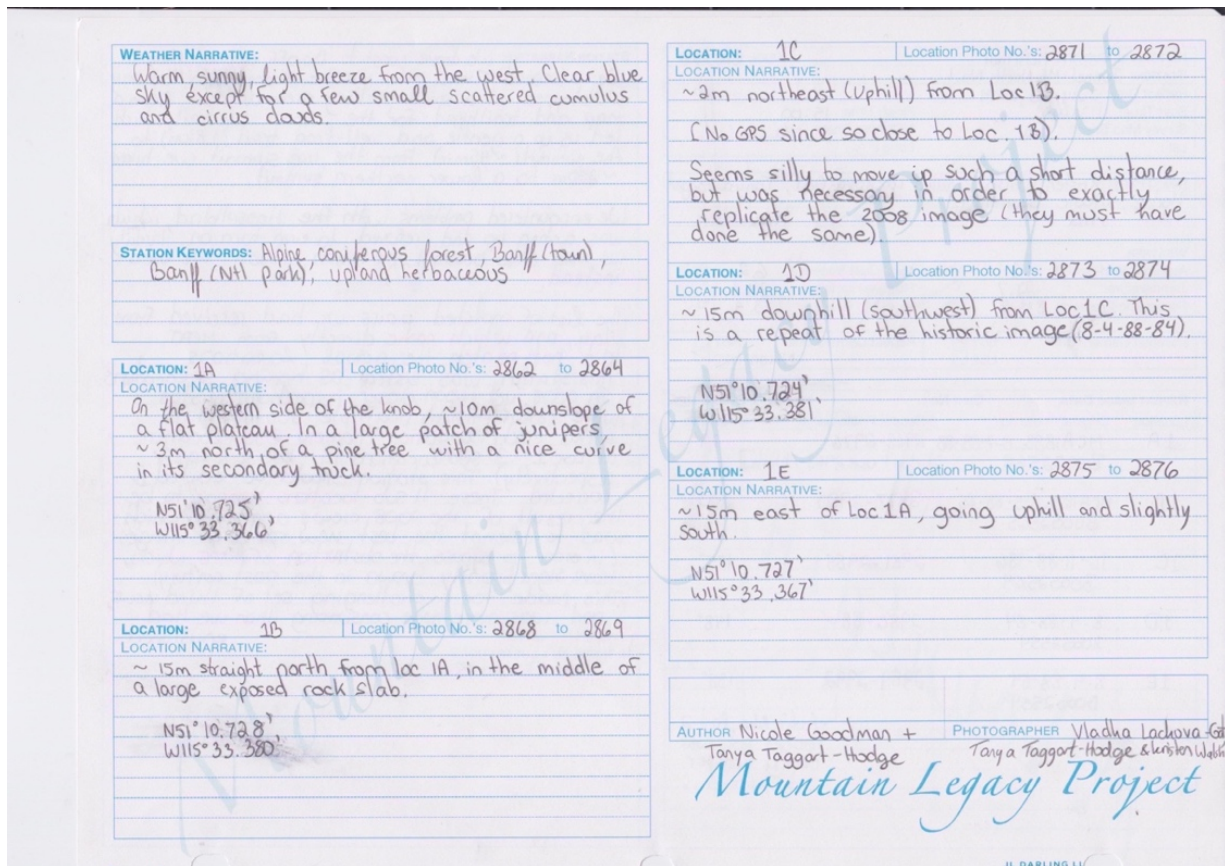
having strong communication and leadership skills is always stressed when working in extreme environments.

HISTORICAL SURVEY: McArthur		YEAR: 1888, 2008	
STATION: Tunnel Mt North No. 1			
Repeat Date: July 23, 2014			
Start Time: 11:30 AM	Finish Time: 15:00		
Survey Map Sheet: n/a	NTS Map Sheet: n/a		
Lat.:	Long.:		
Hiking Party: Kristen Walsh, Vladka Lackova-Gat, Tanya Taggart-Hodge, Nicole Goodman.			
Pilot: n/a	R.W. Call Sign: n/a		
WEATHER			
Average Wind Speed: 2.1 Km/h	Max. Gust Speed: 6.2 Km/h		
Temperature: 22.7 °C	Relative Humidity: 39.6 %		
Barometric Pressure: 833.8 hPa	Wet Bulb Reading: 13.4 °C		
Location Camera Unit: LC1 <input checked="" type="checkbox"/>	Repeat Camera Unit: HB1 <input type="checkbox"/>		
LC2 <input type="checkbox"/>	Nikon HB2 <input checked="" type="checkbox"/>		
REPEAT IMAGE DATA			
Card No.:		Internal GPS Active <input checked="" type="checkbox"/>	
Location	Original Photo no.	Repeat Photo no.	Azimuth:
1A	MCA1888-8-7-88-88 B0002568	2968-2976 [don't use 2968-71, too low]	24°
1B	MCA1888-8-5-88-85 B0002565	2977-2980	200°
1C	16-11-88-186 B0002564	2981-2985	175°
1D	8-4-88-84 B0002554	2986-88	148°
1E	8-4-88-84 B0002554	2989-2992	138°
			looks like last 2 images got lost during transfer onto laptop...
STATION NARRATIVE: We drove west to Banff along Hwy 1. We accessed Tunnel Mt via the Tunnel Mt Parkway. We stopped at a small parking area across from a map and trailhead for the Tunnel Mt trail which led us up a gentle and well-trod trail (1.8km) to the summit (~45min). From the true summit we hiked ~350m to a lower, northern summit.			
We encountered problems with the Hasselblad, which was acting up and refused to even turn on. Luckily we had also brought the Nikon, which we used instead.			
The list of matched pairs we had received from Ray, and which came directly from MEAT, did not match the actual locations. This station was listed as having 3 locations in 2008, yet upon closer inspection photos were taken from multiple sub-locations within each location (namely 5 sub-locations at loc 1, 3 sub-locations at loc 2 & loc 3 respectively). This station should be edited & corrected. These 11 sub-locations appear to be the result of the 2008 crew's approach, which was to attempt the best, new for each image (in order to bypass the obstruction of trees, which have significantly grown in the past century). This made for a challenging set of third years, and was more time consuming than we had envisioned.			
IS THERE AN ILLUSTRATION?			
YES: <input type="checkbox"/>			NO: <input checked="" type="checkbox"/>

Figure 3-10. Field Notes taken at Tunnel Mt North in July 2014 (page 1)

### 3.4.10 Effective Crew

The core 2014 field crew consisted of Kristen Walsh, Nicole Goodman, Vladimira Lackova, and myself (Appendix B). Mary Sanseverino, Eric Higgs, Rick Arthur, Rob Watt and Brent Davis also joined us at different times during the field season, and Rick Arthur provided support and liaison with Alberta Agriculture and Forestry throughout. Field teams ranged from two to eight, although working in pairs was most common.



**Figure 3-11.** Field Notes taken at Tunnel Mt North in July 2014 (page 2)

Repeat photography is most efficient when undertaken as a team endeavour; having two or more sets of eyes to determine the tripod location and to subsequently verify the alignment is stronger than one. Each person brings a different strength to the process.

For example, some team members were strong at locating stations from the helicopter during reconnaissance flights, whereas others were better at finding the exact location on the ground. We capitalized on each other's strengths, but also took turns with each role. All four of us were therefore comfortable with locating stations, taking notes, taking the photographs and collecting the metadata. One crew member would generally hold the gridded image next to the other crew member with the camera in order to enable easier alignment (Figure 3-13). The photographer of that station would align the camera first, and then invite another crew member (generally the note-taker) to verify the alignment prior to taking photos. This process could be repeated numerous times before both team members agreed on the exact alignment. It should be noted that

the 2007, 2008, 2009 and 2010 MLP field crews all contributed to this research. Some of their images were used as part of the analysis in my project.



**Figure 3-12. Steep terrain on Mt. Lady MacDonald.** Kristen Walsh and Vladimira Lackova carefully negotiate the ridge [Brent Davis].

### 3.5 Image processing

Upon completion of the fieldwork, images were processed before they could be analyzed. All images were downloaded onto MLP field laptops as well as two external hard drives every night following the day's work. Images were then processed in Adobe Lightroom 5 by enabling profile corrections. This lens correction tool adjusts distortion, chromatic aberration, vignetting and perspective correction (Mansurov, 2013a). This correction reduced distortion, thereby enabling a more accurate classification of land cover types.

There are two types of distortion in photography: optical (i.e. lens distortion or lens error) and perspective. When optical distortion occurs, physically straight lines are

deformed and appear curved in images (Mansurov, 2013b); every lens distorts the light entering it in some way; enabling profile corrections adjusts for this. Perspective distortion can be seen through objects in the foreground appearing larger than those in the background of the image.



**Figure 3-13. Camera alignment at Bridgland’s 1928 Stn.477.** Kristen Walsh and Tanya Taggart-Hodge discussing the camera alignment [Nicole Goodman].

Mansurov explains perspective distortion by saying that, “all lenses have the same perspective — it is the camera-to-subject distance that determines perspective, not the focal length” (Mansurov, 2013b).

Working with oblique angle terrestrial landscape photographs is challenging (Stockdale, Bozzini, Macdonald, & Higgs, 2015). It is only recently that the WSL Monoplotting tool has been developed as a means to extract spatially referenced vector data from such photographs and create a transformed aerial view from the oblique photograph (Stockdale et al., 2015). In contrast, my investigation focused on relative photograph area without attempting such rectification, that is to say I did not transform the oblique images onto a common image plane. A 2002 study conducted in Jasper National Park provided the rationale and justification for using relative photograph area

in oblique images as a reliable measurement (Rhemtulla et al., 2002). Specifically, Rhemtulla et al. (2002) assessed relative vegetation cover in 20 image pairs taken from 11 stations in 1997 and compared those results to those arising from the quantitative assessment of two sets of 1991 aerial photographs over the same area (64km<sup>2</sup>); they found results to be within 2% of each other for 11 of the 14 cover types, and between 2-6% accuracy for the other three cover types (Rhemtulla et al., 2002). Thus, classified oblique image data showing relative photograph area of land cover classes is a strong proxy for spatially-explicit analyses. More recently, repeat photography has been confirmed to be an effective methodology for analyzing past landscape change and processes (Cerney, 2010). Furthermore, Cerney (2010) points out that fluvial environments make for highly interesting repeat photography subjects.

Most importantly, the technique of repeat photography has been used frequently in the field of fluvial geomorphology (Butler, 1994; Cerney, 2010; Graf, 1978; 1979; Osterkamp, Hupp, & Schening, 1995; S. W. Trimble, 2009; Webb & Leake, 2006) and a summary of repeat photography studies looking at vegetation change, landscape-level change and human-induced change can be found in Cerney (2010).

Mastering involves identifying four common points (usually topographical features in the horizon line of the repeat image) in both images and subsequently cropping the repeat image in order to create an exact overlay of the historical image. This process was undertaken using the MEAT mastering tool, custom developed by Chris Gat, for all image pairs included in this study. The mastering procedure involves the selection of two corresponding images (e.g. a historic and its repeat) and aligning the repeat to match the historic. Four control points are selected in the repeat image, with the best results arising with points both in the foreground and horizon line, spread across the image. Once the tool is run, the alignment can be verified using a slider and the control points can be modified if required. Once proper alignment has been achieved, the user can confirm and save the newly aligned images. It involves scale, translation and rotation.

All images used in this analysis were mastered from high resolution digital scans (approximately 100MB each image) of historical glass plate negatives, and repeat images (120-160MB each image) taken with a medium format or medium-format

equivalent digital camera. Modern images are aligned, rotated, and oriented for height/width precision (in pixels) (Christopher Gat, Branzan Albu, German, & Higgs, 2011). Typically, the field of view is wider in modern day images, which entails mastering the repeat to the historical, never the reverse. Following the mastering process on MEAT, selected images were downloaded at a high resolution and subsequently re-formatted using Adobe Photoshop. Even though these image pairs were already mastered, and thus precise overlays, their pixel count was not identical at this point, often due to additional pixels in the sky of the repeat image. This problem was addressed by manually adjusting the height and width (in pixels) of each image pair using Adobe Photoshop in order to ensure they were homogenous across the entire dataset. This did not affect my analysis or my results because the pixels being cut during this adjustment were in the sky. This step is imperative, as the custom software used in this study to delineate pixels in different land cover types (Image Labeler) and subsequent calculation to measure changes in pixels from one classification category to another would be deemed useless if not comparing images which share the same total number of pixels. Having gone through this process, images were saved in a defined file structure.

### 3.6 Choice of classification system

Alberta Vegetation Inventory Interpretation Standards, including the Alberta Vegetation Inventory (AVI) primary classification were consulted as a guide for establishing the landscape classification categories used in this study. As the study area is located within Alberta's provincial lands, which are managed by Alberta Agriculture and Forestry as well as Alberta Parks, I sought to align with existing classification schemes in order to enable practical comparisons with other studies, as well as make my data accessible to those with decision-making power. The AVI system functions at a fine scale, using air photos with homogenous polygons as the smallest unit areas. In this scheme, the division first occurs between vegetated (>6% plant cover) and non-vegetated lands (<6% plant cover), then within these broader categories, between anthropogenic and natural land areas. Within these, there are

numerous sub-categories, progressively moving towards a finer scale. Sub-categories of 'anthropogenic' and 'natural land areas' include: industrial, settlement areas, agriculture, non-forest, forest, mineral and water. A detailed breakdown of the entire AVI classification can be found in the Alberta Vegetation Inventory Interpretation Standards document (Alberta Sustainable Resource Development, 2015).

The classification categories used in this study were a modified version of the AVI system. The modification was necessary because the AVI system's scale is too fine, but it provides a powerful foundation on which to work. For example, within the forest cover category, AVI distinguishes between crown closure, species composition, height and origin and timber productivity rating, all of which are 1) overly specific for the purpose of this study and 2) not always discernible in the image pairs. On the other hand, there are some categories in the AVI system which I was able to use directly without modification, such as "Industrial" and "Settlement Areas" (Table 3-2). Although there was originally an agriculture category, it was discarded due to its absence from the study area.

Thirteen classification categories were used for mapping fluvial station images (Table 3-2). The five fluvial categories (1 through 5) were then reduced to two categories ((14) riverine wetland and (15) lacustrine wetland) for regional station images, while all other categories remained the same (Table 4-2).

As the segmentation of fluvial images overlooking the Bow and Elbow required more detailed fluvial classes (water surface, bare exposed bar, vegetated bar, river island and floodplain), thirteen classification categories were deemed necessary (Table 3-2). On the other hand, the classification of regional images was meant to complement the geographical coverage provided by the images overlooking the Bow and Elbow and was instead focused on vegetation cover. In these images, any water pixels were either included in *riverine wetland* if they were part of a river channel or *lacustrine wetland* if they comprised a lake. This resulted in a total of fifteen distinct classification categories used at different stages of the analysis. There were 26 image triplets in the fluvial segmentation, and 35 image pairs in the regional segmentation. As triplets contain pairs, this results in a total of 61 image pairs (historic-repeats), and an additional 26 third views, resulting in a grand total of 148 images in the dataset.

### 3.7 Application of classification system

Classification was accomplished using a pixel-based change detection technique by manually segmenting images using Image Labeler, a custom software tool developed at the University of Victoria (Jean et al., 2014; Jean, Branzan Albu, et al., 2015b). A lasso tool was used to delineate land cover types and code each pixel based on the classification categories. The image classification process was completed by myself and a trained research assistant, Guillaume Richards. It took an average of 2.5 hours to code all pixels in a given image using Image Labeler. This task was completed using an Intuos3 Wacom drawing Tablet (PTZ-930). Resulting from this process was a segmentation mask associated with each image (Figures 3-14, 3-15, & 3-16 and Appendix C). Each mask was then compared to that of its pair (historic mask - repeat mask), using a custom-designed change detection code also developed at the University of Victoria by Frederic Jean. The code in question was a python script that Frederic developed specifically to yield statistics from the image masks I manually segmented. Its function was to compare the same pixels in the historic and repeat photos (or third views) to determine the change in pixels. Running this software code resulted in the creation of a transition matrix saved in excel, demonstrating the change in pixel count from one category to another between historic and repeat images throughout the dataset (Jean et al., 2014; Jean, Albu, et al., 2015a). It enabled the calculation of the percent cover of each category in both historic and repeat images. The processing of the masks was completed by Frederic Jean, the creator of Image Labeler and a postdoctoral fellow in the Department of Electrical and Computer Engineering at the University of Victoria.

A specific order was followed for the segmentation process. A test trial comprising three stations was undertaken first in order to ensure the proper performance of Image Labeler and the subsequent software code. The segmentation of fluvial images was undertaken first, followed by that of regional images.

This led to a distinct transition matrix for each set — one comprising the results of the fluvial images, and one for those of the regional images. It also yielded individual transition matrices for each photo pair or triplet. Repeat images were classified first,

followed by their associated historic image. In the case of triplets, the third view was completed after the repeat but before the historic.

This study uses a comparison of contemporary colour photographs with historic black-and-white images. In the ideal, images of exact same quality and nature would be compared. Because of their quality and colour, the current colour images yield more detailed information in their segmentation than their historic, black-and-white counterparts. This then raises a question of how to best undertake comparative analysis working with pairs of current colour images with historic black and white images.

**Table 3-2. Classification system.** Vegetation, snow/ice, sand/gravel/rock and anthropogenic classes remained constant throughout the analysis. A more detailed fluvial classification was used for those images overlooking the Bow and Elbow rivers (categories 1 through 5), whereas all water pixels were either included in riverine or lacustrine wetland for the regional images.

Land Cover	Location	Categories
Fluvial	Bow & Elbow valley	1. Water surface 2. Bare exposed bar 3. Vegetated bar 4. Floodplain 5. River island
		6. Riverine wetland 7. Lacustrine wetland
Vegetation	Regional	8. Coniferous forest 9. Broadleaf/mixedwood 10. Regenerating areas 11. Grassland herbaceous
Snow/Ice	All	12. Snow/Ice
Sand/gravel/rock	All	13. Sand/gravel/rock
Anthropogenic	All	14. Industrial/recreational 15. Settlement areas

The option of stripping the colour from the modern images so pairs of black and white images were compared was considered. However, a test conducted by Hyeone Park on my behalf using four independent image pairs from the MLP database demonstrated that doing so introduced a significant error in the classification of two key areas: the broadleaf/mixedwood and grassland herbaceous areas.

In this trial, the results of the black-and-white to black-and-white classification were compared to those of the black-and-white to colour classification. The error margin was minimal for all land cover categories except for the two mentioned above. A classification error of 94.2% for broadleaf/mixedwood forests and 34.1% for grassland herbaceous areas was identified when only using the black-and-white to black-and-white comparison. This means broadleaf/mixedwood forests were misclassified 94.2% of the time and grassland herbaceous areas 34.1% of the time when conducting black-and-white to black-and-white classification. Because of these margins of error, I chose to proceed with the black-and-white to colour comparison.

**Table 3-3.** Definitions of Classification Categories

	<b>Classification Category</b>	<b>Definition</b>
1	Water surface	Visible water - part of active channel
2	Bare exposed bar	Unvegetated bar area subject to frequent inundation but perhaps exposed if photos taken at low flow; part of the active channel, Inundated for significant period each year
3	Vegetated bar	Has annual or low perennial shrubs: subject to inundation, perhaps annually, but not for so long as to inhibit growth: possibly transiting to floodplain by sediment entrapment -- part of channel zone  Inundated annually for short period or at least within 2-3 years
4	River Island	Island formations within the river channel that are covered in mature vegetation (not part of channel zone as they are no longer flooded)

		Shrubby vegetation (Willow, Salix, Cottonwood) and/or coniferous forest.
5	Floodplain	Located below terraces but above the channel zone. Shrubby vegetation (Willow, Salix, Cottonwood) and/or coniferous forest.
6	Coniferous Forest	Mature stands of conifers
7	Regenerating Area	Young stands and/or recent fire and/or logged area
8	Broadleaf/mixedwood	All deciduous trees
9	Grassland Herbaceous	Meadows, grassy and shrubby areas at higher elevations
10	Sand/gravel/rock	Non-vegetated land areas beyond channel zone (rock barren, sand, cutbank, weathered rock)
11	Ice/snow	High altitude permanent ice/snow
12	Industrial/recreation	Gravel pits, surface mines, geophysical activities, permanent right-of-way (road, trails, highways and railroads), transmission lines, pipelines, power lines, peat extractions, recreational facilities
13	Settlement areas	Cities, towns, villages, hamlets, cottages, ribbon residential, rural residential, rural recreational (e.g. cottages)
14	Riverine wetland	Wetlands in the channel of rivers and streams; includes riparian or streamside habitat, as well as water surface of rivers
15	Lacustrine wetland	Includes permanently flooded lakes and reservoirs (includes dammed river channel), intermittent lakes and tidal lakes

From this analysis, it appears that colour enables a more precise and accurate segmentation of images due to clues provided by colour changes. Segmenting the modern image in colour first enabled a more informed assessment of the historic image as the colours in modern images were used as clues for texture changes indicating the

presence of certain land cover types in historic images. This represents a benefit of conducting black-and-white to colour comparisons.

Residential areas, roads, manicured lawns, hedges and horticultural areas were grouped in the settlement area category, whereas highways and roads that were not in the immediate vicinity of settlement areas were instead classified as industrial/recreational. When <5 individual trees were observed in the vicinity of residences, they were grouped with settlement areas, whereas larger groups of trees were classified as coniferous forest. Any clear modification of the landscape that showed signs of being actively maintained was classified as industrial. The exception to this rule was areas that had previously been modified but were now apparently regenerating. For example, a former portion of a golf course was no longer being used, and shrub vegetation was now visibly returning; this section was segmented as a regenerating area while the rest of the golf course was included in recreational/industrial. Grassy areas that were part of recreational facilities (ski resort, golf courses, baseball pitches etc.) were placed in recreational/industrial, while other grassy areas that were not in and around towns or in such facilities were included in grassland herbaceous. Groups of mature trees in grassland herbaceous zones were classified as coniferous forest; on the other hand, if these were younger tree stands, they were classified as regenerating. In cases of homogenous tree growth of younger stands in a grassland, the area was labelled as regenerating. If a tree or other natural feature was blocking a component of a lake or river channel, assumptions were made by categorizing it as part of the underlying category (e.g. water surface), rather than skewing the pixel count by classifying it as coniferous forest. This was done only when confidence as regards the underlying category was strong (e.g. tree in front of a lake). The occurrence of such obstacles was rare.

### 3.8 Limitations

There are eight limitations to the methodology that emerged in the course of this research.

## **1. Unequal weighing of pixels across the landscape**

Some stations are represented by only one image pair, whilst others have several, creating a bias. For example, Tunnel Mt North which overlooks the municipality of Banff is the most heavily represented, with seven triplets. The number of image pairs or triplets from each station included in the analysis depend on (1) how many existed at that station and (2) how many met the selection criteria. Tunnel Mt North simply had more historical images available (twelve), seven of which met the selection criteria.

A choice was made to include all available high quality imagery that consistently met the selection criteria, rather than limit the number of image pairs or triplets included from each station. Because some stations only had one image pair, a homogenous sample would have resulted in only one image pair being analyzed at each station, thereby significantly reducing the sample. The number of pairs or triplets for each station ranged from one through seven, with the mean being 2.1.

## **2. Overlapping views**

There was no overlap in images taken from the same station, nor was there overlap in any of the regional pairs. Of the 26 triplets taken in the Bow and Elbow valleys, a small amount of overlap was found in three sets of triplets, with the overlap representing less than 10% of the image in each case. This resulted from different views of the same valley-bottom from different mountain tops. The cases of overlap occurred between a Gap Lake-and Mt. Lawrence Grassi South triplet, a Lady MacDonald and Grotto Mt. triplet, and a North Quirk and South Quirk triplet. For this study, this degree of overlap does not alter the conclusions.

## **3. Lack of even distribution of stations**

I opted to include the largest number of stations that met the criteria across the study area as larger sample sizes generally lead to increased precision (Hsu & Robbins, 1947). Not all 32 stations in the sample were spread out evenly; some areas, such as the Bow and Elbow valleys are over-represented compared to others. The majority of

stations are found on the eastern side of the study area rather than the west. The western border of the study area has scattered representation, most of which is concentrated in one pocket of stations near Kananaskis Lake South and another on the northern edge of the study area. Although this represents a limitation in terms of a representative sample for the entire study area, it is a strength in terms of providing a thorough view of the changes occurring in the Bow and Elbow valleys, which after all are the primary areas of concern for flooding affecting the residents of Banff and Canmore and recreational facilities in Kananaskis Country. The process of selection stations was rigorous and prioritized the best regional representation possible based on available image pairs.

#### **4. Tracing error**

Two people were involved in the image segmentation process. Because of this, minor differences in interpretations could arise. This was minimized by setting clear protocols, training my assistant on these protocols and working closely with him when questions arose. The most likely examples where interpretation differences could arise are with the regenerating areas, broadleaf/mixedwood and grassland herbaceous areas. Historical images were much more challenging to segment than repeat images. This was at times due to the occasional presence of blemishes due to flaking or mishandling (i.e. thumb mark) and/or the fact that the glass plates have since broken. The use of the drawing tablet enabled much higher precision and reduced tracing error.

#### **5. Accuracy of repeat tripod location**

It can be highly challenging to reach sub-meter accuracy in the repeat photography process, especially when limited by site conditions, time, and weather. The process is not flawless, and some error does occur. The subsequent exact alignment of images through the mastering process followed by manual adjustment of height and width (of pixels) significantly reduced any possible alignment error.

## **6. Perspective distortion**

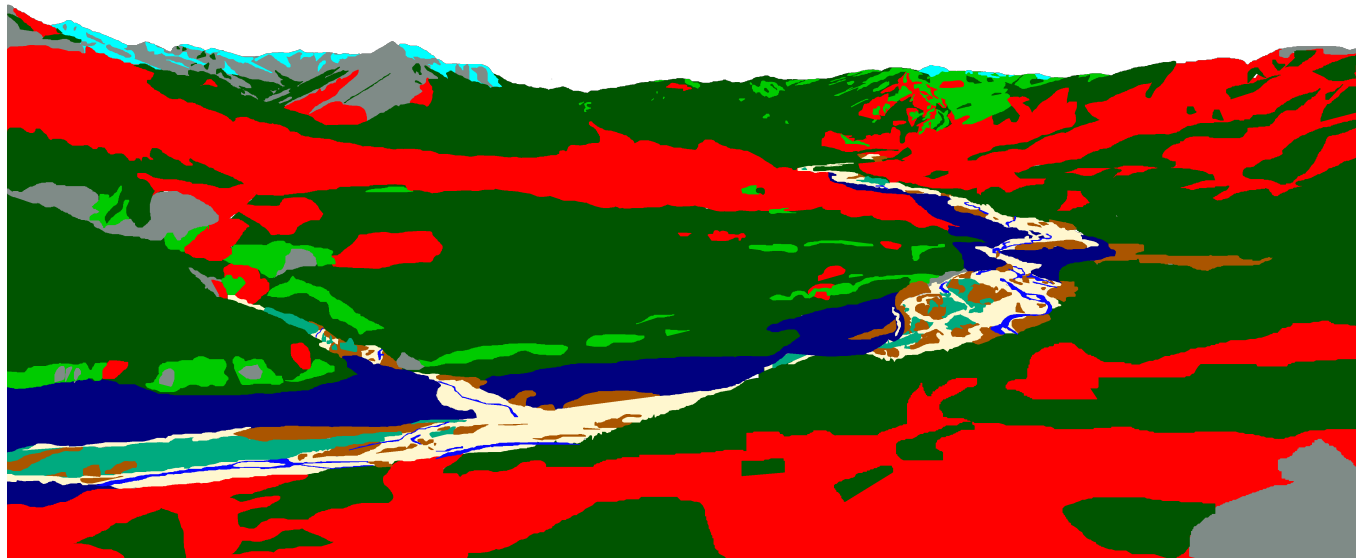
Perspective distortion results in objects in the foreground appearing larger than those in the background of the image, leading to an over-representation of foreground pixels compared to those in the background. I removed all lower elevation stations as well as image pairs with objects in the foreground to significantly reduce perspective distortion. Jeanine Rhemtulla's work (Rhemtulla et al., 2002) also serves as an indication that such error does not appear to be as significant as expected. Further testing is needed to understand how many image pairs are required to diminish the perspective distortion.

## **7. Scale of data**

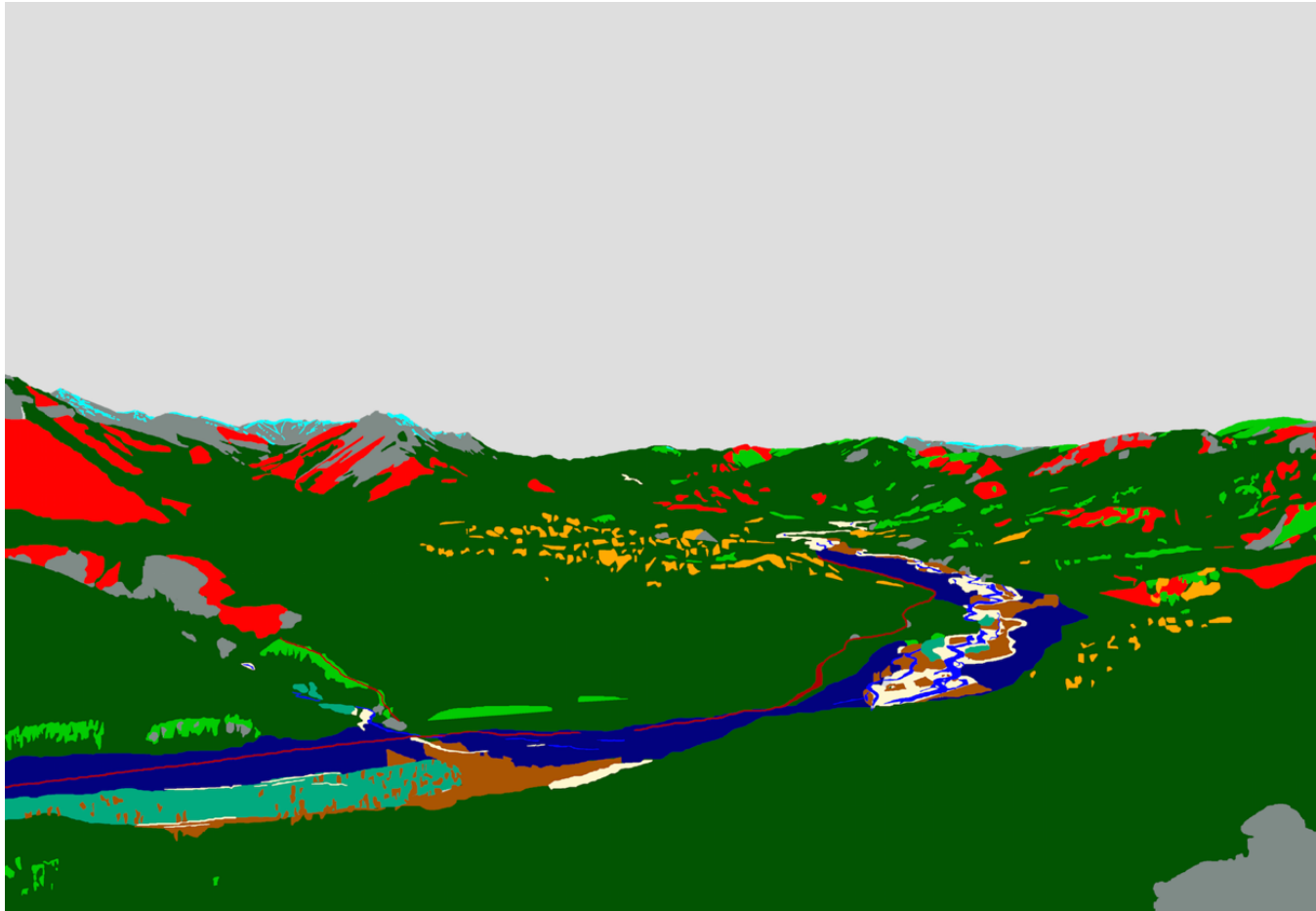
The results of this study can only be extrapolated at the scale of the data; it is not possible to make claims on land cover types other than those analyzed. For example, it is possible to discuss changes only in coniferous forest, not those that occurred at an individual species' level. The scale of the classification categories was carefully chosen to align with existing systems while enabling the measurement of broad trends. The nature of this imagery means it is not always possible to discern at a species level, especially not in black and white historic images. Having a larger sample size using broader categories was favoured over having finer categories requiring more classification effort.

## **8. Comparison of colour with black-and-white images**

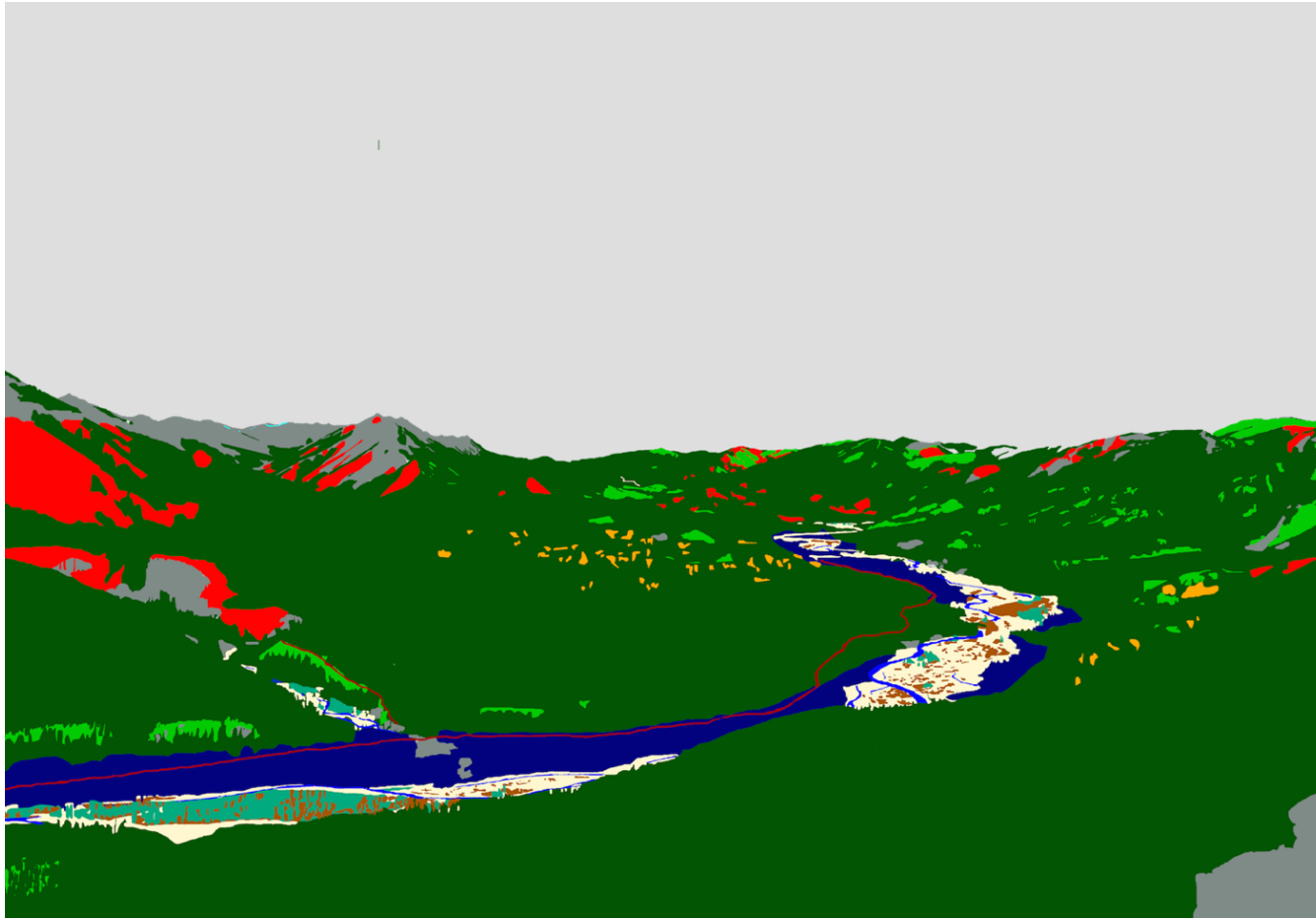
This project uses a comparison of current colour to historic black-and-white counterparts. In principle, the difference in nature and quality of images over time introduces a limitation to the analysis. However, reducing the likelihood of classification error resulting from a black-and-white to black-and-white comparison and improving the accuracy of the classification through the use of colour was favoured, even though this resulted in the comparison of images of a different nature.



**Figure 3 14. Image Labeler mask for The Knob 1895.** As the dataset consists of high resolution image pairs (or triplets) acquired in the Canadian Rocky Mountains, extracting critical information about ecological change requires the manual segmentation of images using Image Labeler. A drawing tool and colour legend are employed to draw the extent of different land cover types over top of the image, leading to the creation of a mask such as this one. Masks are then compared using an algorithm to attain the exact pixel change in each land cover type, as well as the direction of change between pixels. Coniferous forests are in dark green, regenerating areas in red, grasslands in light green, floodplain in dark blue, vegetated bar is brown, bare exposed bar in cream, water surface in light blue, river islands in teal, and sand/gravel/rock in grey.



**Figure 3-15. Image Labeler mask for The Knob 2008.** As the dataset consists of high resolution image pairs (or triplets) acquired in the Canadian Rocky Mountains, extracting critical information about ecological change requires the manual segmentation of images using Image Labeler. A drawing tool and colour legend are employed to draw the extent of different land cover types over top of the image, leading to the creation of a mask such as this one. Masks are then compared using an algorithm to attain the exact pixel change in each land cover type, as well as the direction of change between pixels. Coniferous forests are in dark green, regenerating areas in red, grasslands in light green, floodplain in dark blue, vegetated bar is brown, bare exposed bar in cream, water surface in light blue, river islands in teal and sand/gravel/rock in grey.



**Figure 3-16. Image Labeler mask for The Knob 2014.** As the dataset consists of high resolution image pairs (or triplets) acquired in the Canadian Rocky Mountains, extracting critical information about ecological change requires the manual segmentation of images using Image Labeler. A drawing tool and colour legend are employed to draw the extent of different land cover types over top of the image, leading to the creation of a mask such as this one. Masks are then compared using an algorithm to attain the exact pixel change in each land cover type, as well as the direction of change between pixels. Coniferous forests are in dark green, regenerating areas in red, grasslands in light green, floodplain in dark blue, vegetated bar is brown, bare exposed bar in cream, water surface in light blue, river islands in teal and sand/gravel/rock in grey.

## Chapter 4 – Results

### 4.1 Introduction

In this chapter, I provide an overview of the results on land cover changes stemming from the analysis of 148 images located in the study area (Figure 4-1). The extent (in %) of land cover classes in historic and repeat images is first discussed in Section 4.2. This offers a representation of the land cover types which are most dominant in this landscape. Section 4.3 presents the percent change for each land cover class. The use of percent change should be interpreted carefully and always in context; for example, a 1215% increase in the anthropogenic classes may raise flags to the outside eye, yet it should be understood in the context of this footprint having gone from 0.19% to 2.46%, which represents a relatively minute portion of the overall landscape analyzed. Sections 4.4 and 4.5 demonstrate the nature and direction of changes measured, first with what the landscape has become, and second with what the landscape was historically. This chapter then narrows in at the valley level, comparing historic images with 2008 images for the Bow and the Elbow valleys (Section 4.6).

One of this study's distinguishing features is the completion of third views (repeats of repeats). The changes observed over the 6-year window between the repeats and third views are presented in Section 4.7 for the Elbow and in Section 4.8 for the Bow. The repeat images were taken between 2008-10 whereas the third views were completed in 2014, resulting in a dataset that provides a view of the landscape before *and* after the major 2013 flood event. Section 4.9 focuses on fluvial changes for portions of the Bow and Elbow rivers pre- and post-flood. Not all trends observed regionally were mirrored at the valley level. The chapter's key findings are summarized in Section 4.10. The eight results categories were carefully chosen to look at the image data from as many angles as possible. All transition matrices are in Appendix D.



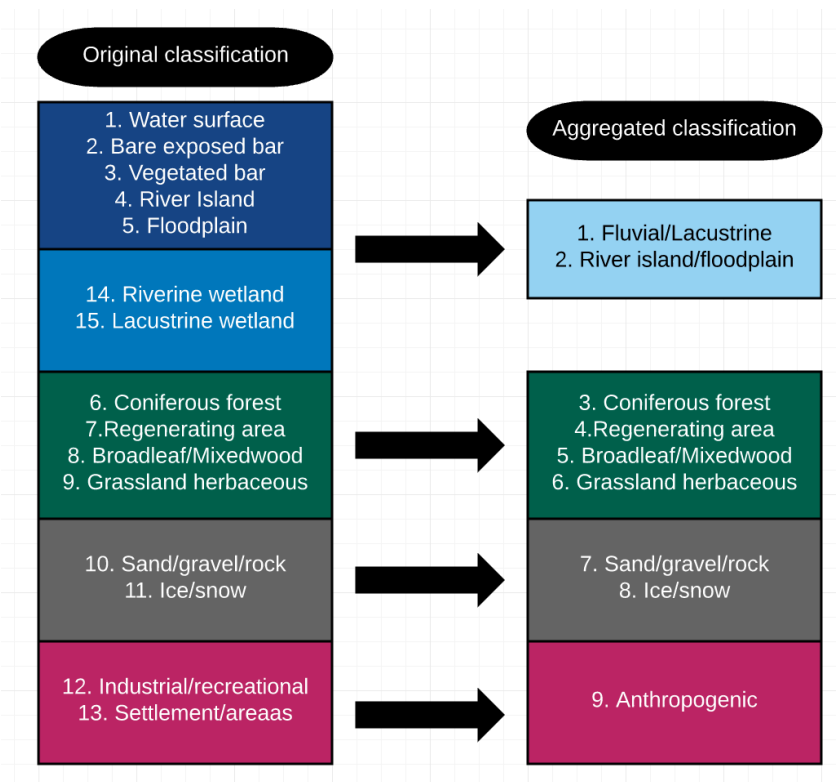
**Figure 4-1. Montage of landscape changes seen in study area.** The top left image taken at Phantom Crag East in 1888 demonstrates a regenerating area, whereas the exact same part of the landscape photographed in 2009 (top right) depicts a new tributary as well as a mix of floodplain vegetation and shrubs. The bottom two images taken from Forget-me-not ridge demonstrate how much variation can occur in the channel zone, particularly in the case of a river such as the Elbow where new channels are cutting through the landscape and sand bars are being inundated.

## 4.2 Aggregation & extent of land cover classes

The following four results sections (4.2 to 4.5) aggregate results from the thirteen categories used to analyze the fluvial station imagery into nine more generalized classes (Figure 4-2). There is a specific rationale for having opted to aggregate from 13 to 9 classes. It was not possible nor desirable to maintain the level of detail in fluvial change across the entire dataset; only the Bow and Elbow images had been classified at a finer fluvial scale. The detailed fluvial classes were preserved as such in sections 4.6 to 4.9, providing a detailed account of fluvial changes in the Bow and Elbow.

Although some of the regional stations did encompass segments of other rivers and lakes in the region, these were classified more coarsely into the two new categories of lacustrine and riverine wetlands. It was therefore sensible to have one aggregated fluvial/lacustrine category for the entire dataset in order to discuss overarching change in all sixty-one (historic-repeat) image pairs. The river island category was aggregated

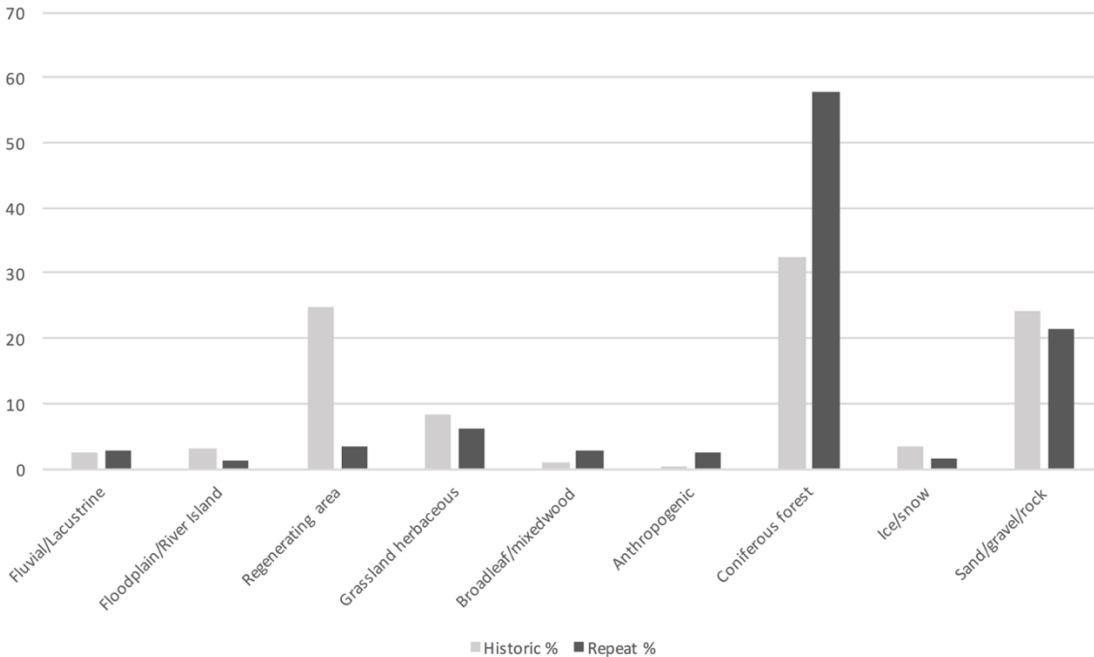
with floodplain, as they are ecologically comparable, even though they have fluvial geomorphological differences. Industrial/recreational and settlement areas were condensed so as to have one metric of the direct human footprint on the landscape. These aggregations result in nine classification classes (Figure 4-2). The percent coverage of each aggregated land cover category was determined by combining the transition matrix from the fluvial stations with that of the regional stations. Pixel counts were then converted to percentages.



**Figure 4-2. Classification categories for synthesized results.** Illustrates the nature of the aggregation of classification categories conducted to present the general results stemming from the analysis of 61 image pairs (historic-repeats) throughout the study area. The numbering used in the left hand boxes mirrors that used in Table 2.6 and Figures 2.6.1 & 2.6.2 whereas the numbering used in the right hand boxes is the new numbering used to reference the condensed categories discussed in the results sections 3.2 to 3.5.

The three most dominant land cover classes at the turn of the 20<sup>th</sup> century were coniferous forests, regenerating areas and sand/gravel/rock whereas today they are coniferous forests, sand/gravel/rock and grasslands (Figure 4-3). Even though

grasslands have the third largest extent in modern images, their extent has decreased in modern images compared to historic images.



**Figure 4-3. Extent of historic and repeat land cover classes.** This histogram represents the overall extent (in % coverage) of each land cover category for the historic image (light grey) compared to the repeat images (dark grey).

### 4.3 Change in land cover classes

Percent change in land cover categories was calculated for each aggregated land cover category  $[(\text{New value} - \text{Old value}) / (\text{Old Value})] * 100$ . In the historic imagery, settlement and industrial/recreational areas combined represented 0.19% of the landscape analyzed compared to 2.46% in the repeat images. Even though this represents a small portion of the overall landscape, this represents a percent increase of 1215%. Today, human settlements, industrial and recreational areas are all present in the study area.

The next most notable increases occurred in forest cover, both for broadleaf/mixedwood and coniferous forests. Although broadleaf/mixedwood forests

represent a relatively small portion of the overall landscape. they were found to have more than tripled (231%). Coniferous forests have nearly doubled in extent over the past century, representing a percentage change of 79%, essentially replacing regenerating areas.

**Table 4-1. Percentage change in land cover classes over past century.** Organized from most abundant to least abundant in the modern landscape.

Classification Category	Percent Change (%)
Coniferous forest	79
Sand/gravel/rock	-11
Grassland herbaceous	-29
Regenerating area	-86
Broadleaf/mixedwood	231
Fluvial/Lacustrine	3
Anthropogenic	1215
Ice/snow	-48
Floodplain/River Island	-61

The aggregated category of river channels and lakes as well as the category of sand/gravel/rock have remained mostly unchanged. Grasslands have diminished by 29%. Half of the ice and snow in historical images was no longer present in the modern images. Although the floodplain’s geomorphology does not change over a century time-scale, the percent cover of this land cover category experienced a decrease (-61%) in the analysis due to floodplain areas being covered by human settlements and/or the infill by coniferous forest. Regenerating areas decreased in accordance with the increase in mature coniferous forests; in other words, most of the areas that had been recently burned, logged or contained younger tree stands a century ago have become mature coniferous forests today.

## 4.4 What the landscape has become

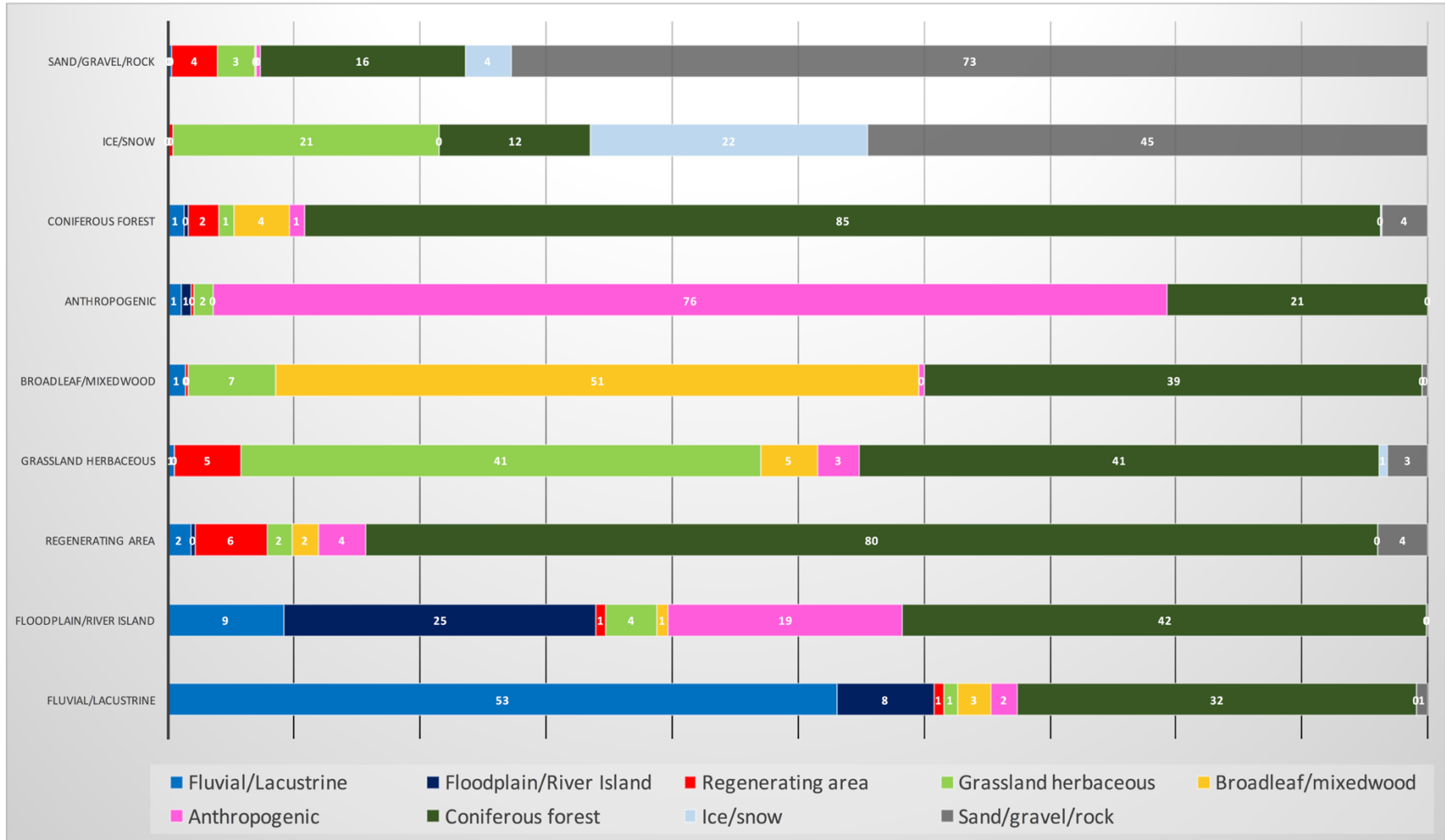
My analysis has so far shown the proportion of each land cover category in the historic and repeat images across the study area, and the gains and loss of each type. In this section, the focus is on the dynamics of this change, not only its overall magnitude. It describes what the landscape has become, and what proportion (represented as a percentage) has shifted from one category to another (Figure 4-4).

Almost all historic coniferous forests have remained coniferous forests in the modern images; only a negligible amount has shifted into other categories. A similar trend is apparent in the anthropogenic metric, where areas that had a direct human footprint historically have remained a focal point for continued human presence. Nevertheless, one fifth of these historic anthropogenic areas have now become mature stands of coniferous forest.

Roughly half of the broadleaf/mixedwood forests of the past remain so today; the rest has primarily shifted into coniferous forest. A similar pattern is evident with grasslands, most of which have either remained the same or shifted into coniferous forest. Regenerating areas have undergone a major transformation, the larger part of which have become coniferous forest.

Areas of sand, gravel and rock have primarily remained the same; just under one fifth have shifted into coniferous forest. A very small proportion has become ice, snow, regenerating areas or grassland herbaceous. Ice and snow has experienced an interesting shift; the majority of areas formerly covered by ice and snow are now either rock or alpine tundra (classified as grasslands). A smaller portion has shifted into coniferous forest.

Floodplain and river island areas have experienced a scattered transformation; a quarter remained the same, a small portion has been integrated into lakes and rivers, a larger part has become mature forest and a fifth has now been developed for human use. Finally, only half of the fluvial and lacustrine areas have remained unchanged; the bulk of the other half has become forest or floodplain.



**Figure 4-4. Land cover changes across study area.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. Each stacked bar includes the percentage value for each land cover type. For example, 16% of what was historically sand/gravel/rock has become coniferous forest, as is visible in the top bar.

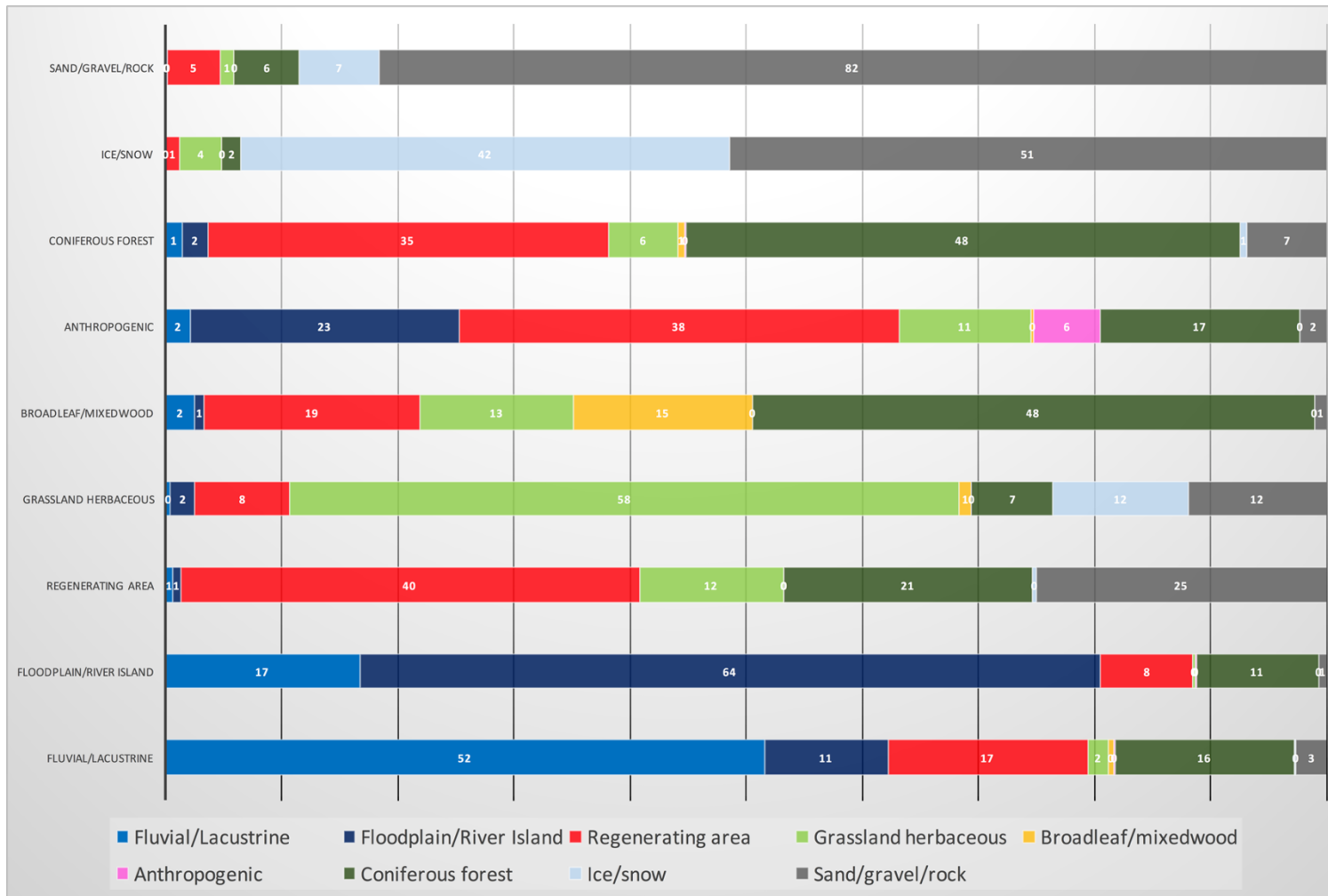
## 4.5 What the landscape was historically

It is equally valuable to consider the layout of the landscape at the turn of the 20<sup>th</sup> century in contrast to that of today, as the normalizing factor (the denominator) changes from what was to what is. In Section 4.4, the focus was on the transformation from historic to modern. In this section, the focus is on understanding the historic origins of the modern landscape (Figure 4-5). The distinction may be subtle, but it is important. For example, knowing that 23% of current settlement areas land cover is built on the historic floodplain has direct management applications (Figure 4-5).

Modern-day sand, gravel and rocky areas were also primarily sand, gravel and rocky at the turn of the 20<sup>th</sup> century. A small percentage used to be ice and snow or coniferous forest. Today's ice/snow was almost equally divided between ice/snow and sand/gravel/rock areas in the past.

A significant portion of coniferous forest used to be regenerating areas. Broadleaf/mixedwood forests of today have grown where regenerating areas, grasslands, coniferous forests and broadleaf/mixedwood forests of the past used to be. Grasslands have remained the most constant out of all land cover types, with the exception of sand/gravel/rock. One fifth of today's regenerating areas used to be mature forest stands; a quarter were rock and an even smaller portion were grasslands. The majority of modern regenerating areas were also regenerating one hundred years ago.

Roughly one fifth of today's human settlements and/or industrial and recreational areas were built on the historic floodplain. The rest was divided across regenerating areas, grasslands and coniferous forest. Nearly a fifth of today's floodplain was underwater a century ago; while the vast majority of the rest was also floodplain historically. Half of today's fluvial/lacustrine areas were not under water in the past; instead, they were regenerating areas, floodplain or coniferous forest.



**Figure 4-5. Historic composition of present-day land cover.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. Illustrates the historic composition in relation to the present-day land cover across the study area. Each stacked bar includes the percentage value for each land cover type. For example, 38% of what is classified as anthropogenic in modern images was formerly classified as regenerating areas in the historic images.

## 4.6 Elbow vs Bow comparison (historic-repeat)

Recreational areas were visible in the modern Elbow imagery, albeit they only represented 0.36% of the area (Table 4-2). In the Bow, the anthropogenic-coniferous transition resulted in 13% of historic settlement areas being converted to mature coniferous forests, and 43% of historic industrial/recreational areas returning to mature coniferous forests (Figure 4-7). In contrast, the coniferous-anthropogenic transition consisted of 7% of the historical coniferous forest having been converted to settlement or industrial/recreational classes (Figure 4-7). In the Bow, 28% of the historic floodplain is now covered in settlement areas and/or industrial/recreational areas (Figure 4-7). This is not the case in the Elbow valley, where there are no settlement areas along the portions of the Elbow that were analyzed. In the Elbow, only 1% of the historical floodplain was classified as industrial/recreational in the 2008 images (Figure 4-6).

The Elbow river's channel zone decreased from 2.45% to 1.38% in the historic-repeat comparison. As for the Bow, the channel zone went from 4.45% to 4.33%. The Elbow's bare exposed bars decreased by 56% and vegetated bars by 40% over the past century (Table 4-2). In the Bow, the bare exposed bars and vegetated bars were reduced by 75% and 22% respectively (Table 4-3).

Coniferous forests still dominate, with 91% of historic coniferous forests still being present in the Elbow in modern imagery (Figure 4-6), and 80% in the Bow (Figure 4-7). Grasslands in the Elbow have tended to remain constant (31%) or transform into coniferous forests (56%) (Figure 4-6). A large portion of historical grasslands in the Bow (66%) have been converted to coniferous forest, while 13% are now settlement or industrial/recreational areas (Figure 4-7). Regenerating areas almost always transform into mature coniferous forests, whether in the Elbow (Figure 4-6) or the Bow (Figure 4-7). The river island class tended to be more volatile (Figure 4-6 and 4-7).

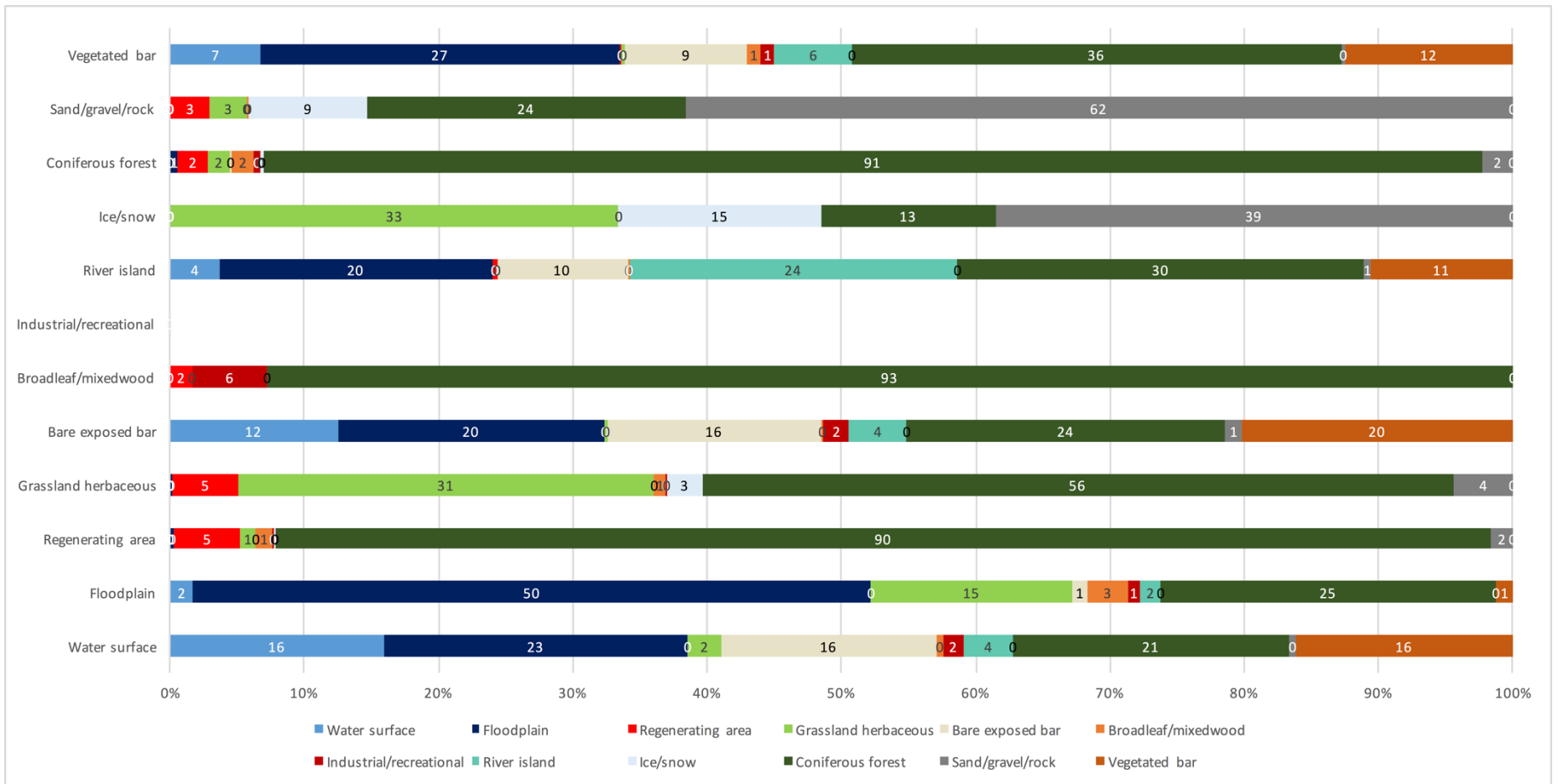
Only 15% of what was historically ice/snow in the Elbow valley remained ice or snow in the repeat images; the rest had become grasslands, sand/gravel/rock or coniferous forest (Figure 4-6). Almost all (98%) of historic ice and snow identified in the Bow had disappeared and was identified as sand/gravel/rock in the repeat imagery (Figure 4-7).

**Table 4-2. Comparison of historic and repeat land cover categories in the Elbow valley between 1895-97 and 2008.**

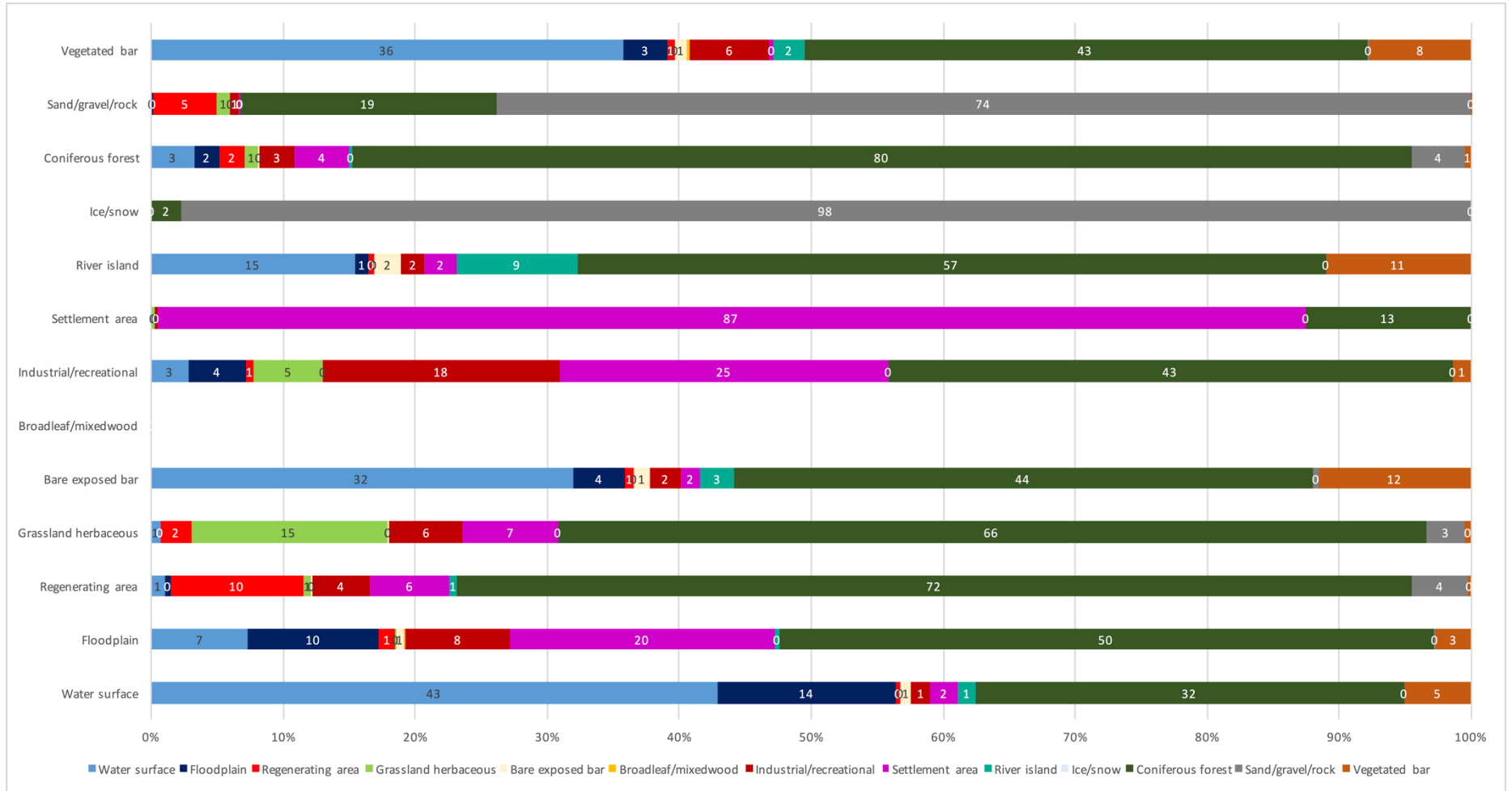
	Historic (%)	Repeat (%)	Percent Change
Water surface	0.52	0.39	-26
Bare exposed bar	1.07	0.47	-56
Vegetated bar	0.86	0.52	-40
River island	0.32	0.26	-17
Floodplain	3.91	2.92	-25
Coniferous forest	45.35	70.33	55
Regenerating area	22.12	2.79	-87
Broadleaf/mixedwood	0.34	1.20	250
Grassland herbaceous	4.60	4.92	7
Ice/snow	4.19	2.35	-44
Sand/gravel/rock	16.72	13.49	-19
Industrial/recreational	0	0.36	N/A

**Table 4-3. Comparison of historic and repeat land cover categories in the Bow valley between 1888-90 and 2008-10.**

	Historic (%)	Repeat (%)	Percent Change
Water surface	2.87	3.41	19
Bare exposed bar	0.59	0.15	-75
Vegetated bar	0.99	0.77	-22
River island	0.30	0.37	25
Floodplain	9.11	1.84	-80
Coniferous forest	15.59	54.02	247
Regenerating area	32.87	5.29	-84
Broadleaf/mixedwood	0	0.02	N/A
Grassland herbaceous	8.82	1.96	-78
Ice/snow	0.03	0	N/A
Sand/gravel/rock	27.96	22.95	-18
Industrial/recreational	0.22	3.43	1453



**Figure 4-6. Transformations from historic to 2008 land cover classes in the Elbow.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. Each stacked bar includes the percentage value for each land cover type. For example, the first bar represents ‘vegetated bar’, demonstrating that 7% of what was historically part of the vegetated bar is now water surface, while 27% has shifted into floodplain. There is no stacked bar for industrial/recreational as this land cover class was absent from the historical landscape.



**Figure 4-7. Transformations from historic to 2008-10 land cover classes in the Bow.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. For example, the first bar represents ‘vegetated bar’, showing that 36% of what was historically classified as vegetated bar is now water surface. There is no stacked bar for broadleaf/mixedwood as this land cover class was indiscernible from the historical landscape.

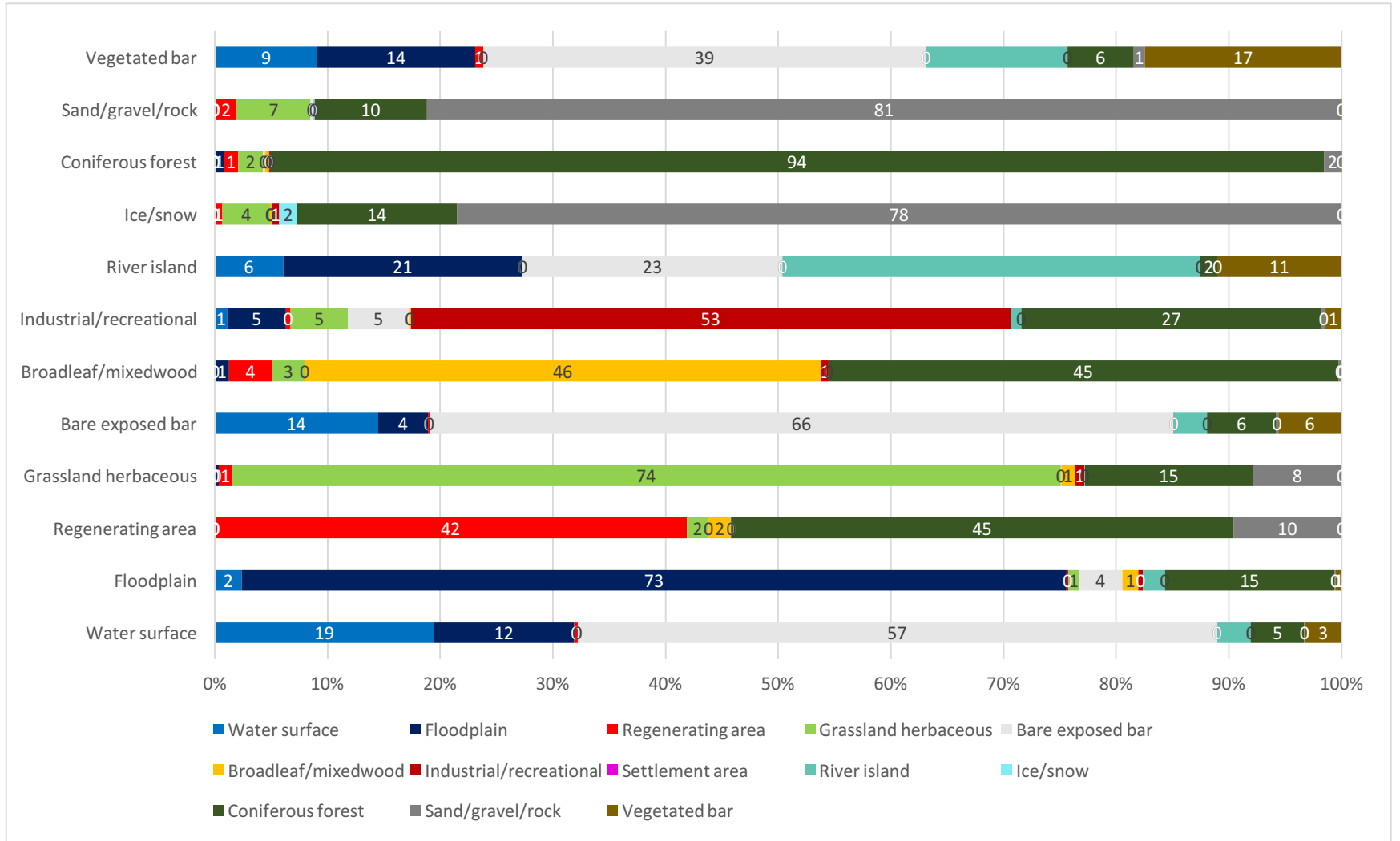
## 4.7 Elbow (pre-and-post flood)

Below are the results from 13 image pairs (repeat and third view) from seven stations in the Elbow valley (Table 4-4 & Figure 4-8). Third views are repeat images that correlate not only with a historic image but also a prior repeat image. The historic landscape is not discussed in this section. The most dominant land cover class is coniferous forest, followed by sand/gravel/rock. The other land cover classes cover the remaining 15% of the landscape.

Over a 6-year period, the most visible change in the portion of the Elbow valley analyzed is the exponential increase in the bare exposed bar, and the disappearance of ice and snow (Table 4-4). Vegetated bars in the river channel decreased significantly (-61%) over this time interval (Table 4-4). Broadleaf/mixedwood forests declined by nearly 20% (Table 4-4). The analysis shows an increase in grasslands (28%) (Table 4-4).

**Table 4-4. Percent change in land cover classes between 2008 and 2014 images in the Elbow valley.**

Land cover	2008 (% cover)	2014 (% cover)	Percent change
Water surface	0.40	0.33	-18
Floodplain	2.88	2.88	0
Regenerating area	3.02	2.55	-15
Grassland herbaceous	4.97	6.31	27
Bare exposed bar	0.52	1.12	118
Broadleaf/mixedwood	1.18	0.95	-20
Industrial/recreational	0.35	0.33	-7
River island	0.26	0.26	2
Ice/snow	2.48	0.06	-98
Coniferous forest	69.83	70.26	1
Sand/gravel/rock	13.60	14.75	8
Vegetated bar	0.51	0.20	-61



**Figure 4-8. Transformations between 2008 and 2014 in the Elbow valley.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. For example, the first bar represents ‘vegetated bar’, demonstrating that 39% of what was formerly part of the vegetated bar is now bare exposed bar. There is no stacked bar for settlement area as this land cover was not found in the Elbow.

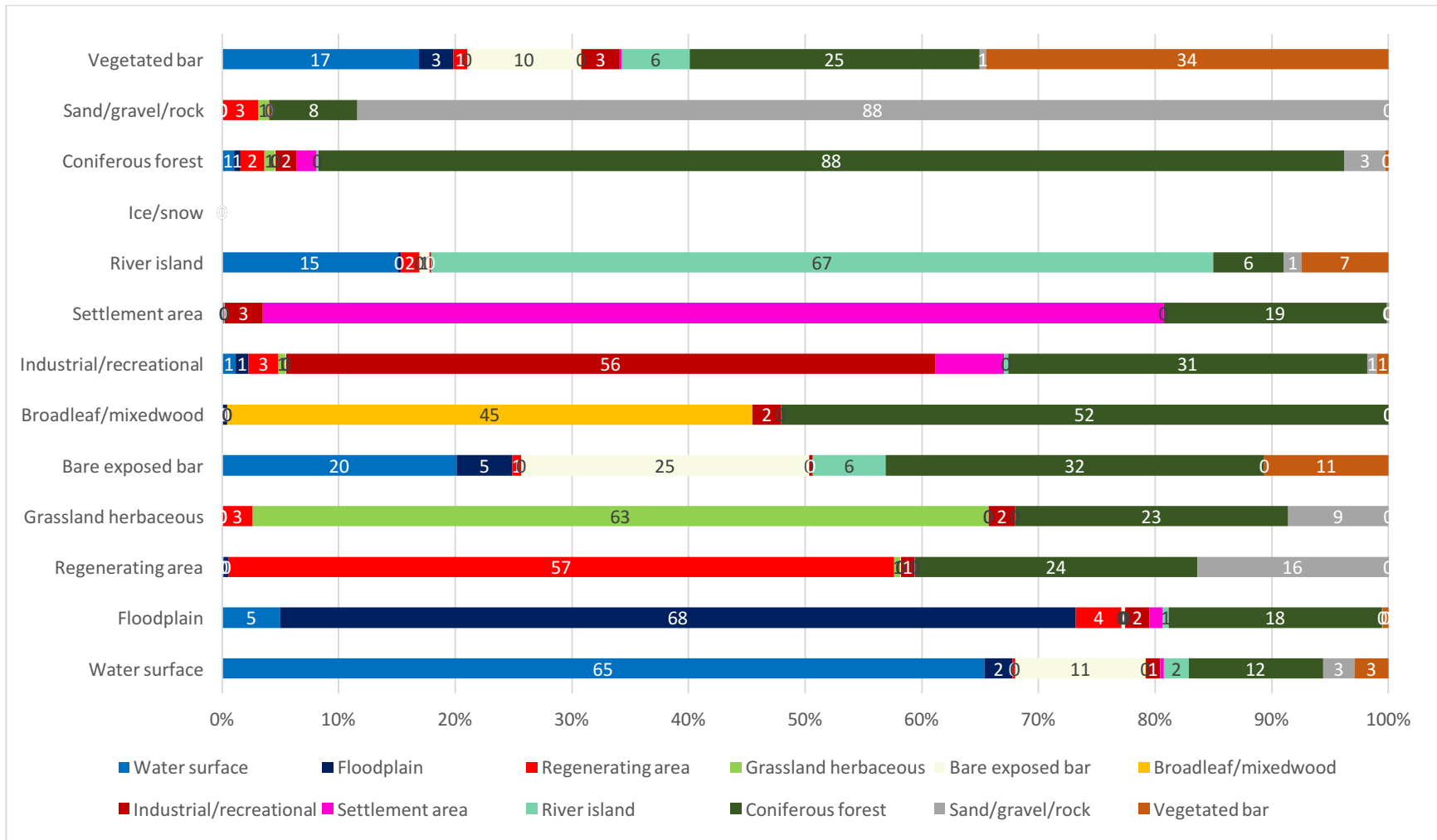
## 4.8 Bow (pre-and post- flood)

Below are the results from 13 image pairs from six stations in the Bow valley between Banff and Exshaw. The historic landscape is not discussed in this section. The extent of coniferous forest remained the same in the Bow between 2008-2014. When calculating percent change for land cover categories (Table 4-5), it became evident that the most substantial changes in the Bow occurred in the river channel particularly a nearly three-fold increase in the bare exposed bar category. Section 4.9 presents these fluvial changes in further detail. The river island class was measured to have increased by 32% between 2008 and 2014. All of the forest and vegetation categories remained close to constant. Figure 4-9 depicts where the transformations have occurred within land cover categories.

Just over half of the area represented in the imagery is covered in coniferous forest while nearly a quarter is sand/gravel/rock. Settlement areas represent nearly 6% of the region captured, as do regenerating areas. The Bow river, although significant to the area as it visibly winds through the valley, represents under 5% of the total superficie analyzed. There is very little change visible between 2008 and 2014, to the exception of changes in the channel zone.

**Table 4-5. Percent change in land cover classes between 2008 and 2014 images in the Bow valley.**

Land Cover	Repeat (%)	Third View (%)	Percent change
Water surface	3.46	3.21	-7.1
Floodplain	2.03	1.87	-8.2
Regenerating area	5.31	5.06	-4.7
Grassland herbaceous	2.00	2.01	0.5
Bare exposed bar	0.15	0.55	276.6
Broadleaf/mixedwood	0.02	0.02	-2.7
Industrial/recreational	3.36	3.27	-2.6
Settlement area	5.64	5.50	-2.4
River island	0.36	0.48	32.6
Coniferous forest	54.35	54.40	0.1
Sand/gravel/rock	22.57	23.01	1.9
Vegetated bar	0.76	0.61	-20.0



**Figure 4-9. Transformations between 2008 and 2014 in the Bow valley.** Land cover classes are listed on the y-axis while the percentage from each class is listed on the x-axis. For example, the first bar represents ‘vegetated bar’ demonstrating that 10% of what was historically part of the vegetated bar is now bare exposed bar.

## 4.9 Elbow vs Bow fluvial comparison (pre- and post- flood)

The changes measured between 2008 and 2014 for the Elbow River show distinctly different patterns from those observed for the Bow River. The portion of the Elbow's active channel analyzed increased by 58%, and its channel zone by 15%. In contrast, the studied portion of the Bow River's active channel increased by 5% and its channel zone remained unchanged (0.2%). However, these figures obstruct the finer details only visible at the channel scale.

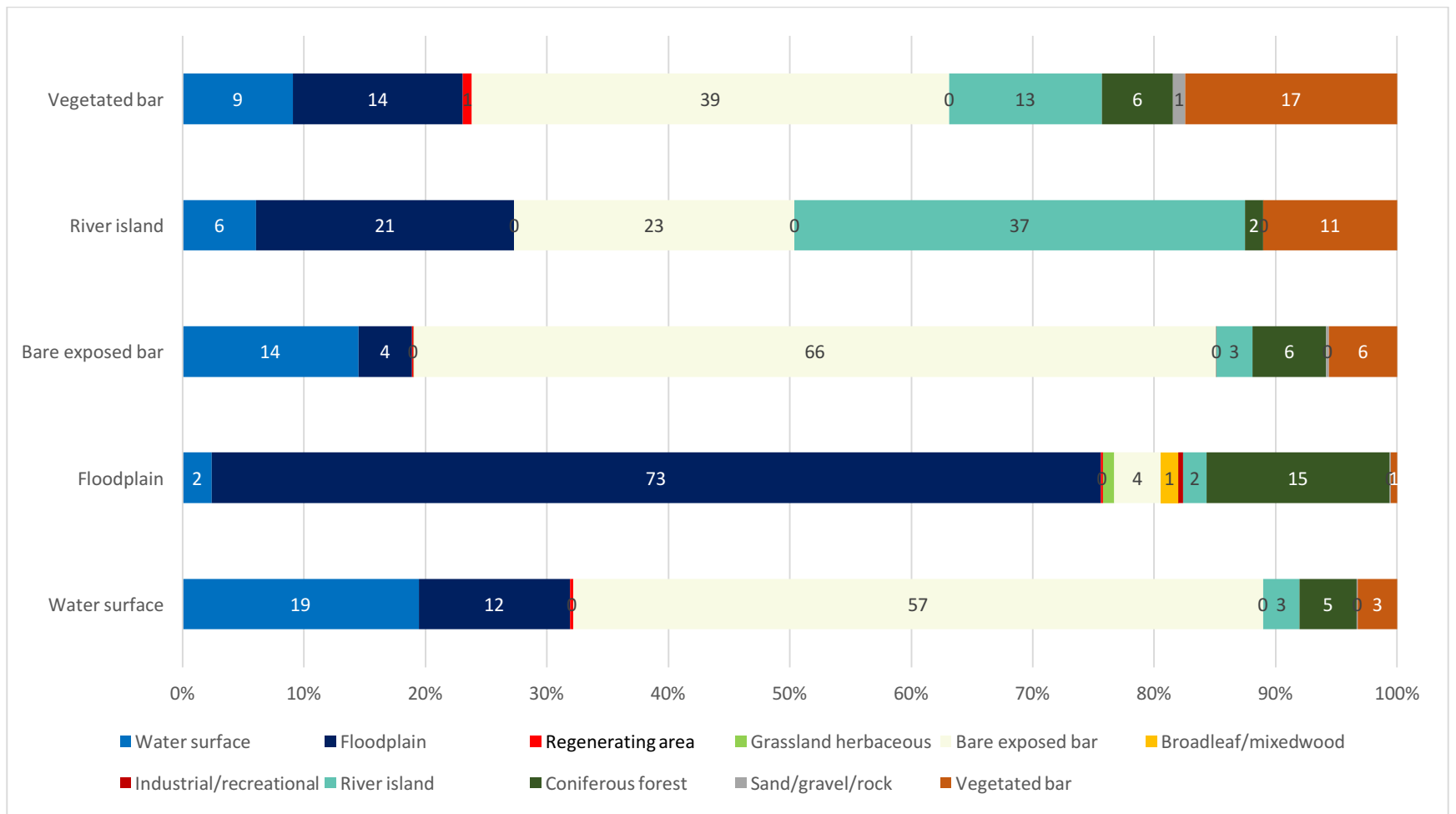
For the Elbow, water surface decreased by 18%, bare exposed bar increased by 118% and vegetated bar diminished by 61%. For the Bow, water surface decreased by 7%, bare exposed bar increased by 277% and vegetated bar decreased by 20%. The direction of these changes is represented in Figures 4-10 and 4-11 below.

### *Elbow*

Water surface is the most volatile of all the categories, especially as water levels fluctuate on a daily basis. Eighty-one percent of what was water surface in 2008 had transformed into other categories in 2014 (Figure 4-10). It appears that what had been water surface in 2008 had primarily become bare exposed bar or floodplain.

The majority of bare exposed bar remained unchanged (66%), while 14% was now underwater and 6% had since grown shrubs, leading it to be classified as vegetated bar (Figure 4-10).

A significant portion of vegetated bar had transformed into bare exposed bar (39%) by 2014, while 17% remained unchanged. Vegetation has grown in some parts of the channel, leading it to be classified as river island (13%) or floodplain (14%) rather than vegetated bar (Figure 4-10).



**Figure 4-10. Pre to post 2013 flood transformation in the Elbow valley.** The different fluvial classes are listed on the y-axis while the percentage from each class is listed on the x-axis. For example, the first bar shows what the pixels which were classified as vegetated bar in 2008 had become in 2014; 9% had become water surface whereas 39% were now bare exposed bar.

River islands, those island formations within the river channel that are covered in shrubby vegetation and/or coniferous forest, underwent some changes between 2008 and 2014 in the Elbow. Although 37% of the area remained unchanged, a portion was instead classified as floodplain (21%). Roughly a quarter of the former river island area had been inundated, resulting in 23% of it being bare exposed bar and 11% vegetated bar. A very small percentage (6%) was now underwater (Figure 4-10).

The majority (73%) of the floodplain observed in 2008 remained classified as floodplain in the 2014 images. However, 15% was now classified as coniferous forest, most likely as a result of the tree stands maturing. The other transformations within this class were minimal (Figure 4-10).

### *Bow*

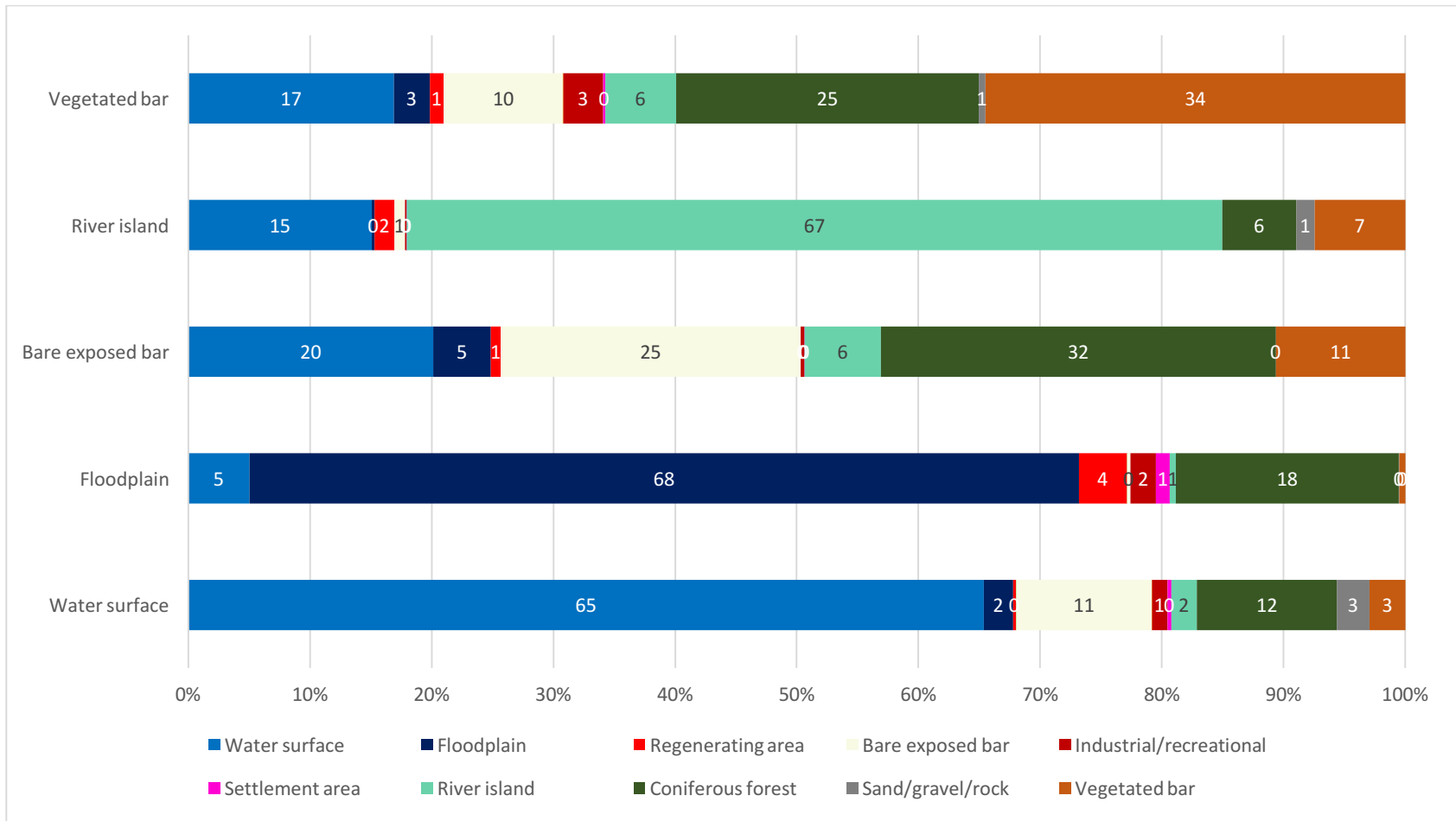
The majority of what was water surface in 2008 remained so in 2014, with some areas not submerged (10% bare exposed bar) and others now covered in forest (12%) (Figure 4-11).

A quarter of bare exposed bars remained unchanged, while a fifth were submerged under water. A larger portion (32%) had experienced forest infill, and 11% of the former bare exposed bars were now covered in shrubs (Figure 4-11).

Approximately 25% of the portion of the Bow's vegetated bar that was analyzed became bare exposed bar (10%) or water surface (17%); 34% remained the same; another 25% shifted to coniferous forest (Figure 4-11).

The river island class remained the most constant of all fluvial classes in the Bow (67% unchanged). Nevertheless, fifteen percent was submerged, and therefore categorized as water surface. A smaller portion became vegetated bar (7%), implying it had been submerged since the repeat, but vegetation had since established on its banks.

The floodplain has remained largely unchanged (68%), with part of it (18%) having transformed into more mature coniferous forest.



**Figure 4-11. Pre to post 2013 flood transformation in the Bow valley.** Demonstrates the pre to post flood transformation in the Bow river between 2008-10 and 2014. The different fluvial classes are listed on the y-axis while the percentage from each class is listed on the x-axis. For example, the first bar shows what the pixels which were classified as vegetated bar in 2008-10 had become in 2014; 17% had become water surface whereas 10% were now bare exposed bar

## 4.10 Summary

Collectively, the results presented in this chapter form a picture of change in the Kananaskis Country study area at the landscape level and specifically along the channels of the Bow and Elbow rivers. Combining a long historical sweep in image analyses between the late 19<sup>th</sup> century and today, as well as studying images shortly before and after the 2013 flood, shows distinct patterns of change.

### Percent coverage - entire study area

Taken as a whole, coniferous forest and sand/gravel/rock are the two dominant land cover classes in this area, both a century ago and today. Regenerating areas were a dominant part of the late 19<sup>th</sup> century landscape (25%) yet have a much lesser extent in the 2008 landscape (4%). All other land cover classes are below 10% in extent, whether in the historical or repeat imagery.

### Percent change - historic vs repeat

The largest land cover conversions found for the study area as a whole between historic images and repeats were for settlement areas, industrial/recreational areas, broadleaf/mixedwood and coniferous forests. Coniferous forests drastically increased over the past century (79%), essentially replacing regenerating areas which fell by 86%. Broadleaf/mixedwood forests simultaneously increased over the same time period (+231%). Settlement, recreational and industrial areas all expanded (combined increase of +1215%), mostly due to the expansion of the townships of Canmore and Banff, transportation networks, and the development of recreational facilities in Kananaskis Country. Ice and snow was essentially halved over the century, while grasslands declined by 29%. Fluvial/lacustrine areas remained close to constant in extent (+3%).

### Bow vs Elbow Historic-Repeat

When narrowing in at the valley-scale and comparing vegetation classes across the past century, very different trends appeared. Forests increased in both valleys, but the percent increase was much greater for coniferous forests in the Bow than in the Elbow, while broadleaf/mixedwood forests increased substantially in the Elbow. Regenerating areas decreased uniformly throughout both valleys over the same time period.

### Bow vs Elbow Pre & Post Flood

The analysis uncovered a very different pattern of change for the Elbow compared to the Bow pre (2008-10) and post (2014) flood, both in terms of vegetation cover and fluvial classes. Coniferous forests covered the same extent in 2014 than in 2008 in both the Elbow and Bow valleys. Broadleaf/mixedwood forests decreased by 20% in the Elbow yet fell by only 3% in the Bow in the same time-frame.

The Elbow river sustained a 15% increase in its channel zone between 2008 and 2014 while the Bow's channel zone remained unchanged. However, the Elbow's and Bow's bare exposed bars increased by 58% and 277% respectively, most likely as a result of the 2013 flood.

In the next chapter, I interpret the results of the foregoing analyses against the backdrop of direct and indirect environmental and ecological changes, as well as exploring what can be known about the effects of landscape level changes on flood regimes and the value of image analysis for fluvial planform study.

# Chapter 5 - Discussion

## 5.1 Introduction

This thesis sought to address two key questions:

(1) what land cover changes are evident through a comparative study of oblique images taken between 1888-1895 and 2008-2014 in the study area?

(2) what are the implications of these changes for flooding and flood management?

The regional sweep of a systematic set of historical and repeat photographs of the flood-affected watershed demonstrated a substantial increase in coniferous forest, broadleaf/mixedwood forests and human footprint in modern photographs compared to their historical pairs. When comparing historical to repeat photo pairs, the degree of increase in coniferous forest cover was much greater in the Bow valley compared to the Elbow. In contrast, grasslands decreased substantially in the Bow, while they increased slightly in the Elbow. When comparing pre- and post-2013 flood conditions (based on 2008 and 2014 image pairs), very different patterns emerged. Coniferous forests covered the same extent in 2014 than in 2008 in both the Elbow and Bow valleys. The Elbow's channel zone increased in the 6-year time period, while the Bow's remained constant. However, bare exposed bars in both rivers increased considerably.

This chapter addresses the second research question, which is to explore the implications of these changes for flooding and flood management. Section 5.2 provides an interpretation of the fluvial geomorphological changes identified while Section 5.3 discusses the implications for flood management. A brief examination of how the province of Alberta approaches flood mitigation, the existing measures being taken to reduce flood risks and impacts, and any additional measures that could be undertaken follows in Section 5.4. Broader challenges and considerations for landscape management and intervention in this region are then addressed (Section 5.5). A brief discussion of what research questions remain to be answered follows (Section 5.6). Section 5.7 contains a short conclusion.

## 5.2 Interpretation of fluvial geomorphological changes

The results from this study point towards forest infill occurring in both the Bow and Elbow valleys over the past century. This serves as a likely explanation for the narrowing of the Elbow channel over the past century. Forest expansion appears to have occurred not only on mountain sides, but also immediately next to the channel zone. The combination of causes that resulted in this change remain to be explored in future studies.

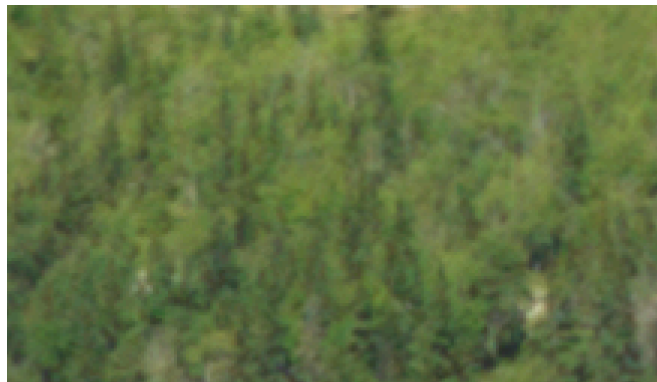
In Section 2.10 I reported on work by others on “before and after” experimental design (CP) in hydrological studies, and that suggests these may be misleading: the only means to accurately measure forest harvesting effects on flooding is through frequency-pairing (Alila et al., 2009; Burt & McDonnell, 2015). One of the implications of this is that predicted changes in the magnitude of streamflow following forest harvest may have been inaccurate, specifically because antecedent soil moisture conditions were not incorporated into the calculations of the chronological pairing method (Brantley et al., 2014, Stahli et al., 2011). When following the revised procedure for peak flow analyses (FP), storms of all sizes were found to become more frequent (USDA Forest Service, 2010).

If forest removal increases both the magnitude and frequency of floods, it would thereby be expected that an increase in forest cover should have a moderating effect on the magnitude and frequency of floods. Both the Bow and the Elbow imagery showed important increases in forest cover in each valley as did the regional imagery. Therefore, one might expect less frequent or lower magnitude floods today than at the turn of the 20<sup>th</sup> century. However, the imagery does not cover the entire drainage basins of the Bow and Elbow rivers, nor do we know to what degree the geographical extent of forest cover influences the correlation found between forest cover and flooding.

If the watershed behaves in a similar fashion to those western U.S. watersheds evaluated by Alila et al. (2009), the increases in coniferous and broadleaf/mixedwood forests found in this study should correlate with a lower frequency of floods in 2014 compared to 1895-1897. A frequency-pairing watershed study (pairing pre- and post-harvest flows by equal frequency as opposed to equal storm input thereby controlling for

both the storm input and antecedent soil moisture conditions) would have to be conducted in the field to confirm this hypothesis.

The Bow valley was nearly all classified as grassland and regenerating areas (post-fire systems) in the late 19<sup>th</sup> century. Today it is substantially forested. Unlike in the Elbow valley, broadleaf/mixedwood forests were barely recorded in the imagery of the Bow, whether in the 1888-1890 imagery or the 2008-2010 imagery. The recorded increase in forest cover was attributed to coniferous forest expansion. It is possible that some broadleaf/mixedwood forests were at times mislabelled as coniferous forests, as some of these forests were very difficult to classify (e.g. Figure 5-1). Also, the comparison of current colour images with historic black and white images does undoubtedly introduce some bias towards more detailed information being extrapolated from the coloured imagery than the black and white.



**Figure 5-1. Challenging land cover classification.** This image illustrates the difficulty that sometimes exist in discerning between forest cover types. This particular segment was classified as coniferous forest; however, it is possible that the change in colouration would indicate the presence of broadleaf/mixedwood forests interspersed in the coniferous forest or simply different species of coniferous trees.

Due to the presence of this margin of error, the 247% increase in coniferous forest should be assumed to represent forest cover generally, including both coniferous forest and broadleaf/mixedwood. The forest and flood literature reviewed for this thesis does not distinguish between the effects of coniferous forest compared to broadleaf/mixedwood forests on flooding, which limits one's ability to tease out any differences according to forest type. To add to the subtleties, some of the broadleaf/mixedwood vegetation was categorized as river island and/or floodplain due to its location in the channel zone. The river island category (islands in the channel

zone covered in trees) experienced a percentage increase of 25% in the Bow, and therefore would support the same pattern of expanding forest cover in the valley found in the forest categories. It is possible that some detail in changes in broadleaf/mixedwood forests was lost by being collected in the floodplain category. Similar to the conclusions made for the Elbow, it could be hypothesized that a frequency-pairing watershed study in the Bow valley would arrive at the conclusion that the magnitude and frequency of floods had decreased in 2008-2010 compared to 1888-1890 as a result of the overall increase in forest cover.

Ultimately, each system is unique and must be understood in its own context; the drivers of flooding in the Bow and Elbow valleys may be very different than those in the western U.S. watersheds analyzed by Alila et al. (Alila et al., 2009). Many variables affect flooding (see Section 2.9), and in the context of climate change today, it is even more challenging and perhaps pointless to isolate the effects of one variable (in this case forest cover) on flooding. What can be concluded is that forest cover does influence the flood regime, and that this relationship should be better understood.

In Section 2.5, the flood record for the Bow is presented based on available records. One of the major insights from that review is that extreme floods were more common before 1910, and one of these (the 1879 flood) had occurred before the historical images analyzed as part of this study were taken in the Bow (1888-1890). This may be due to climatic variables and have very little to do with a sparser forest cover in the Bow valley in the late 19<sup>th</sup> century. However, it is also possible that it is exactly because forest cover was so sparse that such extreme floods occurred in 1879, 1897 and 1902.

While the increased forest cover may be having a mitigating effect on drainage and flood risk at present, warming temperatures, the increased volatility in the timing of spring snowmelt and the increased occurrence of extreme storms as a result of climate change are all likely to increase flood risk for the area. At a global level, the pressures resulting from climate change discussed in Section 2.9 will require improved and adapted water management practices. To this effect, Bates et al. (2008) state that, “while quantitative projections of changes in precipitation, river flows and water levels at the river-basin scale are uncertain, it is very likely that hydrological characteristics will

change in the future” (Bates et al., 2008:4). This underlines the need to adapt water management strategies and policies to align with the most updated knowledge of future climate variability and its effects on freshwater systems. Both mitigation and adaption strategies must be undertaken at appropriate scales; in terms of mitigation, increasing water storage capacity in reservoirs is key, whereas adaptation could include water-use efficiency and water conservation measures (e.g. water recycling, metering and pricing, virtual water trade, reallocation of water to highly valued uses) can be implemented to mitigate some of the stress of drought conditions (Bates et al., 2008).

The results of the present study show that grassland herbaceous and regenerating areas which dominated the late 19<sup>th</sup> century landscape have been almost entirely replaced by coniferous forest and to a lesser extent broadleaf/mixedwood forests, which has implications for flood management in the area. Recent evidence (Alila & Green, 2014a; 2014b; Green & Alila, 2012b) that forests have a notable buffering effect on floods should trigger the investment into further research that directly quantifies the buffer effect of forest cover compared to grasslands during major rainfall events in this area, especially as most major flood events have occurred as a result of heavy spring/summer rainfall events (Neill & Watt, 2001). It also raises questions around the vulnerability of these two valleys if the landscape were to drastically change again; for instance, if forest cover decreased as a result of fire, logging or insect outbreaks.

### 5.3 Implications for flood management

Perhaps less surprising is the increase in direct human footprint, including expansion of settlement and recreational areas, as well as industrial development. Nonetheless, these areas represent a relatively small proportion of the overall study area, and thus the effect of impervious surfaces on flooding would likely be highly localized to development along rivers. Roads result in permanent changes in the hydrological regime within the watershed by concentrating runoff flow, intercepting rainfall and diverting water, and opening access to areas otherwise inaccessible (Gucinski, Brookes, Furniss, & Ziemer, 2001). The findings in this present study could

inform emergency preparedness and community vulnerability assessments when it comes to the direct human footprint on the landscape.

This study has shown that image analyses of oblique photo pairs (and triplets) are valuable for fluvial planform studies and can contribute to an exploration of what can be known about the effects of landscape level changes on flood regimes. It is possible to detect planform changes on the Bow and Elbow Rivers between 1880 and 2014 using oblique photographs, demonstrating an evolution in fluvial geomorphological processes. In the next section, five key land cover changes are recorded for the entire study area and their potential implications for flooding and flood management are presented (Table 5-1).

**Table 5-1. A synthesis of land cover changes and their implications for flood damage mitigation.** The left column contains the highlighted land cover changes, while the other two columns summarize a combination of the conclusions from this study as well as some assembled from the literature.

Change over the past century	Implications for flooding	What does this mean for the future?
<p style="text-align: center;"><u>Forest cover change</u></p> <p>Coniferous forest increased by 79%</p> <p>Broadleaf/mixedwood forest increased by 231%</p>	<ul style="list-style-type: none"> <li>➤ The potential for flooding should be mitigated by an increase in forest cover</li> <li>➤ Our understanding of the relationship between forests and floods continues to evolve</li> </ul>	<ul style="list-style-type: none"> <li>➤ Forests' role in flood mitigation should be valued and included in Alberta's flood mitigation strategy</li> <li>➤ Need to invest more in science to improve flood predictions, particularly regarding the role played by forest cover</li> </ul>
<p>Regenerating areas declined by 86%</p>	<ul style="list-style-type: none"> <li>➤ The hydrophobicity layer (post fire) typically increases flood risk; fire exclusion and the reduction of regenerating areas over the past century should have minimized this effect</li> </ul>	<ul style="list-style-type: none"> <li>➤ Should monitor the effect of the hydrophobicity* layer on flood risk following prescribed burns in the region</li> </ul>

Grassland herbaceous areas decreased by 29%	Unknown	Unknown
Areas of direct human footprint increased by 1215%	<ul style="list-style-type: none"> <li>➤ Roads result in permanent changes in the watershed including: <ul style="list-style-type: none"> <li>• Increased runoff through a concentration of flow</li> <li>• Interception of rainfall</li> <li>• Diversion or rerouting of water</li> </ul> </li> <li>➤ Increase in human presence results in more people and investments vulnerable to flooding. Much more infrastructure susceptible to damage today than a century ago</li> </ul>	<ul style="list-style-type: none"> <li>➤ If impervious surfaces continue to increase over time, risk of flooding will increase</li> <li>➤ Need emergency response systems to deal with increased human presence. Need to replace vulnerable infrastructure with new systems able to handle greater weather extremes</li> </ul>
Fluvial/lacustrine areas increased by 3%	<ul style="list-style-type: none"> <li>➤ This represents a marginal increase that is negligible when considering flooding implications, as this category also includes lacustrine areas, whether natural lakes or dam reservoirs</li> </ul>	<ul style="list-style-type: none"> <li>➤ River channels may in fact remain quite steady over time in terms of their overall coverage, even though they fluctuate significantly at the time of a flood; the same goes for lakes</li> </ul>

\*hydrophobicity refers to the physical property of repelling water

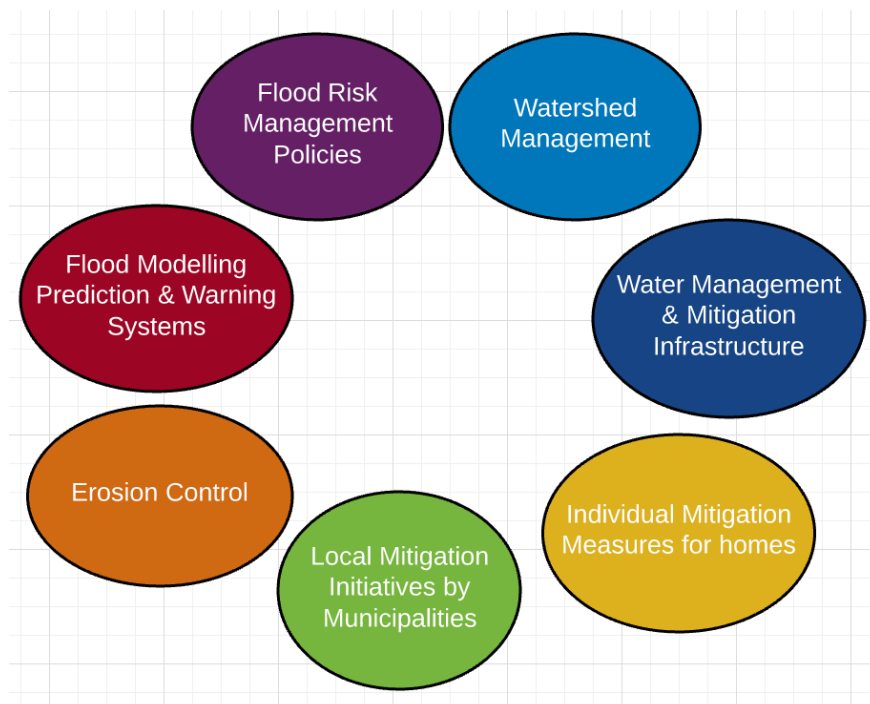
## 5.4 Alberta's Flood Damage Mitigation Strategy

The Province of Alberta has taken a number of steps when it comes to flood mitigation. The presence of human infrastructure on the floodplain represents a serious

risk. Alberta's decision to minimize future development on the floodplain and facilitate the relocation of at-risk homes is prudent. However, the relationship between forest cover and flooding appears to have been omitted from the key provincial flood mitigation report (Alberta Government, 2014). It should be noted that a separate report was published regarding climate change and the planning process for the city of Calgary (CitySpaces Consulting Ltd., 2007).

The present study indicates that the area analyzed underwent significant landscape changes both over the past century, as well as prior and following the 2013 flood in both the Bow and Elbow watersheds. In recent years, temperature and precipitation has been rising in the area as a result of climate change, resulting in the decline in river flows (5.7% in past 90 years) — patterns that are expected to continue (CitySpaces Consulting Ltd., 2007). The Climate WNA model projections presented in Chapter 1 also point towards such a trajectory. The reduction in water flows in the Bow and Elbow rivers present a significant concern for the local population, as it relies almost entirely on these rivers for its water supply. It has been posited that the per capita water use in Calgary will have to be reduced by 50% by 2064 in order to avoid compromising the sustainability of the rivers in this changing climate (CitySpaces Consulting Ltd., 2007). People are not only faced with a projected reduction in their water supply; flooding is also projected to increase as a result of warmer temperatures and increased precipitation.

The 2013 flood event that devastated portions of southern Alberta had impacts that were certainly felt as a result of past planning decisions, such as building of homes and infrastructure on the floodplain. It was triggered by the rare confluence of weather events that led to high levels of rain on snow over a short interval; it is unlikely that such an event could have been predicted or planned for easily. Having an effective flood damage mitigation strategy is nonetheless crucial as Alberta prepares for the future. Following the 2013 floods, a key report titled *Respecting our Rivers - Alberta's Approach to Flood Mitigation* (Alberta Government, 2014) was drafted comprising the key measures (Figure 5-2) to be taken by the Alberta Government to mitigate the impacts of future floods. These measures will be the focus of the subsequent discussion.



**Figure 5-2. Components of Alberta’s Flood Mitigation Strategy.** This figure was created using the list of key priority areas identified in the post-2013 flood report published by Alberta Government. Source: (Alberta Government, 2014)

In order to mitigate the impact of future floods, it is essential that the dynamics of the entire watershed be well understood. Following the 2013 flood, Albertans felt it was important to look at flood mitigation from the perspective of overall watershed management, not only localized mitigation actions (Alberta Government, 2014). This represents an important consultative process with stakeholders across the province, particularly watershed planning and advisory councils, and irrigation districts (Alberta Government, 2014). Another important deliverable is the implementation of the Alberta Wetland Policy (Alberta Government, 2013). Minimizing human-made impacts and maintaining healthy rivers is another priority provincial action, as is the development of guidelines for mountain creek hazards and an inventory of debris hazard locations (Alberta Government, 2014). Although these are commendable goals, practical implementation will be a challenge. The 2014 report (Alberta Government, 2014) does not present *how* such actions will be implemented.

The flood modelling prediction and warning systems provide information and probabilities about when floods may arise and how to communicate this information to those who may be affected. Albertans recognize that weather is highly unpredictable, yet it is still possible to predict how a flood would unfold (i.e. where the water would go) (Alberta Government, 2014). \$8.5 million are being spent on flood hazard mapping and a review of modelling accuracy and forecasting is also being undertaken (Alberta Government, 2014).

Flood risk management policies are essential. It is typically easier to keep people away from water than to keep water away from people (Alberta Government, 2014). The results in this study which focussed on a portion of the upper Bow showed that in this valley, 28% of the historical floodplain is now covered in settlement, recreational and/or industrial areas. Building on the floodplain is an issue for the entire Bow. The present day floodplains of the Bow valley were formed by multiple historical floods. This study's results show that the extent of the Bow's discernable floodplains decreased, albeit slightly between 2008 and 2014.

One of Alberta's key flood risk management policies is to limit future development on the floodplain and relocate families that are currently in high-risk areas. Legislation was passed to the effect of limiting future development on the floodplain following the 2013 flood event (Alberta Government, 2014). This is extremely important as historically, governments have carried the cost of flood defense and mitigation while private developers have enjoyed continued perks of building cheaply on the floodplain (Kocornik-Mina et al., 2015). In addition, population growth continues globally as well as the study area, increasing the concentration of people living in the floodplain. Add to that the absence of a widespread movement towards safer areas, with people choosing to continue to live in flood-prone areas, and it is not surprising floods are among the costliest natural disasters (Kocornik-Mina et al., 2015). Alberta's plan to introduce a relocation program for homes located in the highest risk areas, prohibit further development in the floodplain and evaluate the potential for flood insurance are an important first step (Alberta Government, 2014).

Water management and mitigation infrastructure are perhaps the most commonly discussed initiatives following a major flood. Such infrastructure includes highly

engineered dikes, berms, dams and diversions (Alberta Government, 2014). Such projects are carefully studied prior to implementation; affected communities are consulted and an environmental impact assessment (EIA) is conducted (Alberta Government, 2014). They tend to require careful design and can have steep costs. There are a number of projects on the agenda in this respect including a diversion canal in High River, an environmental review of the Elbow River dry dam, and a feasibility study for an underground diversion in Calgary (Alberta Government, 2014). Engineering reports will be completed for a number of flood prone rivers, including the Bow and the Elbow and upstream mitigation infrastructures will be explored (Alberta Government, 2014).

Erosion control is a response to the tendency of rivers to maintain high, hard, fast and debris-filled flows during a flood. For example, the Highwood river experienced flows 10x that of its June average during the 2013 floods (Alberta Government, 2014). Significant funds (over \$210 million) are being invested in erosion control projects, including some in Canmore, which is in the study area (Alberta Government, 2014).

The final two components of Alberta's mitigation strategy revolve around people and communities explicitly. Local mitigation initiatives currently planned include the creation of municipal recovery toolkits, undertaking community consultations, and implementing emergency management plans. In other words, most of this component is concerned with the management of people. The same applies to individual mitigation for homes, which allocates disaster recovery funding and updates building and repair codes for people's homes (Alberta Government, 2014). There is also no explicit mention of climate change in the 2013 Alberta Government flood mitigation strategy report (Alberta Government, 2014)— a surprising finding, particularly as climate change risks have been acknowledged in other documents (e.g. (CitySpaces Consulting Ltd., 2007)).

Alberta has developed a watershed resiliency and restoration program, focussed on "the creation and/or enhancement of natural systems such as wetlands and riparian areas to improve watershed functioning" (Environment and Sustainable Resource Development, 2013: 2). This program's budget is \$21 million, with NGOs, stewardship

groups, municipalities, First Nations and local authorities all eligible to receive project funds (Environment and Sustainable Resource Development, 2013).

This overview of Alberta's flood mitigation plan along with the conclusions of this study of historic and modern photographs lead to the following recommendations:

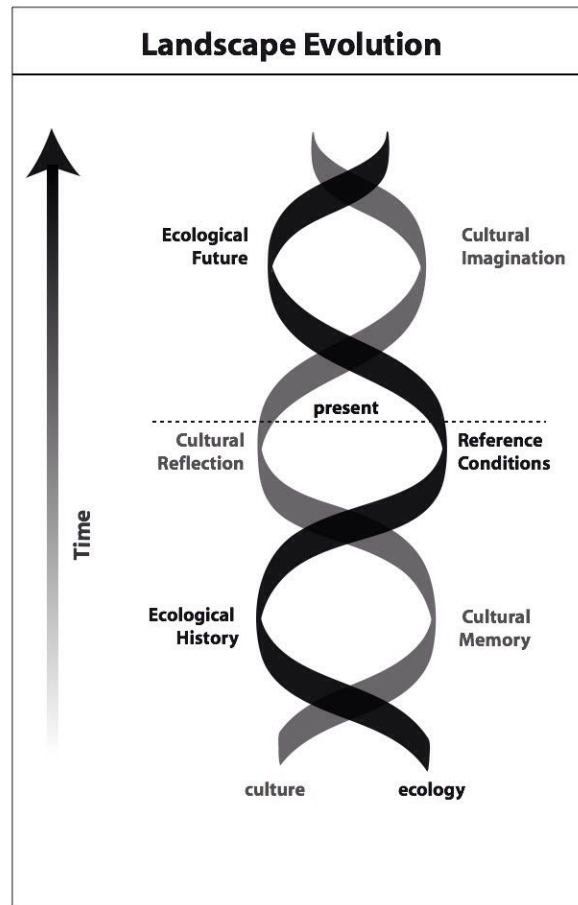
1. A 100-year plan to control and limit development on the floodplains of the Bow, including the relocation of settlement areas;
2. Monitoring of the precipitation and run-off, the storage in headwaters (glaciers, perennial snowbanks, and lakes) and soil moisture at key points in the whole watershed;
3. Watershed-specific research on the relationship between forest cover and flooding specifically, followed by an inclusion of this component in Alberta's flood mitigation strategy;
4. Promotion of resiliency for the Bow watershed, such as that introduced in the watershed resiliency and restoration program;
5. Adoption of climate change mitigation for the area and integration of climate change adaptation into Alberta's flood mitigation strategy;
6. Improvements (and re-design when appropriate) of weather monitoring, prediction, and reporting system to meet the requirements for flood prediction and damage control;
7. Land-use planning that promotes heterogeneity in vegetation cover to reduce vulnerability and restores key ecosystem processes such as fire.

## 5.5 Intervention & Restoration: Challenges & Opportunities

The photographs used in this study capture a legacy of both the changes that have occurred as a result of natural processes as well as those resulting from human activity and intervention in the landscape (management). People's needs and values shift over time, resulting in changing management regimes, while ecosystems are also continuously shifting. We know that a landscape is a mosaic of multiple dynamic ecosystems, all of which are exchanging organisms, water, energy and nutrients (Parks

Canada and the Canadian Parks Council, 2008). As ecosystems shift, people's values and priorities with those ecosystems also shift (Higgs, 2003). Conversely, people's changing values and priorities result in direct and indirect impacts on ecosystems. This has always been the case. As ecosystems change, so too does our understanding of those ecosystems (Higgs, 2003). Higgs (2003) states that, "what makes a landscape is a continual interplay between human activities and ecological processes. Human participation in landscapes also changes over time in response to shifting values about appropriate action." (260) (Higgs, 2003) (Figure 5-3). Where the challenge lies is in ensuring that policy is tailored and adapted to this interplay, rather than disconnected from the changing needs and values of people affected by a given policy, or the ecosystems connected to it.

Not only is historical knowledge key to the science of restoration ecology, practice of ecological restoration and for environmental management broadly speaking (Higgs et al., 2014), but we are also in an era of rapid change and uncertainty, where our understanding of ecological legacies has become crucial to inform better decision-making. It is becoming increasingly recognized that we cannot nor should we attempt to maintain ecosystems in a fixed state when their very nature is to be in constant flux (Hobbs, Hallett, Ehrlich, & Mooney, 2011). We have already been intervening in ecosystems at a global scale (Steffen et al., 2015); why not develop approaches that allow intelligent, informed and mindful intervention in ecosystems (Hobbs et al., 2011)? Hobbs et al (2011) have proposed just this through what they have termed 'intervention ecology' — "the science of meaningful and thoughtful intervention in ecosystems" (449) (Hobbs et al., 2011).



**Figure 5-3. Landscape Evolution Model.** Change takes place in response to the changing landscape; ecology and culture are always connected through time. People reflect in the present about the past through historical knowledge and an awareness of reference conditions leading to an imagined future. Source: (Higgs, 2003)

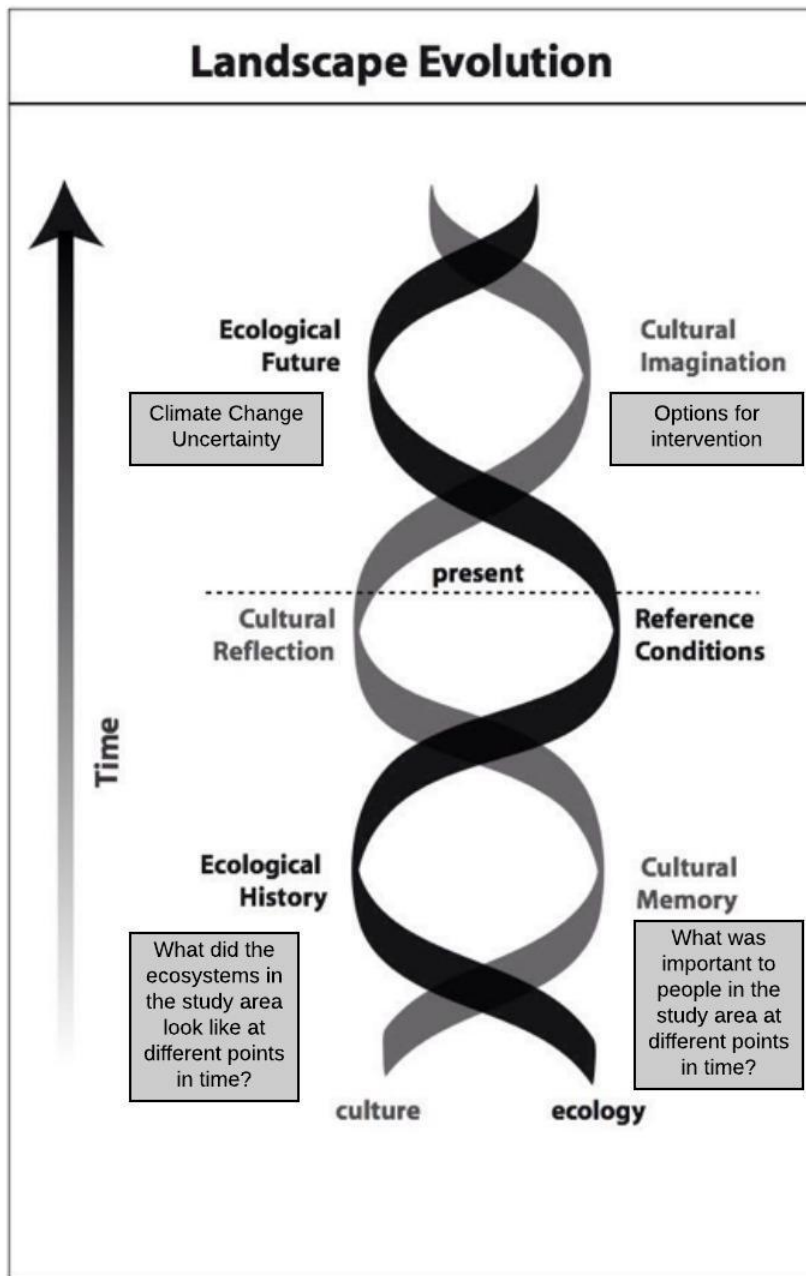
Intervention ecology encompasses conservation biology (the practice of maintaining a desirable ecosystem state) and restoration ecology (the practice of moving away from a current undesirable state) (Hobbs et al., 2011). As ecosystems are shifting so rapidly, the lines between conservation biology and restoration ecology are becoming more blurred (Hobbs et al., 2011). A rapidly expanding global human population, changes in wildlife and their needs, introduction of technologies and rapid expansion of novel ecosystems (Hulvey et al., 2013) represent important considerations. This leads to a significant challenge of knowing whether, how, when and why to intervene in ecosystems.

In order to develop a thoughtful and effective intervention approach for the area of the present study, it will be important to reflect on how this landscape might evolve to

fit new conditions, and how human practice and management can simultaneously evolve through adaptive management. Higgs explains that, “a broader social interpretation is necessary to evaluate good restoration – by proposing that ecological values must share the stage with cultural ones” (Higgs, 2003). Encompassed in this is the need to manage for future change. In order to think through these questions, it is essential to explore the interplay between people’s changing needs and values through time and the changing ecosystems for this region (Figure 5-4).

Understanding the changing needs and values of people living in the Bow watershed over centuries is a formidable challenge in itself, and a detailed synthesis of these changes is beyond the scope of this thesis. However, the choice of a route to the west through Kicking Horse Pass rather than Kananaskis pass discussed in Chapter 1 serves as an example of cultural memory, specifically illustrating that what is important to people shifts through time, particularly as a result of changing technologies (horse to train or cars). Our best local knowledge at any given point in time simply cannot predict the changing needs or technologies of people in the future (Roots, 1998). Nonetheless, if the geologist James Hector of Palliser’s party had not noted the presence of coal deposits at what became Canmore and near Banff, and the potential of the resources of this area for supporting new technologies, it may have never been developed into the major transportation artery that it is today.

The study area has a rich ecological history. The Kananaskis Valley was said to be a region of extensive open parkland with a large population of Stoney peoples prior to European colonization (Roots, 1998). In fact, the photographs studied demonstrate this shift from grasslands in the 19<sup>th</sup> century to the expansion of healthy spruce and pine forests throughout the entire region. It is possible that this open grassland ecosystem arose in part due to aboriginal fire management. Fires tended to be produced with an understanding of their cause and effect on the ecosystem and each species’ relationship to fire (Figure 5-5) (Anderson, 2014).



**Figure 5-4. Modified Landscape Evolution Model.** In order to reflect on people’s changing needs and values, it is helpful to ask “what was important to people in this area at different points through history? What were the key drivers that influenced them?” (cultural memory). Through ecological history, we can then consider the different ecosystem states for the study area. These two key considerations then provide a basis on which to ponder the various options for intervention (cultural imagination) within the scope of climate change and uncertainty (ecological future). It is impossible to develop tailored policies and an adaptive management approach without first understanding the human and ecosystem legacies. Source: (Higgs, 2003)

The reasons behind aboriginal burning of temperate forests in North America have included: (1) the ash from burning could be used as fertilizer for agricultural endeavours (2) it drove game and enhanced grass for wild game (3) it improved visibility through the removal of vegetation, enabling easier travel and hunting (4) it served as protection by killing off insects, rodents and reptiles and (5) it could foster the growth of edible wildflowers (Anderson, 2014; Kristensen & Reid, 2016; Stewart, 1963). Some have gone as far as saying that fire is arguably the most important change agent when it comes to modifying or maintaining ecological communities (H. T. Lewis & Ferguson, 1988), namely through the creation of increased diversity in the fauna living within them (Rowe and Scotter 1973 in (H. T. Lewis & Ferguson, 1988)). One could posit that dense forests proved to be of very little use compared to the benefits of burning in the study region of southern Alberta, particularly as Lewis (1982 & 1985) and (Williams, 2002) have shown that the forests of western North America had already been significantly modified by aboriginal peoples' use of fire upon the arrival of the first Europeans, often to enhance habitat for subsistence hunting. Furthermore, lower elevation sub eco-regions such as Montane areas tended to get much more frequent fire than upper foothill ecosystems (R. Arthur, personal communication, September 15, 2016). As Oltmann (1997) explains, "these early widespread forest fires affected stream flow rates on the eastern slopes and resulted in a decrease in the retentive capacity of the watersheds that was, in part, responsible for the floods in Calgary in 1884 and 1897" (41).

Yet, the narrative is complex and multi-faceted. Logging began as early as 1883 in the region and continued for the subsequent five decades (Roots, 1998). The majority of homes built in Calgary were made of wood from the Bow and Kananaskis valleys, and the rails for the new railway were laid on ties from this valley (Oltmann, 1997). This would indicate that the forests visible in the modern photographs are in fact second-growth forests. Today, it is heavily forested. We know that climate change is leading to unprecedented increased regional and seasonal temperatures as well as significant alterations of existing fire regimes, potentially extending fire seasons and/or the frequency and severity of fires (Weber & Flannigan, 2011). These changes are already

being felt in the region with increased wildfires in the past several years (Flat Top Complex Wildfire Review Committee, 2012).



**Figure 5-5. Lighting of 1918 grassland fire.** Image P138 from the Provincial Archives of Alberta captures a member of the Blackfoot as he lights a grassland fire. Source: (Kristensen & Reid, 2016)

How can these two sides of the equation be brought together to inform policy-making and more specifically, intervention in the form of restoration, and what are the management lessons from this study of historical changes?

This area was under very different management one hundred years ago than it is today, having been primarily managed by First Nations peoples at the turn of the 19<sup>th</sup> century, and subsequently being colonized by European settlers. Climatic and environmental variables together with cultural views are all shifting rapidly. Perhaps it is more important than ever to understand the past in order to better inform the future, as volatile as it may be. Some may believe that the value of historical references in informing restoration goals diminishes when environmental variables shift so drastically (Millar, Stephenson, & Stephens, 2007). The present study has shown that it is important and necessary to understand the system's past states, key components, flows

and feedback loops in order to devise a restoration strategy. Any form of historical knowledge helps understand the complex dynamics of change at play in any given ecosystem.

The historical images analyzed in this study paint a portrait of a landscape that was undergoing its own changes at that time as a result of it being the early settlement period. Such changes included the construction of the CPR, coal mining, the creation of new parks, and changing fire regimes. The triplets revealed a dynamic landscape that further illustrates the disturbance dynamics before and after the major 2013 flood. The intensification and acceleration of anthropogenic modifications to the landscape are having ripple effects on ecosystems and landscapes.

Parks Canada's guidelines for ecological restoration list several recommendations and/or considerations when conducting hydrological restoration. These range from restoring habitat features such as floodplains, riparian systems, terraces and gravel bars, to removing dams entirely in order to restore natural processes (Parks Canada and the Canadian Parks Council, 2008). Designing flow regimes with specific ecological, cultural, economic and recreational goals in mind may be the only feasible option for a watershed such as the Bow, where the river's flow has already been tampered with for decades (Acreman et al., 2014).

It would be ill-advised to arbitrarily take the landscape at any given point in history as an appropriate target for restoration; instead, it should be recognized that humans have been active agents of change in the landscape for millennia, and that the best restoration approach for this region would be one whose goal is a parallel care for humans and ecosystems in the present-day while taking into account the historical range of variability for both shifting human values *as well as* shifting ecosystem states. In this case, history is valuable as a reference, legacy, demonstrating a range of variability, and enriching cultural connections, as well as an experiment and/or scenario for the future (Higgs et al., 2014). The implications of pre and post settlement land management practices should be explored in greater detail, for instance the implications of the reduction in regenerating areas as uncovered in this study. Developing a landscape management framework that is tailored to the current climate of uncertainty is paramount (Hobbs, Higgs, Hall, Bridgewater, et al., 2014b).

## 5.6 Questions for Future Research

In the course of this project, orthorectified 2013 aerial photos of the Bow valley as well as select photos of alluvial fans from 1947, 1950, 1962, 1972, 1975, 1984, 1997, 2008 and 2013 were acquired from BGC Engineering, but were not used in this study. There is potential for future studies of the area to uncover visible land cover changes in these images and compare them to those found in the oblique imagery.

As was noted in the recommendations, it would be worthwhile to undertake watershed-specific research on the relationship between forest cover and flooding in this area. Simultaneously, the impacts of the expanded settlements areas, logging roads, and impervious surfaces on the flood regime could be assessed.

It is undoubtedly valuable to deepen an understanding of different states of the Bow watershed as a result of varying climatic and disturbance regimes (e.g. Watson & Luckman, 2001's dendroclimate work), and model forward in terms of future climate change impacts (e.g. St Jacques, Sauchyn, & Zhao, 2010's work).

Finally, the MLP research teams might well focus on enabling the automated mastering of image triplets resulting in images of equal width and height (in pixels), continuing the development of computer visioning and analytical software, measuring the margin of error in using colour to black-and-white comparison compared to black-and-white to black-and-white comparison, and establishing a well-defined baseline land cover classification scheme for image analytics in the collection (for continuity and comparability amongst studies).

## 5.7 Concluding remarks

This thesis grappled with the challenge of understanding dynamic ecosystems through a study of land cover transformations over the past 130 years in the Bow watershed of Alberta. A particular focus was given to the relationship between land cover transformations and flooding, while the discussion expanded into some ideas for intervening in ecosystems undergoing rapid change.

A major flood event happened in the study area despite the massive buffering effect of a huge shift in the % cover of forest in the Bow and Elbow basins over the past century. Climate change threats are looming. These factors combined do not form a promising picture for flood damage mitigation in the near future. Floods will continue to occur in this region; this is out of our control. However, what we do about mitigating flood damage is certainly within our grasp.

We live in a rapidly changing world, where the need to understand ecosystems and how they change through time is becoming more prominent. Much of the discourse around our present epoch, the Anthropocene, focuses on global environmental impacts caused by human activity (J. Wu, 2013). As we move into an era of increased uncertainty and global environmental change, we must use all forms of knowledge and evidence to better understand our relationship with the landscape and its relationship with us.

The results of this study further illustrate that repeat photography can be used to inform policymaking. Policy should always be based on the best available evidence; in this case, the photographs represent the evidence of a changing landscape. Policies concerning the management of the landscape must be based on a clear understanding of what is to be achieved and these goals have to be possible in practice. Ultimately, good policy brings us back to the introduction of this thesis — a parallel care for humans and enveloping ecosystems, using available resources. Priority areas should include a plan to stop development on the floodplains of the Bow, monitoring of precipitation, runoff, storage in headwaters, soil moisture and forest cover throughout the watershed, a climate change mitigation plan as well as watershed resiliency and restoration program, improvements to the weather monitoring, prediction and reporting systems for the province, and finally, land-use planning that promotes biodiversity and the restoration of key ecosystem processes such as fire.

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## Appendix A – Station Lists

**Table A-1. Elbow Stations with third views completed in 2014**

Station Name	Surveyor	Year	# of triplets	Image ID	GPS Coordinates	Mapper
Forget-me-not-ridge	Wheeler	1897, 2008, 2014	2	W97-22-8 B0001668 2356 W97-23-8 B0001670 2363	50°47'41.838"N 114°48'45.45"W	Tanya
Moose Mt. Central	Wheeler	1896, 2008, 2014	1	W96-12-3 B0001672 A0006820	50°56'19.6"N 114°50'17.9"W	Tanya
Moose Mt. West	Wheeler	1896, 2008, 2014	3	W96-2-4 B0001687 A0006817 W96-4-4 B0001684 A0006811 W96-3-4 B0001685 A0006818	50°55'50.5"N 114°50'34.7"W	Tanya
North Quirk	Wheeler	1897, 2008, 2014	2	W97-13-7 B0001573 2432 W97-24-6 B0001570 2425	50°51'8.73"N 114°46'47.982"W	Tanya
Prairie Creek	Wheeler	1897, 2008, 2014	2	W97-13-6 B0001524 6925 W97-14-6 B0001522 6921	50°53'33.51"N 114°48'48.438"W	Tanya
South Quirk	Wheeler	1897, 2008, 2014	2	W97-15-7 B0001593 2472 W97-16-7 B0001598 2480	50°49'37.95"N 114°45'8.37"W	Tanya
The Knob	Wheeler	1895, 2008, 2014	1	W95-8-5 B0001714 2461	50°43'35.16"N 114°50'36.954"W	Tanya

**Table A-2 Bow Stations with third views completed in 2014**

Station Name	Surveyor	Year	# of triplets	Image ID	GPS Coordinates	Mapper
Gap Lake	McArthur	1890, 2009, 2014	1	4-3-90 A0003769 2912	51°3'30.156"N 115°14'57.966"W	Assistant
Grotto Mt	McArthur	1889, 2010, 2014	3	11-3-89 A0004984 7987 9-3-89 A0004986 7982 90-10-3 A0004982 7979	51°5'41.0"N 115°16'57.0"W	Assistant
Mt. Baldy	McArthur	1889, 2009, 2014	2	17-7-89 A0003653 6989 17-8-89 A0003652 7009	51°0'45.0"N 115°3'2.0"W	Assistant
Mt. Lady MacDonald	McArthur	1890, 2009, 2014	2	5-4-89 A0003979 5118 6-6-90 A0003978 5122	51°7'19.596"N 115°19'1.452"W	Assistant
Mt. Lawrence Grassi South	McArthur	1889, 2008, 2014	1	11-2-89 A0004303 A0007051	51°2'55.0"N 115°21'36.0"W	Assistant
Tunnel Mt North No. 1	McArthur	1888, 2008, 2014	4	17-1-88-188 B0002600 2947 17-2-88-189 B0002603 2959 8-7-88-88 B0002568 2972 8-9-88-90 B0002575 2953	51°10'43.59"N 115°33'22.044"W	Assistant

**Table A-3 Regional Stations included in the analysis**

Station Name	Surveyor	Year	# of pairs	Image ID	GPS Coordinates	Mapper
All Smoke	Wheeler	1895, 2008	1	W95-13-5 B_1694	50°44'39.0''N 114°41'22.0''W	Assistant
Cascade	McArthur	1888, 2008	1	19-6-88 B0002503	51°13'42.7''N 115°33'46.4''W	Tanya
Highwood Gap	Wheeler	1897, 2008	1	W97-4-17 B0002133	50°23'9.0''N 114°35'55.0''W	Assistant
Jumping Pound Summit	Wheeler	1896, 2008	3	W96-9-4 B0001556 W96-12-4 B0001559 W96-10-4 B0001553	50°57'3.129501''N 114°54'29.059818'' W	Assistant
Kananaskis Lake South	Wheeler	1914, 2007	3	WHE14-8 B00107 W14-6 B00112 W14-7 B00117	50°35'11.0''N 115°7'39.0''W	Tanya
Marvel Lake	Wheeler	1913, 2010	3	13-274 A0004892 13-273 A0004891 W13-277 A0004897	50°53'40.32''N 115°33'28.26''W	Tanya
Marvel Lake No.2	Wheeler	1913, 2010	2	W13-279 A0004903 W13-280 A0004902	50°53'40.944''N 115°33'30.468''W	Tanya
Mt Alymer East	McArthur	1888, 2009	1	22nd-12-88 A0003839	51°17'55.0''N 115°22'52.0''W	Assistant
Mt.Indefatigable	Dowling	1905, 2009	3	D0W_191 A0003786 DOW_194 A0003775 DOW_193	50°39'27.174''N 115°9'50.916''W	Tanya

				A0003783		
Nichi	Wheeler	1896, 2008	1	W96-23-1 B0001690	50°45'7.472653''N 114°44'50.373584'' W	Assistant
Pakakos Mt North	McArthur	1888, 2009	2	28th-2-88 A0004325 28th-4-88 A0004323	51°19'21.648''N 115°19'55.14''W	Tanya
Phantom Crag East	McArthur	1888, 2009	2	27th-1-88 A0003956 27th-12-88 A0003960	51°17'29.97''N 115°10'12.63''W	Tanya
Powderface Ridge	Wheeler	1897, 2008	1	W97-20-9 B0001718	50°50'40.718126''N 114°50'55.68976''W	Assistant
Sinnot 1	Wheeler	1895, 2008	2	W95-22-5 B0001550 W95-21-5 B0001545	50°43'14.081149''N 114°31'52.038196'' W	Assistant
Sulphur Ridge North	McArthur	1888, 2008	2	12-1-88-128 B0002634 11-10-88-125 B0002627	51°8'49.79''N 115°34'42.55''W	Tanya
Sulphur Ridge South	Wheeler	1914, 2008	3	12-7-88-134 2617 12-4-88-131 B0002612 12-5-88-132 B0002614	51°5'42.94''N 115°31'48.03''W	Tanya
Summit North of Coxhill	Wheeler	1897, 2008	1	W97-3-3a B0001732	51°1'1.151035''N 114°58'34.28128''W	Assistant
The Turret	Dowling	1905, 2009	2	DOW_198 A0004297 DOW_197 A0004299	50°36'9.516''N 115°6'53.382''W	Tanya
Twin Cairns	McArthur	1890, 2010	1	11-6-90 A0004735	51°4'19.2''N 115°48'18.0''W	Assistant

## Appendix B- 2014 Field Crew

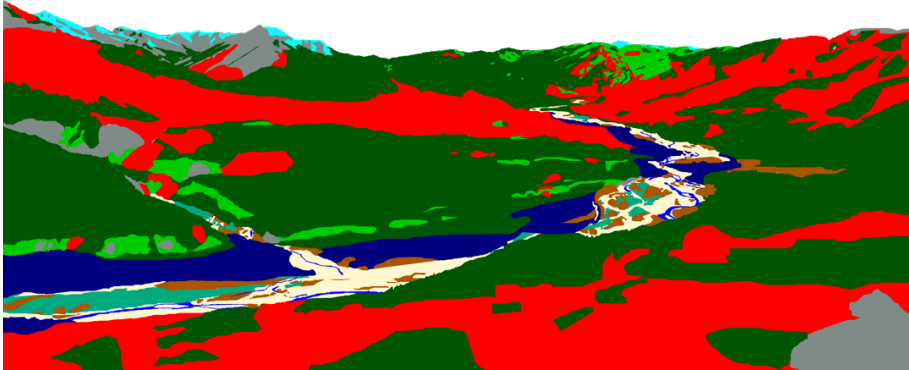


[Left to Right] Rob Watt, Mary Sanseverino, Nicole Goodman, Vladmira Lackova, Eric Higgs, Kristen Walsh, Tanya Taggart-Hodge and Rick Arthur.

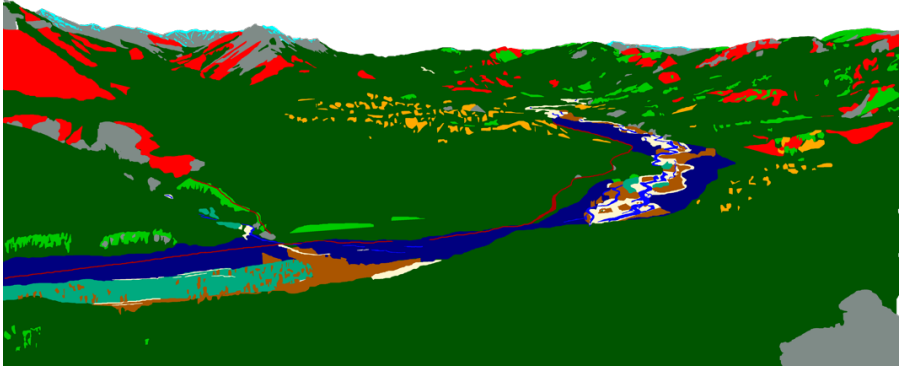
Appendix C – Image Masks

The Knob

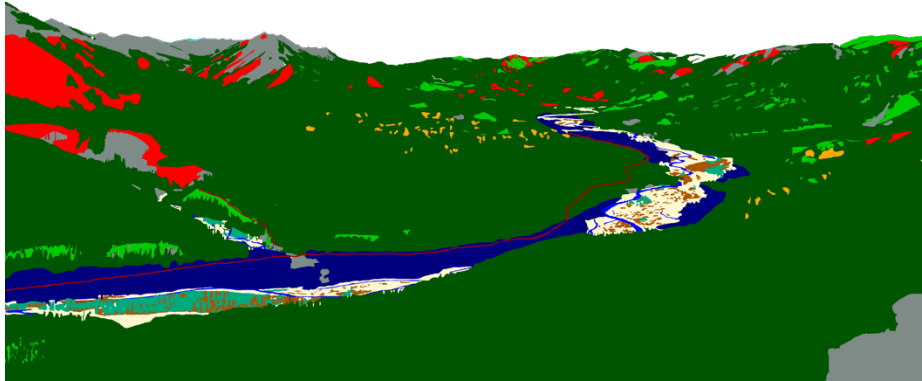
1895



2008

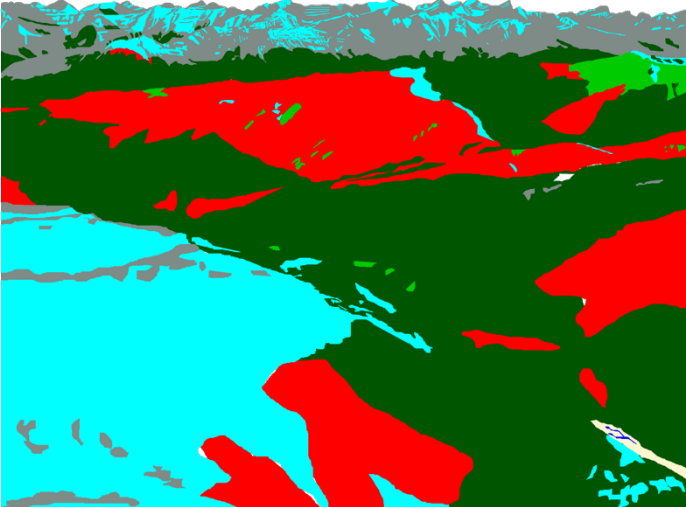


2014

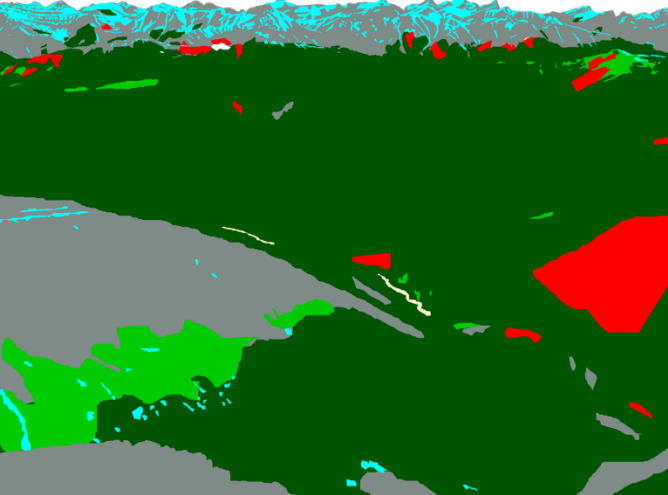


Moose Mt. Central

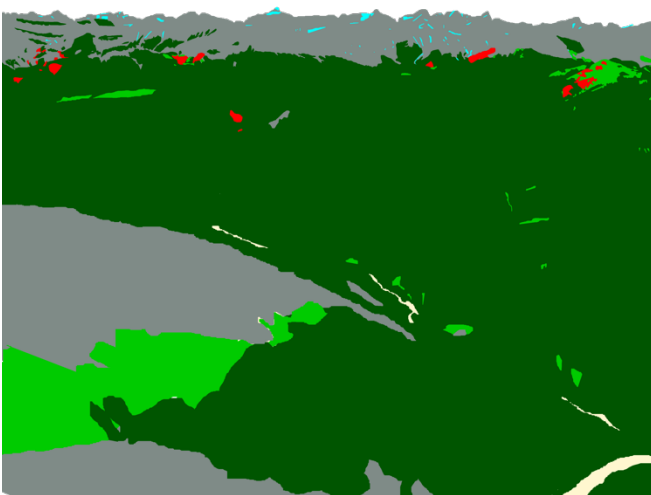
1895



2008

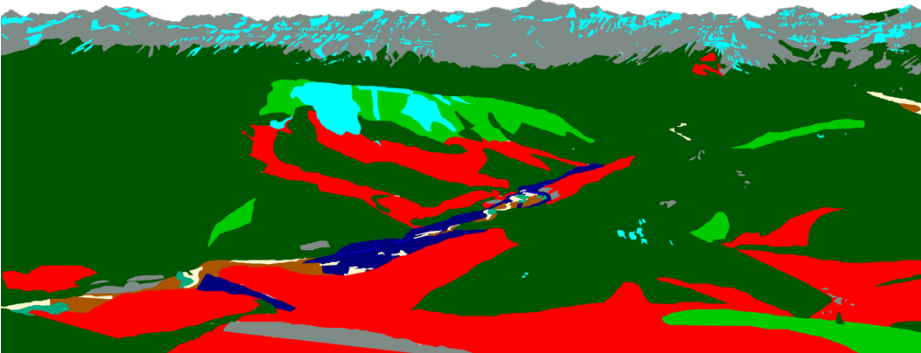


2014

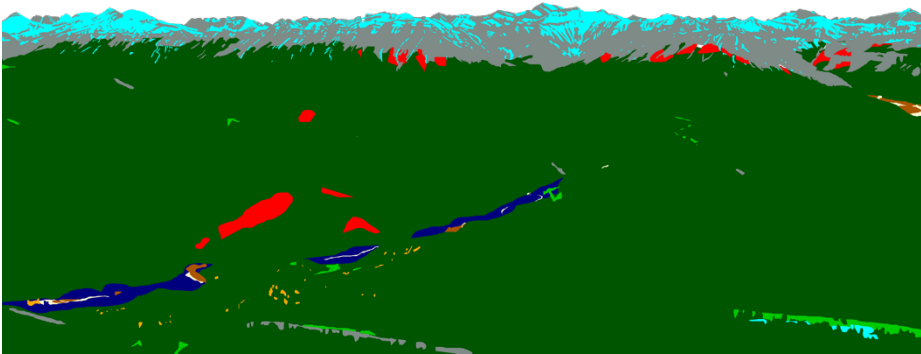


Moose Mt. West - 1

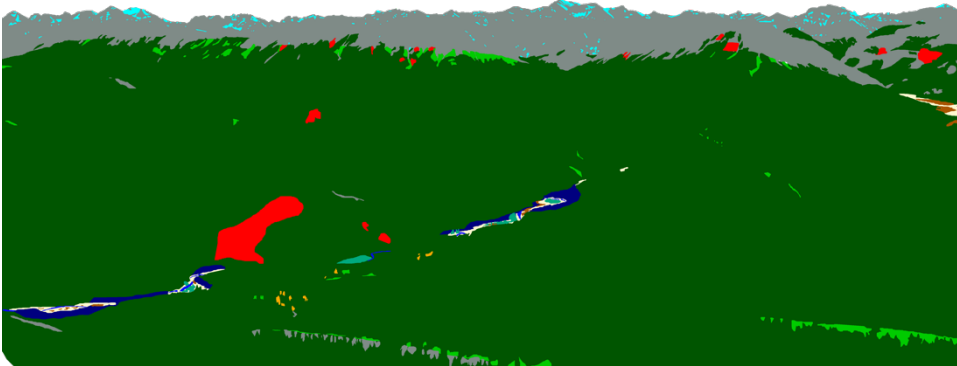
1896



2008

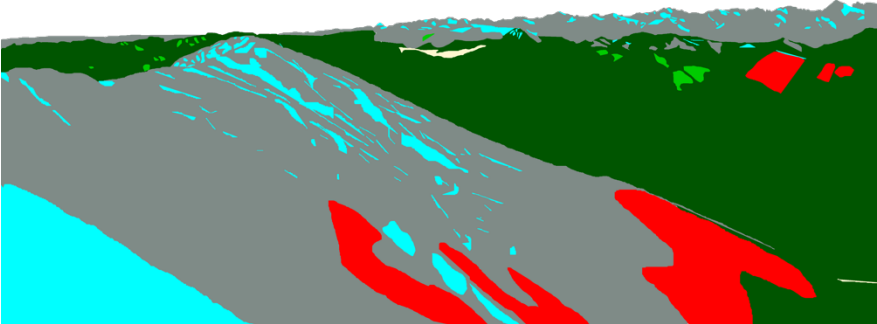


2014

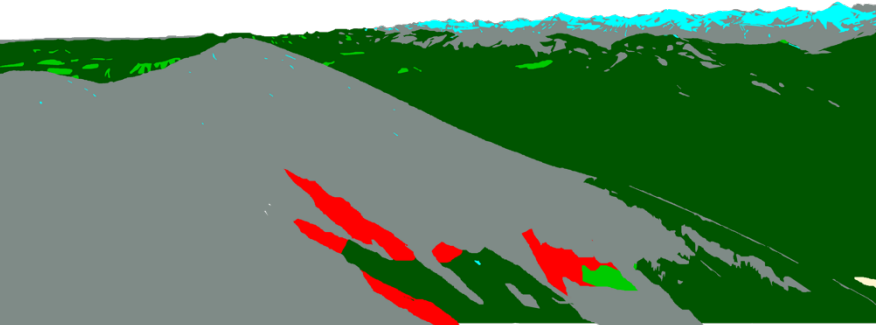


Moose Mt. West – 2

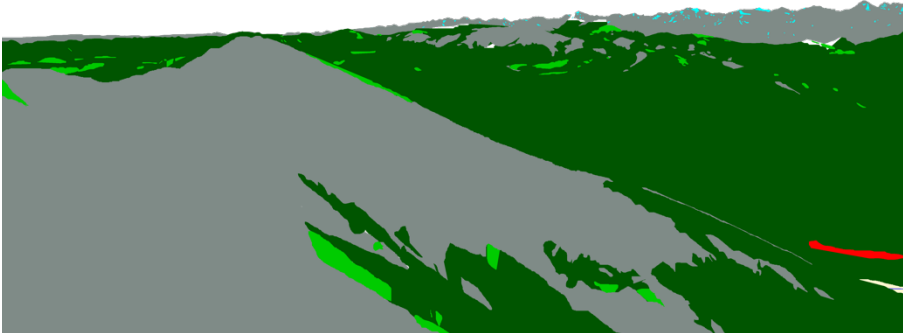
1896



2008



2014

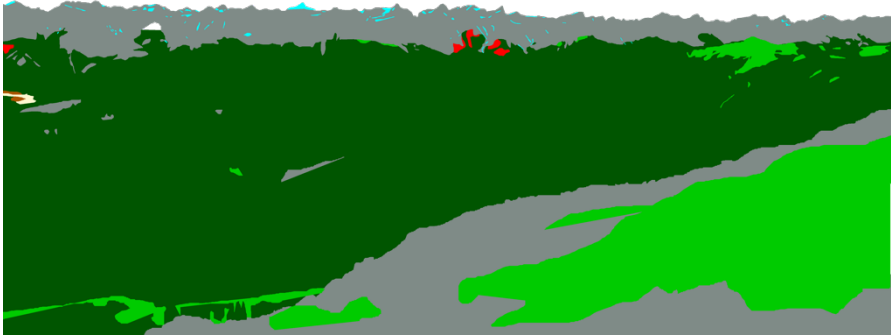


Moose Mt. West – 3

1896



2014



2008

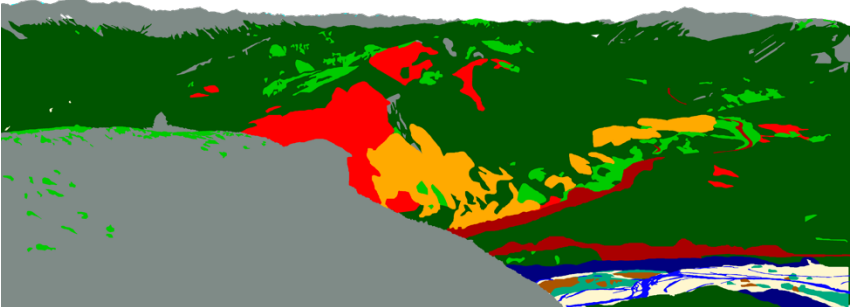


Forget-me-not-ridge - 1

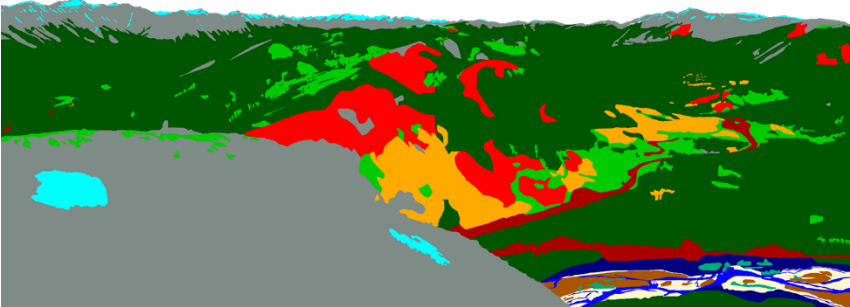
1897



2014

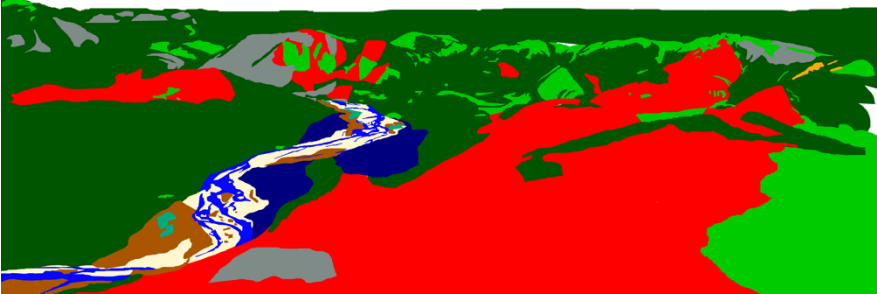


2008

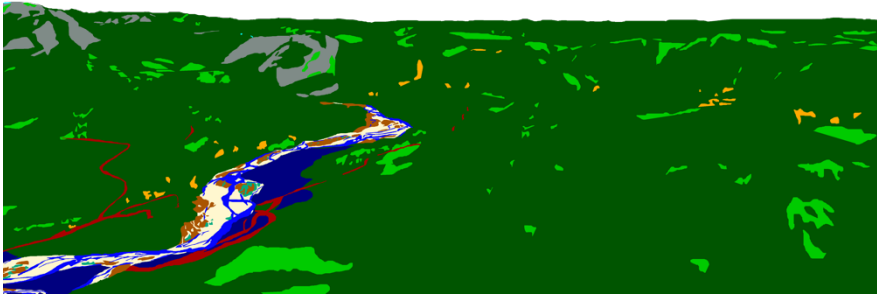


Forget-me-not-ridge – 2

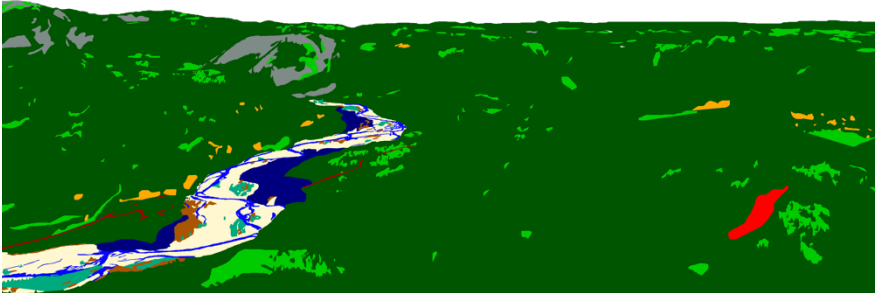
1897



2008

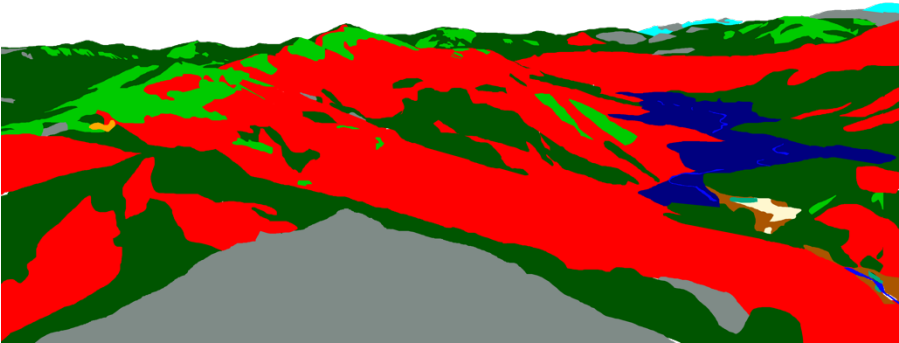


2014

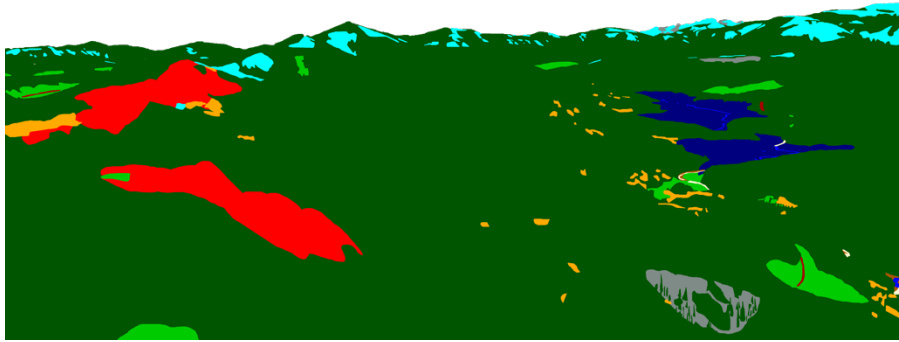


North Quirk – 1

1897



2008

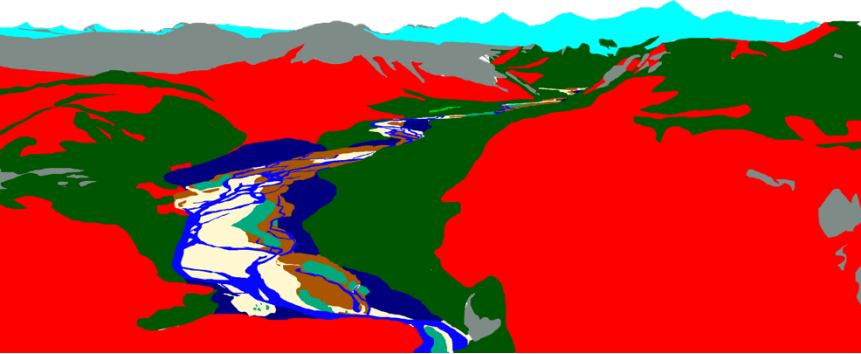


2014

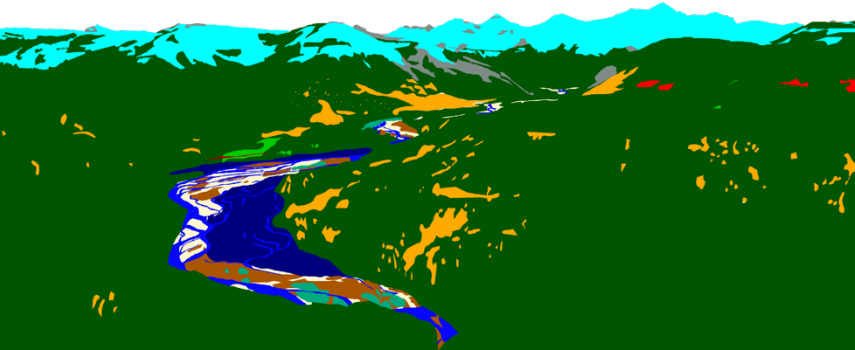


North Quirk – 2

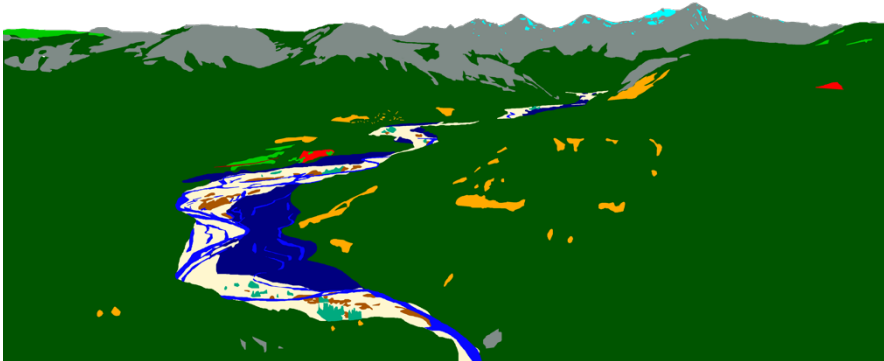
1897



2008



2014



Prairie Creek – 1

1897



2014

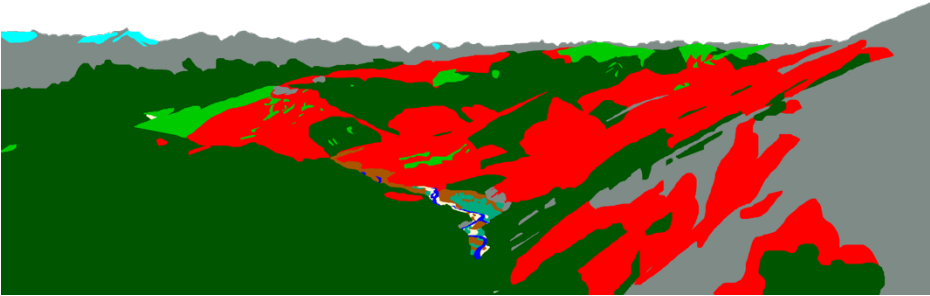


2008



Prairie Creek – 2

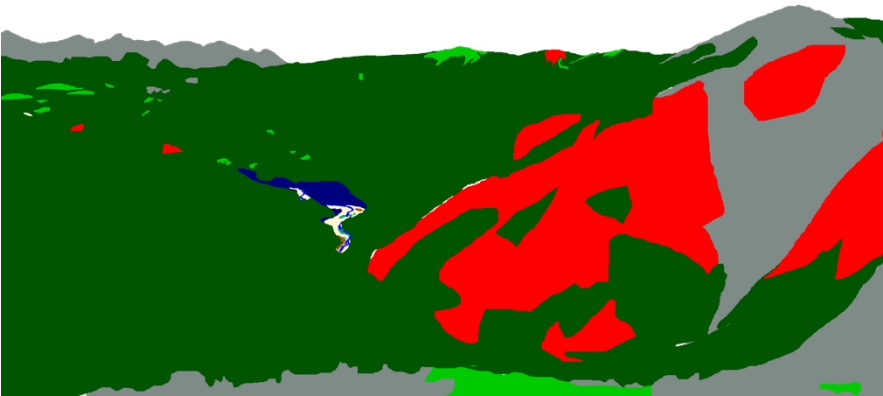
1897



2008



2014

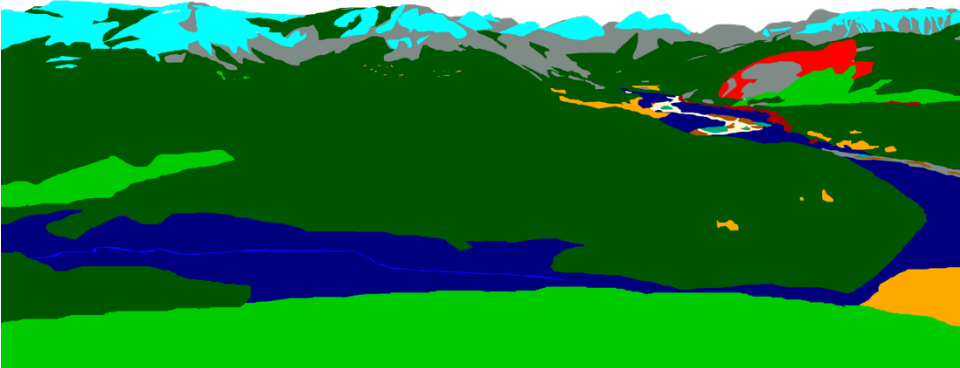


South Quirk – 1

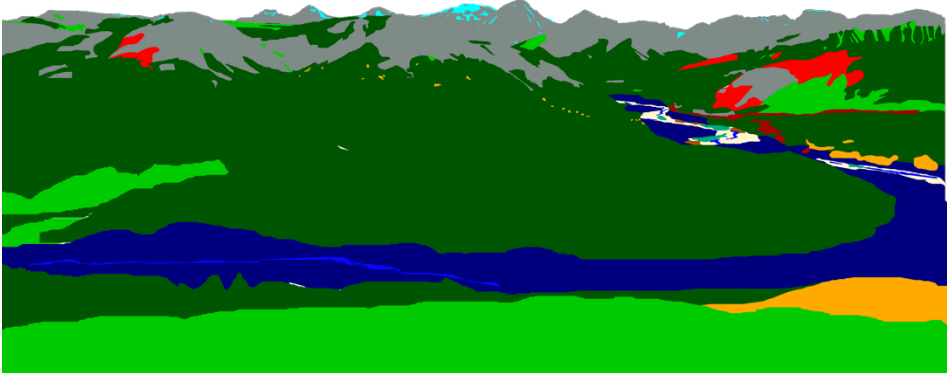
1897



2008

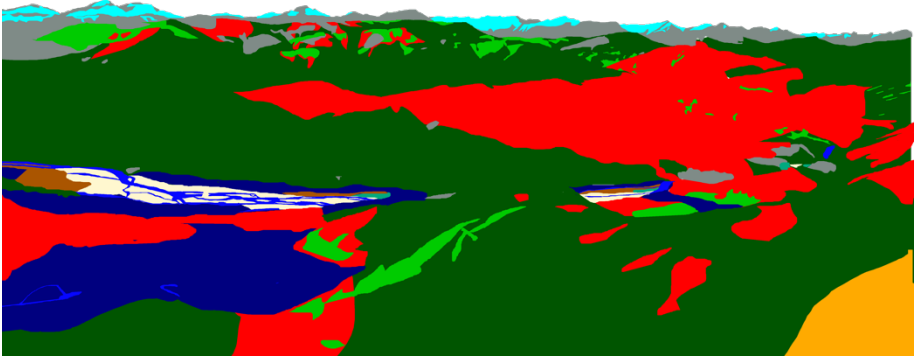


2014

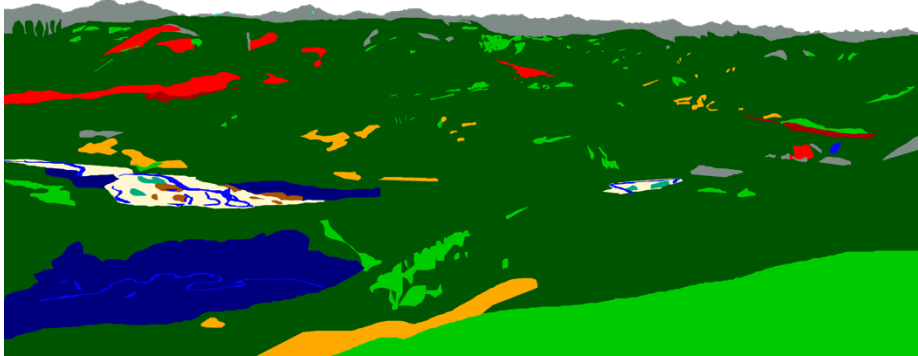


South Quirk – 2

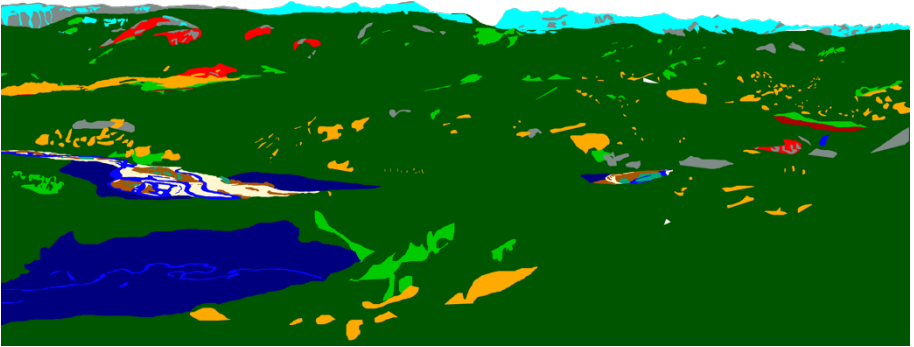
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2014

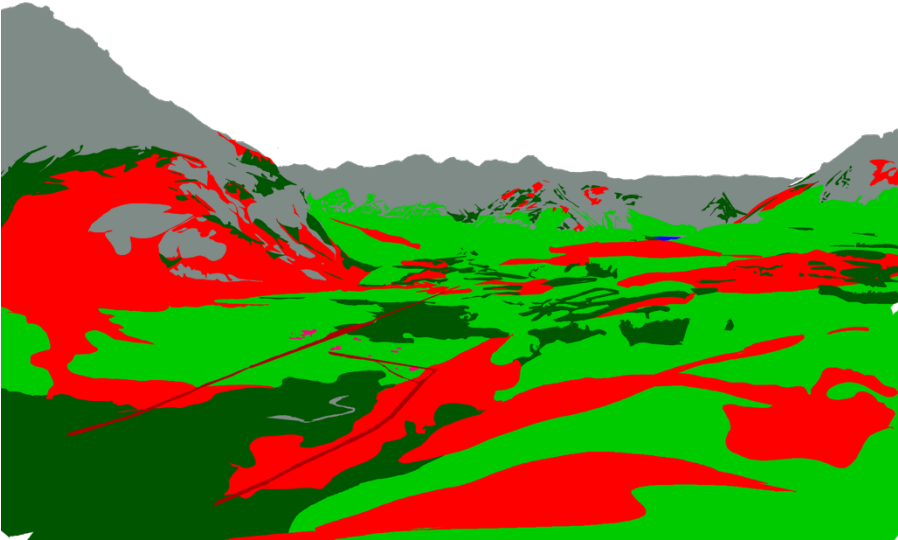


2008

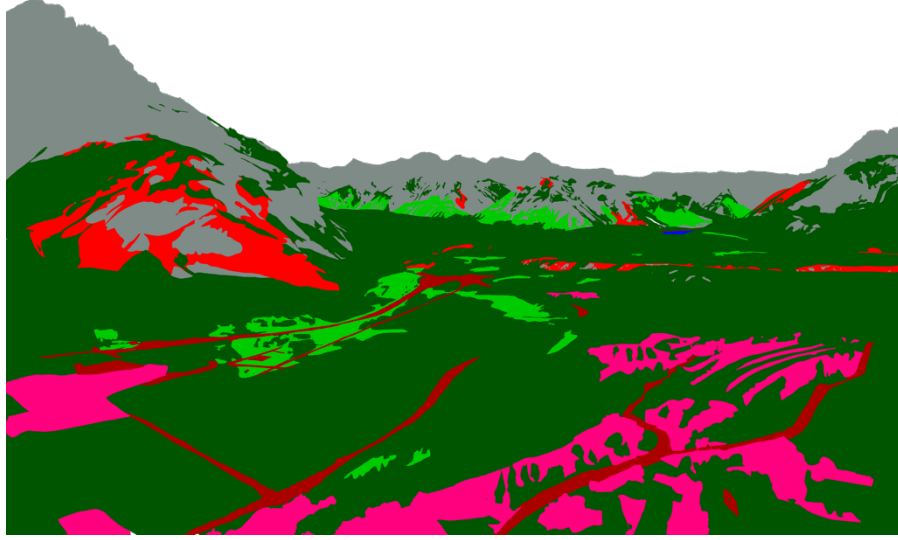


Tunnel Mt North – 1

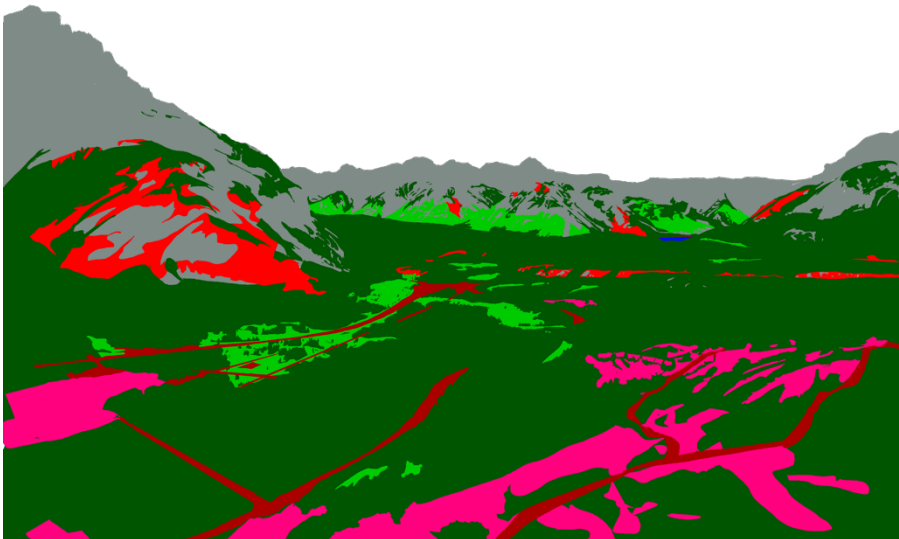
1888



2008

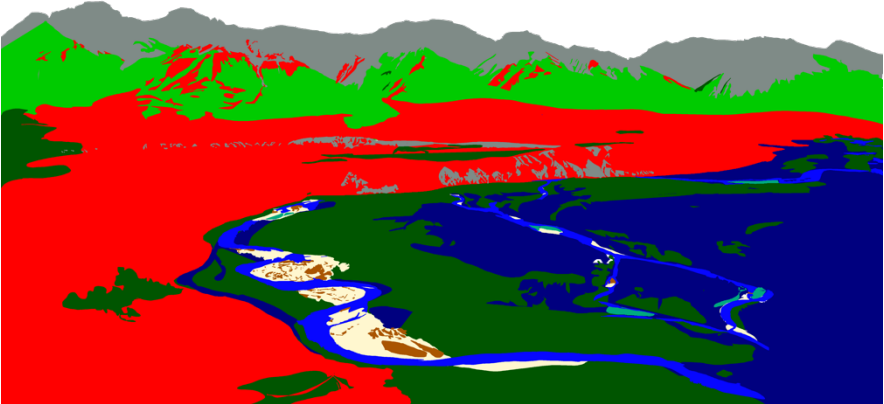


2014

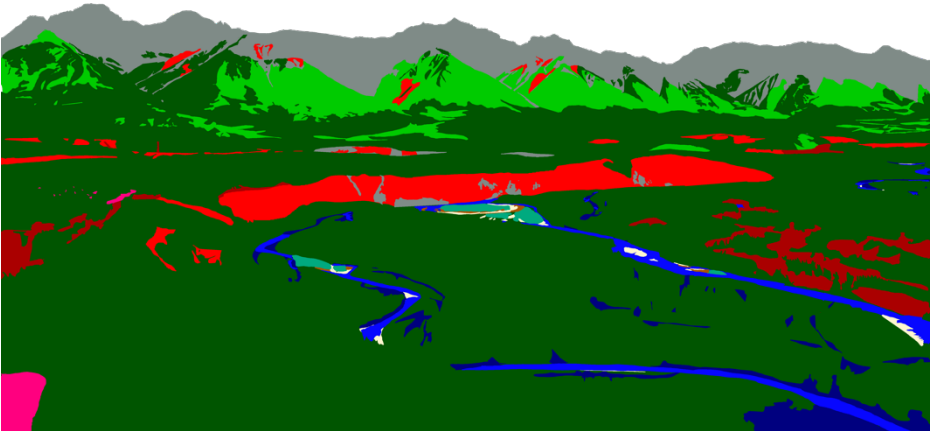


Tunnel Mt North – 2

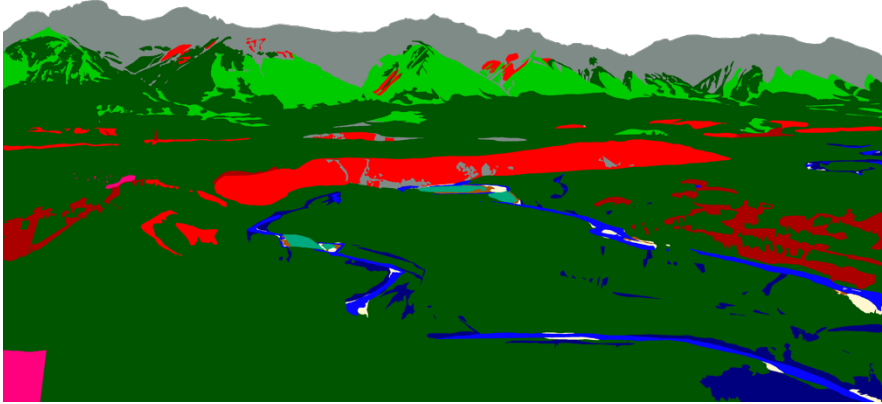
1888



2014

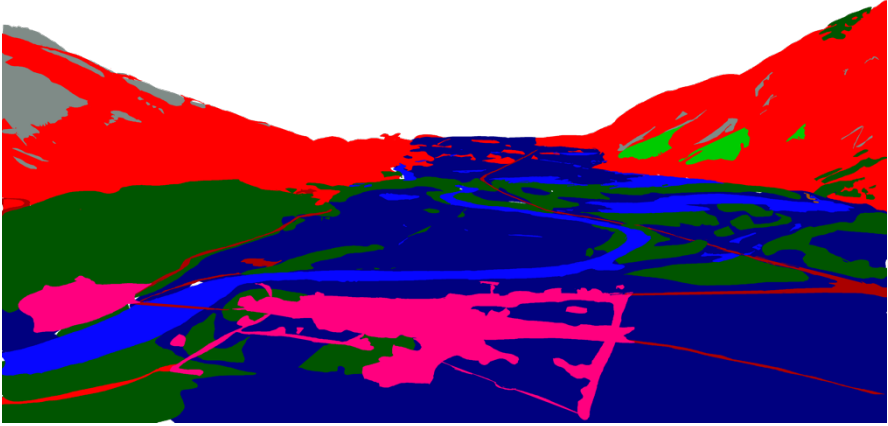


2008



Tunnel Mt North – 3

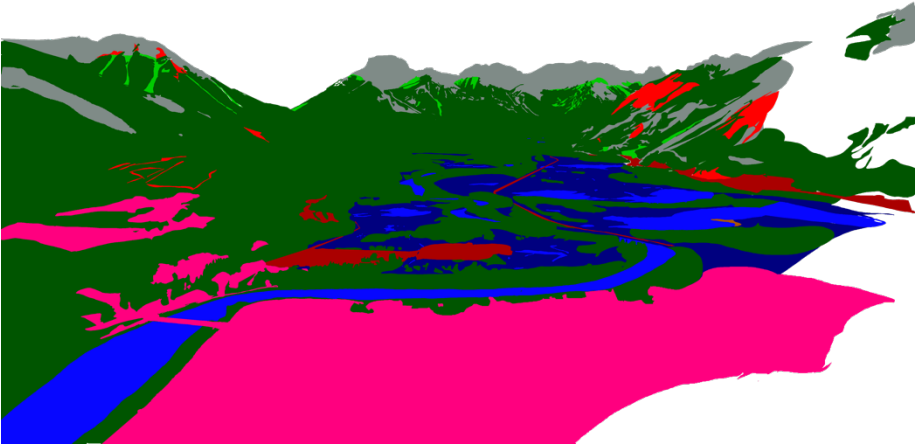
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2008

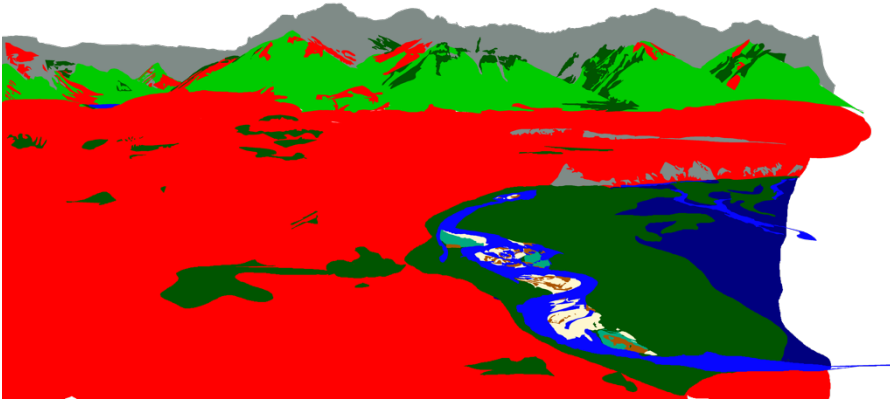


2014

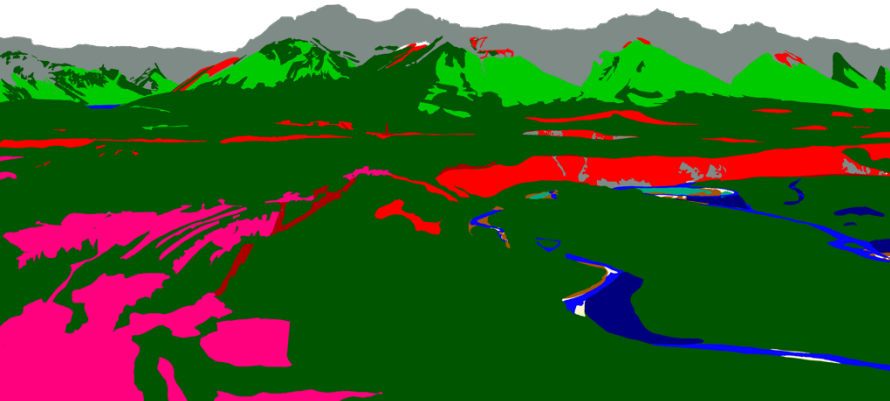


Tunnel Mt North – 4

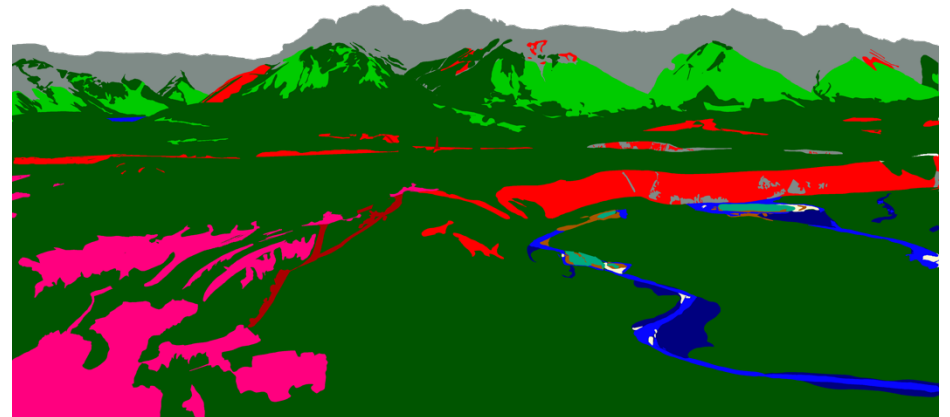
1888



2008

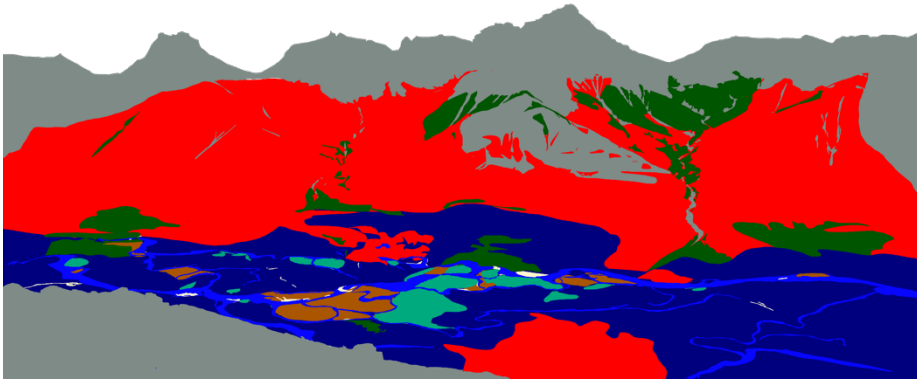


2014

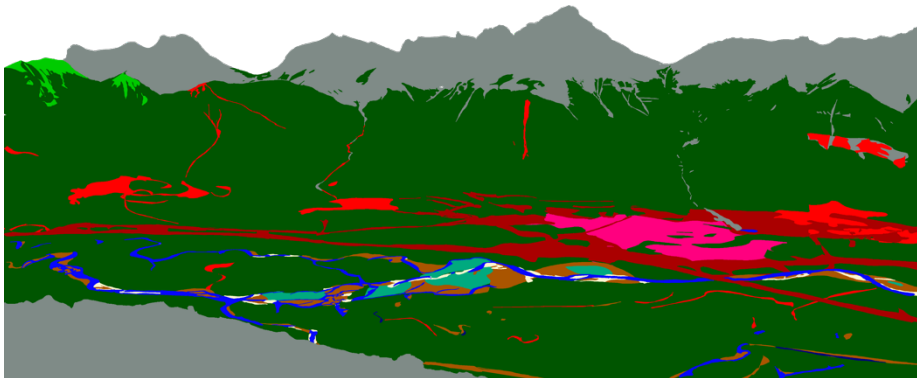


Grotto Mt – 1

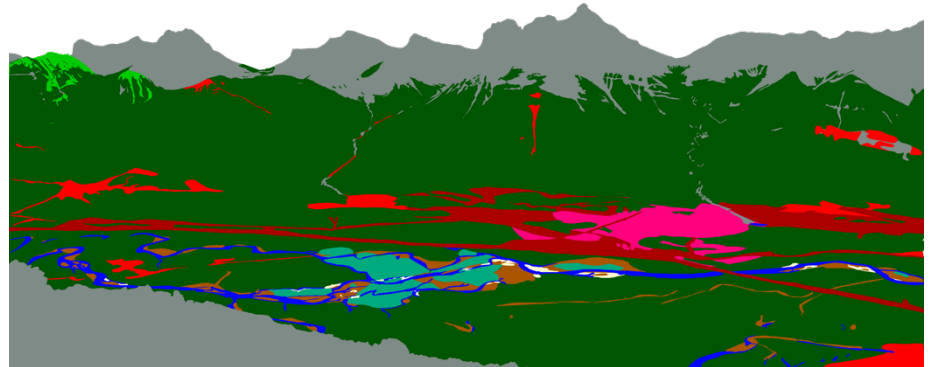
1889



2008

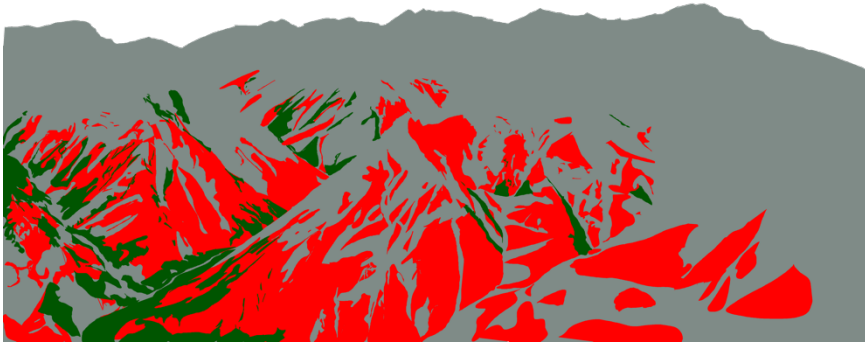


2014

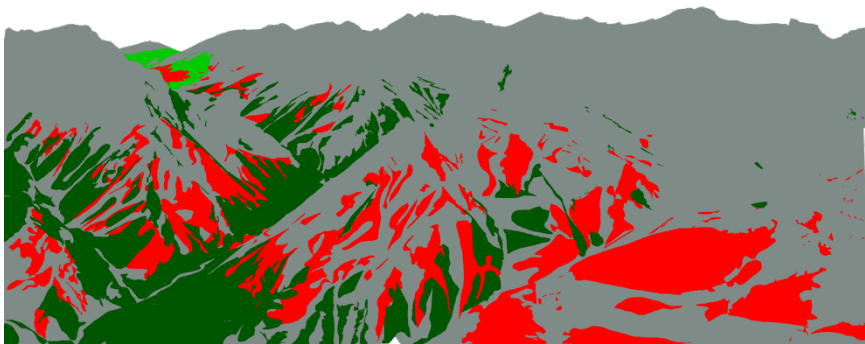


Grotto Mt – 2

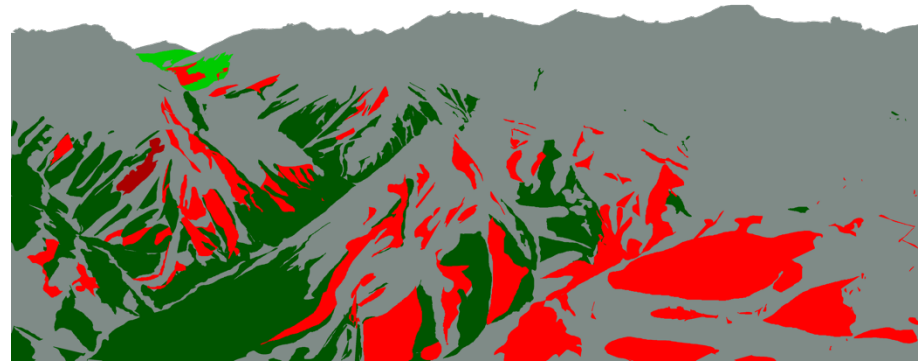
1889



2010

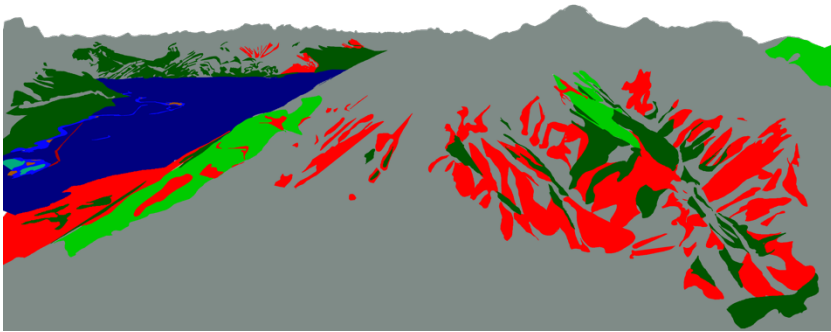


2014

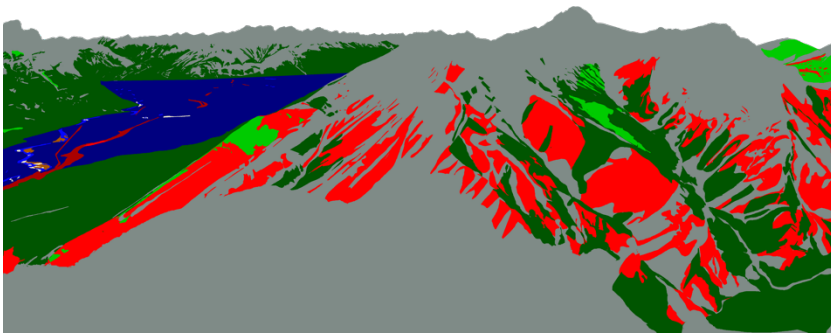


Grotto Mt – 3

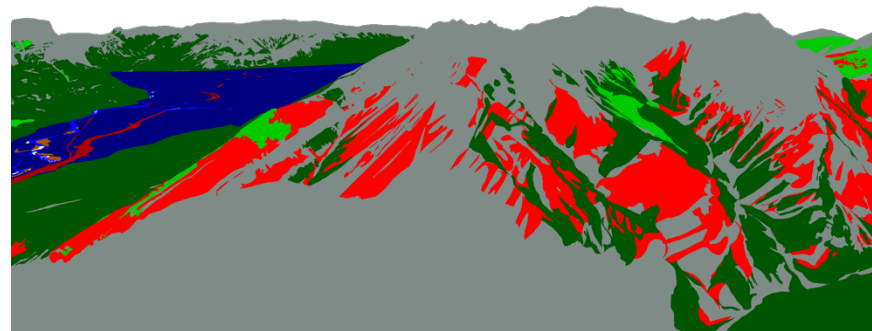
1890



2010

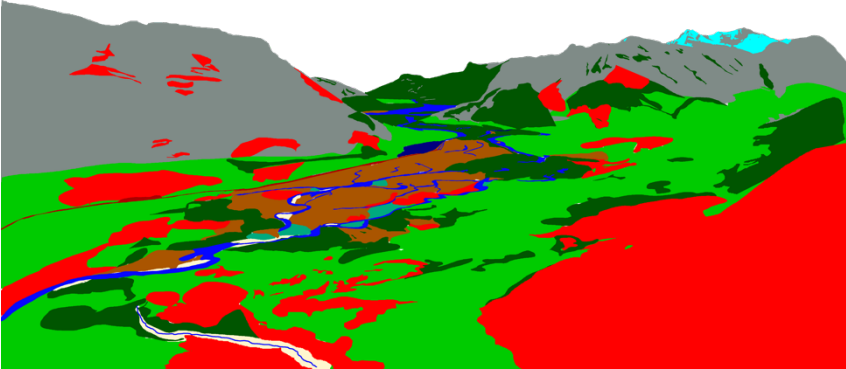


2014

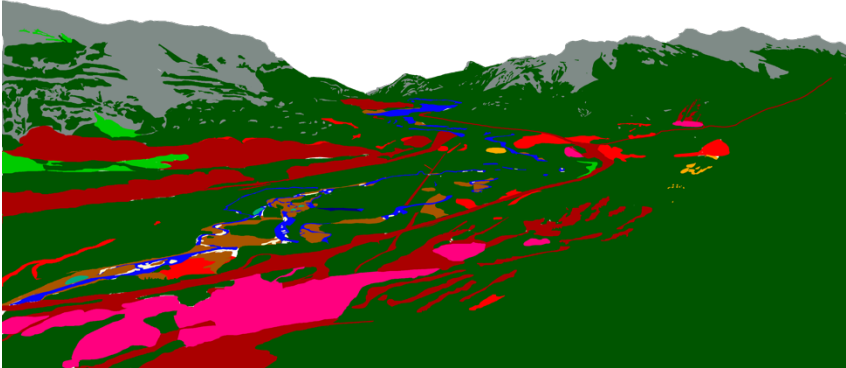


Mt. Lawrence Grassi South

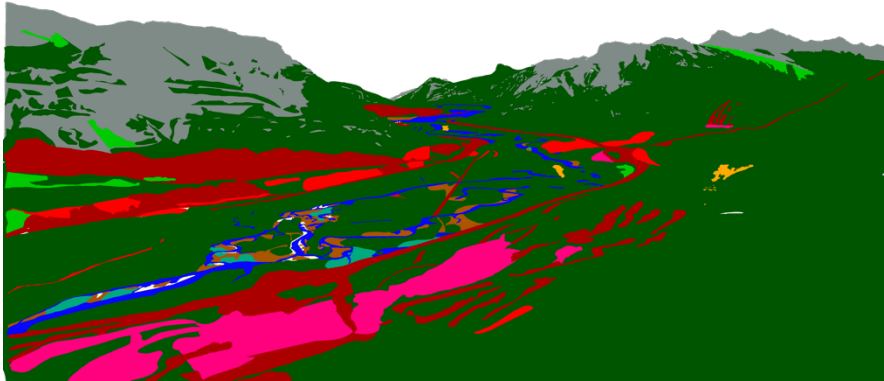
1889



2009

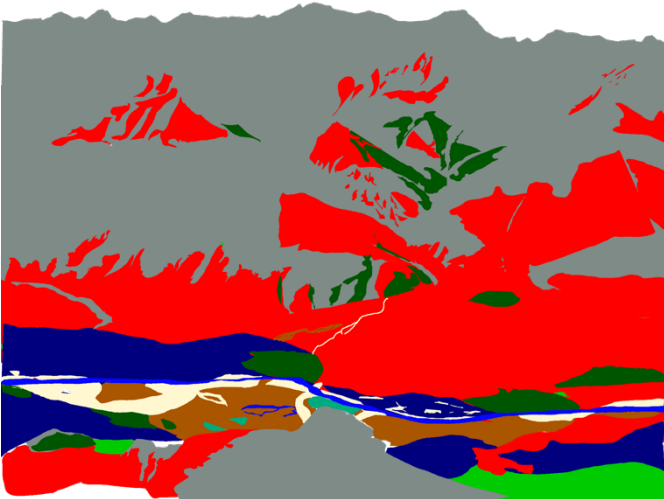


2014

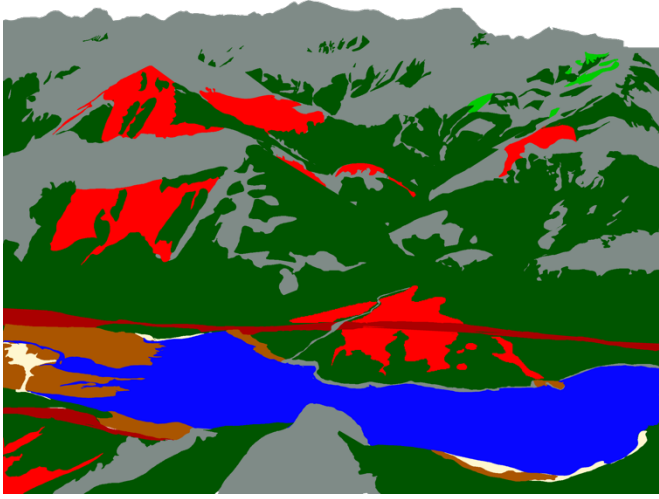


Mt. Baldy – 1

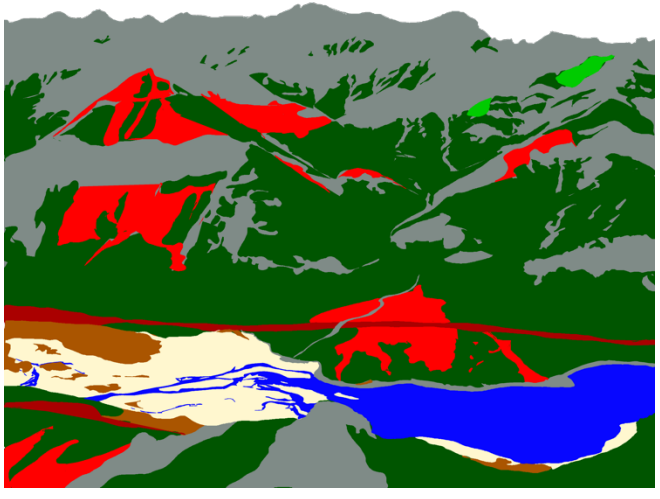
1889



2009



2014

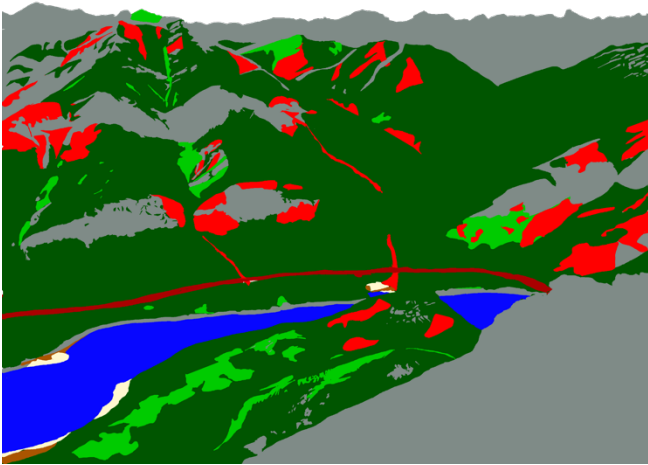
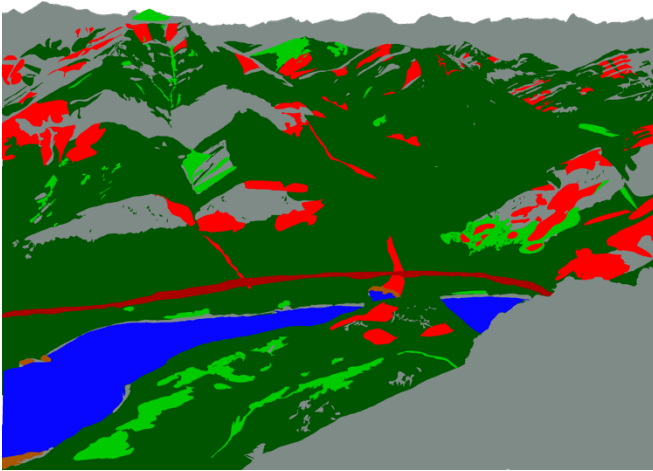
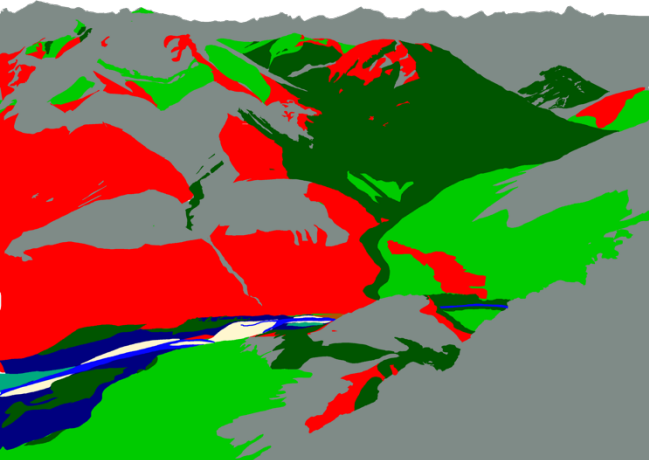


Mt. Baldy – 2

1889

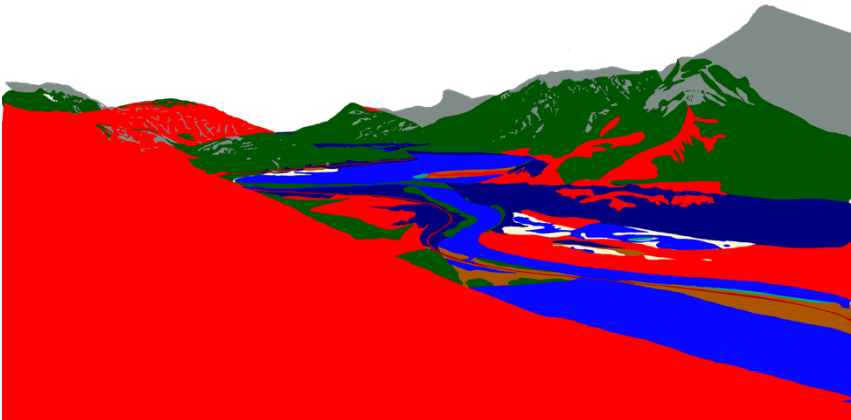
2009

2014

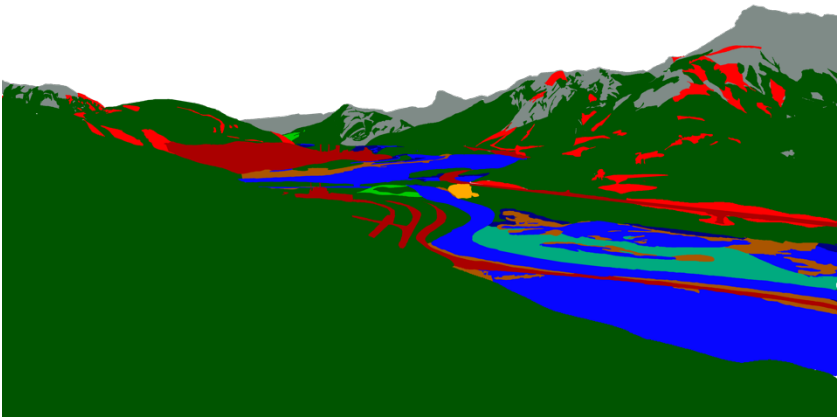


Gap Lake

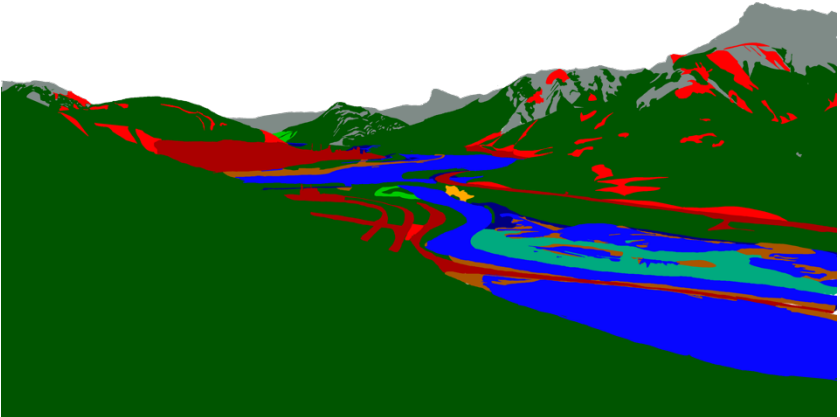
1890



2009

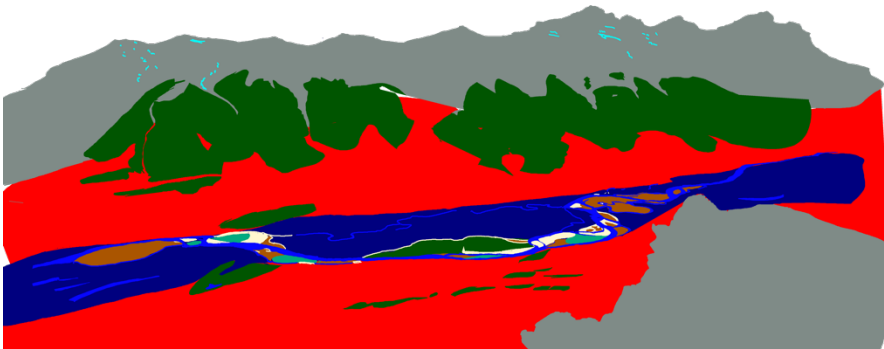


2014



Mt. Lady MacDonald – 1

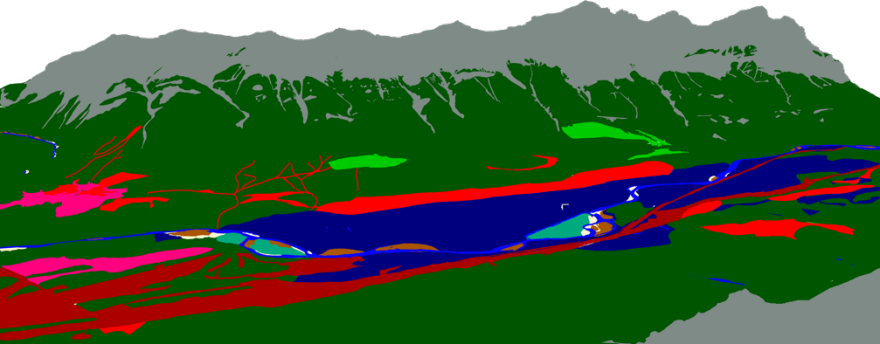
1889



2014

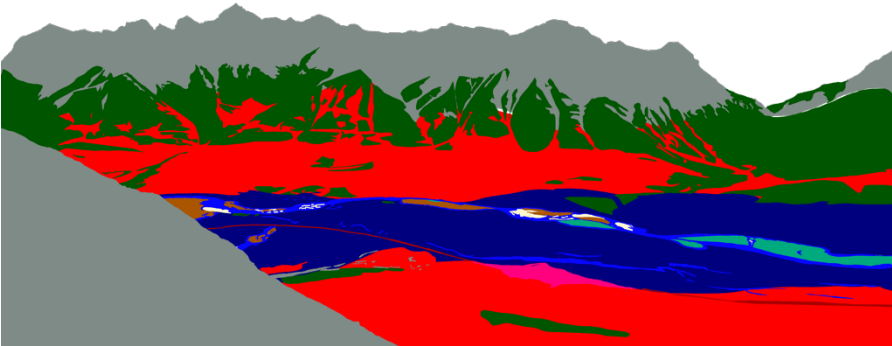


2009

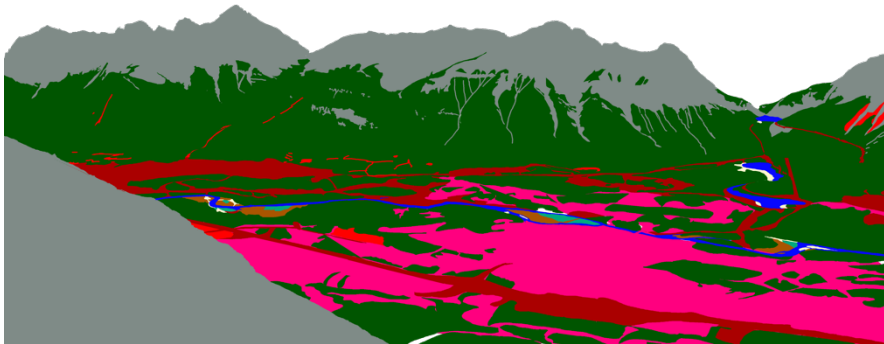


Mt. Lady MacDonald - 2

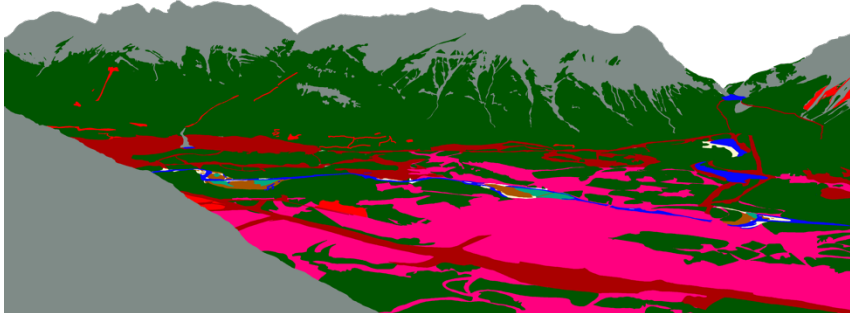
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2009

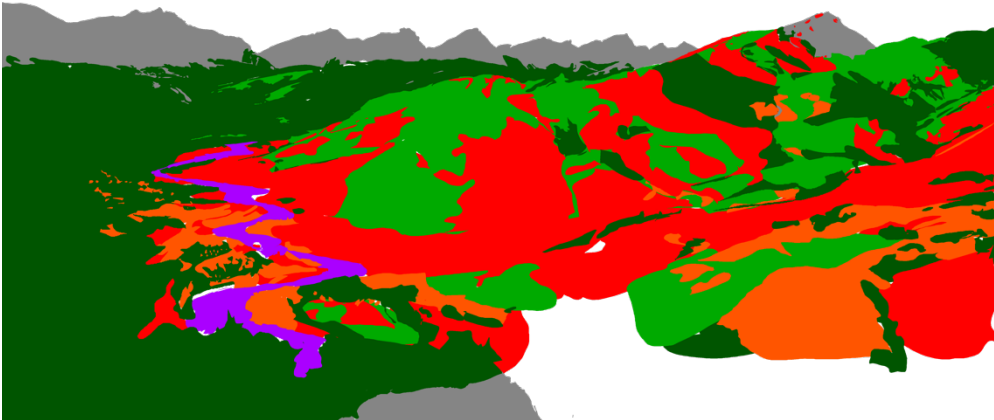


2014

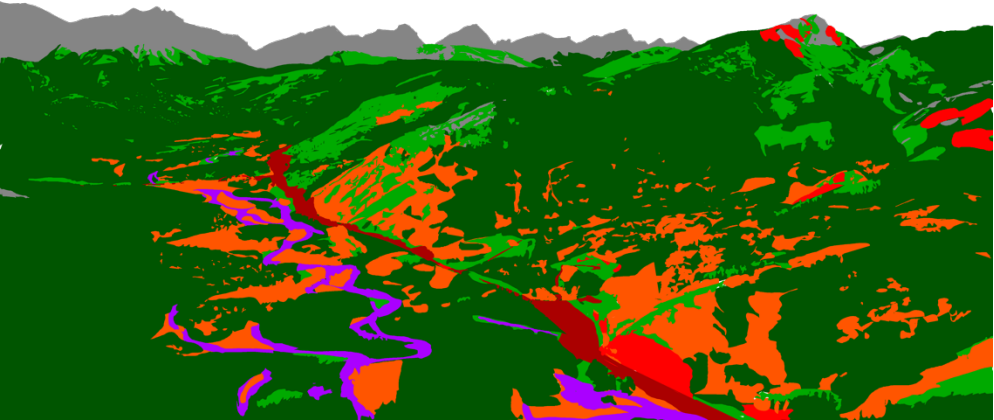


Highwood Gap

1897

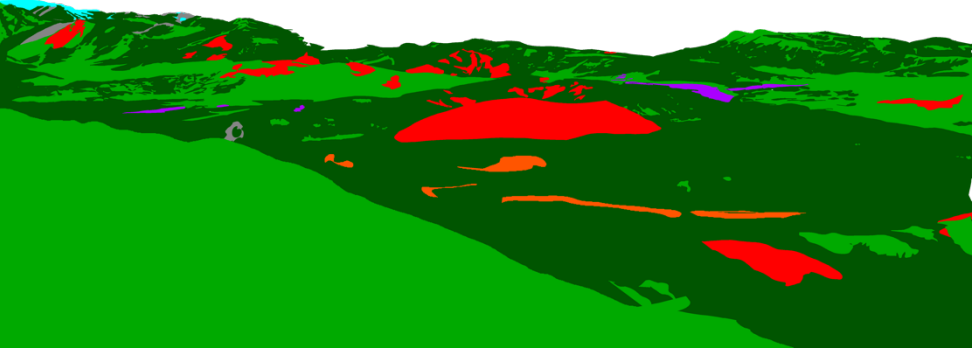


2008

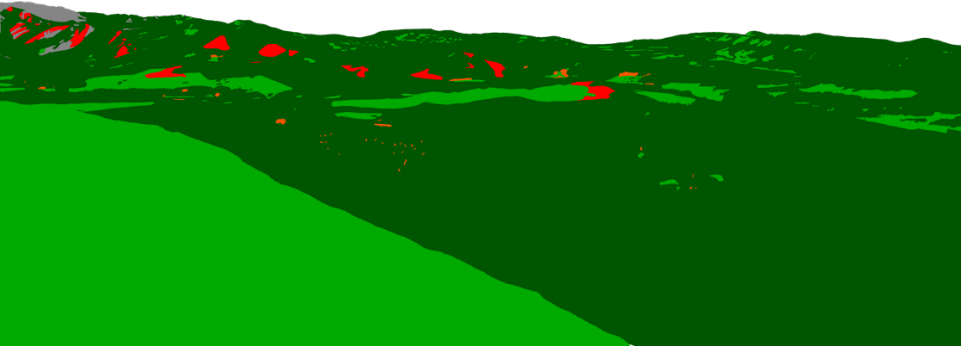


Nichi

1896

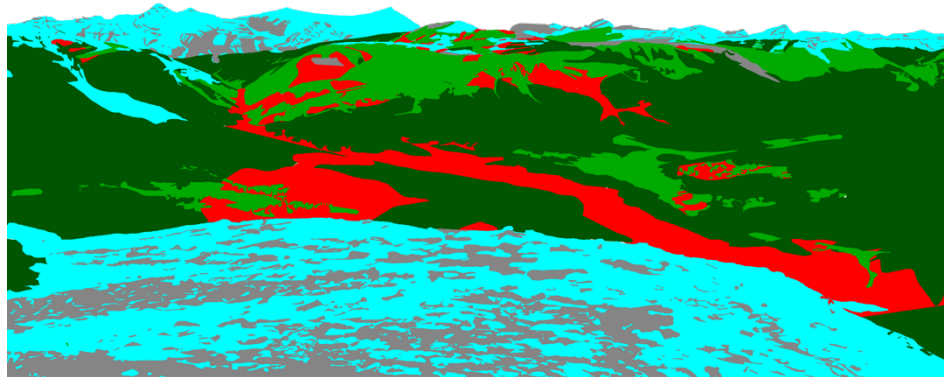


2008

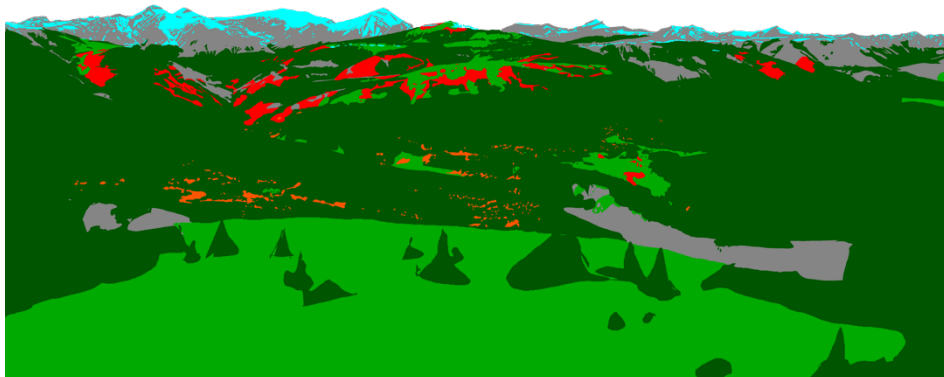


All Smoke

1895

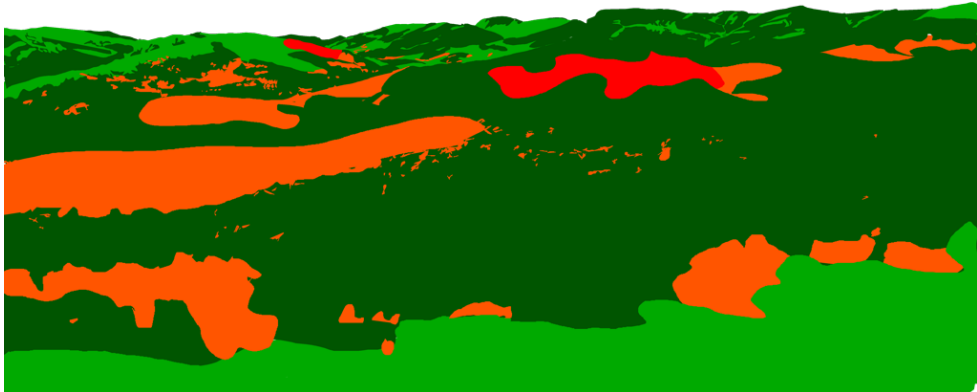


2008

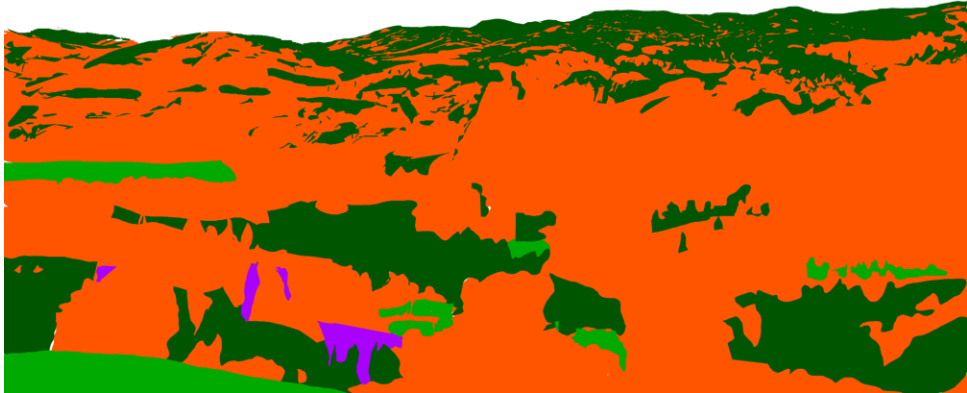


Sinnot 1 – 1

1895

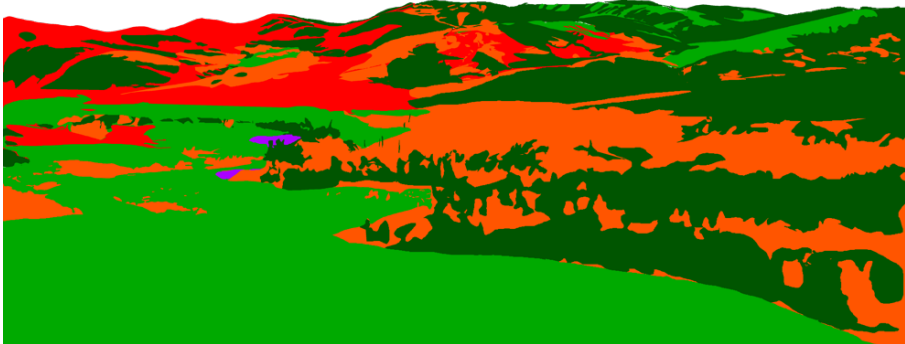


2008

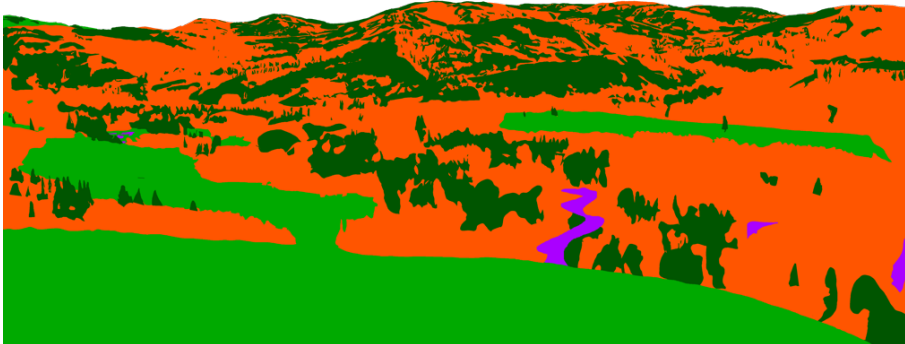


Sinnot 1 – 2

1895



2008

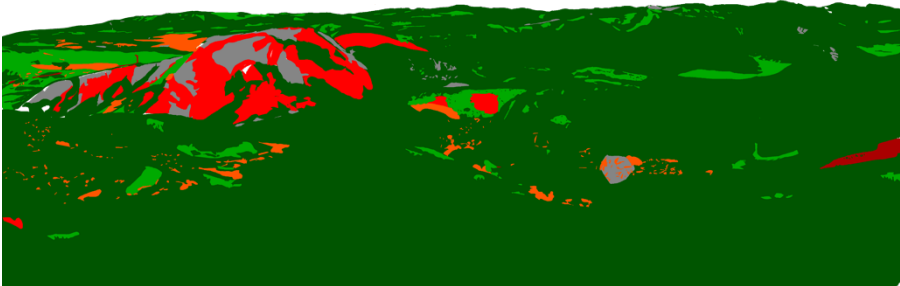


Powderface Ridge

1897

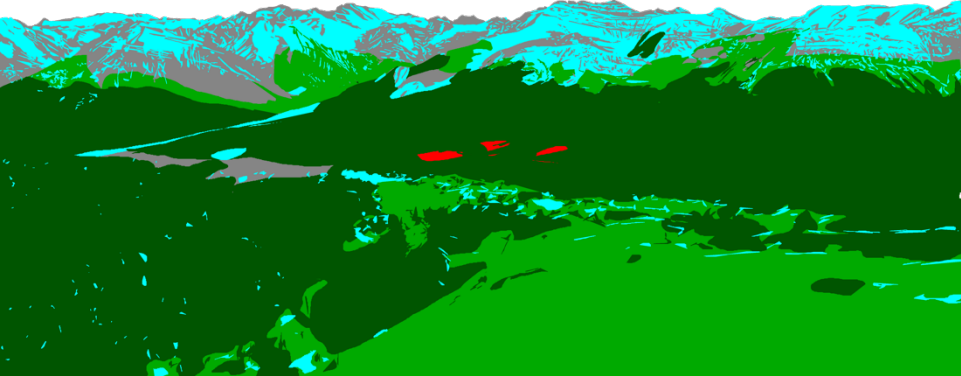


2008

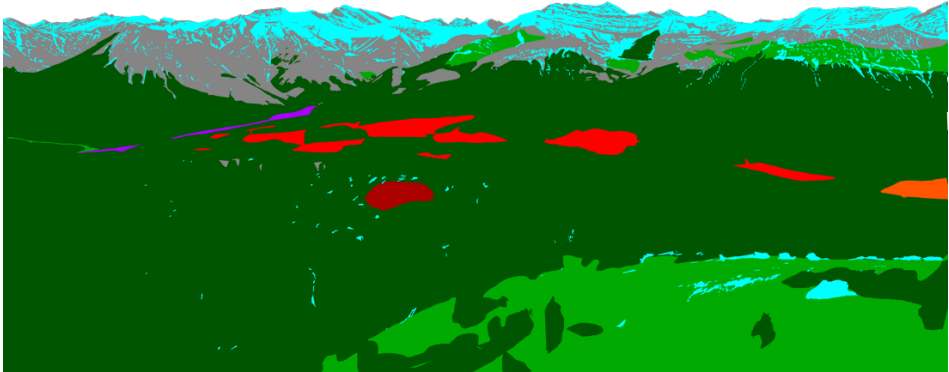


Jumping Pound Summit – 1

1896

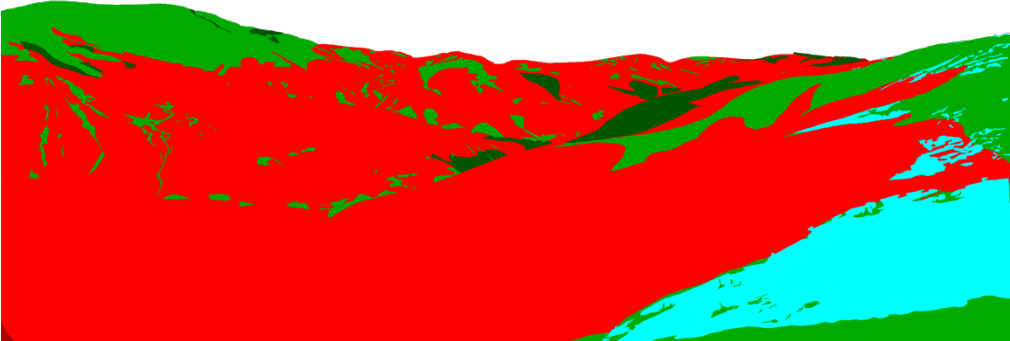


2008

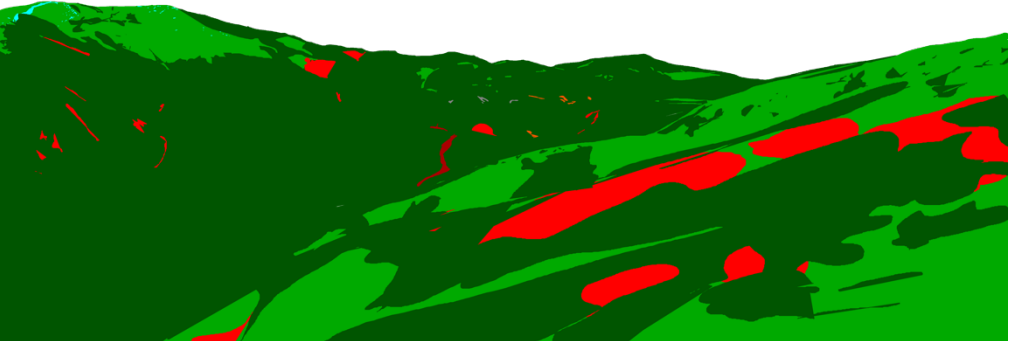


Jumping Pound Summit – 2

1896



2008

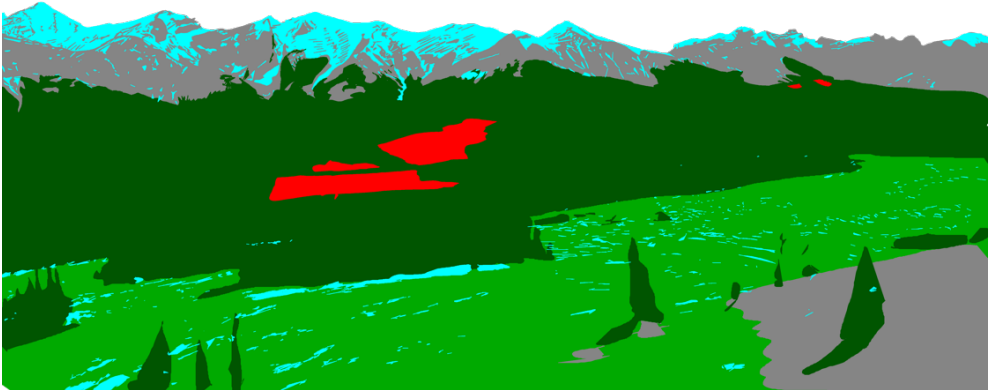


Jumping Pound Summit – 3

1896

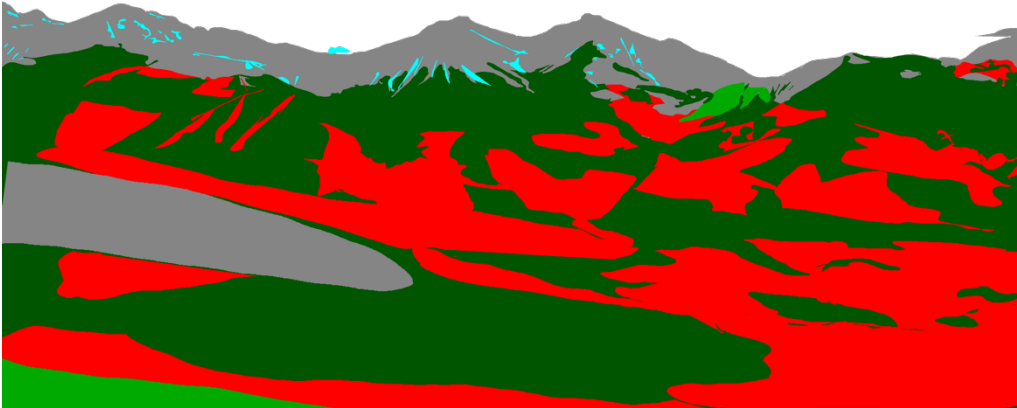


2008

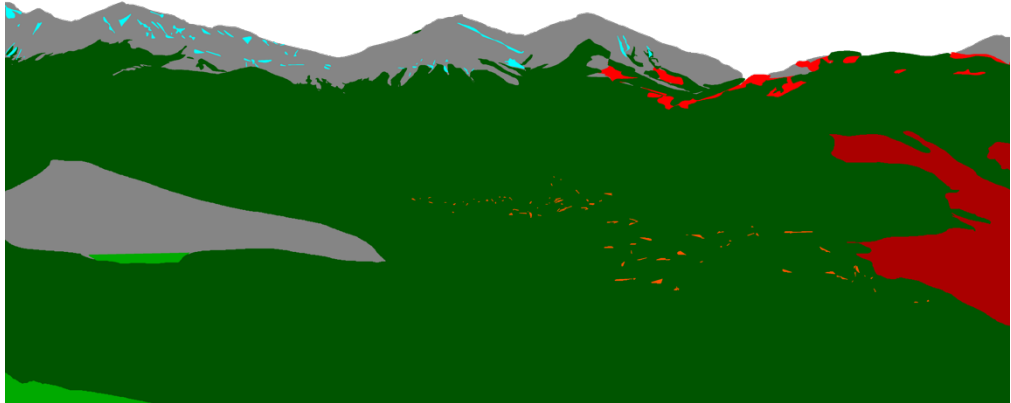


Summit North of Coxhill

1897

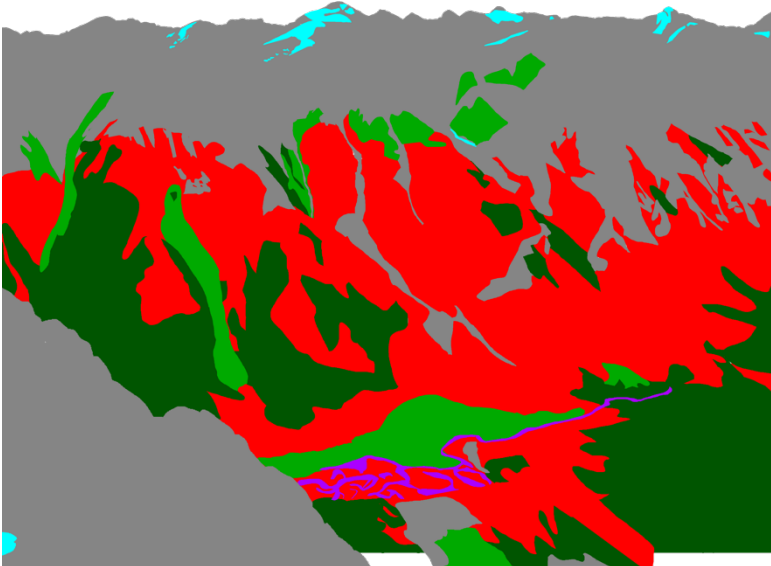


2008

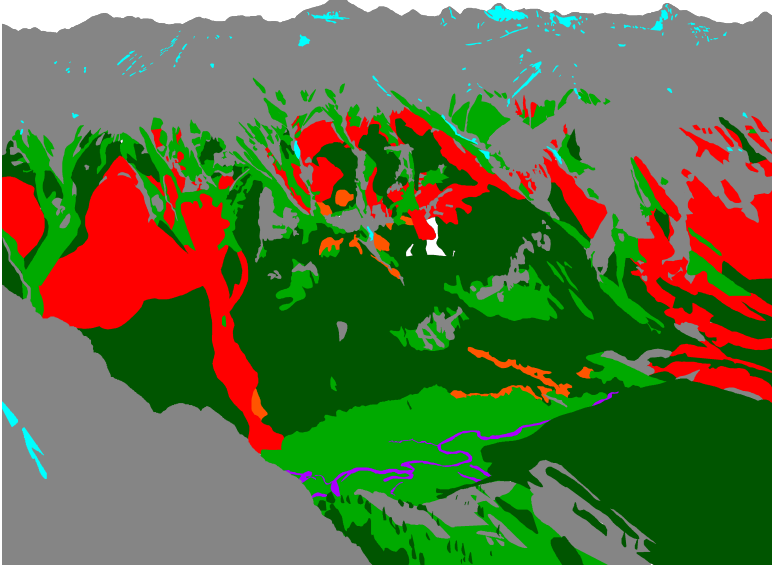


Marvel Lake – 1

1913

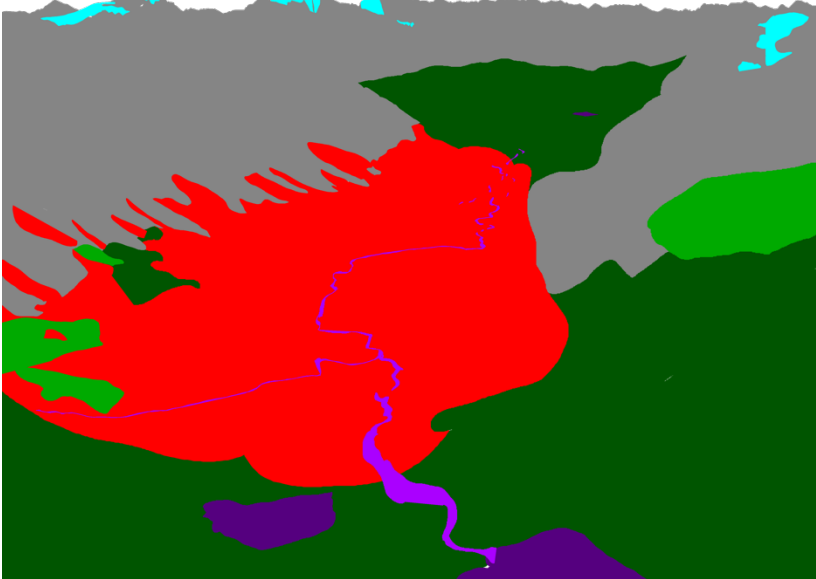


2010

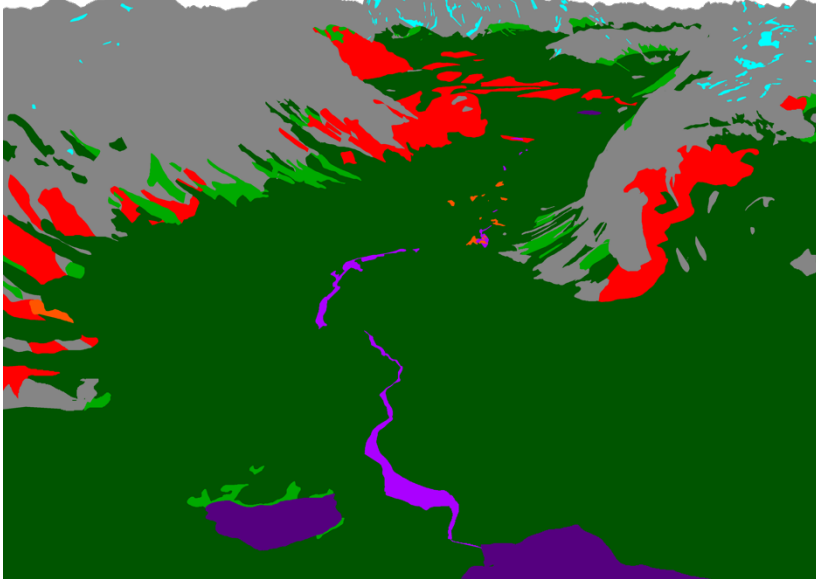


Marvel Lake – 2

1913

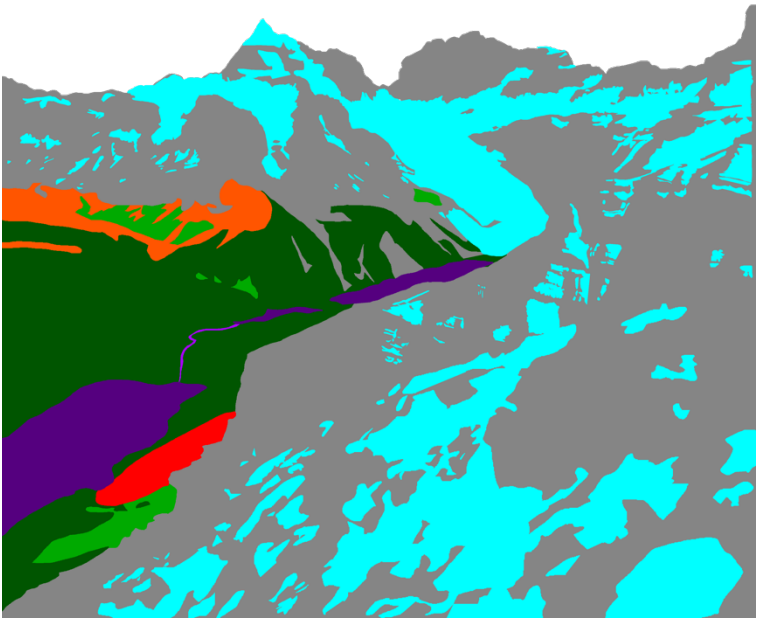


2010

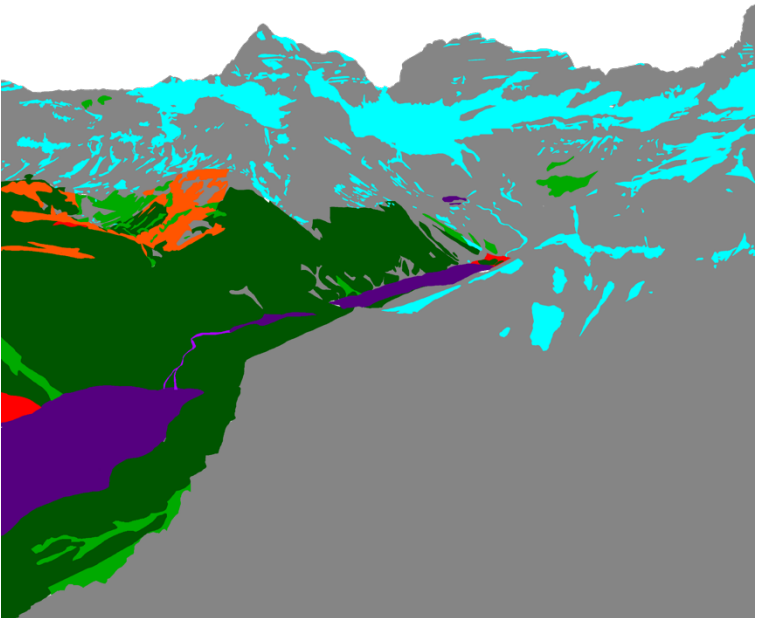


Marvel Lake – 3

1913

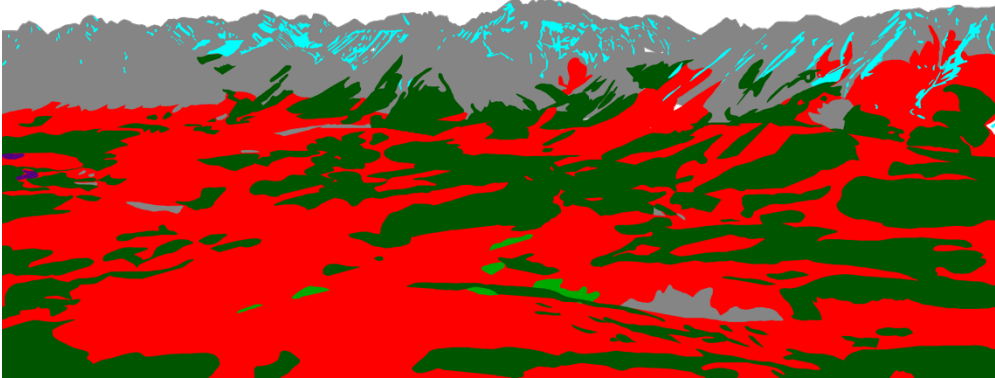


2010



Kananaskis Lake South – 1

1914

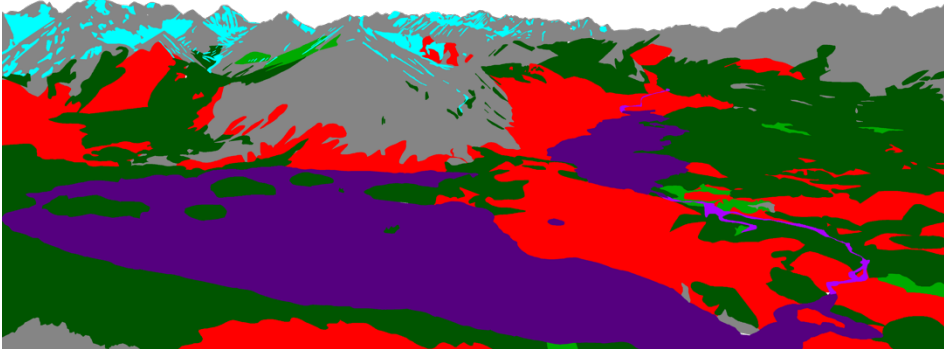


2007

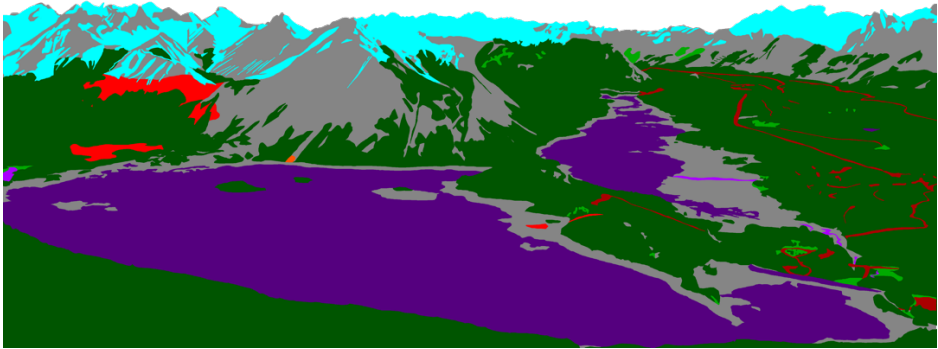


Kananaskis Lake South – 2

1914

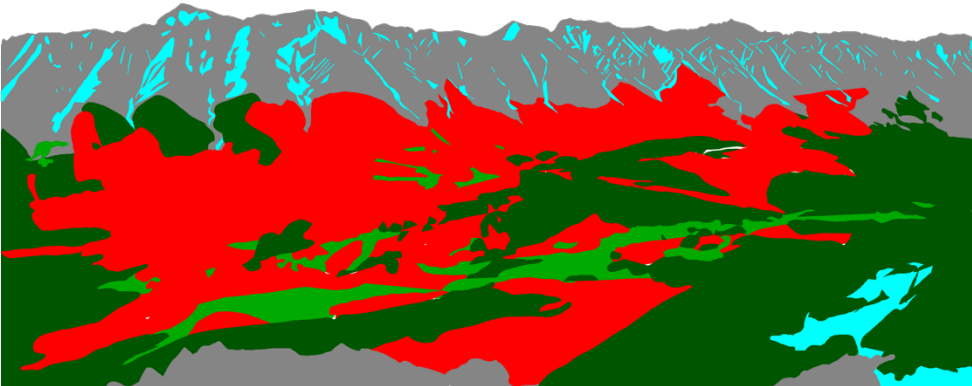


2007



Kananaskis Lake South – 3

1914

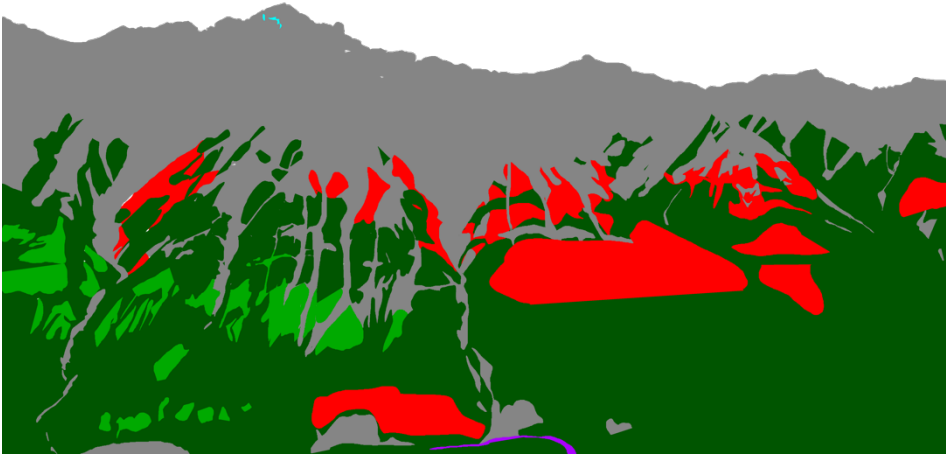


2007



Sulphur Ridge South - 1

1888

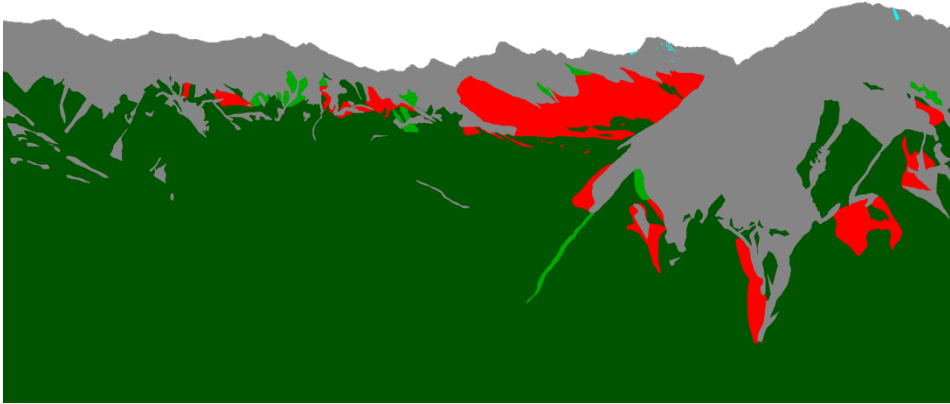


2008

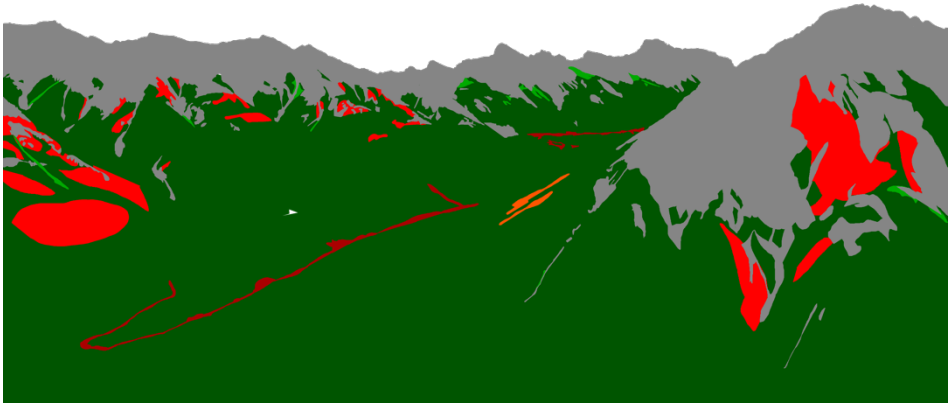


Sulphur Ridge South – 2

1888



2008



Sulphur Ridge South – 3

1888

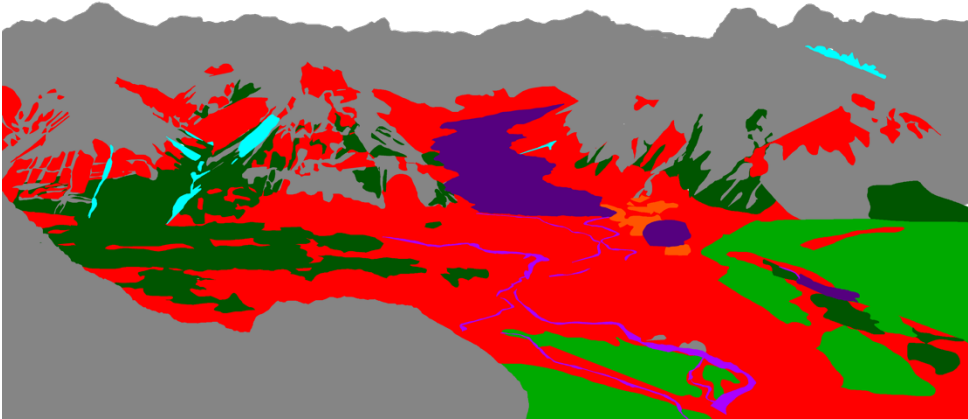


2008

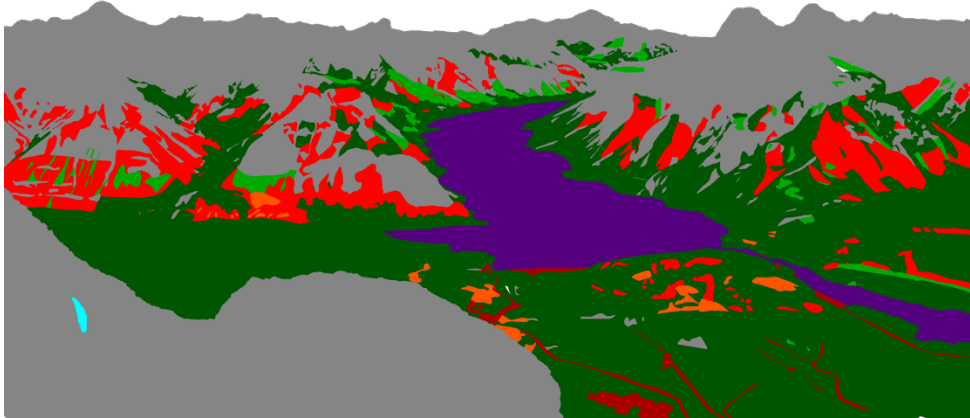


Cascade

1888



2008

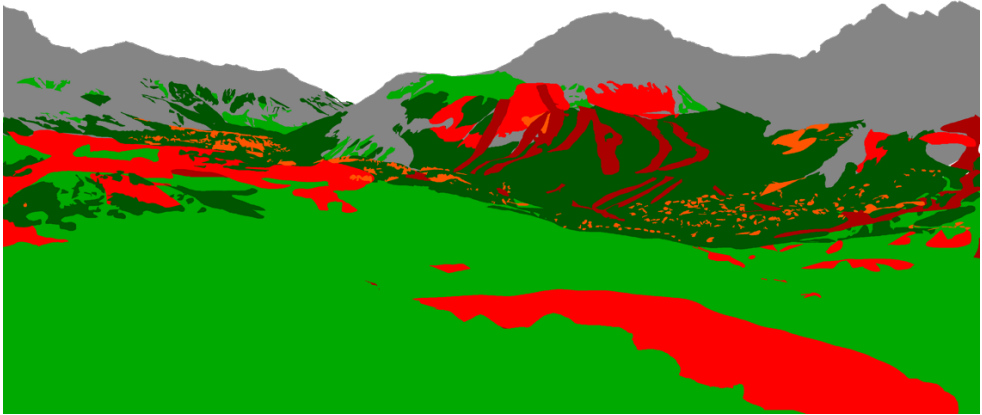


Twin Cairns

1890

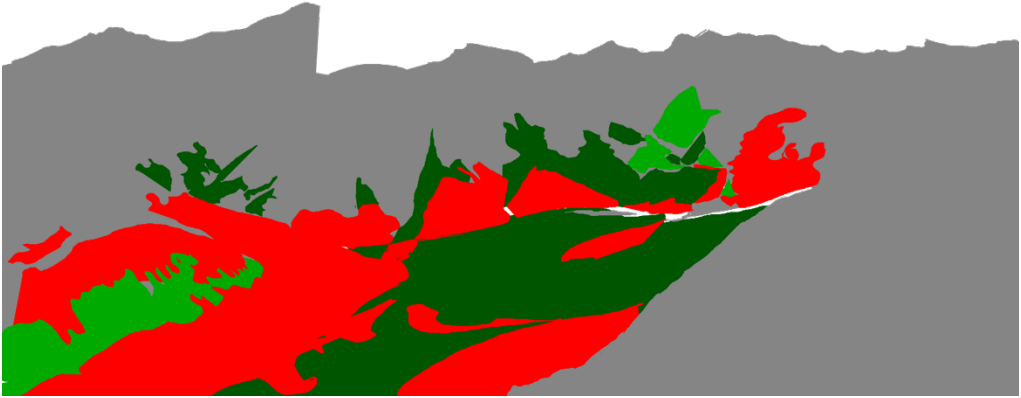


2008

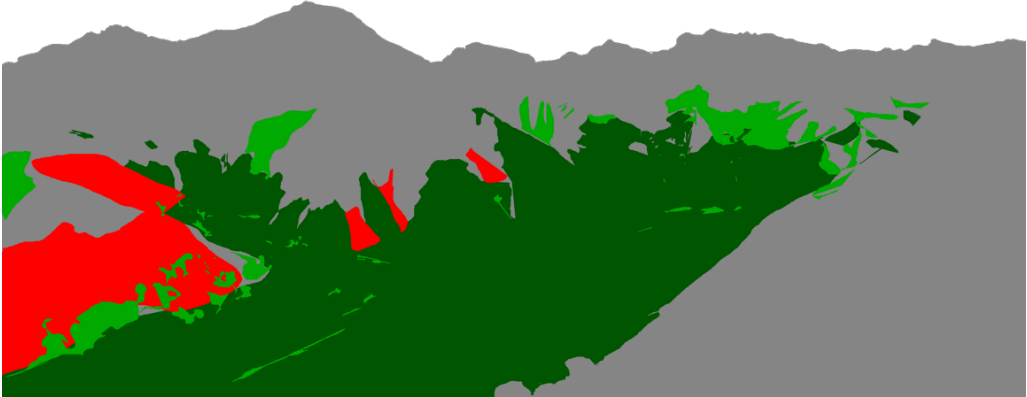


Mt Alymer East

1888



2009

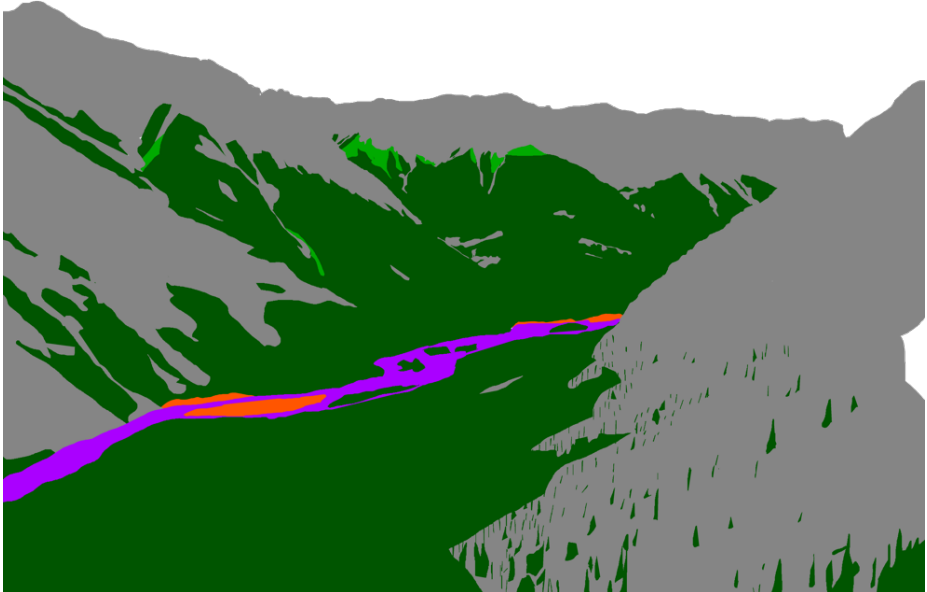


Pakakos Mt North – 1

1888

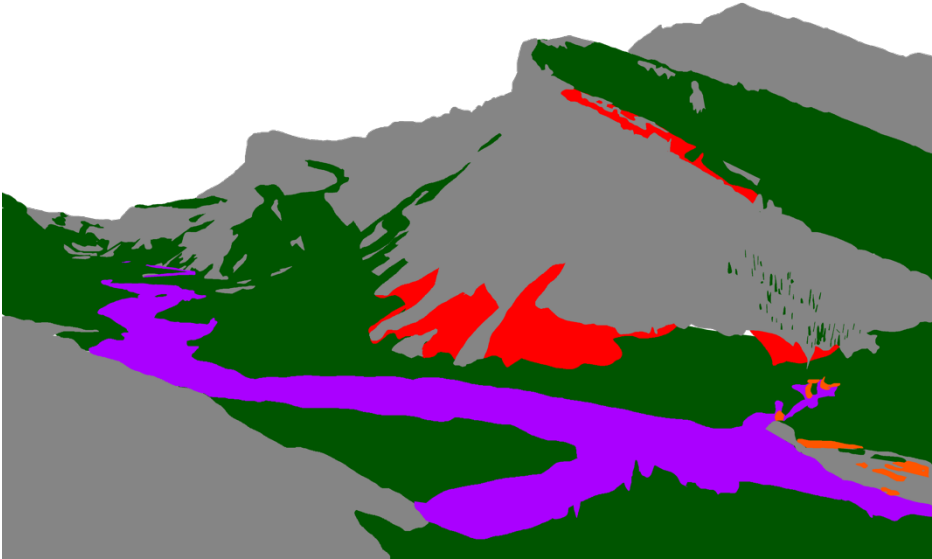


2009

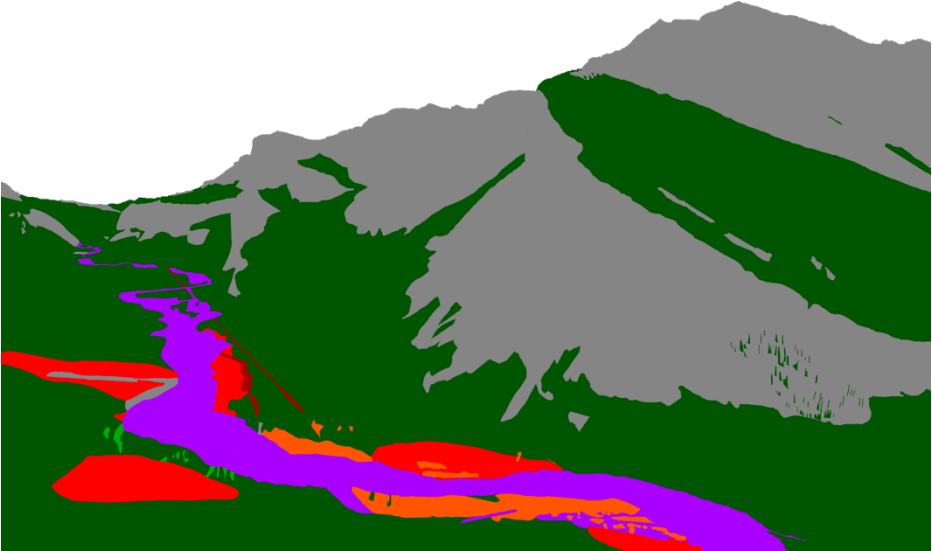


Pakakos Mt North – 2

1888



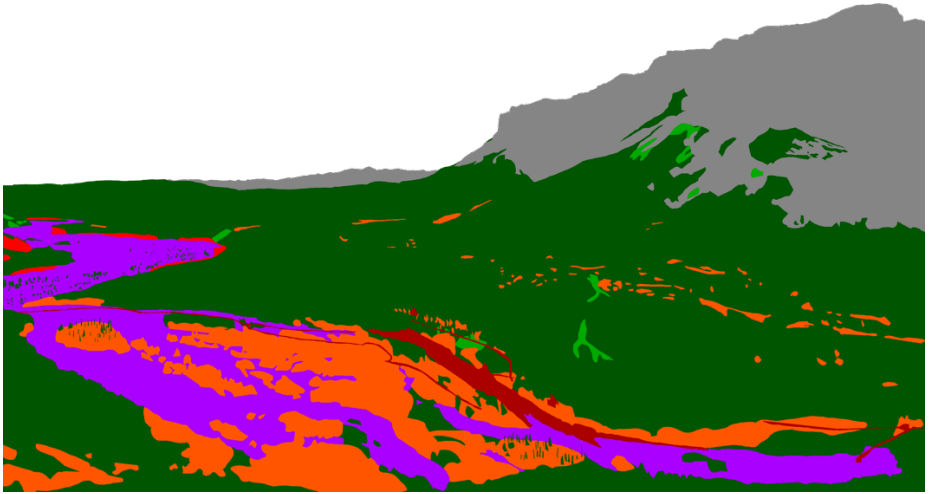
2009



Phantom Crag East -1 1888

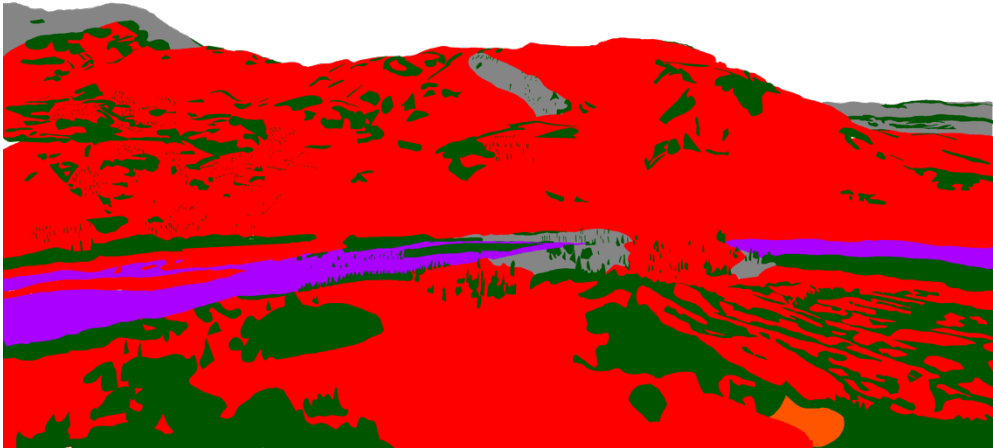


2009

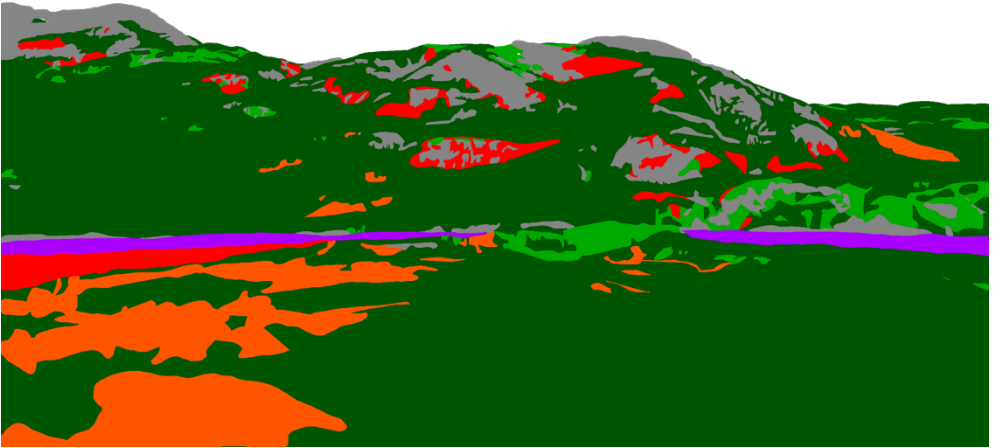


Phantom Crag East – 2

1888

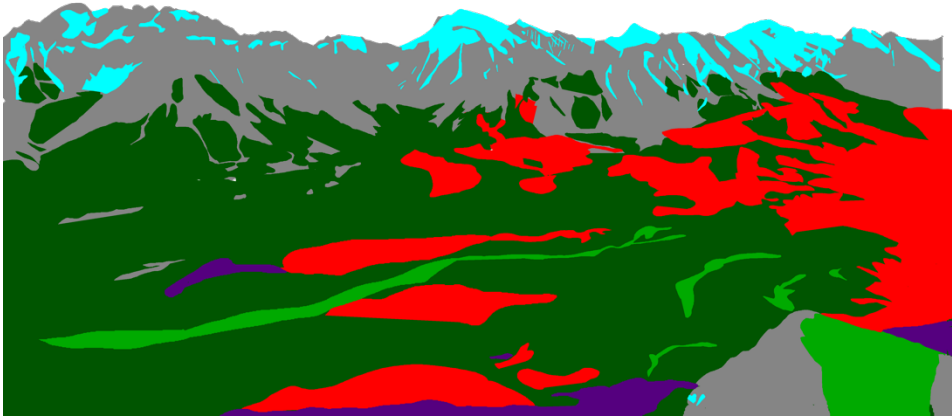


2009

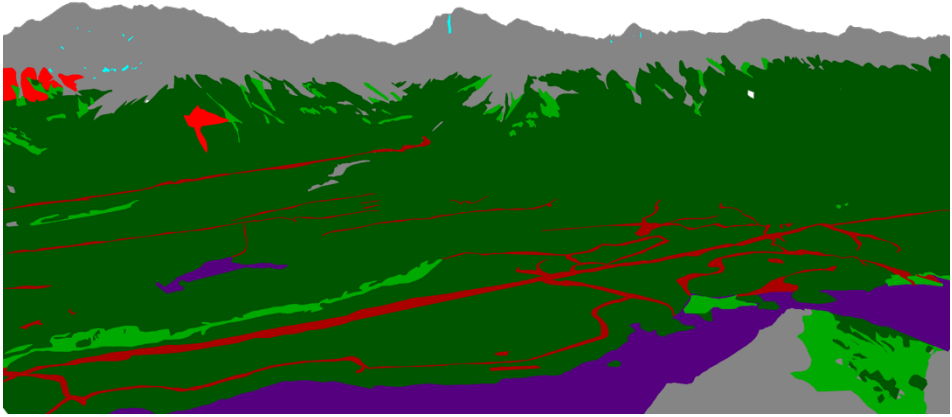


Mt. Indefatigable – 1

1905



2009



Mt. Indefatigable – 2

1905

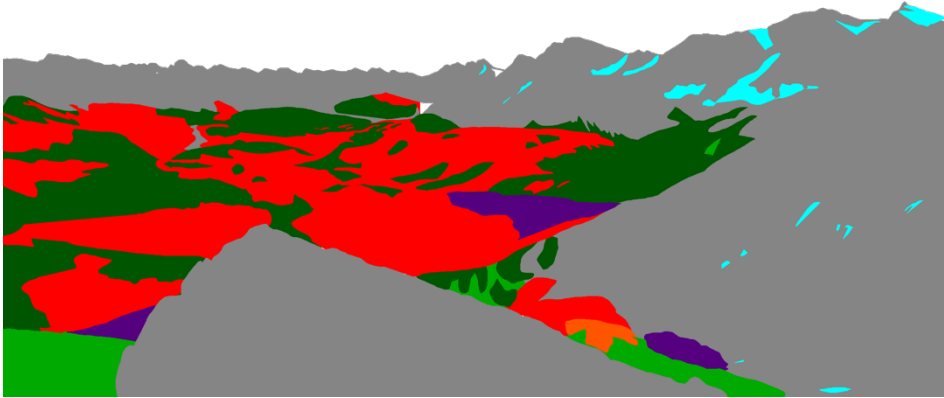


2009

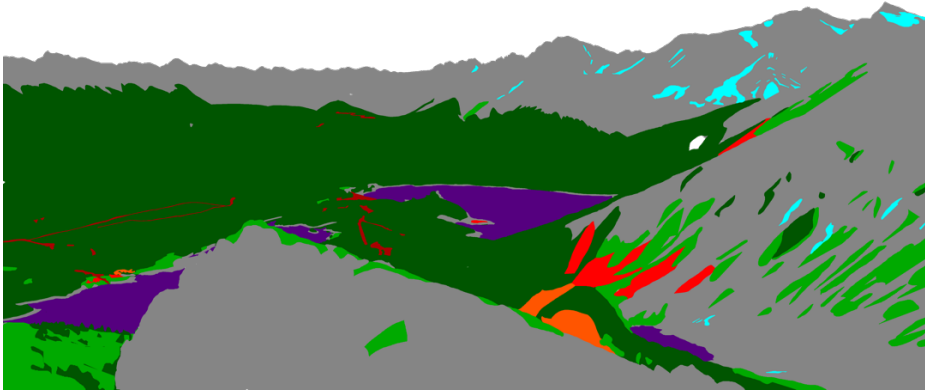


Mt. Indefatigable – 3

1905



2009

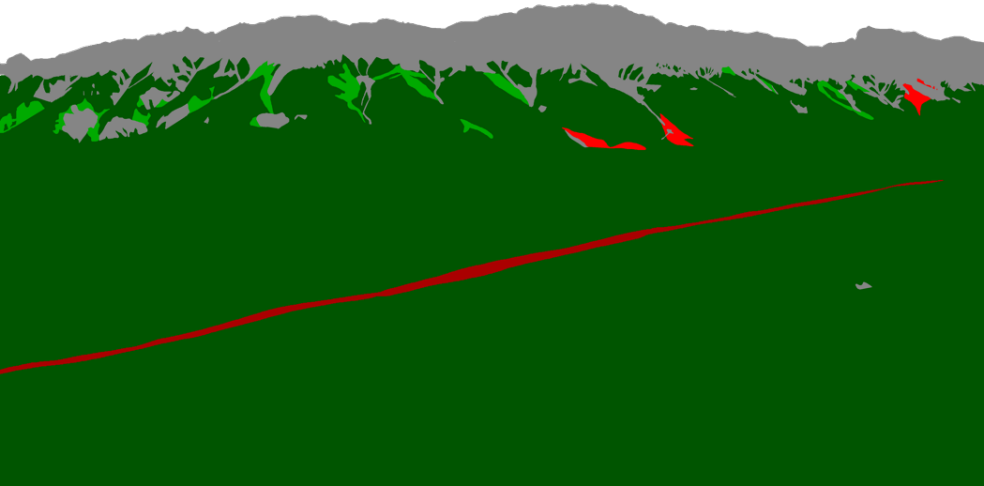


The Turret – 1

1905



2009

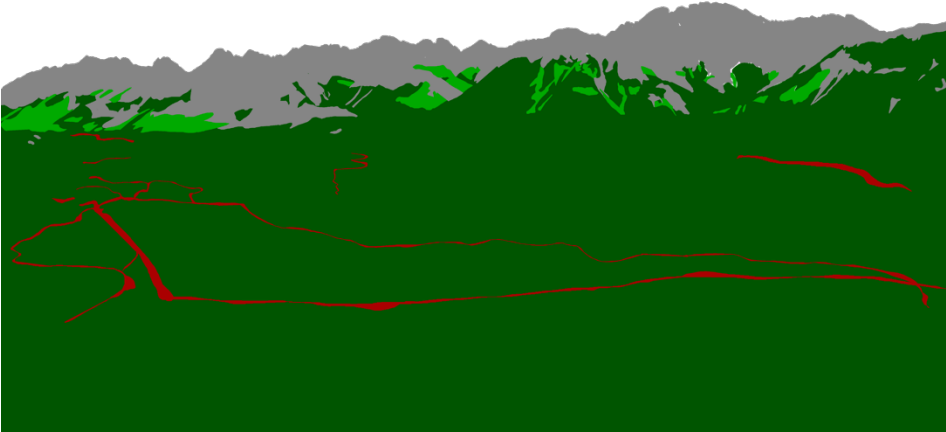


The Turret – 2

1905

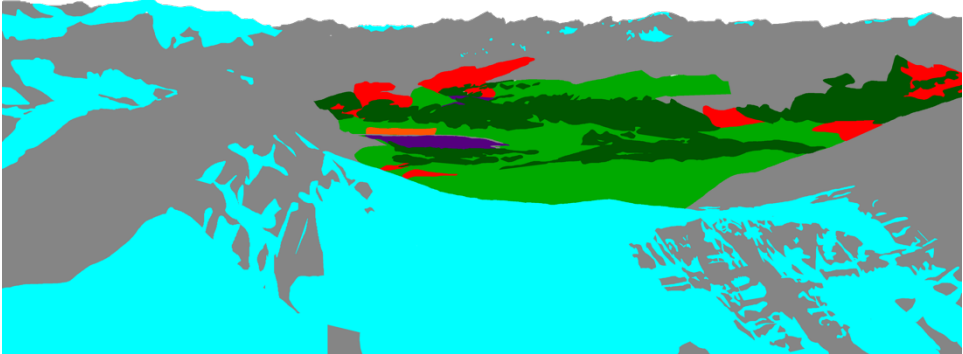


2009

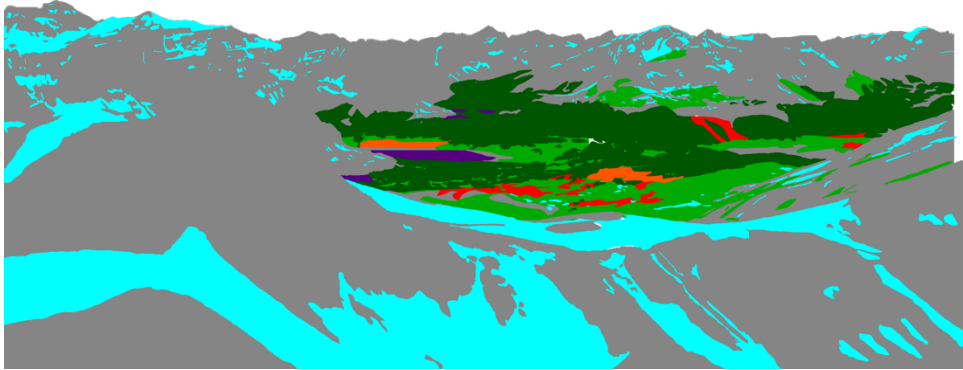


Marvel Lake No.2 – 1

1913



2010

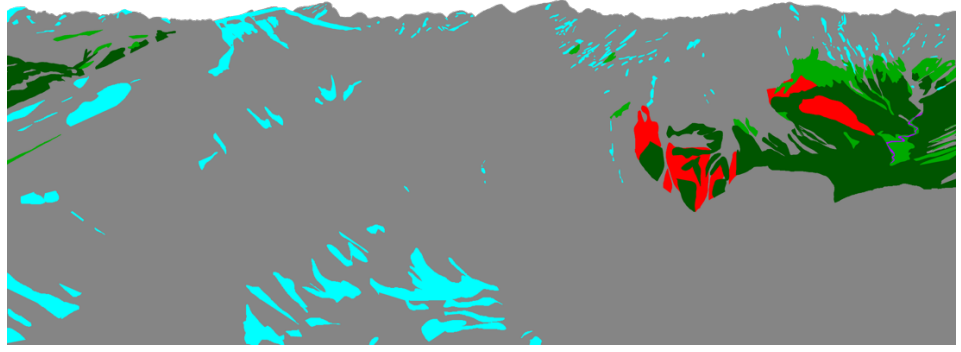


Marvel Lake No.2 – 2

1913



2010

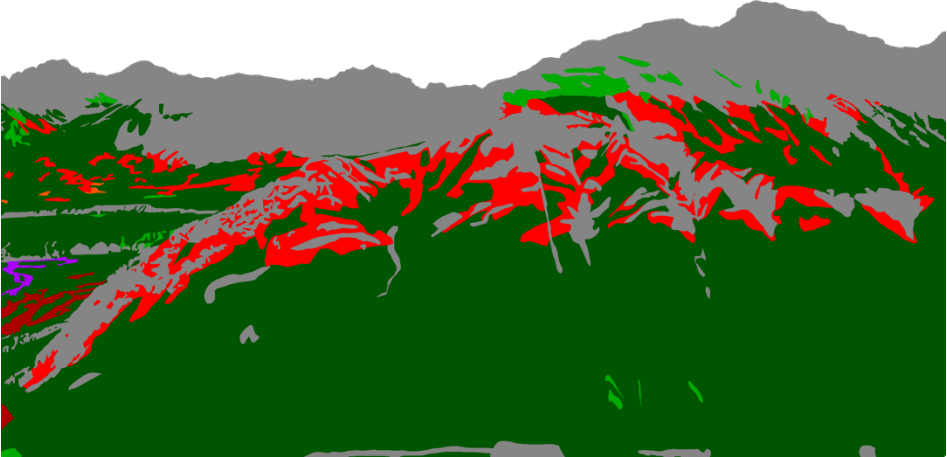


Sulphur Ridge North – 1

1888

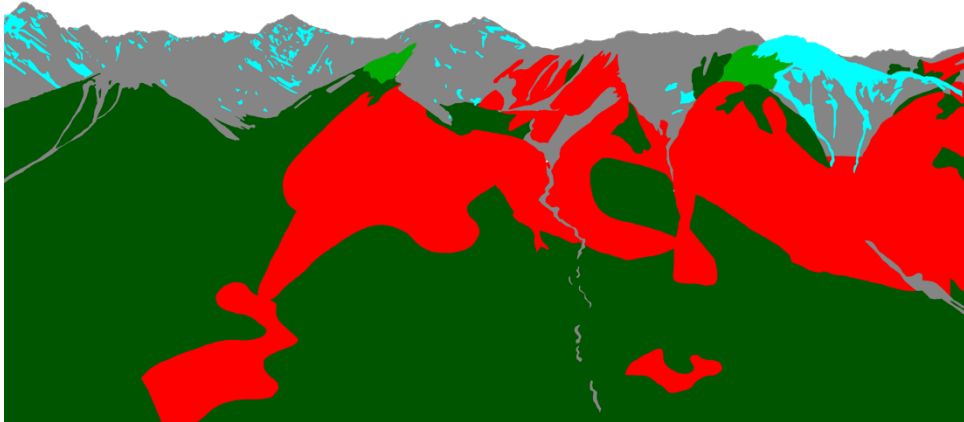


2008

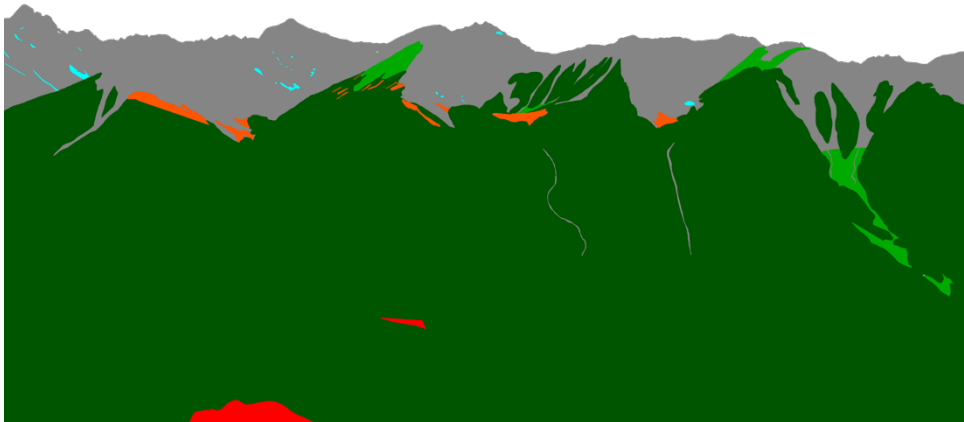


Sulphur Ridge North – 2

1888



2008



## Appendix D – Transition Matrices

### Batch 1 (Bow & Elbow Stations) Results (historic-repeat)

	WS	F	RA	GH	BEB	B/M	I/R	SA	RI	I/S	CF	S/G/R	VB	TOTAL
WS	2173458	393214	14523	19701	201346	3434	79994	94672	94799	0	1664386	5776	365044	5110347
F	1202348	5177166	174251	915531	162136	195699	1244451	2946814	140850	0	8983968	19531	461435	21624180
RA	543141	369903	6538368	743400	18042	406428	2405873	3172041	329459	48364	69770197	2805635	143895	87294746
GH	94763	11964	848453	4349275	22017	67053	796377	1021436	11	185898	13358542	744066	66392	21566247
BEB	509889	362779	6157	3356	302670	3630	52052	14373	94687	0	817723	25160	437572	2630048
B/M	2	0	8494	0	0	0	29337	0	0	0	485440	0	0	523273
I/R	10004	11511	1977	18820	0	0	43615	88562	0	0	150568	0	4912	329969
SA	0	0	0	2824	0	0	2140	909555	0	0	130812	0	0	1045331
RI	104600	116555	3381	0	57659	636	8487	11587	162546	0	419122	2431	104674	991678
I/S	0	0	21258	2130990	0	0	0	0	0	982364	847682	3389180	0	7371474
CF	889125	857659	1957294	1478113	133800	1143421	1004017	1046194	65441	127033	80792540	2300086	157961	91952684
S/G/R	36630	60406	3595480	1125518	2297	19040	300538	32451	0	2405392	15561897	48299279	5552	71444480
VB	665173	407571	12033	5184	134712	17828	109263	5588	112478	0	1160941	6800	285412	2922983
TOTAL	6229133	7768728	13181669	10792712	1034679	1857169	6076144	9343273	1000271	3749051	194143818	57597944	2032849	314807440

WS – Water surface  
 F – Floodplain  
 RA – Regenerating area  
 GH – Grassland herbaceous  
 BEB – Bare exposed bar  
 B/M – Broadleaf/mixedwood  
 I/R – Industrial/Recreational

SA – Settlement areas  
 RI – River island  
 I/S – Ice/snow  
 CF – Coniferous forest  
 S/G/R – Sand/gravel/rock  
 VB – Vegetated bar

Batch 2 (Regional Stations) Results (historic-repeat)

	RW	GH	B/M	I/R	LW	CF	I/S	RA	S/G/R	Total
RW	861560	155413	498870	28358	47007	2251085	67	123291	112335	4077986
GH	47706	21296591	2760363	256135	115600	12247651	284397	2418064	1236252	40662759
B/M	54388	446696	3290018	515	40630	2059557	220	4339	28530	5924893
I/R	0	4	0	0	0	4628	0	0	0	4632
L/W	490	15328	0	1096	4189120	176365	34	347	24347	4407127
CF	1073669	1647462	9198672	1071729	810550	123657047	84353	3677500	6604369	147825351
I/S	13122	3046199	48	1467	7325	2085437	4391767	72493	7524748	17142606
RA	1516357	2909239	3558810	1289713	1170074	78128463	103575	3882870	4464295	97023396
S/G/R	450124	4160726	207665	82590	20287	13614881	4162620	2990192	81913446	107602531
Total	4017416	33677658	19514446	2731603	6400593	234225114	9027033	13169096	101908322	424671281

RW – Riverine wetland

GH – Grassland herbaceous

B/M – Broadleaf/mixedwood

I/R – Industrial/Recreational

L/W – Lacustrine wetland

CF – Coniferous forest

I/S – Ice/snow

RA – Regenerating area

S/G/R – Sand/gravel/rock

Condensed Results for entire dataset (historic-repeat)

	F/L	F/RI	RA	GH	B/M	A	CF	I/S	S/G/R	TOTAL
F/L	10173453	1465528	156351	198982	523762	385396	6070500	101	174418	19148491
F/RI	2092852	5597117	177632	915531	196335	4211339	9403090	0	21962	22615858
RA	3391509	699362	10421238	3652639	3965238	6867627	147898660	151939	7269930	184318142
GH	346478	11975	3266517	25645866	2827416	2073948	25606193	470295	1980318	62229006
B/M	95020	0	12833	446696	3290018	29852	2544997	220	28530	6448166
A	14916	11511	1977	21648	0	1043872	286008	0	0	1379932
CF	3065105	923100	5634794	3125575	10342093	3121940	204449587	211386	8904455	239778035
I/S	20447	0	93751	5177189	48	1467	2933119	5374131	10913928	24514080
S/G/R	514890	60406	6585672	5286244	226705	415579	29176778	6568012	130212725	179047011
TOTAL	19714670	8768999	26350765	44470370	21371615	18151020	428368932	12776084	159506266	739478721

F/L – Fluvial/Lacustrine

F/RI – Floodplain/River Island

RA – Regenerating area

GH – Grassland herbaceous

B/M – Broadleaf/mixedwood

A – Anthropogenic

CF – Coniferous forest

I/S – Ice/snow

S/G/R – Sand/gravel/rock

Elbow Results (historic-repeat)

	WS	F	RA	GH	BEB	B/M	I/R	RI	I/S	CF	S/G/R	VB	Total
WS	126821	179722	0	19526	128044	3377	12185	29411	0	163710	3777	128486	795059
F	102875	3010166	0	893208	64893	180975	52673	93801	0	1488353	804	73729	5961477
RA	5820	93169	1660305	398606	4385	406361	54655	329	48364	30533000	544298	9024	33758316
GH	582	11401	343634	2177333	583	59900	4013	11	185898	3930543	308449	976	7023323
BEB	203258	323679	0	3356	258411	3630	30221	70152	0	386023	20280	328100	1627110
B/M	0	0	8494	0	0	0	29337	0	0	485440	0	0	523271
I/R	0	0	0	0	0	0	0	0	0	0	0	0	0
SA	0	0	0	0	0	0	0	0	0	0	0	0	0
RI	17824	98768	1591	0	47208	636	0	118659	0	146874	2431	51332	485323
I/S	0	0	5567	2133048	0	0	0	0	966538	828684	2465491	0	6399328
CF	44930	369662	1508596	1163955	89797	1143194	345381	13336	126541	62847291	1523240	30600	69206523
S/G/R	460	14480	730488	715585	110	19040	1816	0	2263473	6045725	15717436	1723	25510336
VB	88806	351661	2121	2361	119844	13630	13252	76188	0	478598	4299	163860	1314620
Total	591376	4452708	4260796	7506978	713275	1830743	543533	401887	3590814	107334241	20590505	787830	152604686

WS – Water surface

F – Floodplain

RA – Regenerating area

GH – Grassland herbaceous

BEB – Bare exposed bar

B/M – Broadleaf/mixedwood

I/R – Industrial/Recreational

SA – Settlement areas

RI – River island

I/S – Ice/snow

CF – Coniferous forest

S/G/R – Sand/gravel/rock

VB – Vegetated bar

Bow Results (historic-repeat)

	WS	F	RA	GH	BEB	B/M	I/R	SA	RI	CF	S/G/R	VB	Total
WS	1988310	625444	14502	175	38102	57	67037	94672	65388	1500666	1999	234243	4630595
F	1081123	1460189	173402	11174	87564	14724	1174086	2946814	47049	7298157	20939	392905	14708126
RA	534215	254278	5336689	310678	13291	67	2351232	3172041	329130	38372817	2243503	134871	53052812
GH	94181	1980	335070	2113138	21434	7153	792364	1021436	0	9365241	420601	65416	14238014
BEB	304886	38090	6157	0	11710	0	22054	14373	24535	418629	4685	109915	955034
B/M	2	0	0	0	0	0	0	0	0	0	0	0	2
I/R	9919	15684	1977	18820	0	0	64126	88562	0	152439	0	4912	356439
SA	0	0	0	2824	0	0	2140	909555	0	130812	0	0	1045331
RI	74189	4902	1790	0	10072	0	8487	11587	43887	272248	0	52768	479930
I/S	0	0	0	0	0	0	0	0	0	1227	52863	0	54090
CF	818269	473387	496511	244042	39283	227	658657	1046194	52105	20213493	991929	126845	25160942
S/G/R	35059	42323	2162346	464704	2089	0	298722	32451	0	8785007	33309364	3829	45135894
VB	572090	52225	9912	0	13896	4198	96101	5588	36290	682343	2501	123039	1598183
Total	5512243	2968502	8538356	3165555	237441	26426	5535006	9343273	598384	87193079	37048384	1248743	161415392

WS – Water surface

F – Floodplain

RA – Regenerating area

GH – Grassland herbaceous

BEB – Bare exposed bar

B/M – Broadleaf/mixedwood

I/R – Industrial/Recreational

SA – Settlement areas

RI – River island

I/S – Ice/snow

CF – Coniferous forest

S/G/R – Sand/gravel/rock

VB – Vegetated bar

Elbow (pre and post flood)

	WS	F	RA	GH	BEB	B/M	I/R	SA	RI	I/S	CF	S/G/R	VB	Total
WS	119067	75897	1804	0	346987	0	0	0	18309	0	28926	406	19888	611284
F	106962	3259070	7755	40934	171135	63471	18128	0	86375	0	671544	3799	23394	4452567
RA	0	0	1954957	90797	0	91975	1309	0	0	26	2081296	447253	0	4667613
GH	259	25679	90168	5650783	3090	94349	65883	0	735	0	1148135	602272	0	7681353
BEB	115611	35340	1076	77	527433	0	22	0	23548	0	48659	1605	44968	798339
B/M	24	22827	70086	53096	115	839991	11902	0	0	0	828648	5183	0	1831872
I/R	6069	28269	2139	27755	29617	919	289700	0	5084	0	145403	1563	7835	544353
SA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RI	24377	85407	0	0	92766	0	0	0	149053	0	6043	74	44261	401981
I/S	0	0	24694	164010	0	6594	24322	0	0	61143	545257	3015490	0	3841510
CF	55438	804549	1391505	2355867	213924	367224	92193	0	25597	868	101032723	1651226	30830	108021944
S/G/R	4319	8555	396412	1377379	45624	5490	2815	0	669	25670	2094812	17078499	1751	21041995
VB	71677	110106	5822	0	309286	0	0	0	98944	0	46074	8004	137356	787269
Total	503803	4455699	3946418	9760698	1739977	1470013	506274	0	408314	87707	108677520	22815374	310283	154682080

WS – Water surface

F – Floodplain

RA – Regenerating area

GH – Grassland herbaceous

BEB – Bare exposed bar

B/M – Broadleaf/mixedwood

I/R – Industrial/Recreational

SA – Settlement areas

RI – River island

I/S – Ice/snow

CF – Coniferous forest

S/G/R – Sand/gravel/rock

VB – Vegetated bar

Bow (pre and post flood)

	WS	F	RA	GH	BEB	B/M	I/R	SA	RI	CF	S/G/R	VB	Total
WS	3711839	137129	11532	2521	632213	664	72119	18151	119702	653261	153052	165930	5678113
F	168049	2277681	132306	451	9723	0	69995	38040	16754	610923	2676	15890	3342488
RA	16310	30705	4979605	46596	1740	0	100341	6044	123	2109987	1424557	3851	8719859
GH	1237	0	84896	2069069	0	0	74696	0	0	767835	282076	0	3279809
BEB	48611	11432	1913	0	59528	0	735	60	15071	78350	4	25671	241375
B/M	0	123	0	0	0	11899	643	0	0	13761	0	0	26426
I/R	66299	59200	140569	35929	1159	0	3069121	325408	18034	1697824	45673	54367	5513583
SA	14014	0	4817	0	237	0	303653	7151592	0	1771728	12010	61	9258112
RI	90241	1507	9533	0	5247	0	754	65	401075	36354	8905	44637	598318
I/S	0	0	0	0	0	0	0	0	0	0	0	0	0
CF	921573	513275	1814307	794841	64509	12665	1620906	1496991	149958	78526446	3100625	249505	89265601
S/G/R	25978	720	1120093	348380	12116	0	17514	1467	13	2780939	32761360	10016	37078596
VB	211797	36918	14554	0	122533	480	41018	2093	72852	311581	6990	432141	1252957
Total	5275948	3068690	8314125	3297787	909005	25708	5371495	9039911	793582	89358989	37797928	1002069	164255237

WS – Water surface

F – Floodplain

RA – Regenerating area

GH – Grassland herbaceous

BEB – Bare exposed bar

B/M – Broadleaf/mixedwood

I/R – Industrial/Recreational

SA – Settlement areas

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I/S – Ice/snow

CF – Coniferous forest

S/G/R – Sand/gravel/rock

VB – Vegetated bar