CLIMATE CHANGE IMPACT ON THE HYDROLOGICAL FUNCTIONING OF MOUNTAIN LAKES: A CONCEPTUAL FRAMEWORK

A Thesis Submitted to the

College of Graduate and Postdoctoral Studies

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

In the Department of Geography and Planning

University of Saskatchewan

Saskatoon

By

Daniel Amaro Medina

Permission to Use and Disclaimer Statement

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

DISCLAIMER

Reference in this thesis to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other uses of materials in this thesis in whole or part should be addressed to:

Head of the Department of Geography and Planning
117 Science Place
University of Saskatchewan
Saskatoon, Saskatchewan S7N 5C8 Canada

OR

Dean
College of Graduate and Postdoctoral Studies
University of Saskatchewan
116 Thorvaldson Building, 110 Science Place
Saskatoon, Saskatchewan S7N 5C9 Canada

Abstract

Mountain lakes are distinctive water bodies that attract the great attention of researchers. They not only serve as a crucial water resource for the inhabitants of the upland regions but also as an important destination for millions of tourists who are attracted by the beauty of these water bodies. With the increasing concern about global warming, mountain lakes are experiencing changes in their hydrological processes and meanwhile can act as reflectors of those changes. Specifically, due to the fragility of these water bodies, understanding the consequences is significant as it can help to find out whether climate change causes degradations in lake hydrological functioning. The interactions of hydrological processes in mountain lakes with external drivers are usually hard to explain explicitly owing to their complexity. To deal with that problem, scholars tend to use conceptual frameworks, which help to reveal the dependence of a lake on particular hydrologic factors. To identify factors influencing lake hydrological function and their sensitivity to changing climate, a literature analysis was undertaken. The focus was on the Canadian Rocky Mountains where 5155 water bodies were identified using GIS. The main literature sources used to identify factors influencing lake hydrologic function were peer-reviewed articles and books. In total, 10 natural drivers critical for lake hydrological function and 2 main reflectors of climate change impacts on mountain lakes as well as 38 additional sub-factors that characterize each of the factors and reflectors, were identified. Based on that, a conceptual framework for mountain lake hydrological functioning was developed. The major problem that affected the thorough testing of the conceptual framework was a limited number of observations across lakes in the research area. Nevertheless, the conceptual framework is flexible and might be tested across many mountainous regions worldwide that experience climatic changes. Such an opportunity can be realized through the use of quantitative statistical techniques available for large datasets. Overall, the conducted research stresses the problem of a poor degree of hydrological exploration of lakes in mountain regions and presents a useful approach to represent complex interactions of natural drivers and intra-lake processes under rising temperatures.

Acknowledgements

First of all, I would like to thank my supervisor, Dr. Cherie Westbrook, for all the help in accomplishing my research. Especially, for showing me the significance of mountain lake ecosystems and motivating me to study these objects. Without her support, I might not have been able to overcome the challenges posed by the pandemic and perform this thesis. I also recognize my research committee, Dr. Martyn Clark and Dr. Alec Aitken, for their valuable ideas and advice critical for the thesis progress.

I would also like to thank my research group. I appreciate the opportunity to be a part of this team, even though we did not have a chance to work together in the field. In either way, I gained a lot of useful knowledge from my lab mates because we had so wide range of research interests and everyone was willing to share their skills and ideas to help each other even in the remote environment.

Special thanks I give to my family who was so supportive during my time far from home. They played a big role not only in my degree pursuing process but also in many other aspects of my life. I felt they were always close to me, especially during this challenging pandemic time.

Lastly, I would like to thank my friend Alla Kovalenko, who helped me to with an illustration of natural factors in the alpine catchment using her excellent computer graphics skills. Without her assistance, that picture was impossible to create.

This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) CREATE program (grant #463960-2015), the Canada First Research Excellence Fund (Global Water Futures program), and Alberta Innovates Water Innovation Program.

Table of contents

List of Tables

List of Figures

Chapter 1. Introduction

In recent decades, global warming is considered a crucial concern as it causes changes in ecosystems across the various regions of the world. Literature provides many attempts to assess the impact of climate change on the hydrology of water bodies worldwide. For instance, some researchers characterize shifts in lake hydrology caused by climate change (Argyilan & Forman, 2003) and others explain the influences of global warming with the importance of identifying the water balance components and trophic status of a lake (Gibson et al., 2016). Specifically, comprehensive investigations of ecosystem responses to climatic variability and change are not limited to only conducting field research and collecting data. Additionally, researchers test hypotheses or theories that might explain those changes (Rigler & Peters, 1995). Nevertheless, the majority of the studies focusing on the hydrology of the lakes in lowlands. Much less is known about the climate change impact on mountain lake hydrology. It is a big gap in modern research as mountains are usually highlighted as "water towers" that provide a great deal of water for human needs all over the world (Messerli et al., 2004). Even there are valuable studies that provide a detailed description of fluctuations in lakes' hydrological regimes under the various natural factors (Ptak et al., 2017) focusing just on individual lakes may not bring enough understanding of how global warming affects the uplands. Particularly, the selected region for the present study lacks hydrological data because the water bodies of the Canadian Rockies are not observed properly. Certainly, there are great studies conducted in that region (Beierle et al., 2003; Hood et al., 2006, 2007). However, these studies focus on particular natural factors (e.g. geomorphology, past glaciation, or groundwater) that may influence the hydrology of the lake. Those studies do not reflect the overall impact of climate change on lake hydrological functioning. In the present research, the term *hydrological functioning* encompasses the complexity of lakes' hydrological processes and their interactions with natural drivers within the catchment. Under natural drives, groundwater, glaciers, drainage rate, and other similar objects that can affect hydrological functioning through global warming are considered.

Generally, the assessment of climatic effects on lake hydrology requires long-term monitoring data (at least 20 years). Long-term observations across many years define the range of natural variability of ecological systems and provide evidence on how climate change may affect the inner lake hydrological processes (Kratz et al., 2003). Nevertheless, such kind of observations is challenging to obtain, especially in mountain regions, due to the lack of hydrological and meteorological stations in those regions (de Jong, 2015). Considering the scarcity of available data to discover global warming impacts on lake hydrological functioning led to the development of such approaches as classifications, conceptual frameworks, and models helping to describe the complexity of natural interactions more precisely and illustratively. Specifically, creating the classification of lakes can be useful for a deeper understanding of the natural drivers' integrity in influencing the lake hydrology as suggested by multiple studies. For example, Turner et al. (2010) created a process-based classification for the group of lakes in the Yukon Territory. Another study was accomplished by Winter (1977) who classified the lakes in the north-central United States according to their interactions with atmospheric water, surface water, and groundwater. However, a valuable classification can be developed with large sets of data and field measurements. In this case, the development of the conceptual framework seems to be more useful as it has a more theoretical and hypothesis basis. For instance, Zaharescu et al. (2016) developed a framework to identify the main landscape elements that are critical to sustaining lake ecosystems in high-altitude basins in the Pyrenees.

An important challenge to consider while working with the aforementioned tools is to define a proper set of natural drivers that are crucial for the hydrological functioning of the lakes. Each of those drivers should have a specific position on the conceptual framework so as not to derange the logical structure of the created tool. The range of information presented in the literature sources is very wide and different researchers stress the importance of various natural drivers depending on the region they working on and applying their approach for. For that reason, it is crucial to analyze thoroughly those opinions and come up with a well-reasoned list of natural features for the tool developed in the present research. One of the best ways to do so is to conduct an extensive literature analysis as was suggested by some scholars (Rocco & Plakhotnik, 2009).

Thus, the purpose of the present thesis is **to conceptualize how climate change might affect mountain lake hydrological functioning.** The main objectives are as follows:

- To identify the main natural drivers of mountain lake hydrological functioning.
- To develop a conceptual framework of high-elevation lake hydrological functioning.
- To identify methods for testing the created conceptual framework.

- To hypothesize changes in the hydrological functioning of the lakes under climate change.

1.1 Thesis layout

The present thesis consists of six chapters. In this section, a brief description of the content of each chapter will be described.

The first chapter, “Introduction”, brings the actuality of the present research and highlights the main challenges that researchers facing during the studying of the mountain areas. Additionally, insight on possible approaches, helping to overcome those challenges is provided.

The second chapter, “Literature review”, encapsulates the existing knowledge and exploration of the actual topic by other scholars. The chapter is divided into multiple sections where the information about general mountain hydrology, important natural drivers for hydrological processes in upland lakes, climate change influences on alpine areas, possible tools to analyze and describe those changes as well as research gaps are summarized.

The third chapter, “Methodology”, represents a key approach, which was used for the research conduction. The chapter begins with a geographical description of the study region. Following that, the delineation of the research area and the logic of the concept of selection of the appropriate natural factors to describe the climate changes on mountain lakes are described. Further, the steps of conceptual framework development, potential ways of its testing are discussed, and data sources used to collect the metadata about the lakes in the region are presented.

The fourth chapter, “Results”, begins with a representation of the distribution of the water bodies across the study regarding their surface area and elevation. Further, the categories with factors and sub-factors selected to describe climatic change impacts on lake hydrological function are illustrated. The following section explains the logic of a created conceptual framework considering chosen natural factors and presents a developed tool. The chapter ends with the representation of data availability for the selected area on the example of the 23 lakes with some degree of available data. A detailed analysis of metadata for these water bodies is performed.

The fifth chapter, “Discussion”, outlines the main advantages and drawbacks of the developed framework. Further in the chapter, a detailed analysis is performed, comparing studies that used approaches similar to the developed tool in the present study. In addition to that, possible analytical options to test the conceptual framework are discussed. The chapter ends with a description of the minimal needed criteria sufficient to conduct the comprehensive analysis of mountain lake hydrological functioning.

The sixth chapter, “Conclusions”, summarizes the key findings of the thesis, highlighting the aim of the research and describing how each of the objectives was fulfilled.

Chapter 2. Literature review

The literature review starts by outlining mountain regions distributed across the world, identifying their geological and ecological conditions, as well as characterizing their climatic particularities. Following that is a section on mountain hydrology part which illustrates the natural mechanisms that are crucial for streamflow generation in mountains, highlights the importance of these environments as a water source for humans, and emphasizes the difficulties related to conducting hydrological research in mountainous areas. The third part of the literature review focuses specifically on the hydrology of mountain lakes and introduces the natural drivers that play a key role in controlling the inner lakes' hydrological processes showing examples primarily from Canada and the USA. Further, the insight on climate change impacts on these drivers and the consequences of that for the Rocky Mountains is provided. Bearing that in mind, the following part reports on the tools and approaches existing in the literature that are used to describe and explain the complexity of natural drivers' interactions with lakes in light of globally rising temperatures. Further, the concrete studies that used clarifications, conceptual models, or conceptual frameworks are analyzed in detail. The literature review ends with the identification of current research gaps and highlighting key challenges to answer the question about the influences of climatic variations on mountain lakes' hydrological function.

2.1 Mountain regions

Mountains are substantial components of the Earth's surface. It is estimated that about 36% of the world's land area is composed of mountains, highlands, and hills (Gerrard, 1990). There are multiple definitions proposed to define mountains but overall those regions are extremely diverse and it is difficult to achieve consistency of description there (Fairbridge, 1968). Generally, any useful definition should reflect relative relief, slope steepness, and land volume. Price (1981) discerned that a relative relief of 1000 m includes many mountain ranges worldwide: European Alps, Pyrenees, Caucasus, Himalayas, Andes, Rockies, Sierra Nevada, and more (*Figure 2.1*). At the continental scale, Eurasia has the most extensive land area above 2500 m elevation, in the Tibet Plateau and adjacent ranges. All of the world's mountains above 7000 m elevation are in Asia, and all the 14 peaks above 8000 m are situated in the Greater Himalaya range extending along the southern rim of the Tibet Plateau. After Eurasia, South America has the second most extensive area of high elevation land formed by the mountains and basins of the Central Andes (Blyth et al., 2002). That said, a mountain could not be defined simply by elevation given its variation among mountain ranges. For example, there is a short-grass prairie at around 2000 m elevation in North America and there are vast high elevation plateaus in central Asia. Several researchers rely on a measure of the ‘ruggedness’ of the land – the horizontal distances between ridges and valleys and the vertical distributions that establish the relief – as being fundamental to the delineation of mountains. Based on those relations, Price (1981) defined a mountain as “an elevated landform of high local relief with much of its surface in steep slopes, usually displaying distinct variations in climate and associated biological phenomena from its base to its summit”.

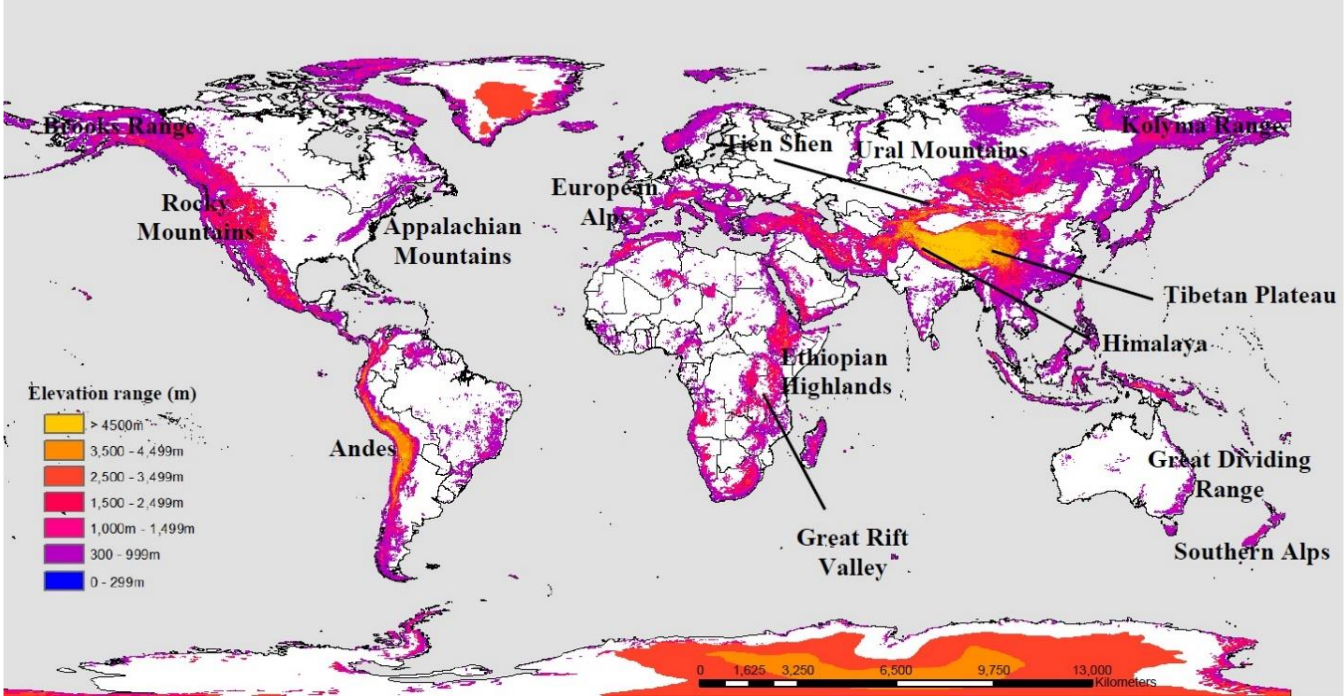


Figure 2.1 Distribution of high-elevation regions across the world
(adapted from Ward, 2016)

Several theories of mountain origin exist, but mostly mountain-building fits into the general theory of sea-floor spreading and plate tectonics (Gerrard, 1990). Mountains are initially formed by tectonic forces and re-shaped by processes like weathering, mass movement, glacial and fluvial action. The majority of the mountain types are volcanic and combinations of folded or faulted rock mass (Selby, 1985).

The opinion exists that mountains are the most complex landforms on Earth. This is because of their distinctiveness and variety of relations between tectonics and structural influences and the activity of surface processes. The form of individual mountains is often governed by rock structure and lithology (Gerrard, 1988). From the geomorphological point of view, uplands are highly geologically active environments. There are numerous examples in the literature of active landslides and mudflows, rockfall events, and erosion occurring there. The glaciation of mountains is also a crucial process as the distribution of glaciers directly influences the allocation of snow accumulation and the amount of incoming energy (Gerrard, 1990). An important characteristic of the glacial landscapes are lakes, which are formed when glaciers retreat, leading to the exposure of a topographic bedrock depression and the creation of distinct hydro-environmental conditions. Such lakes draw considerable attention from researchers as they can outburst, increase hazard potential, and risk downstream (Shugar et al., 2020). Additionally, the formation of glacial lakes significantly reduces sediment transfer dynamics from uplands to lowlands. There is a variety of such lakes across the mountains that exists and each of them is characterized by its geomorphological particularities (Otto, 2019).

Mountains are typically high-energy environments characterized by instability and variability. Strong winds, frequent freeze-thaw cycles at higher elevations in temperate regions, accumulation, and melting of snow masses in some parts, and heavy rainfall in others are common in mountain regions. Collectively, these factors speed up the process of weathering, while altitude and slope hasten the loss of erosional debris (Blyth et al., 2002). Weathering is a crucial process in the mountains. Three types of weathering exist; physical (a mechanical breakdown of rock without any contributory chemical alteration), chemical (involves irreversible chemical change), and biological (affected by the growth of plants and movement of animals). More often, physical weathering is considered more crucial because it includes the unloading process, which is a key for shaping the relief in high mountains, especially in those that are heavily glaciated and tectonically active (Gerrard, 1990). Another notable aspect is temperature patterns in mountainous areas. Air temperatures vary along an elevation gradient, with an average decrease of 6.5°C for every 1000 meters increase in altitude. The dry air at altitude retains little heat energy and causes extreme temperature fluctuations between day and night. Temperature also is a crucial factor determining the natural upper limit of tree growth (“the tree line”) varying locally and with latitude, from around 5000 m in parts of the tropics to near sea level at high latitudes (Blyth et al., 2002; Körner et al., 2011).

As many natural processes control their form, mountains are distinct from a geo-ecological point of view. Mountainous regions are characterized by steep ecological gradients over short distances, with high mobility of water, material, energy, and animals. The steep ecological gradients (also known as zonation) are primarily controlled by altitude and topography. Altitude and topography regulate hydrologic, geomorphic and ecological processes.

Figure 2.2 shows an example of the varied altitude, topography and landscape features common in mountain environments. From a hydrological perspective, the water stored in the valley bottom lake reflects the meteorological and geomorphological conditions at its surface and all the way up to the mountain peak. In spring, for example, the lake would receive snowmelt and shallow groundwater flow from the adjacent mountain, a wetland located nearby, and the surrounding forest. Such environments are unique and particularly sensitive to climate shifts as changes in one natural feature can cause misbalance in the entire natural system.

Figure 2.2 Typical geo-ecological mosaic in mountains of Glacier National Park, Montana (Credit: Lisa McKeon, USGS. Public domain.)

The importance of zonation in mountains was highlighted as an indicator of a strong relationship between geomorphological, pedological, and ecological systems (Gerrard, 1990). That interdependence allows using some of the factors to distinguish spatial zonation of interacting environments. Generally, the system-changing patterns relate to changes in altitude; changes from north to south; and changes from east to west (Gerrard, 1990). The best reflection of those variations is observed in vegetation patterns. For instance, Numata (1972) provided an example of vegetation zonation in the Japanese Mountains in which four zones are identified: alpine, subalpine, montane, and hilly. Each zone was divided into subzones, which included upper and lower areas. Each subzone had a unique vegetation composition. To illustrate the wide range of differences in patterns, it was noted that while the lower hilly subzone had evergreen broad-leaved forest as the main feature, the upper alpine subzone was characterized by the distribution of meadows, deserts, and sporadic shrubs. Lamontagne et al. (1994) offered a conceptualization of the zonation pattern in the Canadian Rocky Mountains (*Figure 2.3*). Their zonation was based on the distribution of four Chaoborus (glassworm, a midge genus) in lakes, according to elevation gradient extending from 600 m in the boreal and aspen parkland ecoregions to 2400 m in the alpine ecoregion of the Canadian Rockies of Alberta (AB) and British Columbia (BC). The main characteristic used to explore the distribution of the species was the middle summer surface water temperature.

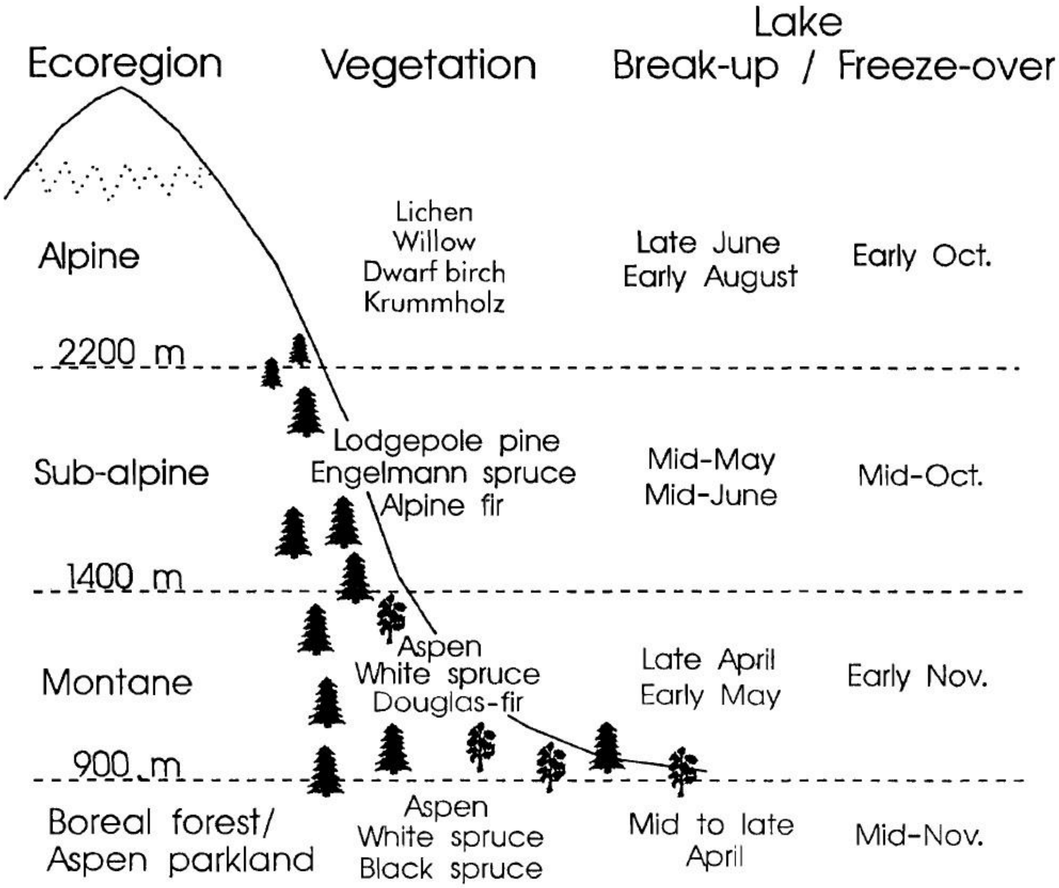


Figure 2.3 Ecoregional zonation pattern of lakes relative to elevation in the Canadian Rocky Mountains (adapted from Lamontagne et al., 1994)

Thus, it is possible to suggest that mountain regions are systems that have a natural environment with distinctive processes, which significantly differ from those occurring in lowlands. The specific zonation patterns vary across mountain ranges depending on the particularities of the natural conditions in their geographic region. Therefore, the importance of a detailed study of high-elevation areas arises as these landscapes may present interactions between natural processes from a different perspective and open wider horizons for their investigation.

2.2 Hydrology of mountain areas

2.2.1 Streamflow generation in mountains

Mountains play an extremely important and distinctive role in the hydrological processes across the planet and the regional hydrology of all continents. The hydrological cycle of mountain basins is a complex interaction of processes influenced both by regional particularities of climatic, soil, geological conditions, and vertical zonal variability together with the slope exposition (*Figure 2.4*). The figure encapsulates substantial natural factors important in water cycling. From a meteorological perspective, major precipitation is as rain or snowfall (depending on the elevation and time of year). Once precipitation reaches the land surface, it is partitioned into evaporation and plant transpiration, infiltration and groundwater recharge; the latter two serve as a feeding source for the river in low-flow periods. Because Figure 2.4 was developed specifically for The Okanagan Water Supply & Demand Project (Spence & Hedstrom, 2015), it considers manmade local water cycles as municipal water and wastewater. Additionally, presented is an agricultural water use that can affect groundwater horizons and adjacent water bodies. As essential components of mountain hydrology, Gerrard (1990) also highlighted the high radiant energy fluxes (e.g. high moisture fluxes in a form of rain and snow, discharge hydrographs influenced by snowmelt and glacier melt processes, poorly developed soils, and vegetation).

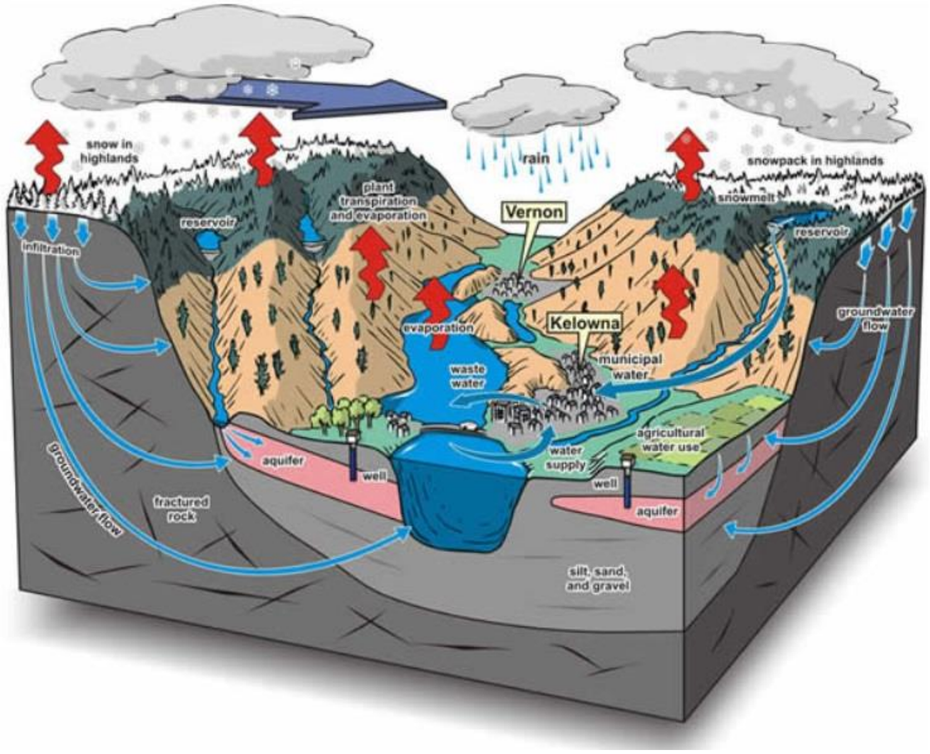


Figure 2.4 Hydrological cycle of the Okanagan basin
(adapted from Spence & Hedstrom, 2015)

Streamflow in mountain areas is often highly irregular and depends on the seasonality of precipitation, snowmelt, and glacial melt. For instance, in continental mountain ranges (e.g. Rocky

Mountains or the Himalayas), snow- and glacial melting are the dominant runoff processes (Bales et al., 2006; DeBeer & Pomeroy, 2017; Wang et al., 2017). Major rainfall-induced floods in mountains often occur when the winter snow cover is minimal, while internal drainage systems of glaciers are well-developed. Extreme floods occur when a period of maximum meltwater from the glacier combines with the intensive rainstorm for a continuous period (Röthlisberger & Lang, 1987).

There are three main runoff types distinctive in mountain environments: snowmelt-dominated, glacier-dominated, and rainfall-dominated. Example hydrographs for rivers in each runoff regime are presented in *Figure 2.5* and details of their locations are presented in *Table 2.1*.

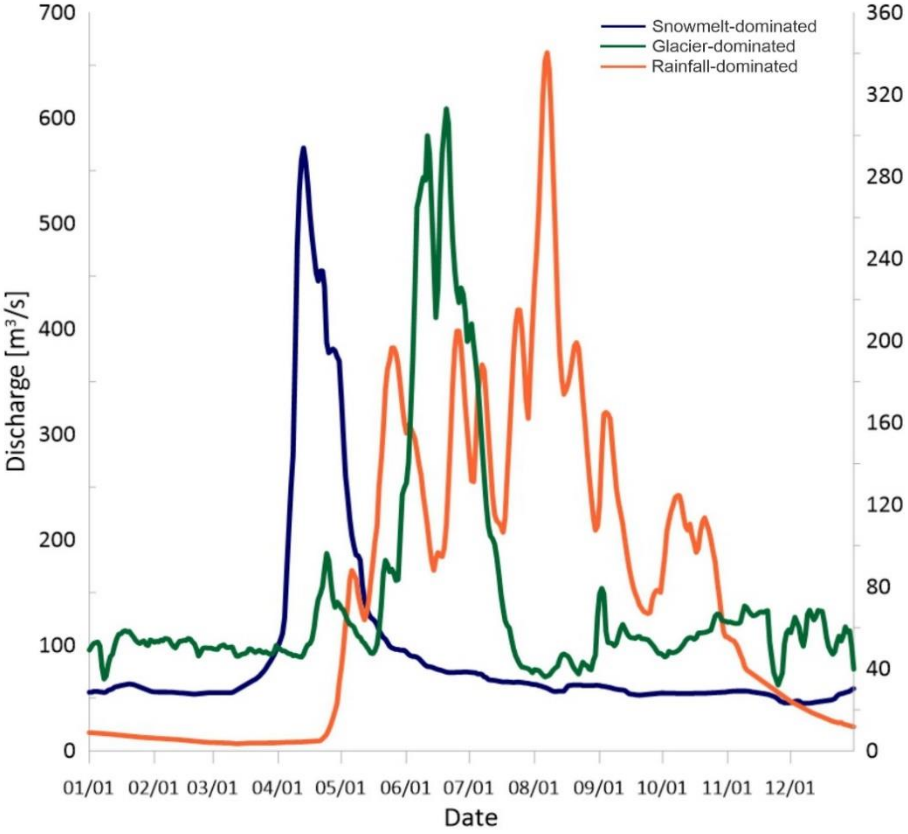


Figure 2.5 Examples of characteristic hydrographs for the three runoff types: snowmelt-dominated, glacier-dominated, and rainfall-dominated (sources: https://gmvo.skniivh.ru; https://www.bafg.de)

Table 2.1 Location information for the example rivers presented in Figure 2.5.

River name	Hydrologic station name	Country	Basin area at the station (km^2)	Characterized runoff type
Ural	Orenburg	Russia	82300	Snowmelt-dominated
Missouri	Toston	United States	37993	Glacier-dominated
Nemilen	Timchenko Village	Russia	9950	Rainfall-dominated

It can be seen that snowmelt-dominated runoff has the maximum discharge in spring (April - May) that are related to intensive snowmelt across the watershed. Meanwhile, for the glacier-dominated runoff pattern discharge peak is shifted further comparing to the snowmelt-dominated type and occurs in the middle of the summer (primarily July). This can be explained by enhanced glacial melt happening at that time of year. For the glacial-dominated runoff, the discharge increase due to snowmelt is also common as can be seen on the graph. However, this increase is much lower than that related to glacial melt. The rainfall-dominated runoff, in turn, has a specific tendency comparing to both previous types. The discharge increase also starts with snowmelt in early May but the largest values runoff reaches only by the end of the summer (August-September). This trend is common for the monsoon climates, where rain is present consistently throughout the summer with increasing rates towards the beginning of the fall. That fact explains multiple discharge peaks over June and July.

It is distinctive for the mountain regions when multiple runoff regimes are present within one catchment. For example, a partially glaciated basin will be characterized with a glacial meltwater runoff regime in parts with significant glacial coverage. Meanwhile, upper but un-glaciated areas will experience a snowmelt runoff regime and in the lower parts of the basin, a runoff will be controlled by rainfall (Gerrard, 1990).

Several studies concluded that stream discharge varies due to the factors discussed above and others. In glacierized basins, for example, glacier outburst floods (jökulhlaups) can produce a dramatic but transient increase in stream discharge. The best conditions to provoke such an event is when a glacier occupies the main river valley while the tributaries are ice-free. Subsequently, it results in the rapid release of the water trapped in the tributaries through an ice dam. Sometimes, ice-dammed lakes form due to sliding that causes the significant movements of ice mass and blocking of the rivers, which result in flood formation (Hewitt, 1982; Shugar et al., 2020).

Therefore, the streamflow generation processes in mountain environments have different natures, depending on local basin conditions and the type of the dominating source for stream water within the catchment.

2.2.2 Mountains as a water source

Bandyopadhyay (1997) estimated that the proportion of mountain to global runoff varies from 40 to 60 %, demonstrating the importance of mountains in the global hydrologic cycle. Generally, the term ‘‘water towers’’ has been used to describe mountain areas as one of the most important aspects of the runoff from these areas is its importance for water supply and agricultural needs in lowlands (Viviroli et al., 2007). Several studies described the role of mountain runoff in the total discharge of the rivers among different mountain ranges across the world located in various climatic zones. The discovered pattern suggested that in highly arid zones, mountains contribute more than half of the total runoff for the catchments. For example, Viviroli & Weingartner (2004), who researched 22 alpine catchments worldwide, identified that river flow in more arid basins (e.g. Colorado, the Amu-Daria, and the Nile) is 90% dependent on the mountain discharge. Meanwhile, in less arid regions, mountains still may be the major contributor (around 55%) to total runoff. Overall, it was emphasized that the contribution of mountain runoff increases with lowland dryness and becomes crucial when strongly arid conditions occur downstream. Another study conducted by Viviroli et al. (2007) aimed to specify the significance of mountain regions in different parts of the Earth according to the water resources contribution index. The authors agreed that critically important mountain regions are found mainly in the Middle East, Himalayan region, South Africa, parts of the Rocky Mountains, and the Andes. It was also revealed that over one-third (37%) of the global mountain area has a supportive role for lowland water resources (Viviroli et al., 2007).

However, it is not only runoff that can be a substantial source of water in the high-elevation regions. A good example is research by Immerzeel et al. (2020) who assessed the importance of mountains as a water source from the perspective of water tower units. They identified the water tower unit as “the intersection between major river basins and a topographic mountain classification based on elevation and surface roughness”. It was found that there was considerable variability among water tower units to supply different areas. For instance, the Tibetan Plateau, in Asia, had the highest ranking because of the large amounts of water stored in lakes. In South

America, the mountain ranges mostly were prominent water towers, because of large glacier ice reserves and high orographic precipitation rates. Meanwhile, in western Canada, the relevance of the water tower unit was primarily driven by the abundance of glaciers, snow, and surface water. It was also claimed that the water tower units of South America and Asia are more vulnerable than those in North America and Europe because in the first two parts most water tower units are densely populated and heavily irrigated.

On the other hand, scholars face challenges when they attempt to study hydrological processes and natural hazards in mountain environments. It was demonstrated that in many cases there is a lack of higher altitude measuring stations providing precise hydrological data (de Jong et al., 2005a). Further, the number of ground-based observation stations is declining worldwide (Strachan et al., 2016). The problem with a low density of meteorological stations in high-elevation basins is that they poorly capture the diverse hydrology of alpine systems and are not spatially dense enough to perform accurate forecasts of dangerous natural events (Givone, 1990). Similar research stressed that as long as local hydrographs reflecting antecedent conditions in higher altitude sub-catchments are not available, general observations or flood/drought prediction tools remain inadequate (de Jong, 2015). Concerning anthropogenic impacts on alpine water bodies, de Jong (2013a) found that in the Alps, for instance, the most severe hydrological impacts are associated with hydroelectricity, river straightening, and tourism. Pollution from industry and urbanization strongly affects alpine streams and lakes, especially the latter ones as they act as final pollution traps. The randomness and sparseness of hydrological gauges and observation points in the mountains also present challenges to assess mountain water resources and their availability for downstream regions (Viviroli & Weingartner, 2004). Increasingly, researchers rely on a combination of remote sensing and terrestrial observations to solve the challenges of sparse ground-based observation stations (Strachan et al., 2016).

To conclude, it is worth noting that mountain regions are crucial not only from a social point of view, as a source of water for human needs, but also from a scientific point of view, as areas with specific complex hydrology that have to be explored to the patterns of natural processes occurring in those regions.

2.3 Mountain lake hydrology

High mountain lakes (a.k.a. alpine lakes) are identified in the literature as ecosystems located beyond the tree line in the mountains. As was described in section 2.1, the tree line is governed by temperature conditions across the mountainous regions, hence lakes will be considered as alpine laying on different elevations depending on latitude. For example, the alpine zone in Kenya is located between 3500 and 4500 m above sea level (a.s.l.), while in Alaska it is situated between 1000 and 2000 m a.s.l. (Sommaruga, 2001). In some cases, the definition of mountain lakes is also associated with an ecological zonation pattern as it is related to the living conditions of biota and the water chemistry (Pechlaner, 1971). Generally, mountain lakes have common features owing to similar environmental conditions: they have a relatively small surface area, are located in sparsely vegetated catchments, and usually are exposed to extreme climates. Most of these lakes are originated from the last glaciation (around 10000 years ago) appearing because of ice action upon hard bedrocks. Mountain lakes are hardly productive because of the sparse soil and small watershed sizes comparing to the lake volume (Catalan et al., 2009). Alpine lakes are presented in the majority of large mountain ranges worldwide: in the Alps, in the Pyrenees, in the Caucasus, in the Himalayas, in the Rocky Mountains, in the Andes, etc. (Catalan et al., 2006).

From the scientific point of view, mountain lakes draw a great deal of attention not only because they are a major water source, but also because they can help to create an overall picture of the interactions between natural and hydrological processes in a particular region. In different mountain areas, a variety of multiple natural drivers may cause changes in alpine lake hydrology. For that reason, a range of studies exists that aims to define the impacts of those factors on the lakes and identify the most substantial ones. *Figure 2.6* encapsulates the most pronounced natural factors that regulate alpine lake hydrological functioning according to the literature sources. As such, presented are the meteorological parameters (precipitation, solar radiation, evaporation, and transpiration) that were shown to be critical, particularly for influencing lake water levels. In line with that, illustrated are natural factors that mostly appeared in the analyzed literature concerning control in-lake processes in high-elevation regions. Those are glaciers/snowpack, surface inflow/outflow, groundwater inflow/outflow, wetlands, and forest cover. In reality, though, it is challenging to define a particular natural factor playing a major role in regulating lake hydrology as it strongly depends on local natural conditions.

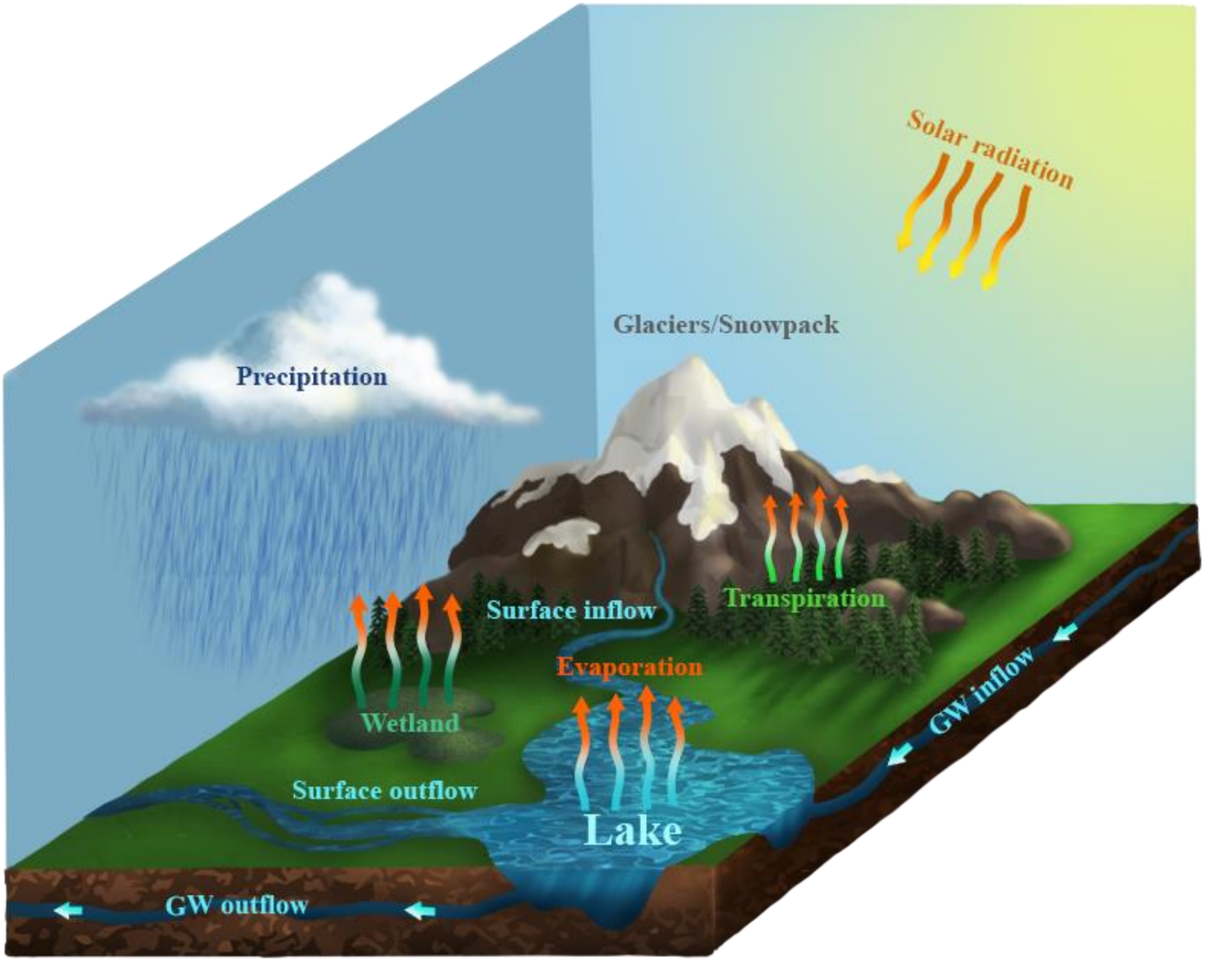


Figure 2.6 Key natural factors for the hydrological functioning of a mountain lake

Several studies consider *hydrometeorological parameters* valuable in controlling lake water levels. In that case, the main regulators are precipitation rates (amount, timing) and evaporation ratios (either low or high). For example, Ptak et al. (2017) studied the hydrological regime of Lake Morskie Oko in the Tatra Mountains (mountain range located along the border between Slovakia and Poland) and documented a sharp decline in lake water levels driven by changes in atmospheric precipitation. Another study, conducted across the lakes in Tibetan Plateau used Landsat imagery to analyze the decline in lake water storage and levels from 1975 to 2015 (Qiao et al., 2017). The researchers found that the main reasons for lake area shrinkage were less precipitation and less glacial meltwater under lower temperature conditions. As the study also focused on comparing glacier-fed and non-glacier-fed lakes, they highlighted that the water storage of non-glacial lakes was unrelated to precipitation rates. Meanwhile, for the glacier-fed, it was noted that lake water storage significantly increased (approximately 20%) with greater precipitation. Similar research was performed in the Himalayan region, where the expansion of glacial lakes was derived under the increased precipitation (Gardelle et al., 2011). There it was discovered that snow and liquid precipitation over the catchment were a direct input for the lake with different time lags. Additionally, solid precipitation was an accumulation input for glaciers and therefore an indirect water input for the glacial lake. Some scholars have highlighted the importance of precipitation in controlling the isotopic composition of lakes (Ju et al., 2017). Regarding evaporation influences, a study conducted by Sturrock et al. (1992) evaluated the energy budget approach to determine evaporation from boreal Williams Lake located in northern Minnesota. For the observations, the *in situ* data from the meteorological station were used. The researchers discovered that the patterns of monthly values of evaporation were not consistent from year to year. This instability influenced the open-water season and extended the frozen period for the studied lake. Additionally, Campos et al. (2016) illustrated a great example of the reservoir morphology effect on the yield-evaporation-spill relationships in reservoirs. The authors discerned that the regulated water yield decreased with the reliability level, while the evaporation and spill losses increased in study reservoirs. Moreover, from 40 reservoirs selected for study, 60.0% were classified as slightly convex, 27.5% as convex, and 12.5% as linear. The Monte Carlo simulation for different reliability levels showed that convex reservoirs generally presented lower water yields than conical reservoirs with the same storage capacities and maximum water depths due to high evaporation losses. The opposite trend was detected for slightly convex and linear reservoirs.

On the other hand, some researchers have argued that *geomorphology and geology* are significant factors influencing lake hydrological processes in alpine catchments as they characterize the quantitative values of these processes (Silar, 1990). In many cases, geology is also considered as a regulator of the groundwater exchange with a water body. At that point, the *groundwater* distribution within the catchment appears to be a critical factor influencing lake hydrology.

For instance, there were some studies conducted in the Canadian Rockies that used the water balance approach to define the role of groundwater in the high-elevation system (Hood et al., 2006, 2007). All investigations were based on field measurements. It was found that groundwater flow to Lake O'Hara was substantial and that it was an important part of the lake water balance (Hood et al., 2006). The authors also pointed out that the reduced influence of the shallow groundwater regime over the summer resulted in the drying of soils and a decline in the lake water level. A year later, Hood et al. (2007) acknowledged that the groundwater contribution was approximately 25–40% of total water inputs to the lake during the peak flow period (late June to early July) and 35–50% toward the end of the summer. Another study conducted in the Rocky Mountains aimed to define the effects of the water loss from the alpine lakes network through groundwater recharge with the application of two water balance models (Liefert et al., 2018). The important result suggested that groundwater outflow regulated the volume of a small alpine lake and caused significant water loss.

Besides the water balance approach, there are several other methods to estimate the importance of groundwater contributions to alpine lakes. For instance, Shaw et al. (2017) evaluated the isotope mass balance approach on Georgetown Lake (Montana, USA) to understand regional groundwater interactions with the water body. This research combining field methods and satellite imagery showed that groundwater inflows were almost twice as high as groundwater outflows (60% of inputs versus 30% of outputs). Moreover, the groundwater inflows were stressed as sensitive to evaporation because it caused their change almost by 20%. Equally important is to assess the groundwater chemical composition influence on the water chemistry of the lakes. For example, Williams et al. (1990) described the groundwater and surface water chemical relations for alpine Emerald Lake (Sierra Nevada, California). They discerned that groundwater discharge during the low-flow period was a major regulator for NO_3, $SO_{4,}$ and silica concentrations exchange within the lake.

Many alpine lakes are strongly influenced by *glaciers*. Several studies exist showing glacier contributions to the hydrological regime of mountain lakes. For instance, a study conducted by Ju et al. (2017) investigated alpine Ranwu Lake in south-eastern Tibet and found that glacial meltwater was the main water source, according to the variety of seasonal variations in isotopic composition. Additionally, Song & Sheng (2016) calculated Normalized Difference Water Index for the alpine watershed in the Tanggula Mountains and found that more than half of the annual source water for lakes with glacierized catchments was glacial meltwater. Similarly, Mark & Seltzer (2003) found that glacier meltwater contributed almost 40% to the annual water balance of the proglacial lake they studied in the Rio Santa basin within the Cordillera Blanca. Research conducted by Pelto et al. (2013) investigated the mass balance of the Brady Glacier in Alaska and documented that the lake area somewhat increased coincident with glacier retreat.

Glacial inputs are also important for the *chemical composition* of the lake's water. Several works studied glacier influences on alpine lake physical properties and water chemistry. In such a way, Slemmons et al. (2013) summarized the results of multiple studies showing that glacial meltwater influences not only lake stratification patterns but also increases the movement of suspended solids to aquatic systems affecting the water clarity. At the same time, Saros et al. (2010), comparing NO_3 concentrations in snowmelt-fed lakes to those in glacier-fed lakes, discovered that nitrogen-cycling rates were higher in the glacier-fed lakes. They attributed that to glacier meltwater that had minor contact with the catchment soils. Another study examined spatial variation in transparency across a set of 33 lakes in the Canadian Rockies (Olson et al., 2018). The researchers discovered that glaciers played a key role in determining what factor regulates water transparency: in glacially fed lakes, transparency was driven by turbidity, while non-glacial fed lakes had transparency mostly affected by dissolved organic matter absorbance.

Particular studies provided evidence on several other natural drivers that can influence lakes' hydrology. For instance, Arp et al. (2006) who analyzed the hydrodynamics and hydrologic regimes of a coupled stream–lake ecosystem in the Sawtooth Mountains, USA, highlighted the role of the *stream inflow* in the regulation of lake's water stage. The authors found that higher inflow rates led to an expansion of lake surface area by up to 20% over the observation period. The important conclusion highlighted that the considerable interannual variation in lake level fluctuations from 0.15 to 0.70 meters was detected across the region. Several studies showed the impact of *wildfires* and *forest disturbance* on stream and lake hydrology. In such a way, Mahat et al. (2016), conducting their research in southeastern Alberta, Canada, discovered that the mean annual peak flows from the burned catchments were 1.4 to 2.2 times higher than those from the unburned catchments. Additionally, the removal of forest floor and vegetation cover caused changes in evapotranspiration and snow accumulation processes in the catchment. A similar study, performed in the Canadian Rocky Mountains documented an increase in total interflow of 8% for burned watershed comparing to unburned one (Springer et al., 2015). On the other hand, it was discovered that the effects of fire on small lakes cause increasing wind stress, leading to deepening of thermoclines and increasing turbidity (Schindler, 2009).

Thus, it was shown that the hydrological processes of mountain lakes are driven by various natural factors depending on the particularities of natural conditions in the region. Even the same natural drivers can differently affect lake hydrology due to variations in the geomorphic and climatic settings of the lake. It was also demonstrated that multiple drivers (external and internal) can be significant for sustaining lakes' hydrological conditions complicating the understanding of those interactions within the mountain basin.

2.4 Changing Climate in the Rocky Mountains

In the modern world, climate change is believed to be an important concern for mountain ecosystems. The evidence of that is provided by multiple studies conducted in different mountain ranges across the world: in the Himalayas (Wang et al., 2013; Zhou et al., 2010), in the American Cordillera (Diaz et al., 2014), in the Andes (Loriaux & Casassa, 2013), in the Alps (Rogora et al., 2003; Thies et al., 2007), in the Ural Mountains (Solovieva et al., 2008). The Rocky Mountains are not an exception from this list and being one of the largest mountain ranges worldwide, also experiencing sequels of climate change. The climatic shifts significantly affect natural conditions across the catchments in that region.

The first part of this section will describe the commonly observed variations in natural drivers across the Rocky Mountains. Specifically, the fluctuations in hydrometeorological factors as *rising air temperatures, increasing liquid precipitation amounts, changing solar radiation income,* and *shifting in snow accumulation and melt* will be illustrated. Further, examples of *glacial shrinking* that has a remarkable reflection on the mountain basins will be provided. Along with that, *variations in groundwater storage,* as well as *shifts in hydrological and ecological regimes of the mountain streams*, will be represented as consequences of climatic change. Lastly, the evidence on *changes in wetland hydrology and forest distribution* in the catchments of the Canadian Rocky Mountains will be shown.

The second part of the section will examine the influences that mountain lakes experience under global warming across the Rocky Mountains. Particular examples including an *increase in lake surface temperature, variations in residence time and productivity* will be given.

2.4.1 Global warming influence on natural factors

2.4.1.1 Hydrometeorological conditions

One of the most notable reflections of global warming is variation in hydrometeorological patterns across the mountain regions. Many literature sources report changes in atmospheric conditions across the Rocky Mountains. For example, Williams et al. (1996) analyzed 40-year trends in temperature, precipitation, and shortwave radiation in Niwot Range located in Colorado Front Range. The researchers observed an overall decrease in annual temperature with high interannual variability. Meanwhile, the precipitation trends were increasing (the overall increase of about 300 mm since the 1950s was affirmed). The shortwave radiation, though, is decreasing with a total decline of 30% of average daily income comparing to the 1970s. It was also highlighted that variations in the three aforementioned patterns could cause substantial changes in chemical concentrations of snowpack meltwater. Another study, conducted by Luckman & Kavanagh (2000) investigated the temperature fluctuations in the Canadian Rockies and discovered somehow different patterns from the previously mentioned study. The authors identified that there was an increase in air temperature of approximately 1.5°C per 100 years. Even though there was a cooler and more stable period (the 1950s – 1970s), the overall trend has grown up. Specifically, the winter temperatures showed the greatest warming trends (around 3.5°C).

Particular studies examined changes in precipitation patterns more closely and found that there is a tendency of shifting from snow to rain precipitation in the region. In such a way, Foster et al. (2016), using atmospheric forcing data, conducted a series of experiments to evaluate the hydrologic sensitivity of mountain regions to changes in precipitation phase from snow to rain on the example of the central Rocky Mountains. The researchers concluded that the replacement of snow precipitation by rain would lead to an increase in evaporation patterns across the basin as well as a reduction of streamflow rate.

Other characteristics affected by climatic changes are snow accumulation and melting processes. For instance, Fyfe & Flato (1999) applied CCCma Coupled Climate Model on the archive of mean monthly values calculated for the period from January 1901 to February 2100. The researchers discerned that the decreasing tendency of surface albedo can likely lead to declining snow accumulation across the Rocky Mountains from an average of 60-70 mm in 1900 to 0 mm by 2100. The analysis of the surface energy budget demonstrated that crucial changes in the net solar radiation inputs were caused by variations in surface albedo and decreased snow cover. On the other hand, Harder et al. (2015), studying a general response of the Marmot Creek basin in the Canadian Rockies on global warming and extreme weather conditions, discovered that climatic changes did not have a notable influence on the snow accumulation and melt besides the decline in the peak snow water equivalent over the study period. The researchers suggested that it could be related to the increased amount of liquid precipitation on higher elevations.

To sum up, it can be pointed that hydrometeorological conditions are very sensitive to global warming across the Rocky Mountains, which consequently can have different implications on the other processes across the region of interest.

2.4.1.2 Glaciers

Another important concern across the mountain regions is the accelerated shrinkage of glacial volumes. Regarding the Rocky Mountains, a wide range of research confirmed that fact. For example, a large-scale study conducted by Bolch et al. (2010) investigated changes in glaciers across British Columbia and Alberta in Canada using Landsat satellite imagery. The researchers found that variance in the glacier area indicates a greater percentage loss for small glaciers rather than for large ones. The authors also stated that the average glacier area decreased by 15 to 25% across the Rocky Mountains from 1950 to 2002.

Many studies reported changes in glacial volumes particularly in the Canadian Rockies. In such a manner, using a combination of GRACE satellite imagery and in-situ observations, Castellazzi et al. (2019) reported that glaciers in the region had thinned around 0.9 m/yr over 13 years (2002-2015). A similar study performed by Tennant et al. (2012) applied Landsat imagery and Enhanced Thematic Mapper (ETM+) to examine the changes in glacier cover in the central and southern Canadian Rocky Mountains from 1919 to 2006. The authors discovered that the overall glacial area decreased by 750 km^2 (45%) across the study region, 17 of 523 glaciers completely disappeared, and 124 split into separated ice fragments. In addition to that, it was underscored that glaciers with an area less than 1 km^2 experienced the most critical areal losses (around 65%). Concerning small glaciers, Luckman & Kavanagh (2000) reached a similar conclusion describing variations in glacier cover of the Upper Bow drainage basin. The researchers estimated that glaciers with smaller areas (< 1 km^2) experienced over 50% loss of their areas. These results support the findings of Bolch et al. (2010).

Particular studies aimed to predict possible global warming influences on glaciers in the Rocky Mountains in near future. In such a way, Clarke et al. (2015) using a high-resolution regional glaciation model and various climatic scenarios, estimated that the glacial area and volume losses will exceed 90% by 2100 comparing to the 2005 values. Moreover, the authors have claimed that projected changes in ice cover could have consequences for aquatic ecosystems, water quality, alpine tourism, and resource development not only in the Rocky Mountains but also on a broader scale across western Canada.

Therefore, the Rocky Mountains experience enhanced glacial shrinkage, which is a crucial problem as it can lead to changes (generally negative) in the natural conditions within the basins, so needs to be a consideration for further investigations.

2.4.1.3 Groundwater

Climatic changes also reflect on the groundwater patterns in the Rocky Mountains. To illustrate that Meixner et al. (2016) described global warming effects on the groundwater recharge across the western US (some study sites were located in the US Rocky Mountains). The researchers highlighted that mountain recharge was very sensitive to climatic shifts and warming temperatures. In addition, the continued warming trend would cause a diminishing of the annual value of snow water equivalent due to declining snow precipitation and increasing evapotranspiration. Consequently, it would lead to a shorter duration of the snowpack and thus lesser recharge.

Focusing more locally, Castellazzi et al. (2019) researched the Canadian Rockies and stressed that there was a significant increase in groundwater storage caused by enhanced glacial melt in the region. At the same time, the groundwater flow was estimated to inhibit glacier meltwater transfers to the rivers by tens to hundreds of years affecting the dynamics of sea-level rise. Another study, conducted in the same region, showed the variations in groundwater table across the research basin (Harder et al., 2015). The investigators stated that the low elevation water table in the shallow well near the stream remained stable, while it decreased in the deep well situated farther from the watercourse. The opposite trend was observed for higher elevation where the shallow well was located far from any stream – here the water table declined. Analyzing these fluctuations in the groundwater table, the researchers made conclusions about impacts of decreased snow accumulation in low elevations as well as increased precipitation at higher elevations on groundwater recharge in those locations.

Even though climate change does not influence the groundwater directly in the majority of cases, the consequences of those influences might reflect negatively on groundwater-dependent natural systems.

2.4.1.4 Mountain streams

Equally important are climate change impacts on the hydrology of mountain rivers. In this instance, a vast range of scientific studies found that the enhanced glacial melting has sufficient influence on the hydrological condition of alpine streams. Generally, glaciers are the main contributors to stream hydrology in the dry season as was verified by Frenierre & Mark (2014). To prove that, Marks et al. (2015) conducted a study in the Wind River Range (Wyoming) and claimed that increased contribution of glacier loss (around 6%) in the stream in recent 15 years was associated with the rapid increase of temperatures in a particular region and lower snowpack in comparison to historical averages. Nonetheless, the contributions of glacier meltwater to stream hydrology may also depend on the glacier area within the basin. Similarly, VanLooy & Vandeberg (2019) researching the same region, used an isotopic approach and reached the same conclusion for watersheds with only a small extent of glacier cover.

In light of the negative impacts of global warming, several studies documented possible shifts in the hydrological regimes of mountain streams. To illustrate, Geiger et al. (2014) investigated the response of rock glaciers in the La Sal Mountains of Utah and acknowledged that these structures had the net effect of increasing total surface runoff from alpine drainage basins. At the same time, it was found that with increased precipitation, the proportion of runoff related to glaciers diminished with little change to total runoff. Another study conducted by Leppi et al. (2012) analyzed mean August discharge across the 153 streams in Central Rocky Mountains to detect climate-driven changes in flow from 1950 to 2008. The researchers discovered that according to 89% of the gauging stations, watersheds across the study region experienced significant declines in late-summer stream discharge over the observation period. According to the authors, the increasing summer temperature trends across the Rocky Mountains noticeably influenced the August discharge of studied streams. Likewise, Stahl et al. (2006) in their study across the catchments in British Colombia (many of those were located in the Canadian Rockies) provided similar evidence suggesting that the decline of the summer streamflow could cause a significant ecological effect on the stream temperature, which would affect distributions of species (e.g. algae and fish). Moreover, the decreasing runoff might harm the species distribution and their rates of growth and development.

Hence, climate change causes significant variations in stream hydrology, mostly negative, as for all the above-mentioned drivers that control natural conditions within the mountain catchment.

2.4.1.5 Wetlands and forest cover

Apart from hydrometeorological conditions, glaciers, groundwater, and streamflow, some other natural factors are substantial for the hydrological function of the lakes in mountain environments. Those are wetlands and forest cover. Despite less coverage of these factors in the literature sources, they are also sensitive to global warming.

To affirm climatic influences on wetlands, Streich & Westbrook (2020) investigated the hydrological processes in Sibbald fen (Canadian Rocky Mountains) under dry summer conditions. As an approach, the authors used field-based observations and a water balance equation to investigate the water fluxes of the study object. The researchers stated that shifts in the hydrology of the fen were caused by the dynamics of seasonal frost and the timeframe of rain occurrence. For instance, it was discovered that with little precipitation and increased evapotranspiration, the fen water table dropped approximately 1 m by the end of the summer. In addition to that, ground frost was pronounced as a key controller for Sibbald fen as it might devastate the water storage of the fen due to thawing under the warmer temperatures.

To assess the global warming influences on the forest cover, Trant et al. (2020) used around 80 high-resolution image pairs to analyze 104 treeline ecotones in the Canadian Rocky Mountains. The authors found that under the rise of annual winter and summer air temperatures in the region, 87% of tree lines had advanced. Moreover, the consistency between the tree line advances was different across the sites and varied from low (0.25) to moderate (0.75). Along with that, there was an increase in tree density for 89% of treeline ecotones, while the rest of them had a tree density that remained the same or decreased. Applying the statistical confidence intervals, the researchers concluded that tree lines at higher latitudes and higher elevations had a significantly greater probability to advance.

In such a manner, climate change reflects on the water storage of mountain fen and controls tree line patterns on high elevations. Even these examples are only from the Canadian Rockies, they might be similar in other mountain ranges, triggering a necessity to study these drivers more deeply.

2.4.2 Reflection of climatic changes on mountain lakes

Similarly, mountain lakes are experiencing significant changes in their hydrological processes as far as they are located in the same environment as all of the aforementioned drivers. Some scientists have examined the impacts of global warming on mountain lakes based on information derived from sedimentation rates and paleoclimate records. For instance, Beierle et al. (2003) defined that increased glacial sediment fluxes in Burstall Lakes (Canadian Rockies) in the early Holocene enhanced organic carbon inputs to the lakes leading to the deterioration of their productivity. Similarly, Shapley et al. (2009) analyzed the carbonate sedimentology of Jones Lake located in Montana, USA. The authors discerned that greater contribution of warm-season precipitation reach with stable oxygen ($\delta^{18}O$) to groundwater in late Holocene “could also contribute to the subdued millennial trend, offsetting the $\delta^{18}O$ effects of shorter lake residence time”.

Particular research documented the changes in lake ecosystem conditions because of climatic influences. Like that, Christianson et al. (2019) examined the changes in surface water temperature across 590 lakes in the Southern Rocky Mountains. The main finding was that the average surface temperature of the studied lakes warmed at the rate of 0.13°C per decade from 1955 to 2016. The investigators suggested that if the warming trend continues, those lakes will be warmer at 1.1°C by 2100, having mixed consequences for biota depending on their living optimum temperatures. A similar study performed by Roberts et al. (2017) aimed to create statistical models of daily mean surface water temperature for 27 lakes situated in Rocky Mountain National Park. The reconstruction of the past lake temperatures (to predict future trends) was done using a modelling approach with the temperature series from the snow telemetry (SNOTEL) sites from 1986 to 2016. The researchers discovered that the mean annual surface temperature will increase at 2.9°C by 2085 comparing to the present conditions. Another remarkable result indicated that the studied lakes are expected to have an increase in ice-free days at 29% by the 2080s.

Some scholars have provided evidence on climate change implications for mountain lakes’ ecosystems derived from other natural conditions in the basin. To illustrate, Parker et al. (2008) studied the sensitivity to climate variations of four alpine lakes located in Banff National Park, Alberta. The investigators performed a principal component analysis of air temperature, precipitation, and snowpack data to identify climatic groups between 1991 and 2003. It was found that the physical, chemical and biological features of the studied lakes differed significantly between these periods. As such, the authors stated that the snow-free period was 33 days shorter and the ice-off date 12 days later in the 2000s compared to the 1990s. In addition to that, concentrations of phosphorus and silica were 10 – 50% lower in those lakes during the 2000s. Meanwhile, the average increase at 80% in dissolved organic matter, as well as shifts in phytoplankton communities, were observed. Two years later, Vinebrooke et al. (2010) compared the global warming impacts on the phytoplankton between Curator Lake and McConnell Lake located in Jasper and Banff National Parks of Canadian Rockies, respectively. The authors discerned that periods of warm temperature stimulated glacial melting resulted in more turbid, colder, and less productive seasons in McConnell Lake. Conversely, in Curator Lake, the impact of climate change on primary production was less notable since the complete ablation of the small local glacier occurred. Substantially, the researchers stressed the ability of local glaciers to abate or even reverse the short-term decadal effects of increased air temperatures on alpine lakes.

Thus, global warming has various consequences for mountain lakes. Mostly, it reflects on ecosystem conditions as a whole owing to the increase in air and, hence, water temperature. Furthermore, the glacial melt influences temperature conditions and productivity rates in the mountain lakes. Despite some positive effects (e.g. the growth of small organisms in the lakes of the Canadian Rockies), the overall trend for the lakes' ecosystems in the Rocky Mountains might be negative with shifts in hydrological processes and the deterioration of living conditions for water biota. Therefore, it is crucial to investigate thoroughly mountain lakes to describe the present and projected impacts of intensive climatic change on their ecohydrology.

2.5 Application of frameworks and classifications for studying lake hydrology

So far this literature review has shown that there are multiple, sometimes interacting factors that regulate the hydrology of mountain lakes. In situations where there are numerous factors seemingly important for understanding a particular phenomenon, an overall picture is needed to organize the ideas. Conceptual frameworks, conceptual models, and classification systems are all analytical tools that can be graphically useful ways of explaining the key factors or variables and the presumed relationships among them in a concise and illustrative way. In this section, differences among conceptual frameworks, conceptual models, and classifications are explained using examples.

A *conceptual framework* is a specific perspective used to explore, interpret, and explain the behavior of the subjects or events the researcher is studying (Imenda, 2014). More generally, it relates concepts, empirical research, and relevant theories to advance and systematize knowledge about related concepts or issues (Rocco & Plakhotnik, 2009). Generally, conceptual frameworks have a theoretical basis and may represent the researcher's synthesis of the literature on how to explain a phenomenon. The researcher(s) outlines the actions required during the study based on given previous knowledge of other scholars and their points of view (Regoniel, 2015). Conceptual frameworks do not always require testing (e.g. creating a summary of the hypothesis of a natural process behavior), and instead can be used to guide.

Regarding conceptual frameworks application, the possibility of performing analysis for a wide range of natural characteristics across the large regions was shown in the literature. As evidence, Read et al. (2015) demonstrated the utility of hypothesis testing within the landscape limnology framework using a random forest algorithm (based on regression tree analysis) on a spatially explicit data set (more than 1000 lakes across the US). Specifically, the researchers tested the relative importance of water quality drivers and hydrologic connectivity across spatial scales for five important in-lake water quality metrics (total phosphorus, total nitrogen, dissolved organic carbon, turbidity, and conductivity). Another study performed by Livingstone et al. (2012) developed the theoretical assessment of palaeo-subglacial lakes by looking at their formation and evolution, and by producing diagnostic criteria for identifying processes in those lakes. Interestingly, the authors applied a series of conceptual schemes (cartoons) to illustrate the importance of the particular characteristics (ice sheet erosion, ice-sheet surface slope, thermal regime, and hydraulic conductivity) on studied lake genesis. In particular, the researchers identified that lakes can form due to local increases in meltwater production or decreases in hydraulic conductivity (*Figure 2.7*). In panel A, *line 1* represents the ability of the bed to drain all the meltwater, *line 2* represents a case when hydraulic conductivity is lowered and more water can be generated than drained and subsequent ponding of excess water, and *line 3* shows a case when hydraulic conductivity is depressed locally and larger amounts of water can pond at the surface. Panel B illustrates the formation of a subglacial lake. *Line 1* shows the free drainage of meltwater, which is possible as permafrost does not influence ice mass. *Line 2* illustrates ice mass advance towards the permafrost zone, increase in meltwater drainage through the sediment, and, consequently, its ponding at the cold-bedded margin.

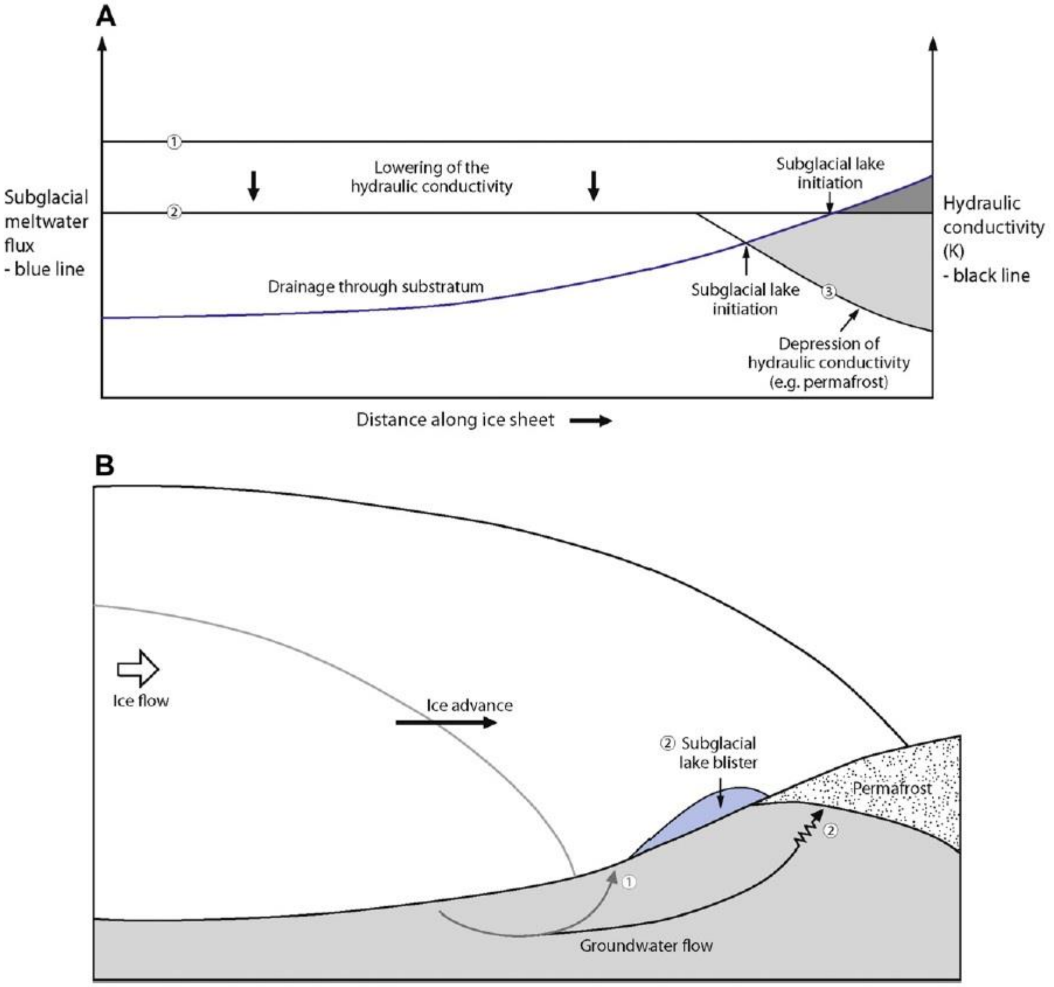


Figure 2.7 A "cartoon" showing the significance of hydraulic conductivity in the origin of the subglacial lake (adapted from Livingstone et al., 2012)

In light of recent climate change, some scholars have also attempted to use conceptual frameworks to reflect its impact on water bodies. For example, Blenckner (2005) schematically combined features of geographical position, geomorphological conditions of the region, lake morphology, and biotic/abiotic interactions to describe responses of lake ecosystems functioning to rising temperatures. For that, the author has used a schematic diagram illustrating "filters" describing each of the feature groups. In a similar way but focusing on another natural factor, Kløve et al. (2014) synthesized current knowledge on the interactions between climate, groundwater, and ecosystems, and examined integrated groundwater management strategies that account for human and ecosystem needs. Throughout the paper, the researchers applied a series of conceptual frameworks explaining how external factors (e.g. climate variability, groundwater extraction, or land use) might affect groundwater levels across large aquifers.

A similar approach is a *conceptual model*. It is a representation of a system, made of the composition of concepts, which help people to know, understand, or simulate a subject the model represents. Another interpretation was suggested by Robinson et al. (2016) who defined a conceptual model as a concise and precise consolidation of all goal-relevant structural and behavioral features of the studied system presented in a predefined format. As such, the model should be sufficiently comprehensive and easily understood by other users, so they can apply it for studying features of the investigated system that characterize its behavior (as outlined from the perspective of project goals). The main purpose of a conceptual model is to be a product for future testing and calculations (for instance, the development of a numerical model). In that case, it is used as “a non-software specific model” describing the objectives, inputs, outputs, assumptions, and simplifications of the future model (Robinson, 2008).

Scientists tend to confine the definition of conceptual models; therefore, the application of those tools has a primarily practical approach. For example, Dinka et al. (2014) used a conceptual model to estimate the water budget of Basaka Lake (Ethiopia), situated in the northern part of the Main Ethiopian Rift at elevation 950 masl. The developed model contained the water balance equation itself and a set of equations, which investigators used for the calculation of process drivers (precipitation, evaporation, groundwater, and surface runoff). Likewise, Charizopoulos & Psilovikos (2016) applied a conceptual model “Zygos” to simulate hydrological processes in the catchment of Xynias drained Lake, Greece. The Zygos model is a lumped conceptual water-balance model containing the monthly time series of rainfall and the potential evapotranspiration as input and implements a soil moisture accounting scheme (*Figure 2.8*). Another study by Gates et al. (2008), specifically aimed to establish a conceptual model of sources and timing of recharge across the lakes in Badain Jaran Desert (a submontane region with elevations ranging from 1100 to 1300 masl in China) using environmental tracers including stable isotopes of water, radiocarbon, and tritium. The authors used the series of equations to estimate lake/groundwater interactions as a basis for the applied conceptual model and developed a schematic conceptual diagram illustrating the recharge pattern in the studied basin.

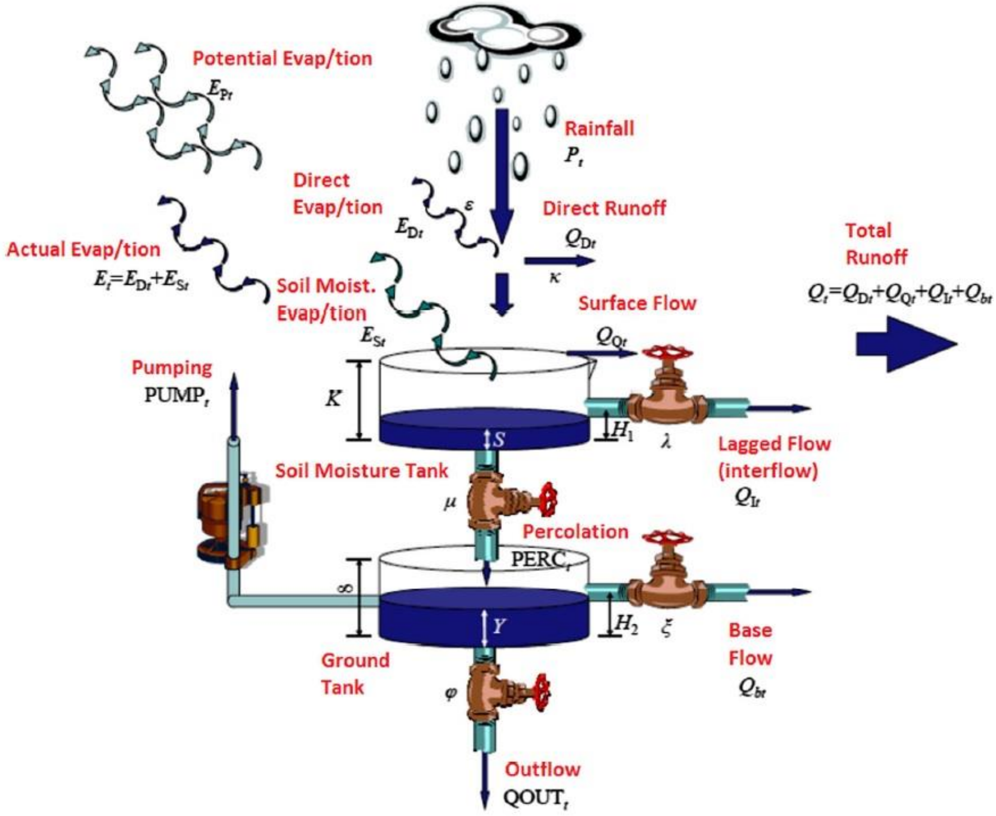


Figure 2.8 Schematic representation of hydrologic processes of the conceptual model Zygos (adapted from Charizopoulos & Psilovikos, 2016)

The third widely applied option among researchers is *classification*. Classification is a systematic arrangement of similar entities based on certain differing characteristics (Miller-Keane Encyclopedia , 2003). This approach is stricter than a conceptual framework or model as it is based on collected data and aims to assign the studied object to a particular class according to a set of characteristics that are describing that object from the author’s point of view. Moreover, classification has a narrower focus as it can be applied only for a particular range of study objects (it is obvious that classification differentiating rivers according to their basin area, cannot be used to classify mammals regarding their habitat, for instance).

Specifically, the classifications are popular among scholars as they help to define specific characteristics of a lake’s hydrological regime. For example, research conducted by Turner et al. (2010) examined the influence of evaporation to precipitation (E/I) ratio on lake water balance across the Old Crow Flats in Yukon. With a help of field observations and satellite images, the authors detected four classes of lakes for a study area: precipitation-dominated, evaporation-dominated, groundwater-influenced, and drained lakes. Further, the importance of the E/I ratio for each of the classes was determined. A couple of years later, Lantz et al. (2015) assessed the impact of the thermokarst and climate on the lakes of the same region. The researchers highlighted the increasing area across multiple water bodies and the critical increase of drainage. Those aspects helped to split lakes into classes according to their areal extent and degree of drainage (*Table 2.2*). Another study, led by Martin et al. (2011) created a classification that maximizes within-class homogeneity and between-class heterogeneity for lake water chemistry from the hydrogeomorphic point of view. The authors also addressed the significance of the scales for variables used for the survey. Regarding mountain regions, a wide range of studies focuses on potentially dangerous lakes that can cause glacier outburst floods. That problem is common for many alpine areas and for that reason scientists classify lakes regarding their geomorphological conditions (presence of rock or moraine dams, glacier erosion, etc.) and assess their sustainability to outburst (Bajracharya & Mool, 2009; Janský et al., 2006; Otto, 2019).

Table 2.2 Lake classification according to changes in the surface areas across 170 studied lakes in the Old Crow Flats (modified from Lantz et al., 2015)

Lake class	Number of lakes (1951-1972)	Number of lakes (1972-2010)	Mean lake area (ha)	Lake area: Catchment area
Catastrophic drainage	4	34	123	0.058 (0.089)
Large bidirectional fluctuation	NA (not applicable)	47	35	0.047 (0.072)
Gradual cumulative decline	NA	12	67	0.144 (0.094)
No threshold change	NA	73	-	0.161 (0.165)

To conclude, it can be said that conceptual frameworks, models, and classifications are useful tools to describe natural processes and their interactions in controlling some functional characteristics of lakes. While classifications are more applied for studying specific characteristics, conceptual frameworks and models are analytical tools that provide a big picture view of a wide range of spatial and/or temporal scales. At the same time, classifications might lead to better and accurate results as they generally use *in situ* observations or satellite imagery as a basis, when conceptual frameworks and models use a more theoretical and schematic approach. Nevertheless, the example of some conceptual models that were applied for the development of numerical models was shown meaning that it is also possible to consider them as a databased tool in some cases. When considering climate change influences on the lake's hydrological functioning, conceptual frameworks seem to be more extensively used because of their synthetic approach and capability to address those impacts on natural systems more concisely.

2.6 Analysis of studies that used classifications, conceptual frameworks, and conceptual models as an approach to assess changes in hydrological processes of the lakes

The majority of the mountain lakes remain unexplored due to their remoteness and inaccessibility. For the same reason, there is a lack of classifications or conceptual frameworks developed for these water bodies in the literature. There are many approaches used for plain regions but the main problem is that hydrological processes and their interactions with natural drivers are different for alpine areas. Consequently, it is usually impossible to apply a conceptual model or classification created for valley lakes to the mountain water bodies.

In this section, the key studies that use classifications or conceptual models/frameworks will be analyzed. Some of them are of the general sense and some were developed specifically for mountain regions. I aim to summarize their ideas and define whether the researchers address global warming concerning the study lakes.

Generally, classifications are found frequently as a tool used for investigations. Specifically, it is common to use them for the separation of in-lake processes or types of lakes in different classes according to their similarities.

The particular study worth highlighting was accomplished by Winter (1977). The factors selected for the classification were believed to control the interchange in the lake (for example precipitation-evaporation rates, streamflow inflow and outflow, lake depth, local relief and geomorphology, texture of the bedrock, groundwater quality type). The main method for classification development was a principal component analysis but for some of the factors, the numerical ranks were assigned due to lack of data. As a result, precipitation-evaporation balance and the water quality parameters had higher factor loading. Geologic and groundwater flow was pronounced as the second-largest group of components. The author claimed that the classification developed in the paper is the first attempt to classify the hydrologic settings of lakes, so it can be improved by introducing their field or laboratory measurements for better performance.

Another valuable research was performed by Bracht-Flyr et al. (2013). As a method, the authors used a steady-state, basin-lake water balance model. Data was collected from governmental websites and processed with ArcGIS. The researchers brought the significance of timescales for the evaluation of lake sensitivity to changes in hydrologic balance (i.e. lakes might not be particularly sensitive to yearly or decadal fluctuations in climate, but may provide high lake sensitivity on longer timescales). Additionally, the authors pointed that developed classification separates the lake surface area ratio and index of aridity domain into ephemeral, permanent, and land cover change-sensitive lake regions with the higher importance of the land cover. The lakes taken for classification are situated across the six continents proving that classification can be applied on a large scale. The researchers also stressed that classification might be useful for planning in the regions where climate has a large influence on surface water hydrology and lake level.

Noteworthy, conceptual models and frameworks do not find such wide use as classifications. However, several studies used these two approaches to conduct their research on broader scales and find relations between climate change and its influence on the hydrology of the lakes.

Particular studies developed conceptual frameworks based on natural factors to emphasize their significance in regulation in-lake hydrology and reflect global warming's effect on it. The paper worth noticing was presented by Zaharescu et al. (2016) who identified the main landscape elements that sustain a lake ecosystem in high-altitude basins. The researchers surveyed over 400 lakes in the Pyrenees based on field data collected during the summer seasons. Their results indicated a strong association between water body size and lake hydrology (type and volume of water input/output). The authors illustrate their framework as a 3D model that reflects the ecotope development and the main drivers affecting it: hydrodynamics, geomorphology, and topography (*Figure 2.9a)*. As the study was conducted in the mountains, the elevation was identified as a primary gradient explaining lake ecotope development and latitude was the second key gradient for lake ecotope variation.

For a deeper understanding of lake hydrological processes, some scholars developed conceptual models with a large set of parameters. An excellent example is a paper by French (1986) that developed a model consisting of a hierarchical arrangement of subsystems, each focusing on a different temporal-spatial scale. In the four-level hierarchical model, one level is geomorphological, two levels are ecological and ecophysiological, and the fourth level is a combination of geomorphological and ecological concepts (*Figure 2.9b*). The model considers the time scale as the alpine geosystem model is a four-level hierarchy, the level including those processes of greatest spatial influence and longest time at the top. Climate is defined as a set of abiotic driving parameters intersecting all levels of the geosystem. Similarly, are the hydrological and geochemical abiotic processes. The aforementioned parameters were treated as a single subsystem because they were considered interdependent processes. The suggested model is relatively complex, covering a wide range of factors, and might be applicable for the whole watershed, for instance.

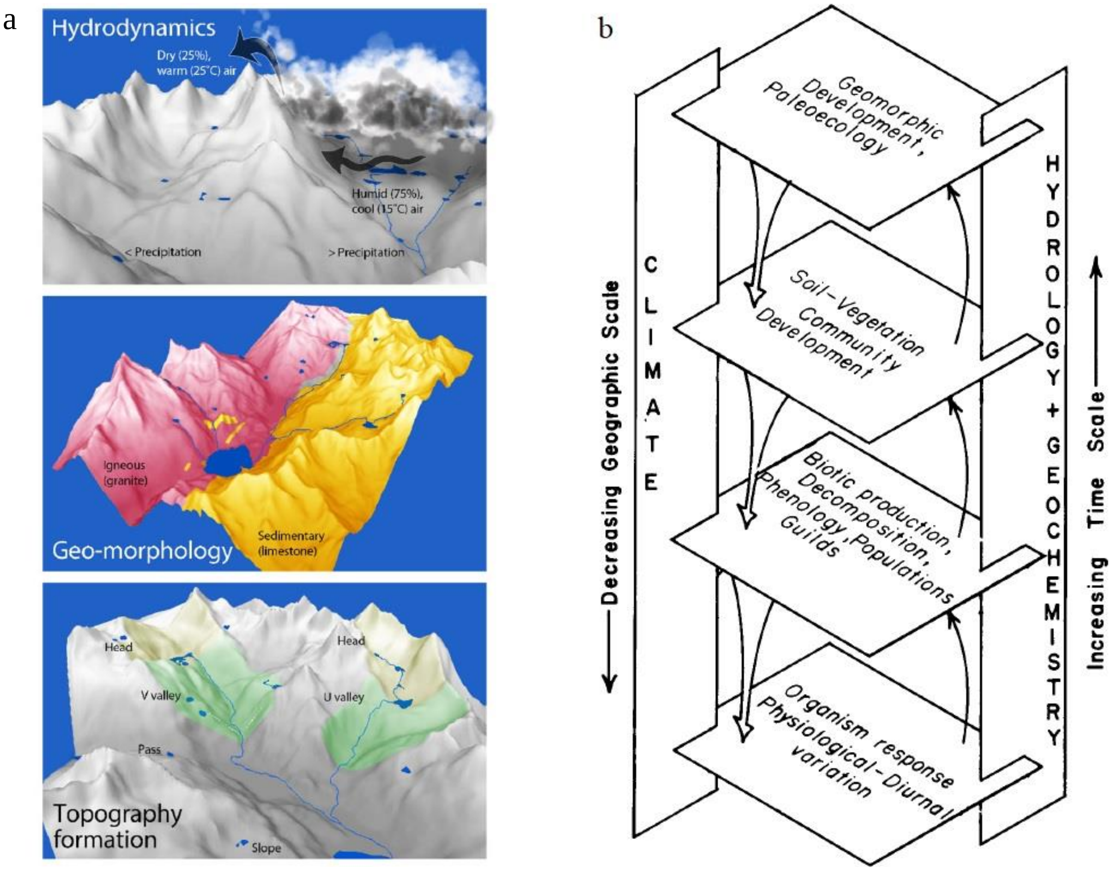


Figure 2.9 a. Conceptual framework reflecting the ecotope development and natural factors affecting it (Zaharescu et al., 2016); *b.* Conceptual model of alpine landscape geosystem developed by French (1986)

The summary of other key classification-based and conceptual framework or model-based studies analyzed in the thesis is presented in *Table 2.3*. The table reflects on the approach and methods used in the study, the utility for the Rocky Mountains, the way of the developed tool presentation, the applicable scale of the study, and its relation to climate change.

Table 2.3 Summary of previous research that used classifications, conceptual frameworks, and conceptual models as a study approach

Author(s) and study title	Study goal	Approach used	Research methods	Utility for the Rocky Mountains	Presentation of a developed tool	Applicable scale	Relation to climate change
Blenckner (2005). A conceptual model of climate-related effects on lake ecosystems.	To present a conceptual approach to understand individual lake ecosystem responses to climatic change and variation.	Combination of conceptual framework and model	To group and structure climatic responses of lake ecosystems, the researcher conducted a literature analysis to identify potentially critical factors for the future conceptual model.	Not stated	The conceptual model is presented as a scheme of two filters: A landscape Filter including the features of geographical position, catchment characteristics, and lake morphology, and an Internal Lake Filter, reflecting on the biotic/abiotic interactions.	The framework can be used worldwide on lakes of different latitudes. There is no evidence of the applicability of the presented method in mountain regions, though.	The researcher provided a strong relationship to climate change from an ecological point of view.
Bracht-Flyr et al. (2013). A hydro-climatological lake classification model and its evaluation using global data.	To develop the classification model against observations from 150 lakes, spanning six continents and to identify lakes having climate and lake area interactions as dominant controls on their water level.	Classification	The simple analytical water balance the model was used. Data on lake area, basin area, and meteorological factors were collected from various sources (publications, GIS measurements, and archives of the International Water Management Institute).	In their classification, the researchers considered the timescale of used factors meaning that a developed tool can be applied in the Rockies.	The plots illustrating the lakes' patterns according to the distribution of A-Φ domains for different continents and climate conditions.	The classification is applicable for plain lakes worldwide.	The researchers stated that classification might be useful in planning as identifying modern lakes where climate has a large influence on surface water hydrology and lake level.

Table 2.3 - continued

Author(s) and study title	Study goal	Approach used	Research methods	Utility for the Rocky Mountains	Presentation of a developed tool	Applicable scale	Relation to climate change
Catalan & Donato Rondón (2016). Perspectives for an integrated understanding of tropical and temperate high-mountain lakes.	To compare the high-mountain lakes of the tropical and temperate climatic areas highlighting common and contrasting features.	Conceptual model	The analysis of previous studies and collected natural data were used to develop a conceptual model based on two main concepts: the airshed-sediments continuum, and the mountain lake district.	The developed tool might not be suitable for the Rocky Mountains because of the different climate conditions.	As the main stage of the study was the development of the conceptual model, the authors present a table with suggested parameters for its creation.	The study is suitable for mountain regions of temperate and tropical climates.	The conceptual model is applicable for the analysis of climate change and its influences on the lakes in the two mentioned climate types.
Driscoll et al. (1991). Adirondack Mountains.	To illustrate the major processes regulating the acid-base status of Adirondack surface waters through the development of the classification system for Adirondack lakes.	Classification	Lakes and watersheds were classified according to the lake type and dominant flow path. The previously conducted US Eastern Lakes Survey in the study region provided the chemical data for the study lakes.	The classification might be applicable for the Rocky Mountains to estimate water chemical characteristics.	The authors provide the results of testing their classification on particular lakes in the Adirondack Mountains.	The developed classification can be applied for a narrow range of goals as it uses only water chemistry and flows patterns as key factors, which is not applicable for every mountain lake.	Not stated
French (1986). Hierarchical conceptual model of the alpine geosystem.	To present the broad general organization of system components and the major interrelationships between them.	Conceptual model	The developed conceptual model consists of a hierarchical arrangement of subsystems, each focusing on a different temporal-spatial scale. The components of a subsystem are joined by flows of matter and energy.	The presented tool should be applicable to the Rockies for studying mountain lakes and catchments.	The conceptual model is presented as a 3D image with each mentioned hierarchical level.	The developed tool is detailed and complex, it covers a wide range of factors and can be applied not only for mountain lakes themselves but also for the alpine basins worldwide.	The author mentioned that climate plays an important role in the model as it represents a set of abiotic driving parameters intersecting all levels of the geosystem.

Table 2.3 - continued

Author(s) and study title	Study goal	Approach used	Research methods	Utility for the Rocky Mountains	Presentation of a developed tool	Applicable scale	Relation to climate change
Hayes et al. (2017). Key differences between lakes and reservoirs modify climate signals: A case for a new conceptual model.	To synthesize differences between lake and reservoir characteristics that are critical for predicting waterbody response to climate change.	Conceptual model	A conceptual model incorporates key differences between lakes and reservoirs in the export of climate-mediated changes in E (energy) and m (mass) to the sediment or downstream river networks. The model also considers the transformation of E and m by the environmental filters. Three of them are incorporated: catchment, waterbody, and management.	The presented conceptual model is probably suitable for small lakes in the Rockies if considering their area and latitude as was stated by the authors.	The authors present their results with two conceptual models of climate-related effects on lake ecosystems and reservoirs built on the Energy-mass (Em) flux.	The created conceptual model can be applied for temperate lakes and reservoirs > 0.04 km². It might work for larger water objects as long as differences in latitude are considered.	The focus of the research stresses that the presented tool is applied to assess lakes and reservoirs' responses to global warming located at different latitudes.
Sánchez-López et al. (2015). The effects of the NAO on the ice phenology of Spanish alpine lakes.	To evaluate how climatic parameters and the ice phenology of Spanish alpine lakes are affected by the seasonal NAO variability.	Conceptual model	A conceptual lake model is formulated based on Pearson's correlation coefficients obtained between season-scale time series of the NAO index, climatic data (i.e., precipitation, air temperature), and limnological variables (ice phenology records).	The developed tool might not be suitable for the Rocky Mountains because of the geographic location (the climate there is unlikely affected by NAO).	The result is presented as a series of diagrams where the main component NAO interacts with climatic conditions and the ice cover of the selected lakes.	The developed conceptual model can be used for coastal alpine regions where NAO has a significant effect on climatic factors.	The researchers developed the conceptual model to analyze the reflections of climate change on mountain lake limnology.

Table 2.3 - continued

Author(s) and study title	Study goal	Approach used	Research methods	Utility for the Rocky Mountains	Presentation of a developed tool	Applicable scale	Relation to climate change
Winter (1977). Classification of the Hydrologic Settings of Lakes in the North Central United States.	To classify the lakes in the north-central United States according to their interchange with atmospheric water, surface water, and groundwater.	Classification	The variables selected for the classification basis control the atmospheric, surface, and groundwater interchange in the lake. All information used in this study was taken from published maps and reports of the U.S. Geological Survey. The main method for classification development was principal component analysis.	Not stated	Maps showing the distribution of selected components of PCA with the studied lakes.	The classification can be applied to plain regions across the world. It may apply to mountain regions.	Not stated
Zaharescu et al. (2016). A Multiscale Framework for Deconstructing the Ecosystem Physical Template of High-Altitude Lakes.	To identify the main landscape elements assumed to sustain a lake ecosystem in high-altitude basins, and model how they organize at different scales to produce a coherent ecosystem functioning.	Conceptual framework	The data collected across 380 lakes in the Pyrenees was treated with statistical analysis tools. To identify and exemplify ecotope units and the spatial interactions between categories of variables the categorical principal component analysis was applied. Further, linear regression was used to examine the potential relationship between ecotope properties and geographical gradients.	The developed framework might be used for the lakes in the Rockies considering the drivers crucial for mountain regions.	The result is presented as a 3D model that reflects the ecotope development and the main drivers affecting it: hydrodynamics, geomorphology, and topography.	The conceptual model can be used on worldwide scales across the mountain regions.	The researchers claimed that the importance of climate for ecotope development is high as gradient changes in climate factors affect not only lake ecosystem composition but also many of its physical and chemical processes.

Table 2.3 - ended

Author(s) and study title	Study goal	Approach used	Research methods	Utility for the Rocky Mountains	Presentation of a developed tool	Applicable scale	Relation to climate change
Bajracharya and Mool (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal.	Understanding the response of glaciers and glacial lakes to rising temperatures for water resources planning as well as managing the potential for GLOF disasters.	Classification	1. The studies use satellite imagery data as a primary source for the research. 2. The approach used for the studies is based on glacial characteristics and physical properties of glacial/moraine/landslide materials. 3. Geomorphology of the region is generally considered as one of the key factors affecting GLOF formation.	Such classifications can be applied in the Rocky Mountains on the sites where the potential GLOF lakes are presented.	Generally, the results are presented as a text or table with identification and a brief description of each lake class or subclass.	Such classifications are developed for various mountain regions across the world. Usually, the lake classes are similar depending on the particular features of the study region and the authors' main goal and approach.	The classifications have a direct relation to climate change as they are created to reflect climate influence on the glacial lakes and characterize possible consequences.
Emmer et al. (2016). 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods.	To classify the lakes in the region, to analyze the evolution of the lakes over time, and to assess the susceptibility of large lakes to outburst floods.						
Janský et al. (2006). Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture.	To present the genetic classification of the lakes with an indication of the degree of risk of their rupture.						
Otto (2019). Proglacial Lakes in High Mountain Environments.	To summarize the importance of proglacial lakes for geomorphic systems in high mountain environments.						

2.7 Research gaps

Summarizing the findings and information presented in the section, the following question arises: *what do we know about the hydrological functioning of alpine lakes in the Canadian Rocky Mountains?* This is a crucial question, as mountain lakes are not only considered as a substantial water resource for downstream agriculture and communities but also serve as a habitat for a wide variety of water organisms. Furthermore, mountain lakes can behave as reflectors of the complex hydrological processes occurring within a watershed.

Considerable research provides evidence that mountain basins are sensitive to global warming. It is well stated that climatic changes provoke variances in natural drivers and shifts in mountain lakes' ecosystems. However, much less is known about the interactions between those natural drivers and lakes under the rising temperatures. Certainly, there are pieces of literature showing contributions of particular natural characteristics to lake hydrology. Nevertheless, the exploration of the combined influences of these characteristics on mountain water bodies in light of climate change is sporadically illustrated in scientific research. That raises a challenge, considering the importance of such an assessment to get a better understanding of climate change reflection on mountain lakes (hydrological function concept). Another difficulty is related to the local focus (e.g. considering only a small area within a large mountain range) of most of the conducted research. Subsequently, it is problematic to translate the findings of climatic changes to other mountain ranges due to remarkable differences in natural conditions. The problem is complicated by the fact that the role of natural drivers in regulating lakes' hydrology varies depending on the region as well. For instance, in one basin the groundwater paths are the most critical for lake sustaining while in another one, glacial retreat or enhanced streamflow affect the lake's ecosystem. Moreover, the different time scale of the natural drivers influences their role in contributions to the hydrological function of the lake, emphasizing that discovering their compound contributions is needed. Generally, the local scale of the studies can be related to the poor hydrologic exploration and sparsely available data for mountain regions, hence the impossibility to conduct deep and fully distributed research. Specifically, that problem is critical for Canadian Rocky Mountains as turned out from the analysis of literature sources. Finally, the unexpanded application of conceptual frameworks across the studies in the scientific field complicates the performance of a thorough analysis of global warming influences on mountain lakes. Conceptual frameworks were shown to be strong tools to hypothesize the interactions among natural systems within the catchments in different environments. Therefore, these tools should be widely applied in scientific research to assess the possible fluctuations in the hydrological processes of mountain lakes under changing climate even concerning the pressing shortage of data.

Chapter 3. Methodology

3.1 Physiographical description of the study region

The Canadian Rockies is the largest range in the Rocky Mountains spanning 1450 km and covering an area of 180 000 km^2 (*Figure 3.1*). The eastern boundary is the Interior Plains, which is a vast land between the Canadian Shield and the Rocky Mountains; the western boundary is the Rocky Mountain Trench. Toward the north, the Liard River separates the Canadian Rockies from the Liard Lowland and the Hyland Highland. The southern boundary is the Marias Pass, where the Canadian Rockies extend 125 km to Montana (USA) and includes Glacier National Park. Owing to the uniqueness of the region and its significance to Canada, much of the Rockies are protected by designation as National or Provincial Parks.

The map presented in *Figure 3.1* does not include the very southern part of Canada and the US part of the Canadian Rockies as there was no map coverage provided by an open data source.

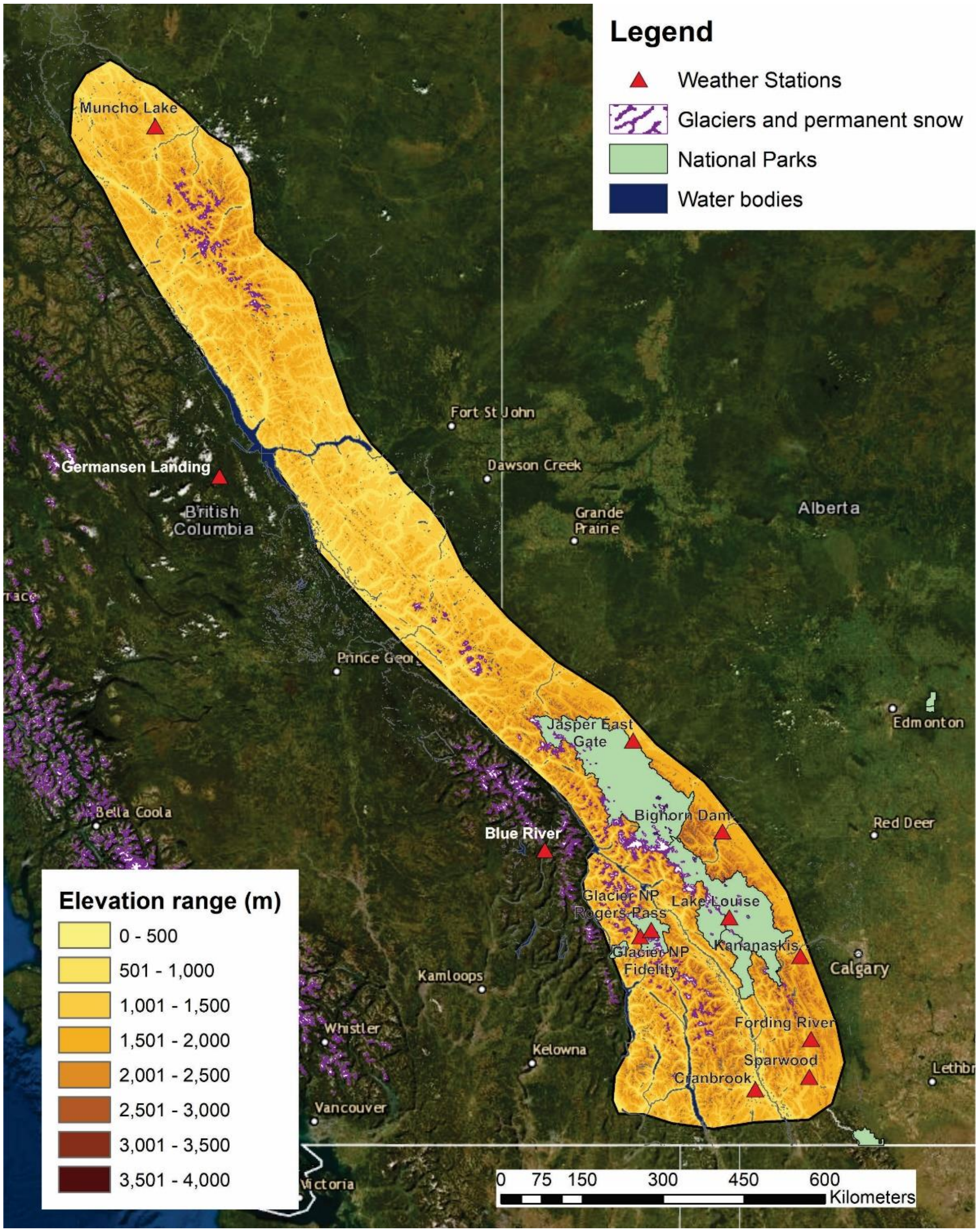


Figure 3.1 Map of the Canadian Rockies

There are four main divisions defined in the Canadian Rockies, extending from south to north: Border Ranges, Continental Ranges, Hart Ranges, and Muskwa Ranges (*Figure 3.2*). The Border Ranges extend from the US border to 49.3°N latitude. The relief there is characterized by peaks up to 2600 and rugged relief. The Continental Ranges then extend from this point northward to 54°N latitude. This region represents the most spectacular part of the Rocky Mountains, including the second-highest falls in British Columbia (Takakkaw Falls – 366 m), and the highest peaks in the Canadian Rockies (Mt. Robson – 3954 m, Mt. Columbia – 366 m, and Mt. Assiniboine – 3618 m). The Hart Ranges are the lowest and least rugged part of the Rocky Mountains and extend from the Continental Ranges north to the Peace River, with summit elevations averaging 2300 m (Holland, 1964). The lowest elevations presented are Pine Pass – 869 m and Monkman Pass – 1082 m. North from the Peace River to the Rabbit Plateau, elevations in the Muskwa Ranges gradually rise from about 2500 m to 3200 m and then drop back down to 1500 m. The highest peaks in this region include Churchill Peak (3200 m) and Mt. Lloyd George (2917 m). In general, the Canadian Rocky Mountains reflect the strong control of the underlying bedrock, which predominantly consists of faulted and folded sedimentary rocks (Bobrowsky & Rutter, 1992).

The foothills have a varied relief along with their entire extent (700 – 2350 m). The more characteristic for this region is a gradual decrease in elevation and relief from west to east. The Rocky Mountain Trench marks the transition between two larger physiographic systems. It extends from north of the Yukon border to northern Montana and has a length of 1600 m (Slaymaker & McPherson, 1977).

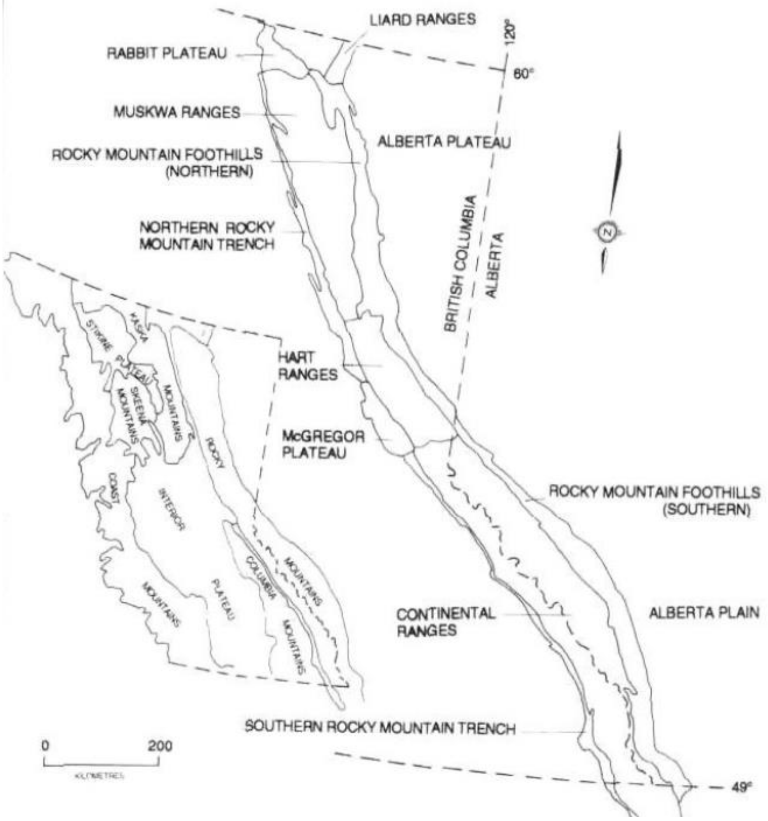


Figure 3.2 Physiographic regions of Canadian Rockies (adapted from Bobrowsky & Rutter, 1992)

3.1.1 Geological features of Canadian Rocky Mountains

The Canadian Rockies were formed by extreme shortening in the sediments of a vast series of flat and overlaid thrust faults (Keating, 1965). Surface exposures include rocks ranging in age from Tertiary to Precambrian. The Tertiary and Mesozoic parts are composed mainly of sands, silts, and shales, in contrast to the Paleozoic parts which are predominantly carbonates, and the Precambrian parts which are argillites, quartzites, and carbonates

Glaciers played a critical role in the landscape formation of the Canadian Rocky Mountains. Throughout the Quaternary, repetitive glacial cycles, having three ice sources (Laurentine Ice Sheet, Cordilleran Ice Sheet, and Montane ice) remarkably changed the physical form of the region. The glacial history of the Rockies is reflected with glacial forms (e.g. cirques, aretes, and horns) presented across eastern ranges and in the northern and southern ends. The ice that created those forms has already gone but glacial erosion is still active, especially in the central Rockies along the continental divide. That erosion leads to the creation of specific landforms, icefields, which are large glaciers covering upland areas at high elevations. For example, there is a string of icefields between Kicking Horse Pass and the northwest corner of Jasper Park; the largest is the Columbia Icefield with an area of 300 km^2 (Andrews & Barry, 1978).

The bedrock structure is very diverse across the study region. Primarily it consists of a westerly thickening wedge of folded and faulted Proterozoic and Jurassic carbonates and elastics including limestone, quartzite, dolomite, chert, shale, slate, and sandstone. In the Main Ranges, Cambrian-Devonian rocks are dominant, while the Front Ranges are represented with Devonian-Jurassic rocks (Tipper et al., 1981). The Foothills are underlain by folded sedimentary rocks ranging in age from the Precambrian to Tertiary, with most of the bedrock of Cretaceous age. The Muskwa Ranges in the northern Rocky Mountains are composed of quartzites, slates, limestone, and conglomerates. The Hart Ranges are dominated by quartzite and limestone. The Border Ranges in the southern Rocky Mountains consist of limestone, argillites, siltstone, and sandstone (Bobrowsky & Rutter, 1992).

Particular attention should be paid to the geological structure of the central and southern Canadian Rockies as the main study area is located there. The major geologic subdivisions are presented in *Figure 3.3*. Provided is also the description of each geologic subdivision from east to west:

- The Interior Plains, underlain by an undisturbed sequence of Paleozoic, Mesozoic, and Cenozoic sediments directly overlying a westward dipping Canadian Shield (Bally et al., 1966).
- The Foothills, are formed by large and flat thrust sheets involving Paleozoic carbonates, with some frontal imbrications. In the southern Foothills the deformation is primarily thrust faulting but in the northern Foothills only folding is visible at the surface. Within the Foothills a topographic distinction is observed between low shaly rocks relief and high sandstones relief (Dahlstrom, 1970).
- The Front Ranges, which are formed by thrust sheets, mainly involving Paleozoic carbonates and Precambrian carbonate and clastic rocks. The sheets there are bounded by faults extending on tens of kilometers.
- The eastern Main Ranges are composed of Precambrian and lower Paleozoic sediments. Within the eastern Main Ranges, the structures are broad, open folds with relatively few thrusts and normal faults. The Western Main Ranges are different as structures there are tighter and the rocks are cleaved.
- The Western Ranges, characterized by intensive cleavage and thrusting toward both east and west. In this subdivision, faults are steep and can be normal, thrust or strike-slip. Much of the structure is surficial and is restricted to the rocks above the thick quartzite of the Lower Paleozoic.
- The Rocky Mountain Trench is a broad linear valley showing evidence of normal faulting on its boundaries.
- The Purcell Mountains is a large, thrust-faulted anticlinorium, involving thick sequences of Proterozoic and lower Paleozoic sediments.
- The Selkirk-Moncishee is represented by extensive gneiss complexes, by more or less discordant granitic intrusives, and by Paleozoic and Mesozoic clastic rocks (Bally et al., 1966; Dahlstrom, 1970).

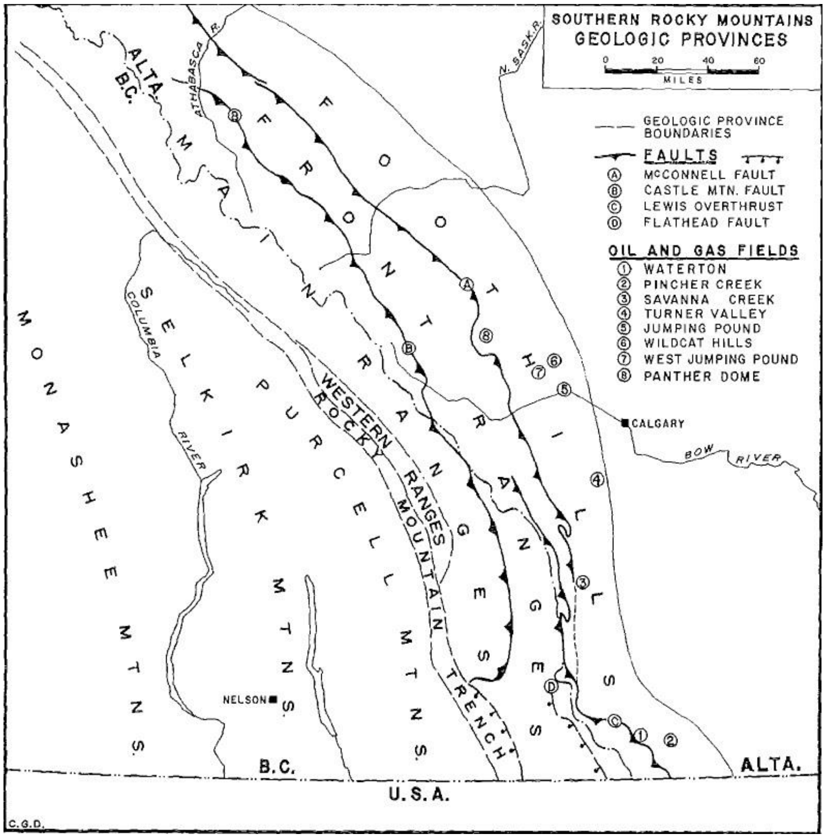


Figure 3.3 Geologic subdivisions of central and southern Canadian Rocky Mountains (adapted from Bally et al., 1966)

3.1.2 Climate conditions in Canadian Rocky Mountains

The Canadian Rocky Mountains are affected by variable climatic patterns due to their considerable latitudinal and altitudinal range. Generally, the dominating factors affecting the region are prevalent west winds, orographic effect, and proximity to the Pacific Ocean. The weather pattern is strongly affected by the barrier nature of the Canadian Rockies, which makes the eastern slope cooler and drier than the western slope. The climate controls regional vegetation patterns, landforms, weathering of rocks, soil formation, distribution of animal life, and dominant hydrological processes.

Three major climatic gradients exist within the Rockies. The first is elevation: the higher is the elevation, the cooler the air. The second climatic gradient is latitude: the further north a site is, the cooler the air temperature regime will be. The third gradient crucial for these mountains is the precipitation pattern. The western slopes of the Rockies generally receive more moisture than the eastern slopes due to the prevalence of western winds (Elias, 2002). As well, the type of precipitation and amount reaching the surface varies greatly throughout the altitudinal gradient and by the time of year (Harder & Pomeroy, 2013).

Overall, the Canadian Rockies are considered a cold region. Thirty-year (1981 – 2010) annual air temperature normals are variable, ranging from 0.2°C at Lake Louise (1524 masl) to 6.0°C at Cranbrook (940 masl) (*Table 3.1*); however, there are few government operated weather stations at high elevations. The amplitude of temperatures is also variable: from -35°C (sometimes below -40°C) in January to +35°C in the middle of July. Several studies documented changes in temperature patterns over the 20th century across the region (e.g. Kittel et al., 2002). For instance, in the Southern Canadian Rockies, annual and seasonal mean minimum temperature increased significantly from 1900 to 1998 (from +1.0°C to +2.5°C/century), and diurnal temperature range decreased (from -0.5°C to -2.0°C/century) (Zhang et al., 2000). There were also notable significant increases in maximum and minimum temperatures (annual means +1.5°C to +2.0°C per 50 years). From 1950 to 1998 for both northern and southern Canadian Rockies with larger changes in the north.

The distribution of the precipitation is also highly irregular across the region. Thirty-year (1981 – 2010) annual precipitation normals vary from 385 to 2000 mm depending on the location and elevation of the meteorological station (*Table 3.1*). Both annual and seasonal precipitation rates have also increased throughout the 20th century (Zhang et al., 2000). As such, in the southern Canadian Rockies, precipitation increased by 5% to 40% since 1900. Also important to consider are climatic-induced changes in the ratio of snow to rain (Harder et al., 2015).

Table 3.1 Annual temperature and precipitation for the last climate normal (1981 – 2010)* for selected stations in the Canadian Rockies and adjacent mountain ranges

Station name	Station ID	Province	Geographic coordinates		Elevation (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)
			N	W			
Cranbrook A	1152102	BC	49°36'44.00"	115°46'55.00"	940	6.03	385
Sparwood	1157630	BC	49°44'43.00"	114°52'58.00"	1138	4.42	613
Fording River Cominco	1152899	BC	50°08'55.00"	114°51'18.00"	1585	0.93	617
Kananaskis	3053600	AB	51°01'39.08"	115°02'05.06"	1391	3.63	639
Glacier NP Mt. Fidelity	117CA90	BC	51°14'17.50"	117°42'05.30"	1890	0.50	2038

Table 3.1 – ended

Station name	Station ID	Province	Geographic coordinates		Elevation (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)
			N	W			
Glacier NP Rogers Pass	1173191	BC	51°18'06.06"	117°31'00.00"	1330	1.94	1495
Lake Louise	3053760	AB	51°26'00.00"	116°13'00.00"	1524	0.22	544**
Blue River A	1160899	BC	52°07'44.50"	119°17'22.30"	690	4.76	1024
Bighorn Dam	30506GN	AB	52°19'00.00"	116°20'00.00"	1341	3.04	503
Jasper East Gate	3063523	AB	53°14'00.00"	117°49'00.00"	1003	4.08	599
Germansen Landing	1183090	BC	55°47'07.90"	124°42'05.20"	766	1.45	553
Muncho Lake	1195250	BC	58°55'48.00"	125°46'00.00"	837	0.38	512

* *Source:* Canadian Climate Normals - Climate - Environment and Climate Change Canada (weather.gc.ca)
** Presented value was derived from less than 20 years of available precipitation data that meet WMO “3 to 5 rule”

3.1.3 Hydrological particularities of Canadian Rocky Mountains

Hydrologically, the Rockies store a great deal of water and serve as a critical water resource for Western Canada (Bonsal et al., 2020). Rivers are one of the key pathways that move water from the peaks where most precipitation falls to the lowlands where water use is highest. Several important rivers have their origin in the Foothills region including the Oldman, Bow, North Saskatchewan, Peace, and Liard rivers. The southern trench is drained by the Kootenay and Columbia Rivers, the central part by the Fraser River, and the north-central portion by the Parsnip and Finlay rivers (Slaymaker & McPherson, 1977). The largest river in the region is the Liard River with an average flow of 1350 m^3/s; the second-largest stream is the Peace River with a flow measured at 1050 m^3/s. The discharge varies significantly across the Canadian Rockies. The lowest streamflow rates are usually observed in March, even though some rivers have those in February. The greatest discharge is related to the peak of glacial melt, which occurs in late June or early July. Some streams may have the maximum runoff in May – June owing to the snowmelt process. Nevertheless, meltwater from the glaciers contributes to the majority of annual flow to the rivers across the region (Historical streamflow summary , 1991). The natural lakes in the Rockies are another major water feature. The largest natural water body in the region is Maligne Lake (22.3 km long), located in Jasper National Park. The deepest lake is the Upper Waterton Lake with a depth of 148 m. Mostly, the lakes in the Canadian Rockies were created by glacial activity. Because of that, local lakes generally have a distinctive turquoise-green color. It comes from the finely ground sediments produced by glaciers, so-called rock flour, which consists mostly of silt (Benedict, 1991).

3.2 Research design

As outlined in the literature review, conceptual frameworks are useful tools for describing the interlinkage of hydrological processes under limited data situations. Given their value, a conceptual framework approach was used to characterize the hydrological functioning of the mountain lakes and the anticipated climate change impacts on them. There are many studies dedicated to creating classifications or conceptual models for the lakes and different researchers use various approaches and sets of natural factors that can drive internal lake processes. Generally, those factors are incorporated if they are crucial in a particular region of study, meaning they depend on local natural conditions.

3.3 Methods

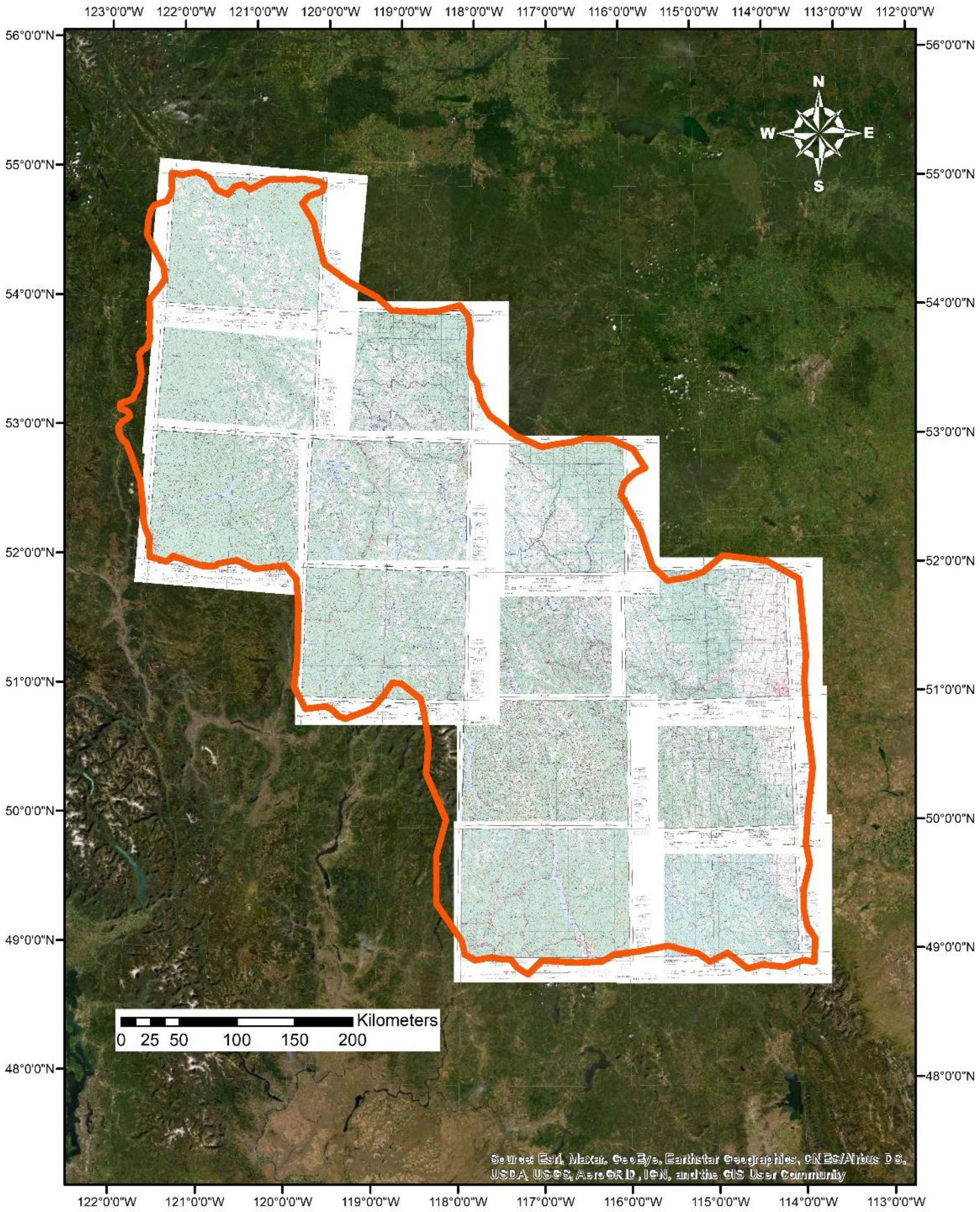
To develop a conceptual framework for the present study, a wide range of literature was analyzed. Particularly, the focus was on peer-reviewed articles that suggested the set of particular drivers used for the research. The possible natural drivers for the future conceptual framework were selected, primarily from the perspective of mountain areas. In other words, attention was paid to factors, representing the definition of global warming's influence on the hydrological functioning of mountain lakes. The logic underlying factors choice is described in section 3.3.2.

3.3.1 Research area

Selected for the study was the southern and central part of the Canadian Rockies (*Figure 3.4*). The area of a study region was estimated to be 236 550 km^2.

The delineation of the region was performed using ArcGIS 10.4 and Digital Topographic Raster Maps (https://open.canada.ca/data/en/dataset/d248b5be-5887-4cfb-942f-d425d82e6ea9). It is worth noting that the research area does not cover all the Canadian Rockies. This fact can be explained by the available map coverage provided by Natural Resources Canada. The maps are given as tiff-images of scale 1:250000 with corresponding map sheet numbers for a selected territory (https://ftp.maps.canada.ca/pub/nrcan_rncan/raster/topographic/250k/). Many of the raster maps for the northern part of the Canadian Rockies were not available on the website.

Water bodies were identified using GIS shapefiles, retrieved from the open-access National topographic database (https://open.canada.ca/data/en/dataset/1f5c05ff-311f-4271-8d21-4c96c725c2af). Under "waters bodies" the lakes, as well as reservoirs, were considered, as shapefiles included data for both types of these water objects. The shapefiles themselves were accessed via Natural Resource Canada's website (https://ftp.maps.canada.ca/pub/nrcan_rncan/vector/ntdb_bndt/250k_shp_en/). Additionally, presented is a kmz-file (archive_BNDT_250k_index.kmz) that helped to match the location of shapefiles with a corresponding map sheet number from Digital Topographic Raster Maps on the Google Earth (https://ftp.maps.canada.ca/pub/nrcan_rncan/vector/ntdb_bndt/index/). For each water body, the surface area was calculated via the option "Calculate Geometry" in the attributes table, and elevations were extracted using the ArcGIS toolbox (Spatial Analyst Tools – Extraction – Extract by Polygon). Further, the distribution graph of the water bodies with altitude and surface area across the study region was plotted (*Figure 4.2*). During the delineation of the research area, the borders of existing watersheds within the region were used as benchmarks.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3.4 Study region and available map data coverage

3.3.2 Identification of features critical for lake hydrological function

It is relatively complicated to define particular natural drivers that are crucial for the hydrological functioning of high-elevation lakes. One of the main challenges is that among mountain regions, natural conditions differ, meaning that various drivers might work as climate change indicators. To identify drivers influencing lake hydrological function, a literature analysis was undertaken. As the main information sources, peer-reviewed articles and books were used.

The scholarly papers were accessed through the Google Scholar database. Keywords including main drivers (e.g. glaciers, groundwater, and drainage rate), approach for the research (e.g. developing the conceptual framework/model or classification), and an object of interest for present research (mountain, high-elevation, or alpine lakes) were applied as the search parameters. Additionally, as a key searching option "climate change" was used because it was crucial to identify how other scholars address that factor in their research. Moreover, it was useful to look through references of the papers retrieved from Google Scholar. That helped to extend a range of sources because, authors referred to the previous studies with the same goals, approaches, or study objects, for instance. Generally, the search gave a wide range of results - from 50000 to 250000 scientific documents depending on the combinations of the keywords. The most related to the present study and representative papers were analyzed. Concerning books, the Library of the University of Saskatchewan was used as a key source. Mainly, the books were retrieved as online versions from the library website but, in some cases, paper-based versions were investigated. Information from books was used primarily for a physical and geographical description of the study region.

Summarizing the information on natural drivers obtained from the published literature, I started with broadly listing natural factors that are critical in any landscape: altitude, climate conditions, and geomorphological conditions. Added to this master list was a set of factors that can describe global warming influences on the hydrology of lakes. Five main drivers (glaciers, groundwater, drainage, wetlands, and forest) were repeatedly referred to in the alpine lake literature as being relevant to mountain lake hydrological function (e.g. Arp et al., 2006; Hood et al., 2006, 2007; Schindler, 2009; Slemmons et al., 2013) and so were added to the master list. Furthermore, factors describing lake morphology (area and depth) were reported as valuable (Shugar et al., 2020) and so were added to the master list. It was also necessary to identify possible reflectors of climate change's impact on lake hydrology. By summarizing the findings of Argyilan & Forman (2003) and Hauer et al. (1997), I identified lake water storage and lake water chemistry as reflectors.

After the master list was populated, I started to provide a more detailed explanation of the meaning of each natural factor (hereinafter also referred as "*natural driver*") and identify potential specific factors (hereinafter *sub-factors*) for each of them. Involved in the identification of the sub-factors was a consideration of what data are needed to describe the key factors. Initially, sets of sub-factors were identified and formed into groups according to their belonging to one natural driver or another. However, some of the selected sub-factors were hard to estimate even if field-based research had been carried out. It makes little sense to include sub-factors that are difficult to measure or estimate in a conceptual framework as the framework should be testable. Thus, the range of sub-factors was shortened to form the final parameter list.

3.3.3 Putting the framework together

After the definition of common factors and sub-factors, the conceptual framework itself was created. Conceptual frameworks are sparingly used in the hydrological literature in representing how complex processes regulate spatial heterogeneities in the function of a water body type. However, particular studies, applying a conceptual framework for their research, are found in the literature. For instance, Trenberth (1999) implemented a conceptual framework to understand why increasing heavy precipitation should be considered as an indicator of climate change and the following rise of the greenhouse gas rates in the atmosphere. Another research developed a conceptual framework to improve comprehension of water and vegetation in pinon-juniper woodlands through the different scales of landscape "functional units" based on hydrological parameters (Wilcox & Breshears, 1995). Additionally, some other of the non-abundant existing options of frameworks are presented in various manners in the literature (e.g. Gillefalk et al., 2018; Zaharescu et al., 2016).

To develop a valuable conceptual framework, the natural drivers should be logically connected with the maximum similarity to their interactions in nature. This helps to facilitate thinking about water movement through mountain landscapes, and how much movement is regulated by lakes. In the mountain regions, it is obvious that altitude is one of the most crucial aspects, so it has to take a particular spacing on the conceptual scheme. Regarding other drivers, it was critical to identify their interdependence and place them accordingly into the framework. Specifically, the position of the hydrological functioning itself had to be carefully selected as it is the main aspect of the current study. For each natural factor, a particular "block" was created that reflected the name of that driver and a list of supplementary sub-factors for some of them.

Overall, three iterations of the conceptual framework were created before constructing the final one. The first two attempts were discarded, as they did not reflect the interactions among drivers and confused the reader. Even though those schemes encapsulated all the factors, there was a lack of the main feature important for the conceptual framework – a clear visualization of the process. The third attempt was more concise and it introduced the understanding of relations between natural drivers as they were logically spaced and linked in the framework. For example, there was an extension of the geomorphological block with a list of specific sub-factors that added clarification on the options considered in that category. The fourth (final) version included a few improvements of the previous one in terms of linkages between drivers' blocks that made the framework more compact without losing any logical sense.

3.3.4 Potential approaches for testing the developed framework

There are several ways to test a conceptual framework demonstrated in the literature. In the majority of cases, field-based research and collected data, as well as the datasets from open sources, serve as a test basis for a developed tool as was shown by several studies (e.g. Catalan & Donato Rondón, 2016; Kløve et al., 2014; Wilcox & Breshears, 1995). In addition to that, some researchers demonstrated the application of simple equations to assess the roles of particular natural factors that they were focusing on (Bracht-Flyr et al., 2013; Charizopoulos & Psilovikos, 2016; Livingstone et al., 2012).

Another widely applied option to test a developed framework is statistical analysis tools. Specifically, principal component analysis (PCA) and its alternative add-ons find popular use across scholars (e.g. Snelder et al., 2005; Zaharescu et al., 2016). That tool also demonstrated suitable results in testing the framework under missing data with the application of the numerical ranks on particular factors (Winter, 1977). However, it is worth pointing that generally, PCA and similar statistical techniques require large datasets to obtain realistic results. In more detail, possible options for further implementation of the conceptual framework created in the present research will be described in section 5.3.

3.3.5 Data sources for the lakes in the study area

As the research area covers two Canadian provinces (Alberta and British Columbia (BC)), it was necessary to analyze the data provided by the governmental websites of those provinces. Additionally, the data provided by Government Canada seemed to store important pieces of information. The aim was to research the available sources and collect metadata on the elements, presented in the conceptual framework. Therefore, data on geomorphological and geological conditions, hydrometeorological conditions, key natural drivers, lake morphology, water levels, and water chemistry were needed. The online recourses used to collect the aforementioned metadata are presented in *Table 3.2*.

Table 3.2 Sources used to collect metadata for the study region

Source	Link
Alberta Geological Survey	https://ags.aer.ca/index.html
GIS and Geospatial data for Alberta	https://canadiangis.com/data.php#Alberta
Raster maps and information about Alberta environments	https://geodiscover.alberta.ca/geoportal/#searchPanel
Weather stations of Alberta	http://acis.alberta.ca/
Surface water quality data for Alberta	https://www.alberta.ca/surface-water-quality-data.aspx
Groundwater wells data for Alberta	http://groundwater.alberta.ca/WaterWells
Historical data about wildfires in Alberta	https://wildfire.alberta.ca/resources/historical-data/default.aspx
All-water monitoring, meteorological data in BC	https://www.bcwatertool.ca/
Surface water observation sites in BC	https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=0ecd608e27ec45cd923bdcfeefba00a7
BC Lakes Stewardship and Monitoring Program Reports	https://www.bclss.org/document-library
Government Canada open data about surface water monitoring and quality	https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity.htm

Additionally, some data about morphology and water chemical properties for particular lakes in the region were retrieved from (Crosby et al., 1990). A possible source of monitoring changes of some factors (lake area, glacial, or forest coverage) during a long period was considered as satellite images provided by Google Earth and SASGIS (http://www.sasgis.org).

Chapter 4. Results

4.1 Distribution and abundance of water bodies

The GIS inventory identified *5155* lakes and reservoirs in the study area (*Figure 4.1*). The density of the water bodies is 0.023 water bodies/km^2. The surface area of presented water objects ranged from 0.003 to 368 km^2. The distribution of surface area is highly right-skewed. The majority of the water bodies (~98%) have an area less than 2 km^2 (*Figure 4.2*). Only 122 (2.4%) of the water bodies have an area >2 km^2 (for visualization purposes, these water bodies were excluded from *Figure 4.2*).

Lakes and reservoirs occurred at elevations from 354 to 2669 m in the study area. From *Figure 4.2* it is noticeable that water bodies have bimodal distribution over the elevation. Most of them (1542 water bodies) are located at an elevation ranging from 1800 to 2200 m. The second-largest number (1178 water bodies) is situated within 800 – 1200 m. Other water objects are distributed relatively equally across the remaining range of altitudes. The link to a complete dataset containing calculated surface areas and elevations for each water body is presented in Appendix A.

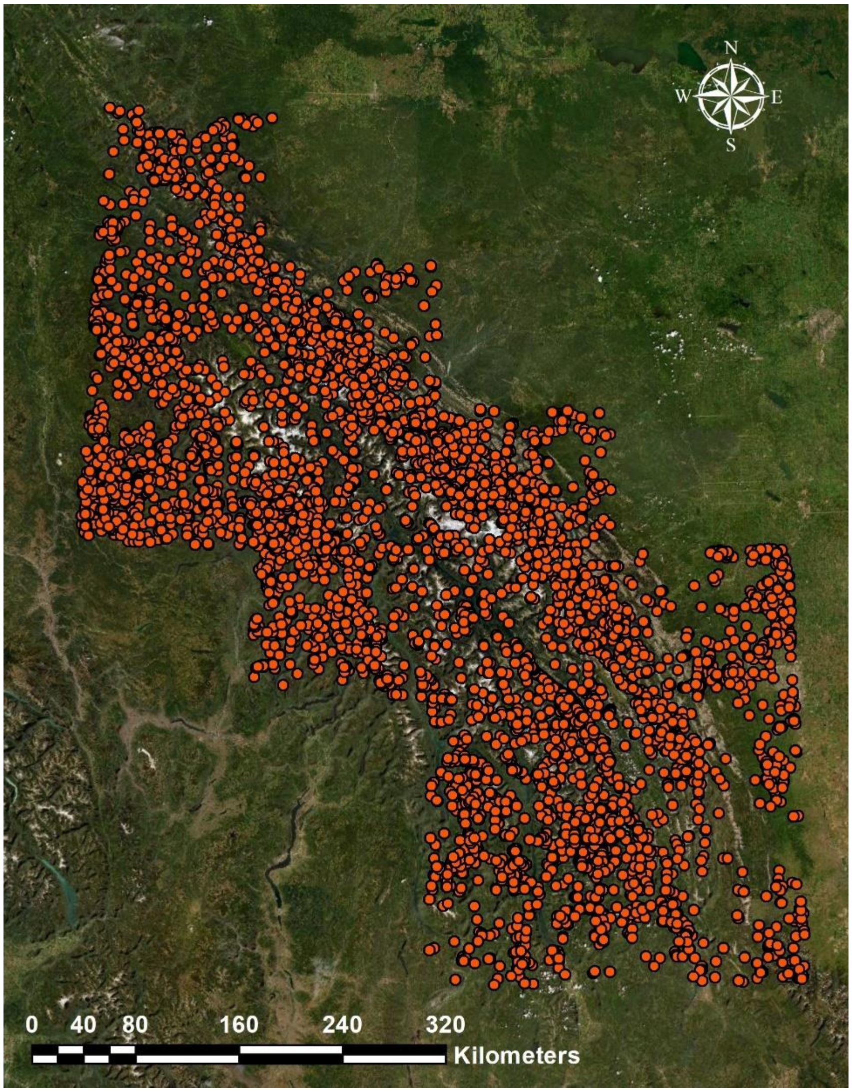


Figure 4.1 Location of water bodies across the research area

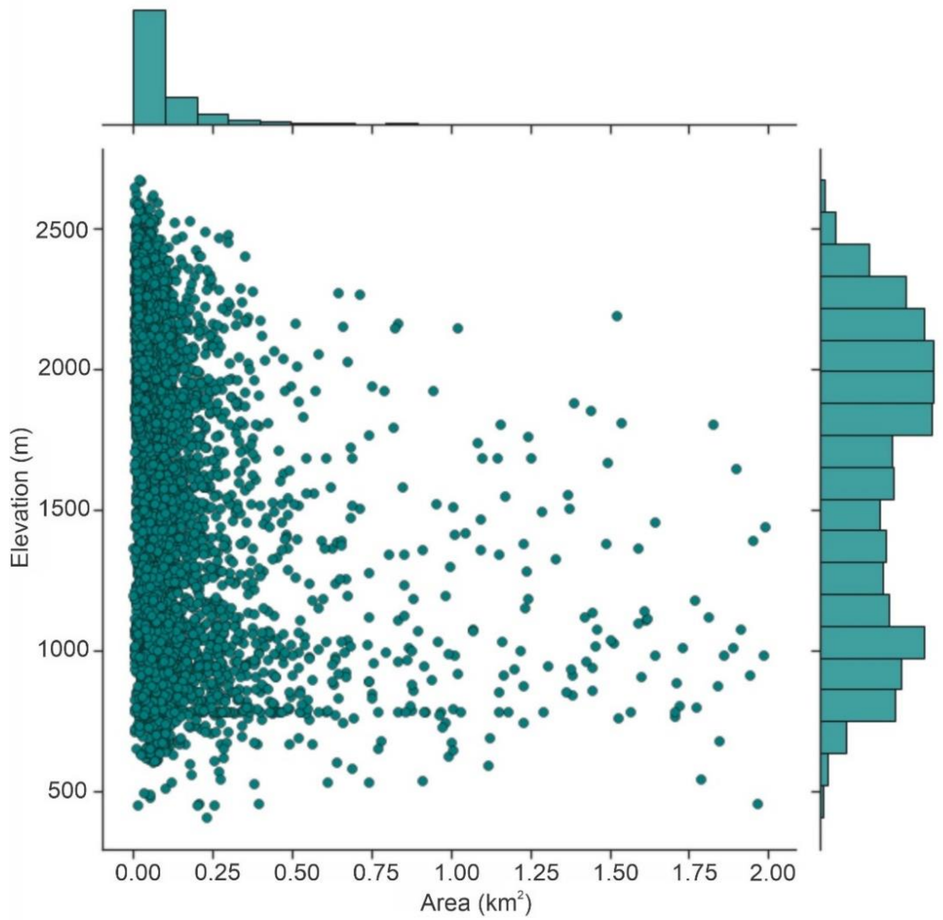


Figure 4.2 Distribution of the area and elevation of water bodies in the research area

4.2 Identification of natural factors and reflectors of climate change crucial for hydrological functioning of mountain lakes

4.2.1 Natural factors

The first challenge in developing a conceptual framework specific to Canadian Rocky Mountain lakes was the selection of the appropriate set of natural factors that influence aspects of lake function. Some factors are regulated by common physical principles regardless of geographic location in the mountains. For example, if soils are permeable in the lake watershed, surface runoff to the lake may be low, but groundwater inputs may be high. Many factors are controlled by altitude and would vary by geographic location. For example, depending on the location and elevation, precipitation rates and other meteorological aspects (e.g. air temperature, evaporation solar radiation) can vary significantly. Changes in those factors affect lake water storage and, sometimes, lake morphological properties. Along with that, geomorphological settings are crucial to consider. Depending on slope incline, surface roughness, and specific particularities of the watershed (e.g. presence of permafrost layer), the rainwater will enter the lake and outflow from it at a different rate. Another key aspect is the natural factors present within the watershed that affect mountain lake hydrology. Those are glaciers, groundwater, wetlands, drainage rate, and others. Any of the aforementioned pieces can contribute to the lake and, depending on the local conditions of the catchment, can become dominant in controlling lake hydrology. For instance, the abundance of glaciers or groundwater in the basin can inform the classification of the lake regime (glacial or groundwater-dominated), while a high wetland area located in proximity to the lake can regulate lake chemical composition or water levels.

After analyzing the literature, defining the significance of the mentioned factors for the lake hydrological function, and selecting the most suitable ones, I started to arrange them into categories for further work. Overall, four categories emerged: i) hydrometeorology, ii) hydrogeomorphology, iii) lake watershed characteristics, and iv) lake morphology (*Figure 4.3*). Each category consists of the natural factors and sub-factors that were chosen according to the literature sources.

The hydrometeorology category includes climate conditions within the catchment. The importance of meteorological characteristics was shown to control lake water storage and area in some cases (Ptak et al., 2017; Qiao et al., 2017; Sturrock et al., 1992). The hydrogeomorphology category consists of altitude, relief, and geomorphic descriptors. Several scholars (Roy & Hayashi, 2008; Silar, 1990) highlighted the significance of each of these variables in describing lake hydrological processes and lake interactions with other natural factors (e.g. lake-groundwater connections). The lake watershed characteristics category encapsulates major natural factors presented in the basin: glaciers, groundwater, drainage rate, wetlands, and forest. Those are the most pronounced factors in controlling lake hydrological conditions -- water storage, chemical composition, and morphometry -- according to scientific literature (Castellazzi et al., 2019; Leppi et al., 2012; Mahat et al., 2016; Mark & Seltzer, 2003; Shaw et al., 2017; Streich & Westbrook, 2020). The lake morphology category includes two principal components, lake area and depth that are critical for lake hydrology (Lantz et al., 2015).

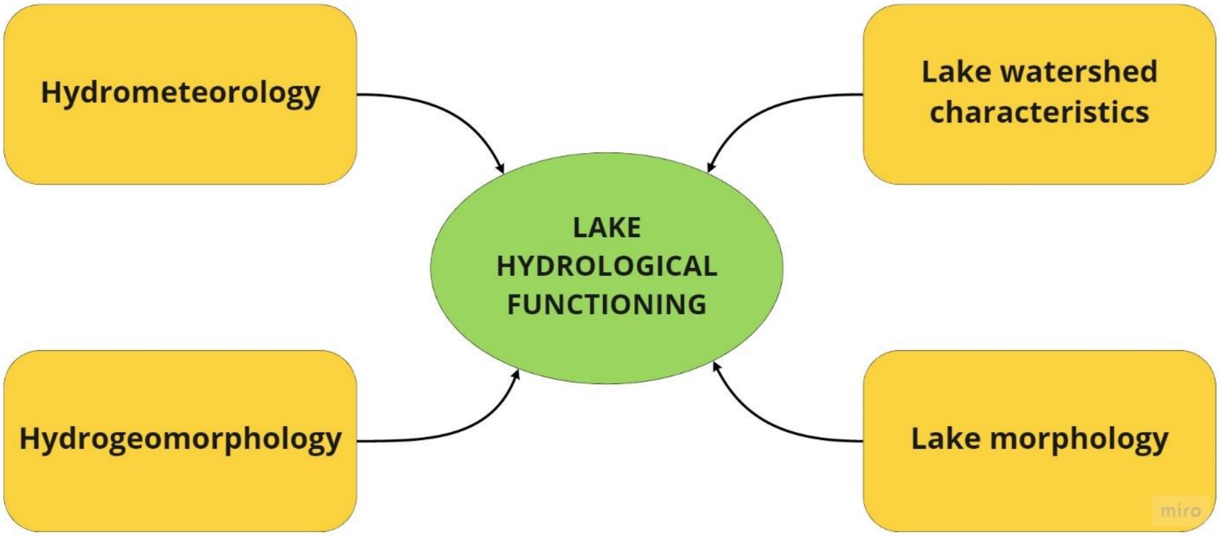


Figure 4.3 Diagram showing four categories of factors selected for framework development

To present the procedure of selection more concisely, *Table 4.1* was created to illustrate the major factors and sets of sub-factors that characterize each of them. Additionally, a possible source where information about a particular sub-factor can be found was considered. This was crucial to define such sources, so I could identify whether is realistic and possible to use any of those factors for my research.

Table 4.1 Master list of main categories, factors, and sub-factors substantial for hydrological lake functioning

Category	Factors and sub-factors	Data source
I. Hydrometeorology	**I a. Hydrometeorology** 1. Precipitation rates 2. Air temperature 3. Wind speed 4. Solar radiation 5. Air humidity 6. Evaporation rates	Online data from meteorological stations across the study region.
II. Hydrogeomorphology	**II a. Altitude** Relative altitude of the lake in the region	1. Surficial and bedrock geology maps of the region. 2. Previously conducted geomorphological or lithological studies of the lakes. 3. Satellite images + ArcGIS. 4. National topographic database (1944-2005) – Natural Resources Canada. 5. Previous research related to studying surface-groundwater interactions within the lakes.
	II b. Relief 1. Regional slope of the land surface 2. Type of the landform where the lake is situated 3. Local relief forms in the immediate lake basin area	
	II c. Geomorphology 1. Shape of the lake bowl 2. Texture of the lake drift 3. Thermokarst within the lake area 4. Permafrost layer within the catchment 5. Hydraulic conductivity of the lake bedrock 6. Glaciers presence within the basin 7. Groundwater connections with the lake	

Table 4.1 - ended

Category	Factors and sub-factors	Data source
III. Lake watershed characteristics	**III a. Glaciers** 1. Percentage of the glacier coverage in the basin 2. Changes in glacier area over the past one or two decades 3. Glacial runoff	1. Online-open sources data. 2. Satellite images + ArcGIS. 3. Previous hydrological research discovering contributions of various natural factors to the lake hydrology in a study region. 4. Descriptive physical-geographical regional studies. 5. Open source provincial government (Alberta and British Colombia) data for groundwater wells. 6. Environment and Climate Change and Natural Resources Canada river discharge database or local provincial government open sources. 7. Database on wildfires in selected provinces.
	III b. Groundwater 1. Groundwater discharge 2. Groundwater levels 3. Groundwater chemical composition 4. Isotopic composition of groundwater	
	III c. Drainage rate 1. Stream discharge 2. Stream water chemical composition 3. Evaporation to inflow (E/I) ratio 4. Turnover rate of water	
	III d. Wetlands 1. Percentage of the wetlands in the basin 2. Chemical composition of wetland water 3. Relation between wetland and groundwater within the lake area	
	III e. Forest 1. Percentage of the watershed covered by forest 2. Density of the canopy 3. Footprints of previous wildfires or forest clearings	
IV. Lake morphology	**IV a. Lake morphology** 1. Average lake area 2. Changes in the lake area over the past one or two decades 3. Average lake depth 4. Maximum lake depth 5. Minimum lake depth	1. Satellite images + ArcGIS. 2. National topographic database (1944-2005) – Natural Resources Canada.

The master list gives an initial overview of the data and available resources. Overall, 10 main natural factors were identified as important in regulating lake hydrological functioning, and 40 sub-factors were defined. To make the various factors describing lake hydrological functioning practical, they must be quantified reasonably easily. I found that it is challenging to find information about some sub-factors included there relying on literature or open-source data. Additionally, separate research was done to identify resources for the estimation of particular characteristics and make it clearer to understand. Finally, some sub-factors that seemed to be more significant for the definition of the hydrological functioning and that were simpler to estimate were added to the table. Owing to the lack of retrievable data, the list of factors and sub-factors important to lake functioning was condensed. There were two main reasons for excluding sub-factors. One reason was that they were hard to calculate without natural data available or the variable was inessential for identifying climate change influences on lake hydrological functioning. A second reason is that some of the sub-factors seemed to be very specific and were not common for the particular study region in the Canadian Rockies (e.g. thermokarst and permafrost holding widespread importance in Northern locations).

Table 4.2 shows the excluded and added sub-factors based on the above-discussed logic. Some sub-factors were simplified. For instance, bedrock geology is easier to discern from the maps rather than deal with the shape of the lake's bowl. The introduction of the "Basin area/lake area relation" factor helps to estimate the interactions between total areas of water bodies in the region. Maximum lake depth is generally used to define lake morphometry; for that reason, average and minimum areas were excluded. Regarding glaciers, runoff as a not representative sub-factor was replaced by lake reflectance to differentiate glaciers from lake surfaces on the satellite images.

Table 4.2 The excluded and added sub-factors

Category	Excluded sub-factors	Added sub-factors
Hydrogeomorphology	1. Shape of the lake bowl 2. Thermokarst within the lake area 3. Permafrost layer within the catchment 4. Groundwater connections with the lake	1. Bedrock geology 2. Presence of the surface inflow/outflow
Lake watershed characteristics	1. Relation between wetland and groundwater within the lake area 2. Glacial runoff 3. Groundwater chemical composition 4. Isotopic composition of groundwater 5. Density of the canopy	Lake reflectance
Lake morphology	1. Average lake depth 2. Minimum lake depth	Basin area / Lake area relation

Table 4.3 provides the full set of factors and sub-factors with an estimation of the timescales over which each acts. Definition of the range over which each sub-factor operates is valuable to understand how it can influence lake hydrology under rising temperatures (Bracht-Flyr et al., 2013; French, 1986). Moreover, the inclusion of information on the time scale can aid in estimating lake resilience to climatic shifts. Time scales, however, are difficult to estimate precisely. Thus, a categorical approach was used. Specifically, three categories describing time scales were identified for each sub-factor: slow (>100 years), medium (decades), and fast (days/months).

Table 4.3 Final list of main categories, factors, and sub-factors substantial for hydrological lake functioning

Category	Factors and sub-factors	Time scale
I. Hydrometeorology	**I a. Hydrometeorology** 1. Precipitation rates 2. Air temperature 3. Wind speed 4. Solar radiation 5. Air humidity 6. Evaporation rates	Fast
II. Hydrogeomorphology	**II a. Altitude**	
	Relative altitude of the lake in the region	Slow
	II b. Relief	
	1. Regional slope of the land surface 2. Type of the landform where the lake is situated 3. Local relief forms in the immediate lake basin area	Slow
	II c. Geomorphology	
	1. Bedrock geology	Slow
	2. Texture of the lake drift	Medium
	3. Hydraulic conductivity of the lake bedrock	Medium / Slow
	4. Glaciers presence within the basin	Medium
	5. The presence of the surface inflow/outflow	Fast / Medium

Table 4.3 - ended

Category	Factors and sub-factors	Time scale
III. Lake watershed characteristics	**III a. Glaciers**	
	1. Percentage of the glacier coverage in the basin 2. Changes in glacier area over the past one or two decades 3. Lake reflectance	Medium
	III b. Groundwater	
	1. Groundwater discharge	Medium
	2. Groundwater levels	Medium / Slow
	III c. Wetlands	
	1. Percentage of the wetlands in the basin	Medium
	2. Chemical composition of wetland water	Medium / Slow
	III d. Drainage rate	
	1. Stream discharge 2. Stream water chemical composition 3. Evaporation to inflow (E/I) ratio	Medium
	4. Turnover rate of water	Medium / Slow
	III e. Forest	
	1. Percentage of the watershed covered by forest 2. Footprints of previous wildfires or forest clearings	Medium
IV. Lake morphology	**IV a. Lake morphology**	
	1. Average lake area 2. Changes in the lake area over the past one or two decades 3. Watershed area / Lake area 4. Maximum lake depth	Medium

4.2.2 Climate change reflectors

In addition to identified natural factors, needed are indicators, or reflectors, that provide integrated, specific, and reliable responses to ecosystem stress (changes in hydrological function).

To identify the potential reflectors, the separate “physical and chemical lake characteristics” category was created including lake water storage and water chemical composition. As was stressed by several studies, those factors act as indicators of climate change on the lake hydrology for many regions surveyed worldwide (Gardelle et al., 2011; Olson et al., 2018; Slemmons et al., 2013; Turner et al., 2010).

Table 4.4 illustrates the factors and sub-factors chosen to describe the reflectors of global warming on the mountain lakes. Included in the table are also time scales and sources where the data could be collected.

Table 4.4 List of factors and sub-factors describing reflectors of climate change impacts on mountain lakes

Category	Factors and sub-factors	Time scale	Data source
V. Physical and chemical lake characteristics	**V a. Water storage**		1. Provincial open data on the morphometry and water levels of lakes. 2. Alberta and British Columbia open data for surface water quality.
	Changes in water storage over the past one or two decades	Fast / Medium	
	V b. Water chemical composition		
	1. pH and electrical conductivity	Fast	
	2. Water temperature		
	3. Transparency (Secchi Disk)	Medium	
	4. Dissolved organic matter	Fast / Medium	
	5. Total phosphorus and chlorophyll-a		

4.3 Logical interpretation of the developed conceptual framework

The factors were assembled in a conceptual framework to describe the climate change influences on the hydrological functioning of the high-elevation lakes (*Figure 4.4*). As the diagram was developed for lakes in the Canadian Rocky Mountains, the key factor is *altitude* as it has been shown by a range of studies to play a major role in controlling hydrological and meteorological processes in this environment. Altitude has influences on geomorphological conditions (for instance, bedrock conductivity might vary depending on altitude due to different geological structures and layers of bedding or incline). Local relief forms and slopes are also subject to change with elevation. The nature of the slope (steep or gentle) can influence the amount of water entering the lake from the watershed. Significantly affected by altitude are hydrometeorological conditions of the basin and they vary across different elevations. Generally, at higher altitudes, there is more precipitation and air temperatures are lower. These two parameters will control other meteorological factors at the particular elevation in most cases.

Moving down to the framework, the blocks with natural characteristics presented in “Geomorphology”, “Relief” and “Hydrometeorology” influence the “Primary natural drivers” block that represents factors that have major influences on lake functionality. Those are glaciers, groundwater, drainage, and wetlands. Geomorphology might have influences on some of the presented drivers, for example, it can determine the presence or absence of glaciers in the basin or stream inflow/outflow. Geological features, for example hydraulic conductivity of the bedrock or a lake’s drift texture are helpful to define groundwater connections with the lake. However, hydrometeorology might have a more critical role for all the natural drivers as it is more sensitive to climatic shifts. For instance, rising air temperatures will enhance glacial shrinkage or increase evaporation rates from wetland surfaces. Variations in precipitation rates influence groundwater levels and differences in precipitation isotopic composition affect the chemical composition of glaciers, surface, and groundwater in the basin. The designed framework encapsulates some other meteorological parameters (e.g. air humidity, wind speed) to reflect impacts of climate on the major natural factors more efficiently.

Consequently, the changes in the state of natural drivers affect the hydrological functioning of the lake. To highlight that, the “Mountain lake hydrological functioning” block is located underneath the “Primary natural drivers” block and there is a direct linkage between them. Most of all, influenced by these drivers is *lake water storage* and *lake water chemistry*. As such, glacial runoff can affect lake water levels and water chemistry (due to different chemical compositions of glacial water and contained sediments) if entering directly into the lake. Related are streamflow conditions, as some of the presented natural drivers can affect rivers and thus surface inflows to lakes as well. In the case of increased glacial runoff, for example, lakes can experience increased inflow leading to fluctuations in water level and potentially changes in water chemical composition depending on the dominant water source for the lake. Fluctuations in groundwater can also influence lake water storage (in particular, water balance if the groundwater part is significant). The chemical composition of the lake can be influenced by groundwater if the connections are present. Wetlands play a somewhat different role from all other presented factors. Wetlands also will affect lake water level but mostly through increasing evaporation across the basin. The wetland connections with the lake can reflect on water chemical composition. Therefore, water storage and water chemistry are key criteria that best reflect the integrated influences of all the above-mentioned factors on the hydrological functioning of the mountain lake and are relatively easy to quantify. This is reflected through connection with the “Change reflectors” block underneath. Apart from water storage and water chemistry, the influences can be observed in some other aspects of lake hydrology. For instance, enhanced glacial melting can affect lake water temperature with subsequent deterioration of ecological conditions and groundwater can be critical for lake sustaining during low flow periods if the water body depends on streamflow water.

In line with the abovementioned factors, the forest might also contribute to changes in lake hydrological function. However, in the framework, it is presented as separate “Secondary natural drivers” block. This is because forest generally has indirect influences on lake hydrology (secondary impact is shown with dashed arrow). However, it does affect natural factors controlling these water bodies. For instance, forest disturbance caused by wildfires was stressed as critical in affecting hydrological conditions within the basin such as altering streamflow or changing snowmelt and sublimation rates (Mahat et al., 2016; Pomeroy et al., 2012) – shown with the linkage to “Primary natural drivers” block. Forests can also regulate climate conditions within the basin (e.g. dense forest coverage increases evaporation rates) – shown with the linkage to the “Hydrometeorology” block. The linkage with altitude shows that it influences forest distribution in the mountains (variations in vegetation patterns due to zonation).

The left sid “Primary natural drivers” block relates to the “Lake morphology” block. This relation reflects the fact that the influences of the main factors (glaciers, groundwater, drainage rate, and wetlands) may change the area and depth of the lake. For example, an increase in glacial meltwater or streamflow inputs may lead to an increasing in the area and volume of the lake. Opposite, evaporation from wetland adjacent to the lake can cause a decline in lake area and volume if the precipitation rates are lower than evaporation rates in the basin.

The time scale of factors is reflected in three different colors on the framework. The sub-factors that have different colors for filling and frame considering two defined options are presented in *Table 4.3* and *Table 4.4*. The color signifies the timescale at which a particular sub-factor operates. Two colors on a particular sub-factor indicate the temporal scale of change is either complex (occurring on multiple time steps) or is highly uncertain. The “Mountain lake hydrological functioning” has a distinctive color to emphasize that it is valuable for the present research.

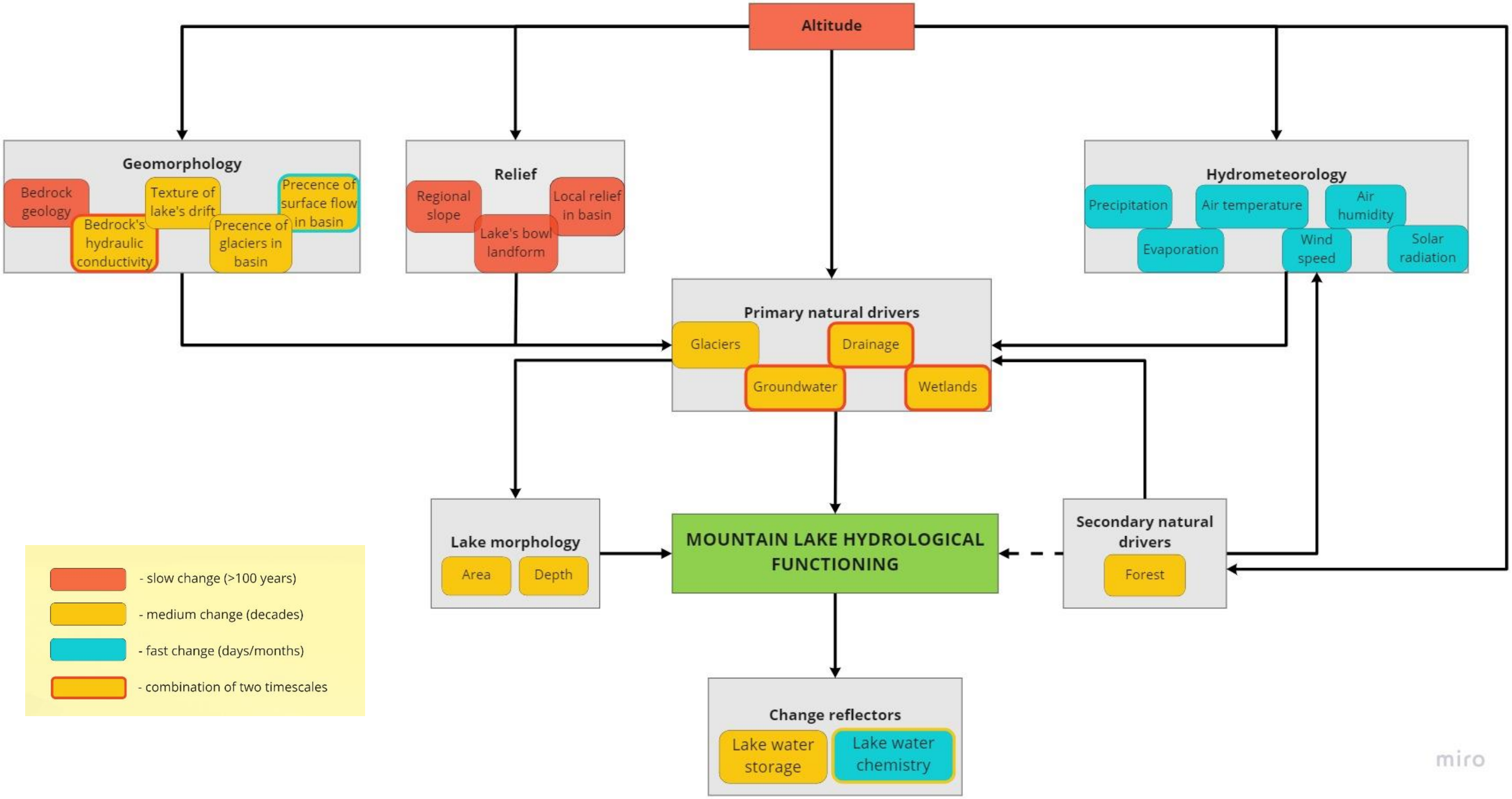


Figure 4.4 The conceptual framework of the mountain lake hydrological functioning

4.4 Data availability for the lakes in the research region

A thorough investigation of available data for lakes in the study area revealed metadata for 23 lakes (*Table 4.5, Table 4.6, Table 4.7*). The location of each of these 23 lakes across the region is shown in *Figure 4.5*. Further, the distribution of those lakes with area and elevation is illustrated in *Figure 4.6*. The more detailed information about the selected 23 lakes is presented in Appendix B.

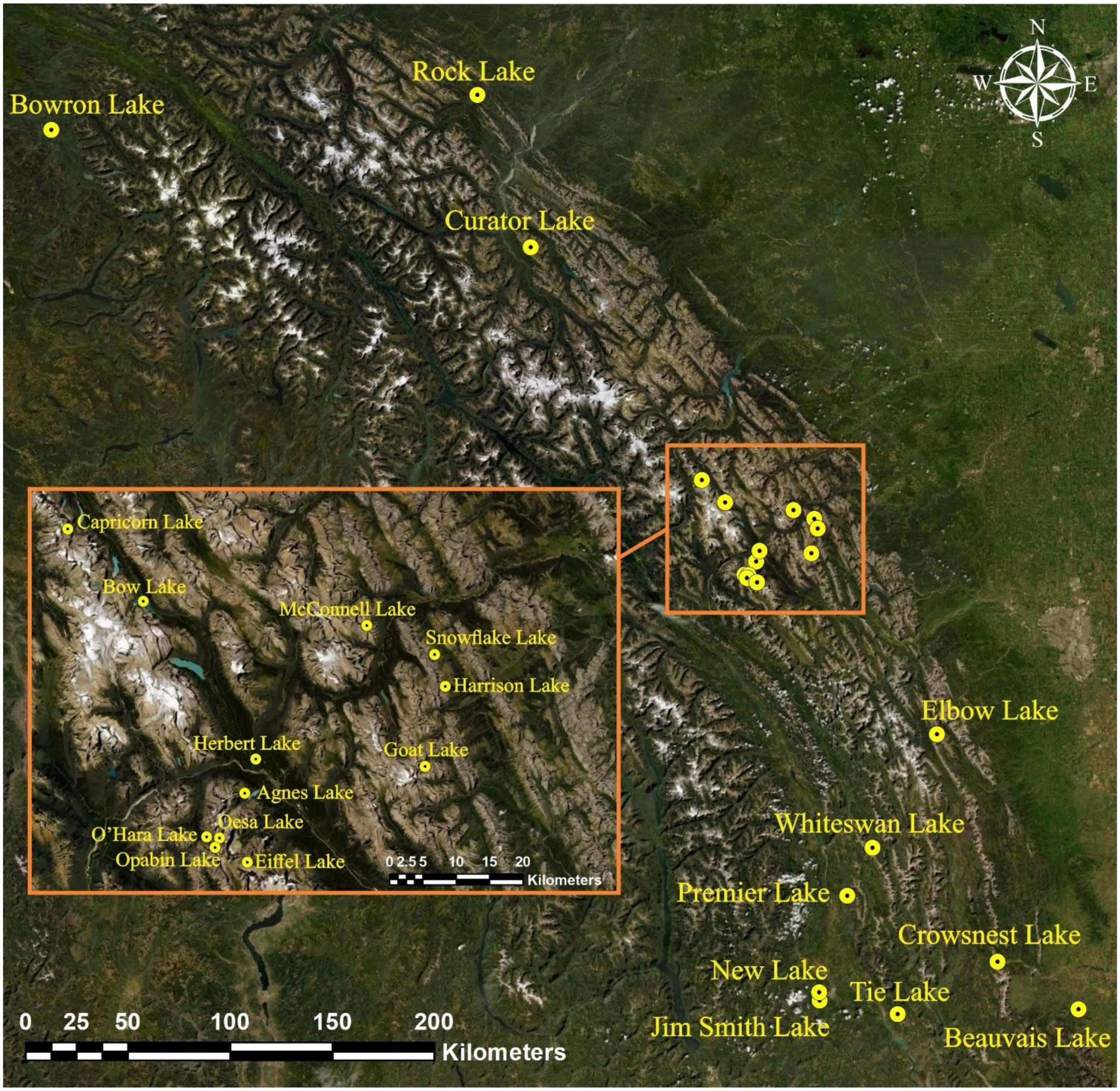


Figure 4.5 Location of the 23 lakes in the study sites with some degree of data needed to define their hydrological functioning

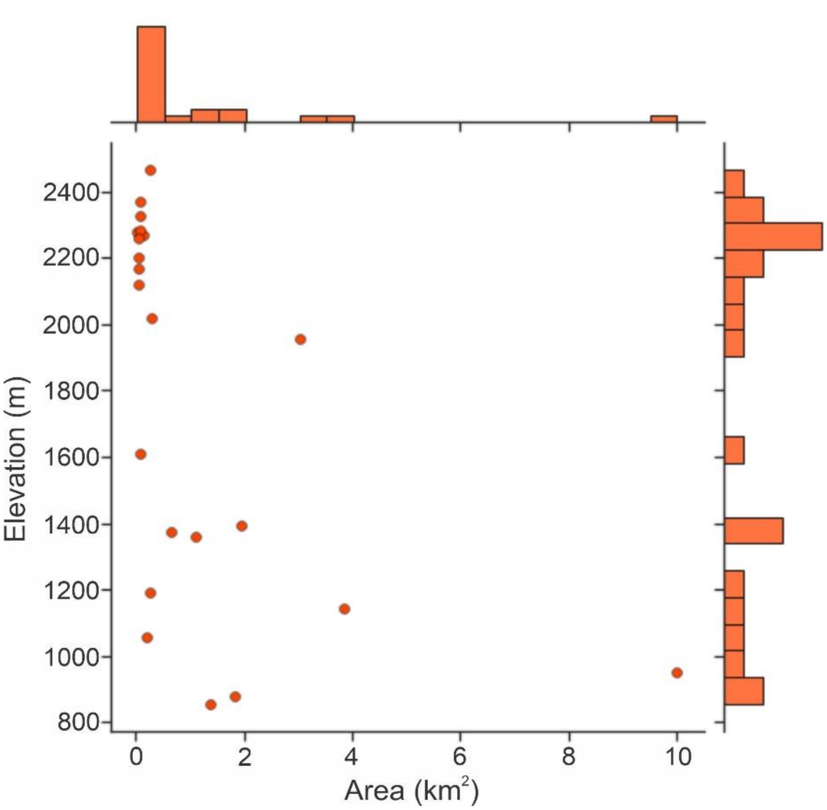


Figure 4.6 Distribution of the surface area and elevation of the 23 lakes with some degree of data needed to define their hydrological functioning

The surface area of the selected 23 lakes with some degree of available data ranges from 0.03 to 10 km^2. It is noticeable that distribution is one-sided as the majority of the water bodies (around 70%) have an area less than 1 km^2. Regarding elevation, lakes are located at altitudes from 855 to 2466 m. The distribution is bimodal as there are two peaks visible. There is one peak that includes 50% of the lakes that lay on the elevations above 2000 m. Another smaller peak is observed for the lakes at the altitudes of 1400-1500 m. Notably, lakes with smaller areas are located at higher elevations, while water bodies with larger areas are situated at lower elevations.

The tables with metadata (*Table 4.5*, *Table 4.6*, *Table 4.7*) clearly illustrate that the region of study has poor hydrological exploration. Overall, open-source data provide limited observations on different natural factors. Regarding climate, only precipitation and temperatures are available. For some stations, those parameters are observed only for short period, so it is difficult to rely on that data to conduct a long-term study. Geological and geomorphological conditions of the region and discerning necessary sub-factors could be done with maps, reflecting these conditions. There is an open database for such maps for Alberta, however, interprovincial differences in data availability were found as there were not the same maps available in British Columbia.

The major problem that significantly affected the further evaluation of current research was limited data on key natural drivers and the reflectors used to describe the hydrological functioning of mountain lakes. From *Table 4.6* and *Table 4.7*, it can be noticed that necessary data is missing and for some of the drivers, there were almost no observations found (e.g. Tie Lake has only one year of groundwater chemical composition data). The same tendency has a chemical composition of wetlands and glaciers, which usually is crucial for estimating influences on in-lake processes. There is extremely limited data available on stream discharge entering the lake (Whiteswan and Jim Smith lakes). The stream chemical composition is presented only for one year near Tie Lake. Reflector factors data are not presented better. For example, of the 23 lakes, only two have data on water levels (O'Hara and Opabin lakes), and that data is temporally limited. Water chemistry was only sporadically observed (reported) and is presented with long intervals between the measurements, depriving the possibility to work with those datasets as a continuous array. A small number of observation stations in the region can explain the poor data availability. Occasional one-year observations for some lakes are probably indicative of them being studied as part of a specific graduate thesis or as part of regional baseline analysis. That is one of the key challenges for study mountain regions – the lack of data, therefore, inability to understand the hydrological cycle of local water bodies and explain climate change impacts on their hydrology.

Satellite coverage is 5 years or less for 12 lakes in the dataset. The 12 lakes are Rock, Curator, McConnell, Herbert, Snowflake, Bow, Capricorn, Goat, Harrison, O'Hara, Opabin, Oesa, Eiffel, Agnes, Elbow, Crowsnest, Beauvais, Whiteswan, and Premier. The high-quality images are limited and available only for particular years, while images for the long term have poor quality and low resolution. Having that kind of limited imagery makes it hard to observe changes in various natural factors over decades or longer periods.

As was stressed, the distribution of the lakes with area and elevation is quite irregular. Those lakes located above 2000 m (52% of the 5155 lakes in the study region) can be considered as alpine (above treeline), while water bodies located on elevations less than 1500 m (39%) belong to sub-alpine or foothills zones. The sporadic data on natural drivers are mostly available for the lakes located lower than 1000 m meaning that it might not be representative to understand climate change impacts on the alpine lake hydrology. Along with that, the number of lakes is extremely limited (23 out of 5155, 0.4%). Even the distribution of those 23 water bodies is similar to overall distribution (all ranges of elevations are considered), the areal distribution is not reflected properly as the maximum lake area for a whole range of water bodies is 368 km^2, while for a given set of 23 lakes, it limits with 10 km^2.

Table 4.5 Metadata collected for the lakes in the study region (part 1)

					Lake area			Climate conditions						
№	Province	Lake name	Elevation (m)	Maximum lake depth (m)	Estimated value (km²)	Changes in the lake's area over past years	Basin area / Lake area	Station name	Precipitation (mm)	Air temp (°C)	Wind speed (m/s)	Solar radiation (W/m²)	Air humidity (%)	Evaporation (mm)
1	BC	Bowron	950	V	V	V	V	Bowron Park (1974-1990)	V*	V	X*	X	X	X
2	AB	Rock	1393	V	V	X	V	Willow Creek 1 (2017-2020)	V	V	V	X	V	X
3	AB	Curator	2275	V	V	X	V	Jasper Warden (2010-2020)	V	V	V	X	V	X
4	AB	McConnell	2326	V	V	V	V	Scotch Camp (2005-2020)	V	V	X	X	X	X
5	AB	Herbert	1607	V	V	X	V	Lake Louise (2005-2020)	V	V	X	X	X	X
6	AB	Snowflake	2368	V	V	V	V	Scotch Camp (2005-2020)	V	V	X	X	X	X
7	AB	Bow	1958	V	V	X	V	Bow Summit (2005-2020)	V	V	X	X	X	X
8	AB	Capricorn	2202	V	V	V	V	Bow Summit (2005-2020)	V	V	X	X	X	X
9	AB	Goat	2466	V	V	V	V	Cuthead Lake (2005-2020)	V	V	X	X	X	X
10	AB	Harrison	2259	V	V	V	V	Cuthead Lake (2005-2020)	V	V	X	X	X	X
11	BC	O'Hara	2020	V	V	V	V	Yoho NP O'Hara Lake (1987-2004)	V	V	X	X	X	X
12	BC	Opabin	2278	V	V	V	V	Yoho NP O'Hara Lake (1987-2004)	V	V	X	X	X	X
13	BC	Oesa	2267	V	V	V	V	Yoho NP O'Hara Lake (1987-2004)	V	V	X	X	X	X
14	AB	Eiffel	2281	V	V	V	V	Lake Louise (2005-2020)	V	V	X	X	X	X
15	AB	Agnes	2168	V	V	V	V	Lake Louise (2005-2020)	V	V	X	X	X	X
16	AB	Elbow	2120	V	V	V	V	Burns Creek (2005-2020)	V	V	X	X	X	X
17	AB	Crowsnest	1360	V	V	V	V	Crowsnest (2009-2020)	V	V	X	X	X	X
18	AB	Beauvais	1373	V	V	V	V	Beauvais Park (2005-2020)	V	V	X	X	X	X
19	BC	Whiteswan	1144	V	V	V	V	Whiteswan Lake (1959-1961)	V	V	X	X	X	X
20	BC	Premier	877	V	V	V	V	Johnson Lake (1989-2020)	V	V	X	X	X	X
21	BC	Jim Smith	1058	V	V	V	V	Cranbrook (1900-1939)	V	V	X	X	X	X
22	BC	New	1192	V	V	V	V	Cranbrook (1900-1939)	V	V	X	X	X	X
23	BC	Tie	855	V	V	X	V	Jaffray (1977-1994)	V	X	X	X	X	X

Table 4.6 Metadata collected for the lakes in the study region (part 2)

			Relief			Geomorphology					Wetlands		Glaciers		
№	Province	Lake name	Regional slope (°)	Landform where lake is situated	Local relief forms	Bedrock geology	Hydraulic conductivity of bedrock (cm/s)	Texture of the lake's bedrock	Glaciers precence in basin	Presence of surface inflow/outflow	Percentage in the basin (%)	Chemical composition of wetland water	Percentage in the basin (%)	Changes in the glacier area over past years	Lake reflectance
1	BC	Bowron	X	X	X	V	V	X	V	V	V	X	V	V	V
2	AB	Rock	X	V	V	V	V	X	V	V	V	X	V	X	V
3	AB	Curator	X	V	V	V	V	X	V	V	V	X	V	X	V
4	AB	McConnell	X	V	V	V	V	X	V	V	V	X	V	V	V
5	AB	Herbert	X	V	V	V	V	X	V	V	V	X	V	X	V
6	AB	Snowflake	X	V	V	V	V	X	V	V	V	X	V	V	V
7	AB	Bow	X	V	V	V	V	X	V	V	V	X	V	X	V
8	AB	Capricorn	X	V	V	V	V	X	V	V	V	X	V	V	V
9	AB	Goat	X	V	V	V	V	X	V	V	V	X	V	V	V
10	AB	Harrison	X	V	V	V	V	X	V	V	V	X	V	V	V
11	BC	O'Hara	X	V	V	V	V	X	V	V	V	X	V	V	V
12	BC	Opabin	X	V	V	V	V	X	V	V	V	X	V	V	V
13	BC	Oesa	X	V	V	V	V	X	V	V	V	X	V	V	V
14	AB	Eiffel	X	V	V	V	V	X	V	V	V	X	V	V	V
15	AB	Agnes	X	V	V	V	V	X	V	V	V	X	V	V	V
16	AB	Elbow	X	V	V	V	V	X	V	V	V	X	V	V	V
17	AB	Crowsnest	X	V	V	V	V	X	V	V	V	X	V	V	V
18	AB	Beauvais	X	V	V	V	V	X	V	V	V	X	V	V	V
19	BC	Whiteswan	X	X	X	V	V	X	V	V	V	X	V	V	V
20	BC	Premier	X	X	X	V	V	X	V	V	V	X	V	V	V
21	BC	Jim Smith	X	X	X	V	V	X	V	V	V	X	V	V	V
22	BC	New	X	X	X	V	V	X	V	V	V	X	V	V	V
23	BC	Tie	X	X	X	V	V	X	V	V	V	X	V	V	V

Table 4.7 Metadata collected for the lakes in the study region (part 3)

№	Province	Lake name	Groundwater		Drainage				Forest		Lake water chemical composition (yrs of observations)	Lake water level (yrs of observations)	Available satellite images (yrs of coverage)
			GW levels (m)	Groundwater chemical composition	Stream discharge (m^3/s)	Stream water chemical composition	E/I ratio	Turnover time of water (hr)	Percentage in the basin (%)	Footprint of wildfires / clearings			
1	BC	Bowron	X	X	X	X	X	X	V	X	1995, 2006-2008, 2015	X	1984-2016
2	AB	Rock	X	X	X	X	X	X	V	V	2019	X	2012, 2013
3	AB	Curator	X	X	None*	None	None	None	V	V	2007	X	2012, 2014
4	AB	McConnell	X	X	X	X	X	X	V	V	2007, 2019	X	1984 - 2016
5	AB	Herbert	X	X	None	None	None	None	V	V	1967, 2017	X	2002, 2012, 2019
6	AB	Snowflake	X	X	None	None	None	None	V	V	1967, 2019	X	1984-2016, 2019
7	AB	Bow	X	X	X	X	X	X	V	V	1994-1995	X	2002, 2004, 2012
8	AB	Capricorn	X	X	X	X	X	X	V	V	2019	X	2002, 2004, 2005, 2016
9	AB	Goat	X	X	X/none*	X/none	X/none	X/none	V	V	2019	X	1984-2016, 2019
10	AB	Harrison	X	X	X	X	X	X	V	V	2001	X	1984-2016, 2019
11	BC	O'Hara	X	X	X	X	X	X	V	X	2004-2005	2004-2017^*	2002, 2004, 2010, 2012, 2019
12	BC	Opabin	X	X	None	None	None	None	V	X	2004-2006, 2019	2004-2018^*	2002, 2004, 2010 2012, 2020
13	BC	Oesa	X	X	None	None	None	None	V	X	2019	X	2002, 2004, 2010, 2012, 2019
14	AB	Eiffel	X	X	None	None	None	None	V	V	2017, 2019	X	2002, 2004, 2010, 2012, 2019
15	AB	Agnes	X	X	X	X	X	X	V	V	1983, 1987, 2018	X	2002, 2004, 2010 2012, 2019
16	AB	Elbow	X	X	X	X	X	X	V	V	1985, 1986, 2008	X	2002, 2010, 2012, 2013
17	AB	Crowsnest	X	X	X	X	X	X	V	V	2007, 2008, 2018	X	2005, 2006, 2009, 2010, 2012, 2013, 2015, 2019, 2020
18	AB	Beauvais	X	X	X/none	X/none	X/none	X/none	V	V	1984-1991	X	2006, 2007, 2010, 2012, 2013, 2015, 2018, 2019
19	BC	Whiteswan	X	X	V (1999-2001)	X	X	X	V	X	1987, 2016-2019	X	2005, 2011, 2012, 2013, 2014, 2016, 2019
20	BC	Premier	X	X	X	X	X	X	V	X	2003, 2004, 2007, 2010, 2013, 2015	X	2004, 2012, 2014, 2018, 2020
21	BC	Jim Smith	X	X	V (1924-1967)	X	X	X	V	X	2000, 2008-2012	X	2004, 2005, 2010, 2012, 2014, 2017-2020
22	BC	New	X	X	X/none	X/none	X/none	X/none	V	X	2000, 2009-2011	X	2004, 2010, 2012, 2014, 2017-2020
23	BC	Tie	X	V (2002)*	X	V (1985)	X	X	V	X	2006-2009	X	2004, 2005, 2010 2016, 2019, 2020

* *Notes*:

- V – data is available or can be estimated according to the collected information.
- X – data is not available or it is insufficient information to calculate it.
- None – there is no presented inflow or outflow for the lake.
- X/none – no data for a discharge or the presence of inflow/outflow was hard to estimate due to the poor quality of the satellite image.
- V (2002) – data is available only for a specified year or period.
- ^ - water level data for O'Hara and Opabin lakes for the indicated periods are presented in He & Hayashi (2019).

Chapter 5. Discussion

The goal of this thesis was to develop a conceptual framework for hypothesizing the hydrological functioning of mountain lakes under climate change. This study has carried out a literature-based selection process of natural drivers critical for the water bodies in high altitudes. Emerging from that analysis were categories of main characteristics and sets of sub-factors deemed as significant for the lake hydrological function. Based on that information, a conceptual framework hypothesizing the hydrological functioning of mountain lakes was developed. The framework highlights not only the interrelationships amongst characteristics and sub-factors but the timescales of the selected factors that serve to identify lake resilience to climatic shifts.

Although data were unable to rigorously test the conceptual framework, possible methods for testing the framework were identified. Most of these methods require large datasets and are not currently applicable for the selected study region. The principal reason for that is extremely limited information on natural factors and lake characteristics. The results suggested that a small number of lakes with some degree of sporadically available data, are distributed irregularly with the area and elevation, therefore will be unrepresentative for the quantitative analysis.

In the following sections, I will illustrate the possibility to apply the developed conceptual framework for hypothesizing potential changes in the hydrological functioning of the lakes under a rapidly changing climate. Further, the research strengths and limitations will be discussed and the designed tool will be compared to other studies that used a similar approach. Finally, the methods suitable to test the framework under sufficient data conditions will be outlined.

5.1 Hypothesizing potential changes in lake hydrological functioning under climate change with the conceptual framework

So far, the present thesis has discussed climate change's impact on natural conditions across the mountain watersheds and their reflection on the adjacent lakes. However, it is also important to understand how a developed conceptual framework will address the fluctuations in the hydrological processes of these lakes. Summarizing information on a wide range of natural factors, a designed tool has a strong basis for hypothesizing potential changes in lake hydrology under global warming. Evidence of globally rising temperatures and sequels of that for mountain regions across the world is broadly discussed in the literature (Diaz et al., 2014; Foster et al., 2016; Rogora et al., 2003). Much less is known about the responses of natural systems to sudden extreme events provoked by climatic shifts. This section aims to illustrate the usefulness of the developed framework to hypothesize changes in lake functioning caused by shifting climate conditions.

In July 2021 an intense heatwave hit northwestern Canada and the United States, and led to the formation of a heat dome created by atmospheric high pressure. That anomaly caused a sharp increase in air temperatures, up to 40 - 45°C in coastal regions of Canada and the US, reaching a record-breaking high of 49.6°C in Lytton, BC, Canada (Vaughan, 2021). The heat dome was situated over the study site. Such an extreme event will affect several factors in the framework. First, directly affected will be hydrometeorological conditions. With such an extreme rise in temperatures will inevitable cause a dramatic increase in evaporation rates as relative humidity will decline. As there was not much precipitation observed during two months (given are the sums of precipitation rates registered for June and July 2021 at some of the weather stations in the region: Grouse Mountain – 119 mm (1103 masl); Whistler Roundhouse – 105 mm (1835 masl); Tatlayoko Lake – 30.7 mm (875 masl); temperature and evaporation can become the major meteorological factors influencing key natural drivers presented in the framework.

From the drivers, glaciers will be affected most of all. Enhanced glacial runoff will be responsible for a rise in lake water levels and changes in lake water chemistry for lakes with glaciers in their watersheds due to introducing glacial sediments that are of different chemical compositions. Increased glacial input will impact ecological conditions of the lakes, including changing water temperature, increasing turbidity, and introducing mineral sediments (glacial flour) that cannot be filtered by particular water biota communities (Sommaruga, 2015; Vinebrooke et al, 2010). Intensive glacial shrinkage can also provoke fluctuations in the lake area and cause appearing of new glacial lakes (Shugar et al., 2020). If a glacial runoff is the main source for the streams across the watershed, these lakes would be the most affected by heat dome-induced glacial shrinkage. At the same time, an outflow of the lake can be altered by rising lake levels. Mostly, it will depend on the water retention time of the lake. In many montane watersheds, water retention during periods of increased runoff is short; therefore, lakes are particularly sensitive to changes in water budget and changes in biogeochemical processes (Hauer et al., 1997). As such, high flushing rates will increase outflow and stimulate plankton growth. However, if the retention period is long, the outflow might not undergo significant fluctuations as most of the incoming water will be retained and mixed in the lake. Intensive stream inflow to the lake can also bring a significant amount of sediments to the lake with their subsequent accumulation that can lead to a gradual diminishing of lake depth. Groundwater is also subject to change under such extreme conditions. Specifically, if the extremely hot weather stayed for a longer period, it would cause a lowering of groundwater levels with a subsequent decline in lake water levels. Such a scenario is of high possibility as mountain lakes were shown to be dependent on groundwater input, particularly during the summer months (Hood et al., 2006). Increased air temperature, will affect wetlands, causing augmentation of evaporation rates from their surface. A wetland presence in the basin in this case will add to overall evaporation causing a decline in lakes' water levels and, potentially, their volume. Further, if evaporation rates remain high and precipitation is still low, such conditions might lead to shrinkage of the glacial-fed lakes in a long term (Li et al., 2014).

A heat dome also led to multiple wildfires across the region. The consequences of wildfires for hydrological conditions in the basin are well documented in the literature (Mahat et al., 2016; Springer et al., 2015). Because the developed framework considers streamflow influence on lake hydrology, it is notable that with a high probability lakes in regions affected most by forest fires might will experience changes in water storage as altered streamflow will bring more water, specifically during the next years' snowmelt period. Additionally, the chemical composition of the lakes can be affected by melting snow or, consequently, summer rainfalls will lush forest combustion products from the watershed.

5.2 Strengths and limitations of the present research and comparison to previous studies

5.2.1 Research strengths

The present study can be considered a useful source for both scientific and industrial spheres. The primary goal of the thesis was to develop a conceptual framework that characterizes climate change influences on the mountain lakes. In light of a relatively small amount of research using a similar tool to study hydrological processes of mountain lakes, the developed conceptual framework adds value to the literature. In addition, unique is a set of natural factors controlling lake hydrological function specified in the thesis.

Although the conceptual framework was created specifically for the environmental conditions of the Canadian Rockies, it can be also adapted to other mountainous areas across the world, which is one of the main framework advantages. Transferability might be possible due to the versatility of the natural drivers and sub-factors considered in the framework. The main consideration factor, *altitude*, influences the natural conditions in mountain ranges all over the world. For instance, Carrivick & Chase (2011) found that local topography and elevation ranges played a critical role in determining annual glacier net mass balance in the Southern Alps of New Zealand. Another study illustrated variations in the isotopic composition of surface waters (lakes, streams, and glaciers) owing to differences in the isotopic composition of precipitation at different altitudes (4200 – 5200 m) at Mt. Kenya in Equatorial East Africa (Rietti-Shati et al., 2000). Other natural drivers presented on the diagram were also shown commonly reported in focused studies for other geographies to be representative and sufficient for analysis of climate change influences on mountain lake hydrology since the overall consequences are mostly similar across the mountain ranges. The differences might arise only because of the local particularities of the region, for example, the presence of North Atlantic Oscillation in coastal mountain ranges (Sánchez-López et al., 2015). However, these particularities can be added as a separate component to the framework and considered for further needs of a specific study. On the other hand, the developed tool is hardly applicable to the lakes located in plain regions. Even though most presented natural drivers (climate, groundwater, wetlands, drainage, forest) are critical in regulating hydrology of prairie or valley lakes, having altitude as a key component narrows the potential geographic applicability of the framework. For example, Devito et al. (2005) argued that in the boreal plain, the topography is one of the least important factors regulating the hydrological processes of water bodies. To suit plain regions, a regionally-specific framework would be needed.

Another major upside of the presented framework is its basis on various types of data. In such a way, it summarizes information on hydrological, meteorological, and geomorphological factors, crucial to investigate the mountain lakes. The applicability of the tool, though, strongly depends on data availability. As was shown for the Canadian Rocky Mountains, governmental open-source data for the region is sparse and incomplete. Even for most common factors (e.g. air temperature or precipitation), the information is limited for most of the basins as the hydroclimatological observation network is thin (Spence et al., 2013). The government provides data most suitable for the general public. Such data might not be appropriate for the needs of extensive hydrological research. There are valuable sources that contain detailed and, usually complete datasets on fluctuations of natural characteristics in mountain areas. For example, the Canadian Rockies Hydrological Observatory operates 35 stations in Kananaskis Country and 15 stations in Banff National Park. Monitored on the stations are meteorological, groundwater, and hydrometric parameters. However, such datasets are restricted, meaning that they are distributed under limited access or research privileges. Making such data pieces available for the research community (e.g. creating an open-access data repository) could enhance at least studying of hydrometeorological properties in regions with data shortage range as the Canadian Rockies. The data inaccessibility for mountain regions raises a question about the quantitative testing of complex tools such as frameworks or models, as they need a strong data basis to function properly (St-Hilaire et al., 2003).

The third notable advantage of the developed framework is that it incorporates the timescales on which natural drivers operate. Considering those are important and the evidence of that was provided by some hydrological studies (Elshafei et al., 2014; Turnbull et al., 2008). Differences in time scales mean that drivers will affect lakes to a varying degree. That fact raises a discussion about the sustainability of lake hydrological function under global warming. In other words, the difference in a time scale of a natural driver can specify a lake's resilience to climatic shifts. For instance, if a lake's hydrology is dominated by its geomorphological conditions (e.g. hydraulic conductivity of bedrock), change in lake hydrology in response to climate change is likely to be slow. In contrast, if a lake's hydrology is driven primarily by meteorological conditions (e.g. precipitation or evaporation), quick response to changes in climate conditions would be expected. The lake in the first example would be relatively resistant to climate changes whereas the lake in the second example would lack resiliency.

The present research also highlighted the relatively poor hydrologic exploration of lakes in the Canadian Rocky Mountains. Specifically, this highlights the fact how limited knowledge of lake hydrological processes and their relation to climate change in this region. Bringing evidence from literature sources (e.g. Christianson et al., 2019), the existing problem is supported with an example of the extremely limited data on the lakes and reservoirs in the selected area across the Canadian Rocky Mountains. This information is important particularly for scientists as it stresses the need to conduct large-scale research in those regions, especially because these lakes tend to be used as water resources (Bonsal et al., 2020; Viviroli et al., 2007). The limited data on the waterbodies in the mountains significantly reduces our understanding of the importance of natural drivers to in-lake processes.

The present study might also be applicable for water management, specifically lake management. The set of the included natural drivers help to get crucial information about a lake's watershed, water chemistry, and morphometric characteristics. As was mentioned, the developed tool can be used for various mountain regions that allow the framework to be applied for site-oriented lake management planning. Summarized information from the framework can help to create an overall picture of the critical lake's and catchment features, identify possible challenges, and make conclusions about the strategy. Further, some other aspects unrelated to the created tool can be assessed and added (e.g. tourism impact). The aspect highlighting a practical value of the framework is that its implementation in mountain lake management is particularly crucial for water planning purposes in mountain regions due to the limited availability of similar approaches in the literature.

5.2.2 Research limitations

Despite the potential usefulness of the developed approach, it is critical to consider its possible limitations and assumptions, and ways to mitigate those limitations.

One of the main limitations of the presented research is that factors and sub-factors chosen for the framework were collected from previously conducted studies, studies that were mostly focused on details of one or a small set of factors. It means that a designed tool in the present study might have a somewhat subjective nature because it primarily bases on the opinions of other scholars about the importance of the natural factors for characterizing climate change impact on mountain lakes, which may or may not have been considered the interactive influence of factors. On the other hand, relatively limited knowledge of the hydrological processes in mountain environments forces the researchers to implement natural drivers based on theoretical assumptions.

Another crucial limitation is that the framework could not be tested on the lakes in the Canadian Rocky Mountains. Because of the poor hydrological exploration of the water bodies in the research area, there was no possibility for any kind of quantitative analysis. Considering that, the developed tool was only compared with the approaches used in similar studies. Again, this introduces some subjectivity on the suggestions for which regions and conditions a designed framework can be applied.

5.2.3 Insight on advantages and disadvantages from analyzed studies

Table 5.1 represents the advantages and drawbacks of the conceptual framework presented in this thesis to previously conducted research. Selected for the analysis is the set of articles presented in *Table 2.3*. Overall, it is notable that a majority of studies tend to use classifications. The main reason for that is the availability of natural data that allows researchers to apply that kind of tool. Many of the presented studies in the table are based on field data, which is a key advantage comparing to my research. Additionally, particular articles applied a wider range of natural factors to perform the analysis. On the other hand, some of the presented classification and conceptual model studies have a narrower focus (e.g. analyzing a restricted set of natural drivers or dealing with specific types of water bodies) that adds some advantage to my study as it can be applied for larger scales and an extensive range of lakes. In some cases, though, it was challenging to compare my approach with some of the illustrated studies and detect any upsides or downsides because of different research perspectives.

Table 5.1 Comparing advantages and drawbacks of the present research to the previously conducted studies

Author(s) and study title	Approach used	**Advantages** comparing to my research	**Drawbacks** comparing to my research
Blenckner (2005). A conceptual model of climate-related effects on lake ecosystems.	Combination of conceptual framework and model	Different research perspective	1. The developed tool considers *only landscape factors* (catchment characteristics and morphometry) and *internal lake processes* (biotic-abiotic interactions). 2. The tool showed successful implications for lakes in different latitudes but whether it is *applicable for mountain environments remains unclear*.
Bracht-Flyr et al. (2013). A hydro-climatological lake classification model and its evaluation using global data.	Classification	The research is based on a steady-state, basin-lake water balance model that predicts basin area to lake area ratio as a function of mean annual climate, quantified by an aridity index (mean annual potential evapotranspiration to precipitation ratio).	The model has two key assumptions: a) both the *lake and the basin receive the same amount of mean annual precipitation*; b) the mean annual *basin evaporation and lake evaporation are identical*.

Table 5.1 – continued

Author(s) and study title	Approach used	**Advantages** comparing to my research	**Drawbacks** comparing to my research
Catalan & Donato Rondón (2016). Perspectives for an integrated understanding of tropical and temperate high-mountain lakes.	Conceptual model	1. The research used field-based data for the model development. 2. The model introduces the "lake district concept" that considers how are lakes distributed in the mountains and how do they connect to lowland environments.	1. The essential focus is *only on the ecological and ecosystem aspects of the lakes*. 2. The created model is applicable to analyze climate change influences on the lakes *only in temperate and tropic climates*.
Driscoll et al. (1991). Adirondack Mountains.	Classification	The researchers used natural chemical data for their classification (pH, ANC, and DOC).	1. The developed classification is *applicable for a narrow scale* as it uses only water chemistry and flows patterns as key factors. 2. The presented tool *does not consider* global warming influences.
French (1986). Hierarchical conceptual model of the alpine geosystem.	Conceptual model	1. The presented conceptual model consists of a hierarchical arrangement of subsystems, each focusing on a different temporal-spatial scale. 2. The tool covers a wide range of characteristics (meteorological, hydrological, geomorphological, soil, ecological) and can be applied not only for mountain lakes themselves but also for the alpine basins worldwide.	Different research perspective
Hayes et al. (2017). Key differences between lakes and reservoirs modify climate signals: A case for a new conceptual model.	Conceptual model	1. The research used natural data from online open sources to develop a model. 2. The developed model can be applied to the lakes and reservoirs as it considers morphological differences between these water bodies.	The key factors used to reflect differences in response to climatic shifts of the study water bodies are *only energy and mass fluxes*, narrowing an application range of the developed tool.
Sánchez-López et al. (2015). The effects of the NAO on the ice phenology of Spanish alpine lakes.	Conceptual model	A conceptual lake model was formulated based on Pearson's correlation coefficients.	A developed tool can be used *only* for alpine regions *where NAO has a significant effect* on climatic factors.
Winter (1977). Classification of the Hydrologic Settings of Lakes in the North Central United States.	Classification	1. All information used in the study was taken from the major watershed maps and reports and unpublished data in the files of the U.S. 2. The collected data was analyzed using PCA to identify the main factors controlling lakes' hydrology.	There is *no evidence* of whether the developed classification can be used in mountain regions and how it considers the climate change influences on the lakes.

Table 5.1 – ended

Author(s) and study title	Approach used	**Advantages** comparing to my research	**Drawbacks** comparing to my research
Zaharescu et al. (2016). A Multiscale Framework for Deconstructing the Ecosystem Physical Template of High-Altitude Lakes.	Conceptual framework	1. The research and developed framework are based on field data. 2. The researchers used a variety of statistical tools (e.g. CATPCA, linear regression) to assess the interactions between variables.	Different research perspective
Bajracharya & Mool (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal.	Classification	1. The researchers use satellite imagery to investigate the lakes across the region. 2. The classification assesses the probability of GLOFs, which are important.	Different research perspective
Emmer et al. (2016). 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods.			
Janský et al. (2006). Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture.			
Otto (2019). Proglacial Lakes in High Mountain Environments.			

5.3 Possibilities for further quantitative implementation of the developed conceptual framework

The developed conceptual framework includes many natural drivers needed to understand the influences of climate change on the high-elevation lake hydrological functioning. As there are (limited) data for only 23 lakes, it is obvious that it is insufficient for quantitative testing of the conceptual framework. Even if there was information on all the necessary factors, it was still unrepresentative as 23 lakes represent just 0.4% of the overall number of lakes across the study region. As was also shown, the areal distribution is quite irregular and does not consider all ranges of surface areas or altitudes across the studied water bodies. That creates difficulties in performing a representative analysis of the hydrological function under climate change for the region.

However, the proposed conceptual framework can be verified through various means. The two most suitable options for data processing I identified are i) Principal Component Analysis (PCA), and ii) Structural Equation Modelling (SEM). The rationale for their selection is explained by their wide use in studies from multiple fields, as well as in studies with somehow analogous tasks and aims comparing to the present study (see for example Battarbee et al., 2002; Sutton-Grier et al., 2010; Villeneuve et al., 2018; Winter, 1977). The following paragraphs describe the merits of each approach.

The main goal of PCA is to explain as much information contained in the data as possible in as few components as possible. The tool searches for the direction in the multivariate space that contains the maximum variability. This is the direction of the first principal component (PC1). The second principal component (PC2) is perpendicular to PC1 and contains the maximum amount of the remaining data variability (Jackson, 2005). This technique could be suitable to test the presented conceptual framework. Specifically, it can help to describe the associations of the natural factors with the selected lakes and highlight the most important natural drivers for the mountain lakes' hydrological functioning. A great example of successful application of principal component analysis was provided by Winter (1977) where PCA was used to define the importance of 13 natural parameters for creating a lakes' classification according to their distribution across different principal components.

SEM is a collection of statistical techniques that allow a set of hypothesized relationships between one or more independent parameters, either continuous or discrete, and one or more dependent parameters, either continuous or discrete, to be examined (Ullman & Bentler, 2003). A simple example of SEM application is its use to detect a relationship between a single measured parameter (increased precipitation) and other measured parameters (changes in water levels, water chemistry, or lake area). Concerning the developed framework, SEM could be a crucial tool to verify the significance of selected natural factors and test whether they were chosen in the right or wrong way. Structural equation modelling is not a widely used technique in hydrological studies; nevertheless, there are some studies in related disciplines. For instance, Sutton-Grier et al. (2010) applied SEM to explore a relationship between ecosystem structure and function through an examination of soil controls on denitrification potential (DNP) in two restored wetlands. Specifically, the authors were interested to identify whether both restored wetland soil ecosystems had similar relationships among soil parameters.

Both PCA and SEM require relatively large datasets. Without the appropriate data available, it is challenging to study the remote water bodies that are so critical for mountain regions. To analyze the natural conditions and make reasonable conclusions, the data should available at least for the factors that are crucial in any natural environment. Those are meteorological factors (air temperature, precipitation, evaporation, solar radiation), hydrological (stream discharge, water stage, groundwater table), geological (relief forms, bedrock geology), morphological (area and depth of the lake), water chemical (pH, electrical conductivity, DOM concentrations). Presented above are the minimal optimum criteria to test the framework and obtain appropriate results supported by the aforementioned techniques or other statistical analysis tools. These data are commonly collected in many kinds of research projects, whereas a field-based, modelling, or satellite imagery approach is used. Hence, the information on these factors should be easily accessible for a scientific community. The best option to store such information would be the development of a public repository that provides access to data collected across the lakes in the region. Making those repositories/storages open-source will give more possibilities to conduct wide-scale studies and investigate interactions of natural processes within the mountain catchments more deeply in the future.

Chapter 6. Conclusions

This thesis aimed to define how climate change will affect the hydrological functioning of mountain lakes. To meet the first objective, a set of natural drivers to describe mountain lake hydrological functioning were identified via a literature analysis and summarizing information from over 130 peer-reviewed papers and 5 books. From the literature analysis, 10 main natural factors and 2 reflectors that characterize climate change impacts on the mountain lake's hydrological functioning were established. In addition, 38 sub-factors that characterize each main factor were introduced.

For the second objective, a conceptual framework was developed using the main and sub-factors to abstractly represent their interactive effect in regulating the hydrological functioning of lakes occurring in the Canadian Rocky Mountains. The key element of the framework was *altitude* because the literature indicated reliance on many process interactions in the mountains in response to it. Further, the remaining sections of the diagram with the natural drivers and sub-factors were clustered into groups important to understand climate change influences on internal lakes' processes. Those groups are "Geomorphology", "Relief", "Hydrometeorology", "Primary natural drivers", "Secondary natural drivers", "Lake morphology", "Mountain Lake hydrological functioning", and "Change reflectors".

The third objective required identifying a suitable method for the developed framework testing. Although a quantitative analysis based on the information on the lakes across the study region was planned, in summarizing data from openly available sources it became apparent that there were hydrological data for only 23 out of the 5155 water bodies in the research area. For some of these lakes, data were sparse and unavailable for several important natural factors in the conceptual framework. Further, the 23 lakes for which some data were available did not represent the full distribution of lakes in the region. The 23 lakes mostly fell within the top 1% of the areal extent, and they had a limited altitudinal range. Even in cases where data was available for more than half of the factors in the conceptual framework, that data had a sporadic character and thus a lot of missing values. Given the data limitations, testing of the conceptual framework was abandoned, and instead, two things were done. First, the framework was compared to published frameworks for other geographic areas. Second, a set of suitable methods for testing the framework was developed.

To compare the framework for lakes in the Canadian Rockies to frameworks describing lake function in other geographies, a literature search was carried out. After reviewing studies that used similar approaches and comparing their results to the present work, 13 papers were deemed most relevant. All of them used classifications, conceptual frameworks, or models to perform their studies. Besides the similar approach used, there were analogies in terms of applicable scale and relation to global warming impacts assessment on the researched water bodies. However, there were some differences. Mainly, those differences were observed in data used for the research and methodology, for example, field data collection or remote sensing. Some research had a narrow focus, for example, an investigation of glacial lake outburst floods. Narrow studies were not applicable for comparison with the conceptual framework for the Canadian Rockies. Finally, not all of the considered studies focused on mountain lakes and instead focused on lakes in plains or hilly regions. For this reason, it was critical to summarize the findings of those studies as researchers stress different factors and use various approaches being concerned on climate change impacts on water ecosystems.

In regard to providing advice for future testing of the developed framework, several options were considered. In the present study, extensive descriptive analysis was undertaken due to lack of the available data for the lakes in the research area. However, if the information about natural drivers considered in the framework was sufficient, particular statistical tools could be applied in this case. Analyzing existing approaches presented in the literature and trying to fit them logically into the created framework, I discovered that the most suitable options for testing the conceptual framework presented herein are principal component analysis (PCA) and structural equation modelling (SEM). PCA could help to describe associations of the natural drivers with the lakes and outline the most important ones for the hydrological function, while SEM could be useful to verify the importance of selected natural drivers within the developed framework. Additionally, the water balance approach could be considered as an option to use, as it would help to specifically study variations of particular factors (e.g. water storage) in the hydrology of lakes under the changing climate.

Given the data limitations for objective 3, the fourth thesis objective – hypothesize changes in the hydrological functioning of the lakes under climate change – was met qualitatively. It could be stated that global warming has diverse influences on the hydrological functioning of mountain lakes but most of them lead to deterioration of a lake's ecological conditions, shifts in hydrological regimes, and changes in the water quality. These water bodies are sensitive and fragile to worldwide and local rising temperatures. The latter fact is valuable because many inhabitants of upland regions rely on the lakes as a primary water resource, so they should be worried about the conditions in those water bodies. The created framework summarizes factors and sub-factors significant for the lakes in mountain areas. The critical components for understanding lake hydrological functioning though will be four drivers that directly interact with these water bodies: glaciers, groundwater, drainage, and wetlands. In such a way, the enhanced glacial melting caused by global warming affects the lake's hydrological characteristics. The most common sequels are increasing surface area, fluctuations in water levels, changes in water chemistry, and rising water temperatures. Hence, the aforementioned consequences will reflect negatively on the ecological state of the lakes. Besides, glacial shrinkage can cause changes in the morphological type of glacial lakes (e.g. from supraglacial to moraine-dammed) leading to a potential increase in glacial lakes outburst floods within the basin area. Along with glaciers, groundwater is a crucial aspect regulating mountain lake hydrology. Fluctuations in groundwater level and flow cause variations in water storage and the chemical composition of the lake water. Moreover, groundwater usually serves as a sustention source for mountain lakes especially in the summer months, for this reason, changes in groundwater levels can have reflections on the lakes somehow similar to those from glacial melting. Meanwhile, the drainage rate is also crucial for mountain lakes. Melting glaciers contribute to streams, augmenting water volumes. Consequently, a glacier melt-enlarged river that enters a lake will provoke greater fluctuations in water levels and perhaps even shifts in surface area in particular cases (e.g. if inflow ratio is greater than evaporation ratio). Furthermore, the disturbance of the watershed (e.g. caused by wildfire) alters the streamflow, and, therefore, can influence the adjacent lake's water storage and water chemistry. Comparing to the three aforementioned drivers, wetlands might not affect directly the lakes but their presence is substantial for the hydrological conditions in the basin. Thereby, wetlands can affect lake water chemistry since a significant difference in the water chemical composition between these two water bodies. In addition to that, the increased evaporation rates from wetland surfaces can likely influence those from the adjacent lake, so that causes changes in the lake's water levels. Considering all these possible effects of natural drivers on the mountain lakes, it is useful to distinguish these water bodies as "reflectors" of the possible consequences of global warming for them as well as for the whole catchment.

Literature Cited

Andrews, J. T., & Barry, R. G. (1978). Glacial inception and disintegration during the last glaciation. Annual Review of Earth and Planetary Sciences, 6(1), 205-228

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. Journal of Great Lakes Research, 29(3), 488–500

Arp, C. D., Gooseff, M. N., Baker, M. A., & Wurtsbaugh, W. (2006). Surface-water hydrodynamics and regimes of a small mountain stream-lake ecosystem. Journal of Hydrology, 329(3–4), 500–513

Bajracharya, S. R., & Mool, P. (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. Annals of Glaciology, 50(53), 81–86

Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. Water Resources Research, 42(8), 1–13

Bally, A. W., Gordy, P. L., & Stewart, G. A. (1966). Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains. Bulletin of Canadian Petroleum Geology, 14(3), 337–381

Bandyopadhyay, J., Rodda, J. C., Kattelmann, R., Kundzewicz, Z. W., & Kraemer, D. (1997). Highland waters—a resource of global significance. In: Mountains of the World: A Global Priority, B. Messerli and J. D. Ives (Eds.), Parthenon, New York and London, 131-155

Battarbee, R. W., Thompson, R., Catalan, J., Grytnes, J. A., & Birks, H. J. B. (2002). Climate variability and ecosystem dynamics of remote alpine and arctic lakes: The MOLAR project. Journal of Paleolimnology, 28(1), 1–6

Beierle, B. D., Smith, D. G., & Hills, L. V. (2003). Late Quaternary Glacial and Environmental History of the Burstall Pass Area, Kananaskis Country, Alberta, Canada. Arctic, Antarctic, and Alpine Research, 35(3), 391–398

Benedict, A.D. (1991). A Sierra Club naturalist's guide to the Southern Rockies: The Rocky Mountain regions of southern Wyoming, Colorado, and northern New Mexico. Sierra Club Books, San Francisco

Blenckner, T. (2005). A conceptual model of climate-related effects on lake ecosystems. Hydrobiologia, 533(1), 1–14

Blyth, S., Groombridge, B., Lysenko, I., Miles, L. & Newton, A.C. (2002). Mountain watch. Environmental change and sustainable development in mountains. UNEP-WCMC, Cambridge

Bobrowsky, P. & Rutter N. W. (1992). The Quaternary Geologic History of the Canadian Rocky Mountains. Géographie Physique et Quaternaire, 46(1), 5–50

Bolch, T., Menounos, B., & Wheate, R. (2010). Landsat-based inventory of glaciers in western Canada, 1985-2005. Remote Sensing of Environment, 114(1), 127–137

Bonsal, B., Shrestha, R. R., Dibike, Y., Peters, D. L., Spence, C., Mudryk, L., & Yang, D. (2020). Western Canadian freshwater availability: current and future vulnerabilities. Environmental Reviews, 18(August), 1–18

Bracht-Flyr, B., Istanbulluoglu, E., & Fritz, S. (2013). A hydro-climatological lake classification model and its evaluation using global data. Journal of Hydrology, 486, 376–383

Campos, J. N. B., Lima Neto, I. E., Studart, T. M. C., & Nascimento, L. S. V. (2016). Trade-off between reservoir yield and evaporation losses as a function of lake morphology in semi-arid Brazil. Anais Da Academia Brasileira de Ciencias, 88(2), 1113–1125

Carrivick, J. L. & Chase, S. E. (2011). Spatial and temporal variability of annual glacier equilibrium line altitudes in the Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics, 54:4, 415–429

Castellazzi, P., Burgess, D., Rivera, A., Huang, J., Longuevergne, L., & Demuth, M. N. (2019). Glacial Melt and Potential Impacts on Water Resources in the Canadian Rocky Mountains. Water Resources Research, 55(12), 10191–10217

Catalan, J., Camarero, L., Felip, M., Pla, S., Ventura, M., Buchaca, T., Bartumeus, F., De Mendoza, G., Miró, A., Casamayor, E. O., Medina-Sánchez, J. M., Bacardit, M., Altuna, M., Bartrons, M., & De Quijano, D. D. (2006). High mountain lakes: Extreme habitats and witnesses of environmental changes. Limnetica, 25(1–2), 551–584

Catalan, J., Curtis, C. J., & Kernan, M. (2009). Remote European mountain lake ecosystems: Regionalisation and ecological status. Freshwater Biology, 54(12), 2419–2432

Catalan, J., & Donato Rondón, J. C. (2016). Perspectives for an integrated understanding of tropical and temperate high-mountain lakes. Journal of Limnology, 75(1S), 215–234

Charizopoulos, N., & Psilovikos, A. (2016). Hydrologic processes simulation using the conceptual model Zygos: the example of Xynias drained Lake catchment (central Greece). Environmental Earth Sciences, 75(9), 1–15

Christianson, K. R., Johnson, B. M., Hooten, M. B., & Roberts, J. J. (2019). Estimating lake–climate responses from sparse data: An application to high elevation lakes. Limnology and Oceanography, 64(3), 1371–1385

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radić, V., & Menounos, B. (2015). Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8(5), 372–377

Crosby, J.M., Bradford, M.E., Mitchell, P.A., Prepas, E.E., McIntyre, L.G., Hart Buckland-Nicks L., Hanson, J.M. (1990). Atlas of Albert Lakes. Mitchell, P., Prepas, E. (Eds). The University of Alberta Press. Edmonton, Alberta

Dahlstrom, C. D. A. (1970). Structural geology in the eastern margin of the Canadian Rocky Mountains. Bulletin of Canadian Petroleum Geology, 18(3), 332–406

de Jong, C., Whelan, F., & Messerli, B. (2005a). The importance of a hydrological research framework for water balance studies in mountain basins. Hydrological Processes, 19(12), 2323–2328

de Jong, C. (2013a). Linking ICT and society in early warning and adaptation to hydrological extremes in mountains. Natural Hazards and Earth System Sciences, 13(9), 2253–2270

de Jong, C. (2015). Challenges for mountain hydrology in the third millennium. Frontiers in Environmental Science, 3(MAY), 1–13

DeBeer, C. M., & Pomeroy, J. W. (2017). Influence of snowpack and melt energy heterogeneity on snow cover depletion and snowmelt runoff simulation in a cold mountain environment. Journal of Hydrology, 553, 199–213

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? Hydrological Processes, 19(8), 1705–1714

Diaz, H. F., Bradley, R. S., & Ning, L. (2014). Climatic changes in mountain regions of the American Cordillera and the tropics: Historical changes and future outlook. Arctic, Antarctic, and Alpine Research, 46(4), 735–743

Dinka, M. O., Loiskandl, W., & Ndambuki, J. M. (2014). Hydrologic modelling for Lake Basaka: Development and application of a conceptual water budget model. Environmental Monitoring and Assessment, 186(9), 5363–5379

Driscoll, C. T., Newton, R. M., Gubala, C. P., Baker, J. P., & Christensen, S. W. (1991). Adirondack Mountains. In Donald F.Charles (Ed.), Acidic Deposition and Aquatic Ecosystems (pp. 133–202). Springer-Verlag New York – Inc

Elias, S. (2002). Rocky Mountains (Smithsonian natural history series). Washington, D.C.: Smithsonian Institution Press

Elshafei, Y., Sivapalan, M., Tonts, M., & Hipsey, M. R. (2014). A prototype framework for models of socio-hydrology: Identification of key feedback loops and parameterisation approach. Hydrology and Earth System Sciences, 18(6), 2141–2166

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., & Cochachin, A. (2016). 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. Catena, 147, 269–279

Fairbridge, R.W. (1968). Mountain and hilly terrain, mountain systems; mountain types. In Fairbridge, R.W. (ed.) Encyclopedia of Geomorphology, Reinhold, New York: 745-761

Foster, L.M., Bearup, L.A., Molotch, N.P., Brooks, P.D., & Maxwell, R.M. (2016). Energy budget increases reduce mean streamflow more than snow-rain transitions: Using integrated modeling to isolate climate change impacts on Rocky Mountain hydrology. Environmental Research Letters, 11(4), 1–10

French, N. R. (1986). Hierarchical conceptual model of the alpine geosystem. Arctic & Alpine Research, 18(2), 133–146

Frenierre, J. La, & Mark, B. G. (2014). A review of methods for estimating the contribution of glacial meltwater to total watershed discharge. Progress in Physical Geography, 38(2), 173–200

Fyfe, J. C., & Flato, G. M. (1999). Enhanced climate change and its detection over the Rocky Mountains. Journal of Climate, 12(1), 230–243

Gardelle, J., Arnaud, Y., & Berthier, E. (2011). Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Global and Planetary Change, 75(1–2), 47–55

Gates, J. B., Edmunds, W. M., Darling, W. G., Ma, J., Pang, Z., & Young, A. A. (2008). Conceptual model of recharge to southeastern Badain Jaran Desert groundwater and lakes from environmental tracers. Applied Geochemistry, 23(12), 3519–3534

Geiger, S. T., Daniels, J. M., Miller, S. N., & Nicholas, J. W. (2014). Influence of rock glaciers on stream hydrology in the La Sal Mountains, Utah. Arctic, Antarctic, and Alpine Research, 46(3), 645–658

Gerrard, A. J. (1988). Rocks and Landforms. Unwin Hyman, London, UK

Gerrard, A. J. (1990). Mountain Environments: An Examination of the Physical Geography of Mountains, Belhaven, London, UK

Gibson, J. J., Birks, S. J., Yi, Y., Moncur, M. C., & McEachern, P. M. (2016). Stable isotope mass balance of fifty lakes in central Alberta: Assessing the role of water balance parameters in determining trophic status and lake level. Journal of Hydrology: Regional Studies, 6, 13–25

Gillefalk, M., Massmann, G., Nützmann, G., & Hilt, S. (2018). Potential impacts of induced bank filtration on surface water quality: A conceptual framework for future research. Water (Switzerland), 10(9)

Givone, C. (1990). Water balance as a basis for water resources estimation and management in mountainous areas. Int. Assoc. Hydrol Sci. Publ No. 190, pp. 57-65

Harder, P., & Pomeroy, J. (2013). Estimating precipitation phase using a psychrometric energy balance method. Hydrological Processes, 27(13), 1901–1914

Harder, P., Pomeroy, J. W., & Westbrook, C. J. (2015). Hydrological resilience of a Canadian Rockies headwaters basin subject to changing climate, extreme weather, and forest management. Hydrological Processes, 29(18), 3905–3924

Hauer, F. R., Baron, J. S., Campbell, D. H., Faush, K. D., Hostetler, S. W., Leavesley, G. H., Leavitt, P. R., McKnight, D. M., & Stanford, J. A. (1997). Assessment of Climate Change and Freshwater Ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes, 11(8), 903–924

Hayes, N. M., Deemer, B. R., Corman, J. R., Razavi, N. R., & Strock, K. E. (2017). Key differences between lakes and reservoirs modify climate signals: A case for a new conceptual model. Limnology and Oceanography Letters, 2(2), 47–62

He, J., & Hayashi, M. (2019). Lake O’Hara alpine hydrological observatory: Hydrological and meteorological dataset, 2004-2017. Earth System Science Data, 11(1), 111–117

Hewitt, K. (1982). Natural dams and outburst floods of the Karakoram Himalaya. In: Glen, J.W. (Ed.) Hydrological Aspects of Alpine and High Mountain Areas. International Association of Hydrological Scientists, Publication 138. IAHS, Washington, pp. 259 – 269

Historical streamflow summary (1991). Published by inland Waters Directorate, Water Resources of Canada, Environment Canada, Ottawa

Holland, S. S. (1964). Landforms of British Columbia, a physiographic outline. British Columbia Department of Mines and Petroleum Resources, Bulletin 48, 138 p

Hood, J. L., Roy, J. W., & Hayashi, M. (2006). Importance of groundwater in the water balance of an alpine headwater lake. Geophysical Research Letters, 33(13)

Hood, J. L., Hayashi, M., & Roy, J. W. (2007). Preliminary assessment of groundwater contribution to the hydrology of an alpine lake in the Canadian Rockies. IAHS-AISH Publication, 318, 39–48

Imenda, S. (2014). Is There a Conceptual Difference between Theoretical and Conceptual Frameworks? Journal of Social Sciences, 38(2), 185–195

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world’s water towers. Nature, 577(7790), 364–369

Jackson, J. E. (2005). A user's guide to principal components (Vol. 587). John Wiley & Sons - Inc., New York

Janský, B., Šobr, M., & Yerokhin, S. (2006). Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture. Limnological Review, 6(January 2006), 135–140

Ju, J., Zhu, L., Wang, J., Cui, Y., Huang, L., Yang, R., Ma, Q., Luo, L., & Wang, Y. (2017). Estimating the contribution of glacial meltwater to Ranwu Lake, a proglacial lake in SE Tibet, using observation data and stable isotopic analyses. Environmental Earth Sciences, 76(5), 1–13

Keating, L. F. (1966). Exploration in the Canadian Rockies and Foothills. Canadian Journal of Earth Sciences, 3(5), 713–723

Kittel, T. G. F., Thornton, P. E., Royle, J. A. & Chase, T. N. (2002). Climates of the Rocky Mountains: Historical and Future Patterns, 59–82 (Chapter 4), in: J.S. Baron (ed.). Rocky Mountain Futures: An Ecological Perspective. Island Press, Covelo, 325 p

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., Rossi, P., Uvo, C. B., Velasco, E., & Pulido-Velazquez, M. (2014). Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology, 518(PB), 250–266

Körner, C., Paulsen, J., & Spehn, E. M. (2011). A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. Alpine Botany, 121(2), 73–78

Kratz, T. K., Deegan, L. A., Harmon, M. E., & Lauenroth, W. K. (2003). Ecological variability in space and time: Insights gained from the US LTER program. BioScience, 53(1), 57-67

Lamontagne, S., Donald, D. B., & Schindler, D. W. (1994). The distribution of four Chaoborus species (Diptera: Chaoboridae) along an elevation gradient in Canadian Rocky Mountain lakes. Canadian Journal of Zoology, 72(9), 1531–1537

Lantz, T. C., & Turner, K. W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. Journal of Geophysical Research: Biogeosciences, 120(3), 513–524

Leppi, J. C., DeLuca, T. H., Harrar, S. W., & Running, S. W. (2012). Impacts of climate change on August stream discharge in the Central-Rocky Mountains. Climatic Change, 112(3–4), 997–1014

Li, L., Li, J., Yao, X., Luo, J., Huang, Y., & Feng, Y. (2014). Changes of the three holy lakes in recent years and quantitative analysis of the influencing factors. Quaternary International, 349, 339-345

Liefert, D. T., Shuman, B. N., Parsekian, A. D., & Mercer, J. J. (2018). Why Are Some Rocky Mountain Lakes Ephemeral? Water Resources Research, 54(8), 5245–5263

Livingstone, S. J., Clark, C. D., Piotrowski, J. A., Tranter, M., Bentley, M. J., Hodson, A., Swift, D. A., & Woodward, J. (2012). Theoretical framework and diagnostic criteria for the identification of palaeo-subglacial lakes. Quaternary Science Reviews, 53(C), 88–110

Loriaux, T., & Casassa, G. (2013). Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context. Global and Planetary Change, 102, 33–40

Luckman, B., & Kavanagh, T. (2000). Impact of climate fluctuations on mountain environments in the Canadian Rockies. Ambio, 29(7), 371–380

Mahat, V., Silins, U., & Anderson, A. (2016). Effects of wildfire on the catchment hydrology in southwest Alberta. Catena, 147, 51–60

Mark, B. G., & Seltzer, G. O. (2003). Tropical glacier meltwater contribution to stream discharge: A case study in the Cordillera Blanca, Peru. Journal of Glaciology, 49(165), 271–281

Marks, J., Piburn, J., Tootle, G., Kerr, G., & Oubeidillah, A. (2015). Estimates of glacier mass loss and contribution to streamflow in the Wind River Range in Wyoming: Case study. Journal of Hydrologic Engineering, 20(8), 2–9

Martin, S. L., Soranno, P. A., Bremigan, M. T., & Cheruvelil, K. S. (2011). Comparing hydrogeomorphic approaches to lake classification. Environmental Management, 48(5), 957–974

Meixner, T., Manning, A. H., Stonestrom, D. A., Allen, D. M., Ajami, H., Blasch, K. W., Brookfield, A. E., Castro, C. L., Clark, J. F., Gochis, D. J., Flint, A. L., Neff, K. L., Niraula, R., Rodell, M., Scanlon, B. R., Singha, K., & Walvoord, M. A. (2016). Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology, 534, 124–138

Messerli, B., Viviroli, D., & Weingartner, R. (2004). Mountains of the world: Vulnerable water towers for the 21 st century. Ambio, 33(SPEC. ISS. 13), 29–34

Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health, Seventh Edition. (2003). Retrieved October 20, 2020, from https://medical-dictionary.thefreedictionary.com/classification

Numata, M. (1972). Ecological interpretation of vegetational zonation of high mountains, particularly in Japan and Taiwan. In Troll, C. (ed.), Geoecology of the high-mountain regions of Eurasia, Franz Steiner Verlag, Wiesbaden, 288-299

O'Connor, K. F. (1984). Stability and instability of ecological systems in New Zealand mountains. Mountain Research and Development 4, 15–29

Olson, M. H., Fischer, J. M., Williamson, C. E., Overholt, E. P., & Theodore, N. (2018). Landscape-scale regulators of water transparency in mountain lakes: Implications of projected glacial loss. Canadian Journal of Fisheries and Aquatic Sciences, 75(7), 1169–1176

Otto, J.-C. (2019). Proglacial Lakes in High Mountain Environments. In T. Heckmann (Ed.), Geomorphology of Proglacial Systems (pp. 231–247). Springer Nature Switzerland AG

Parker, B. R., Vinebrooke, R. D., & Schindler, D. W. (2008). Recent climate extremes alter alpine lake ecosystems. Proc. Nat. Acad. Sci. USA 105: 12927–12931

Pechlaner, R. (1971). Factors that control the production rate and biomass of phytoplankton in high-mountain lakes. Mitt. Int. Verein. Limnol. 19, 125–145

Pelto, M., Capps, D., Clague, J. J., & Pelto, B. (2013). Rising ELA and expanding proglacial lakes indicate impending rapid retreat of Brady Glacier, Alaska. Hydrological Processes, 27(21), 3075–3082

Pomeroy, J., Fang, X., & Ellis, C. (2012). Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. Hydrological Processes, 26(12), 1891–1904

Price, L. W. (1981). Mountains and Man, University of California Press, Berkeley

Ptak, M., Wrzesiński, D., & Choiński, A. (2017). Long-term changes in the hydrological regime of high mountain Lake Morskie Oko (Tatra Mountains, Central Europe). Journal of Hydrology and Hydromechanics, 65(2), 146–153

Qiao, B., Zhu, L., Wang, J., Ju, J., Ma, Q., & Liu, C. (2017). Estimation of lakes water storage and their changes on the northwestern Tibetan Plateau based on bathymetric and Landsat data and driving force analyses. Quaternary International, 454, 56–67

Read, E. K., Patil, V. P., Oliver, S. K., Hetherington, A. L., Brentrup, J. A., Zwart, J. A., Winters, K. M., Corman, J. R., Nodine, E. R., Woolway, R. I., Dugan, H. A., Jaimes, A., Santoso, A. B., Hong, G. S., Winslow, L. A., Hanson, P. C., & Weathers, K. C. (2015). The importance of lake-specific characteristics for water quality across the continental United States. Ecological Applications, 25(4), 943–955

Regoniel, P. (2015). Conceptual Framework: A Step by Step Guide on How to Make One. In Research-based Articles. Retrieved from https://simplyeducate.me/2015/01/05/conceptual-framework-guide/

Rietti-Shati, M., Yam, R., Karlen, W., & Shemesh, A., (2000). Stable isotope composition of tropical high-altitude fresh-waters on Mt. Kenya, Equatorial East Africa. Journal of Chemical Geology, 166, 341–350

Rigler F. H. & Peters R. H. (1995). Science and limnology. In: Excellence in Ecology 6 (Ed. O. Kinne), Ecology Institute, Oldendorf/Lutie Germany

Roberts, J. J., Fausch, K. D., Schmidt, T. S., & Walters, D. M. (2017). Thermal regimes of Rocky Mountain lakes warm with climate change. PLoS ONE, 12(7), 1–17

Robinson, S. (2008). Conceptual Modeling for Simulation Part I: Definition and Requirements. Journal of the Operational Research Society 59 (3): 278-290

Robinson, S., Arbez, G., Birta, L. G., Tolk, A., & Wagner, G. (2016). Conceptual modeling: Definition, purpose and benefits. Proceedings - Winter Simulation Conference, April 2016, 2812–2826

Rocco, S. T., & Plakhotnik, S. M. (2009). Literature reviews, conceptual frameworks, and theoretical frameworks: Terms, functions, and distinctions. Human Resource Development Review, 8(1), 120–130

Rogora, M., Mosello, R., & Arisci, S. (2003). The effect of climate warming on the hydrochemistry of Alpine lakes. Water, Air, and Soil Pollution, 148(1–4), 347–361

Röthlisberger, H., & Lang, H. (1987). Glacial hydrology. In: Gurnell, A.M., Clark, M.J. (Eds.), Glacio-fluvial Sediment Transfer, Wiley, New York, pp. 207–284

Roy, J. W., & Hayashi, M. (2008). Groundwater exchange with two small alpine lakes in the Canadian Rockies. Hydrological Processes, 22, 2838–2846

Sánchez-López, G., Hernández, A., Pla-Rabes, S., Toro, M., Granados, I., Sigró, J., Trigo, R. M., Rubio-Inglés, M. J., Camarero, L., Valero-Garcés, B., & Giralt, S. (2015). The effects of the NAO on the ice phenology of Spanish alpine lakes. Climatic Change, 130(2), 101–113

Saros, J. E., Rose, K. C., Clow, D. W., Stephens, V. C., Nurse, A. B., Arnett, H. A., Stone, J. R., Williamson, C. E., & Wolfe, A. P. (2010). Melting alpine glaciers enrich high-elevation lakes with reactive nitrogen. Environmental Science and Technology, 44(13), 4891–4896

Schindler, D. W. (2009). Lakes as sentinels and integrators for the effects of climate change on watersheds, airsheds, and landscapes. Limnology and Oceanography, 54(6 PART 2), 2349–2358

Selby, M.J. (1985). Earth's Changing Surface, An Introduction to Geomorphology. Oxford University Press, Oxford

Shapley, M. D., Ito, E., & Donovan, J. J. (2009). Lateglacial and Holocene hydroclimate inferred from a groundwater flow-through lake, Northern Rocky Mountains, USA. Holocene, 19(4), 523–535

Shaw, G. D., Mitchell, K. L., & Gammons, C. H. (2017). Estimating groundwater inflow and leakage outflow for an intermontane lake with a structurally complex geology: Georgetown Lake in Montana, USA. Hydrogeology Journal, 25(1), 135–149

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. Nat. Clim. Change. 10, 939–945

Silar, J. (1990). Surface Water and Groundwater Interactions in Mountainous Regions. IAHS-AISH Publication, 190, 21–28

Slaymaker, O. & McPherson, H. J. (1977). An overview of geomorphic processes in the Canadian Cordillera. Zeitschrift fur Géomorphologie, 21, 724-732

Slemmons, K. E. H., Saros, J. E., & Simon, K. (2013). The influence of glacial meltwater on alpine aquatic ecosystems: A review. Environmental Sciences: Processes and Impacts, 15(10), 1794–1806

Snelder, T. H., Biggs, B. J. F., & Woods, R. A. (2005). Improved eco-hydrological classification of rivers. River Research and Applications, 21(6), 609–628

Solovieva, N., Jones, V., Birks, J. H. B., Appleby, P., & Nazarova, L. (2008). Diatom responses to 20th century climate warming in lakes from the northern Urals, Russia. Palaeogeography, Palaeoclimatology, Palaeoecology, 259(2–3), 96–106

Sommaruga, R. (2001). The role of solar UV radiation in the ecology of alpine lakes. Journal of Photochemistry and Photobiology B: Biology, 62(1–2), 35–42

Sommaruga, R. (2015). When glacier and ice sheets melt: Consequences for planktonic organisms, Journal of Plankton Research, 37(3), 509–518

Song, C., & Sheng, Y. (2016). Contrasting evolution patterns between glacier-fed and non-glacier-fed lakes in the Tanggula Mountains and climate cause analysis. Climatic Change, 135(3–4), 493–507

Spence, C., Whitfield, P. H., Pomeroy, J. W., Pietroniro, A., Burn, D. H., Peters, D. L., & St-Hilaire, A. (2013). A review of the Prediction in Ungauged Basins (PUB) decade in Canada. Canadian Water Resources Journal, 38(4), 253–262

Spence, C., & Hedstrom, N. (2015). Attributes of Lake Okanagan evaporation and development of a mass transfer model for water management purposes. Canadian Water Resources Journal, 40(3), 250–261

Springer, J., Ludwig, R., & Kienzle, S. W. (2015). Impacts of Forest Fires and Climate Variability on the Hydrology of an Alpine Medium Sized Catchment in the Canadian Rocky Mountains. Hydrology, 2(1), 23–47

Stahl, K., & Moore, R. D. (2006). Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(6), 2–6

St-Hilaire, A., Ouarda, T. B. M. J., Lachance, M., Bobée, B., Gaudet, J., & Gignac, C. (2003). Assessment of the impact of meteorological network density on the estimation of basin precipitation and runoff: A case study. Hydrological Processes, 17(18), 3561–3580

Strachan, S., Kelsey, E. P., Brown, R. F., Dascalu, S., Harris, F., Kent, G., Lyles, B., McCurdy, G., Slater, D., & Smith, K. (2016). Filling the Data Gaps in Mountain Climate Observatories Through Advanced Technology, Refined Instrument Siting, and a Focus on Gradients. Mountain Research and Development, 36(4), 518–527

Streich, S. C., & Westbrook, C. J. (2020). Hydrological Function of a Mountain Fen At Low Elevation Under Dry Conditions. Hydrological Processes, 34(2), 244–257

Sturrock, A. M., Winter, T. C., & Rosenberry, D. O. (1992). Energy Budget Evaporation From Williams Lake: A Closed Lake in North Central Minnesota. Water Resources Research, 28(6), 1605–1617

Sutton-Grier, A. E., Kenney, M. A., & Richardson, C. J. (2010). Examining the relationship between ecosystem structure and function using structural equation modelling: A case study examining denitrification potential in restored wetland soils. Ecological Modelling, 221(5), 761-768

Tennant, C., Menounos, B., Wheate, R., & Clague, J. J. (2012). Area change of glaciers in the Canadian Rocky Mountains, 1919 to 2006. Cryosphere, 6(6), 1541–1552

Thies, H., Nickus, U., Mair, V., Tessadri, R., Tait, D., Thaler, B., & Psenner, R. (2007). Unexpected response of high alpine lake waters to climate warming. Environmental Science and Technology, 41(21), 7424–7429

Tipper, H. W., Woodsworth, G. J. & Gabrielse, H. W. (1981). Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America. Geological Survey of Canada, Map 1505A

Trant, A., Higgs, E., & Starzomski, B. M. (2020). A century of high elevation ecosystem change in the Canadian Rocky Mountains. Scientific Reports, 10(1), 1–10

Trenberth, K. E. (1999). Conceptual framework for changes of extremes of the hydrological cycle with climate change. In Climatic Change (Vol. 42, Issue 1, pp. 327–339)

Turnbull, L., Wainwright, J. & Brazier, R. E. (2008). A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. Ecohydrology 1, 23–34

Turner, K. W., Wolfe, B. B., & Edwards, T. W. D. (2010). Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. Journal of Hydrology, 386(1–4), 103–117

Ullman, J. B., & Bentler, P. M. (2003). Structural equation modeling. Handbook of psychology, 607-634

VanLooy, J. A., & Vandeberg, G. S. (2019). Late summer glacial meltwater contributions to Bull Lake Creek stream flow and water quality, Wind River Range, Wyoming, USA. Physical Geography, 40(5), 461–480

Vaughan, A. (2021). The heat is on out west. New Scientist, 250 (3342), 10 - 11

Villeneuve, B., Piffady, J., Valette, L., Souchon, Y., & Usseglio-Polatera, P. (2018). Direct and indirect effects of multiple stressors on stream invertebrates across watershed, reach and site scales: A structural equation modelling better informing on hydromorphological impacts. Science of the Total Environment, 612, 660–671

Vinebrooke, R. D., Thompson, P. L., Hobbs, W., Luckman, B. H., Graham, M. D., & Wolfe, A. P. (2010). Glacially mediated impacts of climate warming on alpine lakes of the Canadian Rocky Mountains. Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Verhandlungen, 30(9), 1449–1452

Viviroli, D., & Weingartner, R. (2004). The hydrological significance of mountains: from regional to global scale. Hydrology and Earth System Sciences, 8(6), 1017–1030

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resources Research, 43(7), 1–13

Wang, X., Siegert, F., Zhou, A. guo, & Franke, J. (2013). Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972-2010. Global and Planetary Change, 111, 246–257

Wang, R., Yao, Z., Wu, S., & Liu, Z. (2017). Glacier retreat and its impact on summertime run-off in a high-altitude ungauged catchment. Hydrological Processes, 31(21), 3672–3681

Ward, A. (2016). The extent and value of carbon stored in mountain grasslands and shrublands globally, and the prospects for using climate finance to address natural resource management issues. PhD Thesis, University of Queensland

Wilcox, B. P., & Breshears, D. D. (1995). Hydrology and Ecology of Pinon-Juniper Woodlands - Conceptual Framework and Field Studies. In Desired Future Conditions for Pinon-Juniper Ecosystems (pp. 109–119). U.S. Department of Agriculture, Fort Collins, Colorado, USA

Williams, M., Kattelmann, R., & Melack, J. (1990). Groundwater contributions to the hydrochemistry of an alpine basin. Hydrology in Mountainous Regions I, January 1990, 741–748

Williams, M., Losleben, M., Caine, N., & Greenland, D. (1996). Changes in climate and hydrochemical responses in a high-elevation catchment in the Rocky Mountains, USA. Limnology and Oceanography, 41(5), 939–946

Winter, T. C. (1977). Classification of the Hydrologic Settings of Lakes in the North Central United States. Water Resources Research, 13(4), 753–767

Zaharescu, D. G., Hooda, P. S., Burghelea, C. I., & Palanca-Soler, A. (2016). A Multiscale Framework for Deconstructing the Ecosystem Physical Template of High-Altitude Lakes. Ecosystems, 19(6), 1064–1079

Zhang, X., Vincent, L. A., Hogg, W. D., & Niitsoo, A. (2000). Temperature and precipitation trends in Canada during the 20th century. Atmosphere - Ocean, 38(3), 395–429

Zhou, S. Q., Kang, S. C., Gao, T. G., & Zhang, G. S. (2010). Response of Zhadang Glacier runoff in Nam Co Basin, Tibet, to changes in air temperature and precipitation form. Chinese Science Bulletin, 55(20), 2103–2110

Appendices

Appendix A. Areas and elevations of water bodies in the study region

The estimated areas and elevations for all 5155 water bodies across the research area illustrated in *Figure 4.2* were summarized in the Excel table. Each water body has its index (ID), which matches with one in the shapefile provided by National Topographic Database. The link to the file with the dataset is provided below.

https://github.com/Ecohydrology-westbrook/Amaro-Medina-Daniel

Appendix B. Information about 23 studied lakes in the research area

Table B1 represents detailed information about 23 lakes illustrated in *Figure 4.5*. The summarized are the data on coordinates, area, and elevation of the lakes as well as on the topographic map sheet where the lake can be found.

Table B1 Information about the 23 lakes with some degree of available data

Lake	Map sheet*	ID*	Rectangular coordinates		Elevation (m)	Area (km^2)
			X	Y		
Bowron	93H	42355693	-121.362	53.230	950	10.00
Rock	83E	43830532	-118.266	53.450	1393	1.95
Curator	83C	44079044	-117.861	52.793	2275	0.05
Capricorn	82N	58961306	-116.625	51.773	2202	0.06
Bow	82N	58961470	-116.451	51.669	1958	3.04
Herbert	82N	58961354	-116.221	51.460	1607	0.07
Agnes	82N	58961297	-116.247	51.415	2168	0.04
O'Hara	82N	58961440	-116.329	51.356	2020	0.30
Oesa	82N	58961405	-116.302	51.354	2267	0.13
Opabin	82N	58961209	-116.312	51.342	2278	0.03
Eiffel	82N	58961351	-116.243	51.322	2281	0.07
McConnell	82O	43897300	-115.978	51.638	2326	0.09
Snowflake	82O	43897308	-115.832	51.597	2368	0.08
Harrison	82O	43897658	-115.809	51.554	2259	0.06
Goat	82O	43897369	-115.857	51.447	2466	0.27
Elbow	82J	NaN	-115.008	50.639	2120	0.05
Whiteswan	82J	43998184	-115.477	50.142	1144	3.85
Premier	82G	45574069	-115.654	49.941	877	1.84
New	82G	45574049	-115.849	49.517	1192	0.26
Jim Smith	82G	45574015	-115.846	49.482	1058	0.19
Tie	82G	45574047	-115.326	49.417	855	1.36
Crowsnest	82G	45574040	-114.641	49.632	1360	1.09
Beauvais	82G	45574044	-114.102	49.409	1373	0.66

* Source: National topographic database
https://ftp.maps.canada.ca/pub/nrcan_rncan/vector/ntdb_bndt/250k_shp_en/