The impact of precipitation phase and aquifer type on changing groundwater levels in mountain regions of Canada and the United States

By

Sana Salehi

Submitted in partial fulfilment of the requirements for the degree of Bachelor of Science, Combined Honours in Earth and Environmental Science

At

Dalhousie University

Halifax, Nova Scotia

April 2024

Supervisor: Dr. Lauren Somers

TABLE OF CONTENTS

Contents

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Groundwater in alpine regions plays an essential role in downstream water supply. As the climate warms, mountain water resources are under threat with reduced snowpack, glacier recession, and precipitation phase change that can negatively impact summer streamflow. However, the extent to which such global changes can impact the mechanisms that contribute to groundwater recharge remains poorly understood. This project aims to address the limited spatial and temporal extents of observational studies and enhance our understanding of long-term trends across various geographical boundaries of groundwater in mountainous regions. We analysed a dataset of 171 observation wells from mountain regions across Canada and the US, categorizing wells as snow-dominated, rain-dominated, and high-temperature rain-dominated hydrological regimes based on temperature thresholds. Additionally, we considered three aquifer types (confined, unconfined, and mixed) and the well depth as the potential explanatory variables. We conducted Kruskal- Wallis and Spearman correlation analysis on the above against the groundwater level trends, respectively. Our results indicated a non-significant difference ($p = 0.1687$) between the three hydrological regimes, a statistically significant difference ($p = 0.0182 < 0.05$) in the trends observed between the three-aquifer type, and lastly a weak negative Spearman correlation of $\rho = -0.01089$ between trend and well depth, which is not statistically significant ($p<0.05$). This study emphasizes the value of extending research on mountain groundwater to a larger spatial extent and offers significant insights into how various factors can influence groundwater recharge in mountains.

Keywords: Aquifer type, Hydrological regimes, Groundwater, Precipitation phase, Mountains

ACKNOWLEDGEMENTS

Firstly, I would like to extend my gratitude and appreciation to Dr. Lauren Somers for providing me with the opportunity to work under her supervision and allowing me to explore my interests in the interdisciplinary field of research. Thank you for providing me the chance to assist you and your graduate students on various field expeditions over the summer. Your support, mentoring, and constant guidance have allowed me to gain valuable insights in this field of work. Your encouragement throughout this time has helped me push forward, both professionally and personally, to achieve the goals I have set for myself. I would also like to show my gratitude to my colleagues at the Somers Hydrologic Change Lab for allowing me to join their field expeditions, where I have gained various soft and hard skills.

I would like to thank Dr. Tarah Wright for her feedback and guidance throughout this year. Your constant support and motivation during each class have been pushing me forward to finishing this thesis.

Finally, I would like to thank my family and friends who supported me from the United Arab Emirates, Uzbekistan, Iran, and Canada. Thank you for constantly pushing me forward and holding me accountable, I forever will be grateful. To my family, thank you for always believing in me, providing me with this opportunity, and supporting me throughout my studies, which has enabled me to always challenge myself to achieve greater goal

Chapter 1: Introduction

1.1 Motivation

Due to a lack of storage capacity, mountain groundwater was long thought to be a negligible input to streamflow and downstream water resources (Somers & McKenzie, 2020; Hayashi, 2020). However, it is now recognized that there are plentiful aquifers in mountainous areas that have a large amount of storage and release capacity (Hayashi, 2020). For instance, recent research in the northern Alps revealed that up to 87% of yearly streamflow was generated by groundwater (Chen et al., 2018).

In comparison to lowland areas, mountain regions are experiencing greater temperature rises as a result of climate change (Pepin et al., 2015). In contrast to the normal rate of global warming, which is 0.2 ± 0.1 C per decade, observations in western North America, the European Alps, and High Mountain Asia have shown that mountain air temperatures have been rising over the past few decades at an average rate of 0.3 ± 0.2 C per decade (Hock et al., 2019). Snowpack loss, permafrost deterioration, and glacier recession are all being caused by rising air temperatures in mountainous areas. The effects of climate change on mountain surface water resources include declining late-summer or dry season stream flows, rising surface water temperatures, and rising solute concentrations that may exceed drinking water limits (Barnett et al., 2005; Leppi et al., 2012; Thies et al., 2007; Zhu et al., 2020). Viviroli et al. (2020) projected that by mid-twenty-first century, over 1.5 billion people, which is 24% of the lowland population in the world, would depend on the runoff from mountain regions, compared to 7% in the 1960s.

Understanding the future of alpine water resources requires a thorough understanding of the functions and mechanisms of groundwater flow in alpine catchments, including assessment of climate change implications on groundwater discharge (Halloran et al., 2023). This study aims to improve our understanding of how mountain groundwater systems are changing across Canada and the United States in response to climate change. This study will examine how snow and rain-dominated mountains may be changing differently and how a shift from snow to rain in some mountain ranges due to climate change consequences may impact groundwater recharge.

1.2 Literature review introduction

This chapter will outline the relevant research on the impact of the precipitation phase on changing groundwater recharge in mountain regions of Canada and the US. Firstly, we will explore the significance of groundwater in mountain regions and explain the mechanisms that contribute to the recharge, storage, and discharge of the groundwater. Secondly, it will summarize the current scientific articles that estimate groundwater recharge magnitude and the mechanisms that contribute to groundwater fluctuations, specifically snowmelt versus rainfall recharge. Lastly, we will review the impacts of climate change on the precipitation phase and water resources and compare the different studies across various alpine regions.

1.3 Mountain hydrology and hydrogeology

1.3.1 Mountain surface water

Mountain surface water plays an important role as a freshwater supply for low-lying regions. Mountain regions typically have low evapotranspiration (ET) due to cooler temperatures and sparse vegetation at higher elevations, while high precipitation occurs due to the orographic effects. Mountains also store water as snow and ice which can contribute to streamflow during warm periods. These facts combined allow mountains to significantly contribute to the downstream water supply (Martínez-Cob, 1996; Viviroli & Weingartner 2004). Moreover, mountains can serve as recharge sources for downstream alluvial aquifers due to the heavy precipitation they receive (Immerzeel et al., 2019, Somers and McKenzie, 2020). Viviroli (2007) and Weingartner (2004) have demonstrated that freshwater supplies from mountains are essential to the water supply in nearby lowland areas, particularly in regions with arid or semi-arid climates. The source of this freshwater supply comes from groundwater discharge, runoff from precipitation, meltwater from glaciers, and mountain snowpack (Somers & McKenzie, 2020). In conclusion, high-elevation mountain regions play a significant role as a freshwater storage hub, that holds fresh water in various forms, such as snowpack, groundwater, etc, and these act as a source of downstream water supply in low-elevation areas.

1.3.2 Groundwater in mountain regions

Until recently, mountain groundwater was not recognized as a significant contributor to water storage and downstream water supply due to the specific watershed attributes in the mountain regions, which have been documented in various studies. Groundwater was considered a minimal contributor to mountain streamflow due to the geological characteristics such as the shallow soil development and steep slopes, which were assumed to be short-lived temporary storage reservoirs for groundwater (McGlynn, McDonnel, & Brammer, 2002; Weiler, McDonnell, Tromp-van Meerveld, & Uchida, 2005). Moreover, Manning & Solomon (2005) emphasized the difficulty of characterizing groundwater flow in mountainous areas, arising from the structural complexity of mountain aquifers, specifically the bedrock features, cost, the availability of good data, and the unpredictable climatic conditions of alpine regions.

On the other hand, more recent studies emphasize that groundwater in alpine regions plays a significant role in storage and streamflow. Research done by Rhoujjati (2023) demonstrated that the primary source of groundwater recharge and water supplies for the lowlands downstream is snowfall from the High Atlas Mountains. Moreover, alpine aquifers with large capacities to sustain baseflow in the first order and major rivers during prolonged dry periods were observed from field-based studies (Hayashi, 2019).

In conclusion, although various studies emphasize the complexities of groundwater storage in alpine regions due to the geological characteristics, current studies have shown that mountain groundwater plays a significant role in the hydrological cycle, global water supply, and downstream freshwater resources.

1.4 Recharge mechanisms

1.4.1 Recharge, storage, and discharge.

The groundwater dynamics in mountains are controlled by recharge, storage, and discharge processes. Groundwater recharge is the amount or process of water flowing into the subsurface and reaching the water table, where groundwater is stored (de Vries and Simmers, 2002). Groundwater recharge derives from various distinct pathways. A study by Hartmann (2022), highlighted rainfall and snowmelt as the two main sources of water that contribute to groundwater recharge. Both rain and snowmelt infiltrate into the subsurface and percolate vertically through the unsaturated zone toward the water table. Hartman (2022) also describes indirect groundwater recharge, which infiltrates through riverbeds or lakes, and focused or localized recharge that occurs because of infiltration and percolation through fractures, joints, depression, and sinkholes.

Stored groundwater flows slowly following the hydraulic gradient to a discharge location somewhere downstream. The difference in groundwater process between alpine regions and low relief areas is due to the presence of higher hydraulic gradients and the position of the water table which affect the predominant local flow patterns and discharge rates (Somers & McKenzie, 2020). Moreover, information on groundwater flow directions and stream-aquifer interactions can be obtained from the hydraulic heads (Bresciani et al., 2018).

Somers and McKenzie (2020), summarised various types of water balance studies in alpine regions to quantify groundwater storage, recharge, and discharge. These studies take advantage of the time variations between water inputs that include precipitation-evapotranspiration, snowmelt, glacier melt, and outputs such as stream discharge from a catchment to indicate the transient storage and discharge of catchment water.

These studies highlight that in high-alpine settings, water balance studies can be utilized to measure groundwater recharge, storage, and discharge. Additionally, these studies also emphasize the complexity of internal mechanisms that contribute to the recharge of the groundwater supply and the various outlets of groundwater storage.

1.4.2 Aquifer types

Studies suggest that an array of mountain aquifers serve as the storage reservoirs for groundwater. Aquifers in alpine regions store water that is later released as groundwater discharge through springs or directly into lakes and streams (Alley et al., 2002; Oki & Kanae, 2006). The surficial aquifers, such as those found in talus, moraines, rock glaciers, and alluvial deposits are the most prevalent types of mountain aquifers. During prolonged dry or cold periods, these surficial aquifers frequently exhibit a two-phase recession in which a rapid groundwater discharge is followed by a delayed release of groundwater (Hayashi, 2020). Despite making up only 3% of the basin area, the alluvial aquifer in the Swiss Alps watershed was crucial in maintaining streamflow during a drought by storing groundwater in the catchment and supplying one-third of the total stream discharge. It was also discovered that a sizable amount of groundwater leaves the watershed via the alluvial aquifer beneath the stream channel (Somers & McKenzie, 2020, Käser & Hunkeler, 2016).

In addition to surficial aquifers, bedrock aquifers also convey groundwater flow in mountains. Due to the misconception that bedrock aquifers are impermeable and should be viewed as a groundwater flow boundary, they have frequently been disregarded in the past (Somers & McKenzie, 2020; Markovich et al., 2019). Nonetheless, it is now understood that bedrock aquifers are essential to mountain hydrology, with recharge rates up to 50% of total precipitation and significant groundwater flow (Markovich et al., 2019).

Groundwater in mountains can also recharge aquifers in adjacent lowlands, known as mountain front recharge (MFR), although differing definitions exist in the literature (Markovich et al., 2019). MFR is recharge that originates in the mountain block, which is described as a place with thin soil cover and significant topographic relief. The author proceeded to define the two components that make up MFR, which included the surface MFR; or the infiltration to underlying aquifers from streams originating in the mountain regions; and mountain block recharge; the main subterranean flow from the mountain block to lowland aquifers.

In both surficial and bedrock deposits, aquifers can be categorized as confined or unconfined. In an unconfined aquifer, the upper boundary is the water table, with fluctuations in the hydraulic head due to recharge and discharge, and thus the flow and storage of groundwater are correlated (Dingman, 2015). On the other hand, a confined aquifer is contained in, or covered by, an impermeable or minimally permeable layer of rock or sediment. These layers cause a pressure throughout the aquifer that is greater than the atmospheric pressure, thus when the aquifer is penetrated by a well, the water will eventually rise above the upper boundary of the aquifer (Dingman, 2015).

In short, various aquifer types play a role in how the groundwater system is recharged, and the different ways water is being stored in mountain regions.

1.5 Climate Change

1.5.1 Sensitivity of mountain regions to climate change

Mountain regions are one of the most sensitive areas to the effects and consequences of climate change. The link between global warming and mountain regions arises from the presence of snow and ice, which plays a crucial role in the regional heat balance through the feedback loops of albedo (Knight & Harrison, 2023). Various studies highlighted the concept of elevation-dependent warming (EDW), which refers to a systematic differential in warming rates with elevation in mountains rather than in lowland areas. This temperature increase drives the snow-albedo feedback, with especially rapid temperature increases along the current cryosphere boundary (Pepin & Lundquist, 2008; Scherrer et al., 2012). This warming is expected to increase evaporative demand in mountains as a result of the direct relationship between the temperature and evaporative demand, and/or the indirect relationship between warming and increasing vegetation density and distribution. Increasing ET can reduce river flow and groundwater recharge (Goulden & Bales, 2014). Generally, studies have shown that climate change affects the mountain regions more negatively than the low-lying areas and other ecosystems. Given that warmer temperatures directly increase evaporative demand and indirectly increase the density and elevational range of vegetation, warming is anticipated to result in higher ET in mountain locations (Goulden & Bales, 2014)

1.5.2 Disturbance of recharge and discharge mechanisms

Climate change disrupts the mechanisms that contribute to groundwater recharge and stream flow discharge in mountain regions. Mountain regions with regular temperatures near the melting threshold are likely to experience greater consequences on hydrological systems since a slight temperature change can have a big impact on the ratio of liquid to solid precipitation (Pepin et al., 2022). Moreover, this warmer temperature will result in an earlier spring melt, which will increase the flow from the snowmelt throughout the spring and decrease the amount of water available in the late summer (Barnett et al., 2005; Räisänen, 2023).

Changes to the hydrological mechanisms in groundwater due to climate change can cause counterbalances by which no net change occurs. According to a study in the Alps by Chen et al., 2018, aquifer recharge is expected to rise in the winter and spring but decrease in the summer and fall, these effects are likely to counterbalance one another to some extent. In another study, a calibrated model was used to simulate groundwater dynamics and surface flow between 2070 and 2100 in a Saint-Charles River catchment, in Quebec (Canada). The results indicated an increase of 80 to 150% in winter stream discharges as a result of warmer winters with a shift towards more liquid precipitation and snowmelt. While the summer stream discharges would decrease from 10 to 20% because of increased evapotranspiration (Cochand et al., 2018).

Warming air temperatures also influence groundwater temperature. A near-linear association between groundwater temperature and average land surface temperature has been observed for a global data set with groundwater temperatures ranging from 1 to 31 °C for shallow groundwater down to a depth of 60 m below ground level (Benz et al. 2017). The rate of warming in the subsurface waters is proportional to groundwater recharge. Groundwater warming occurs more quickly in small, shallow unconfined aquifers than in larger, often deep confined aquifers during the recharge of groundwater (Kløve et al. 2014).

In conclusion, studies have shown that climate change affects mountain regions negatively than the low-lying areas and other ecosystems, however, in some snow-dominated regions, the negative effects are counterbalanced by positive climate changes.

1.5.3 Alteration in precipitation phase and amount.

Due to the increase in surface temperatures across the globe, there is an overall shift from snow to rain precipitation and a decrease in snow cover. Various authors emphasized the consequences of increased temperatures, including the decline in the area covered by snow at low elevations, a higher ratio of rain to snow precipitation, a decreasing glacier mass balance, and a reduction in the permafrost area in mountains (Knight, 2022; Räisänen, 2023). Moreover, as temperatures rise, there is a greater chance that precipitation may fall as rain rather than snow, and since warmer air can hold more water the intensity of precipitation will increase. (Räisänen, 2023; Trenberth, 2011; Viviroli, 2011). Snowfall in the western United States is especially vulnerable to end-of-century estimates of warming between +1.4 and 5.4 ∘C (National Climate Assessment 2016), as 20–40% of precipitation occurs at or near freezing (−3 to 0 ∘C) (Bales et al. 2006). A 6 °C increase would jeopardize much of the Sierra Nevada snowpack (above 3000 m) over the leeward (eastern) half of the range, while a 2 °C increase might result in a full month's shorter snow season (Räisänen, 2023).

A study done by Allen et al. (2010) in British Columbia illustrated rain and snowmelt regimes using the groundwater discharge hydrograph for each regime type as seen in Figure 1. This coastal area experiences dry summers and significant winter precipitation. In July, August, and September, the rain-dominated streams have their lowest discharges and the groundwater release to streams (baseflow) often occurs throughout late summer. On the other hand, the snowmelt regime indicates the accumulation of snow in winter, followed by a period of spring runoff and lastly a dried-out summer period (Figure 13b—center graph). Thus, the streamflow is only supported by snowmelt during the late spring and early summer seasons.

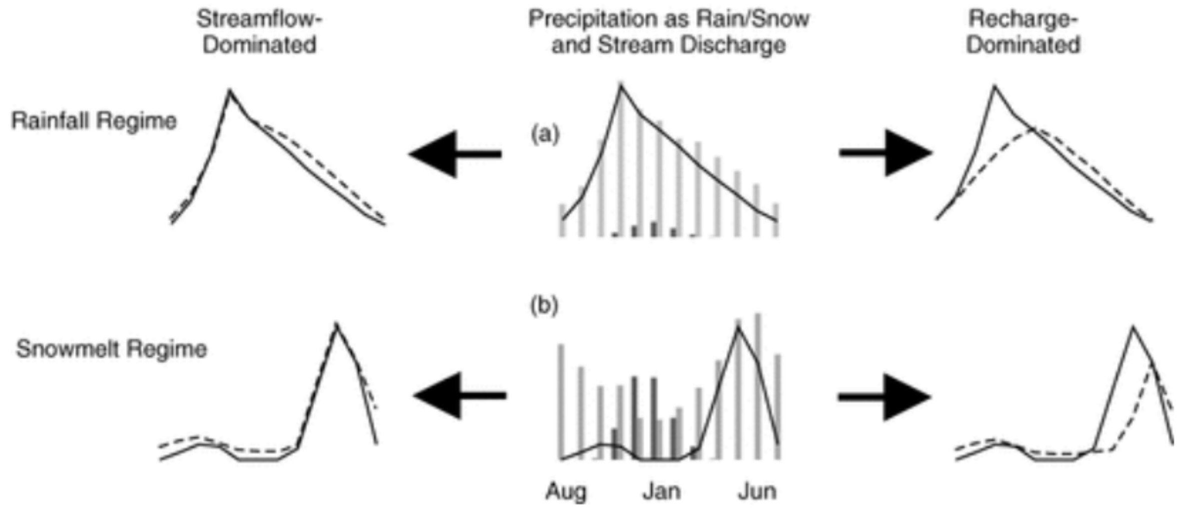


Figure 1: *A diagram that illustrates two different precipitation phase regimes, rainfall and snowmelt regime, and the associated hydrographs (From Allen et al., 2010).*

It has been observed that precipitation amounts fluctuate due to the increase in surface temperatures with elevation. In European mountain regions, a decline in precipitation has been observed, particularly in the spring season (Pisani, Samper & Marques, 2019). On the other hand, precipitation is expected to rise throughout most of High Mountain Asia, especially in the winter (Hock et al., 2019). Moreover, various models presented by Rhoades et al. (2017) indicate the snow water equivalent (SWE, which is the indicator of how much water the snowpack contains) for the winter season in the western USA mountain region would experience a decline from -19% to -38% in mean SWE by 2040-2065. Additionally, by 2075-2100, there will be an average decline in mountain snowfall by -30% and snow cover by -44%, while the SWE will decline by -69% in the western USA (Räisänen, 2023). In another study, the results illustrated that in high-elevation places, the severity (magnitude) of rainfall extremes is increasing at a pace of about 15% per degree Celsius of global warming (Ombadi et al., 2023). In the western United States, Mote et al. (2005) document a decline in yearly snowfall from 1925 to 2000. It is predicted that the amount of snowfall in this area will decrease by approximately 35 ± 10% by the middle of the century and approximately 50 ± 10% by the end of the twenty-first century (Figure 2; Siirila-Woodburn et al., 2021). Hence, in mountainous areas, solid precipitation is predicted to decrease (Figure 2), and numerous studies indicated above have already noted drops in snowfall and snow accumulation (Hock et al., 2019).

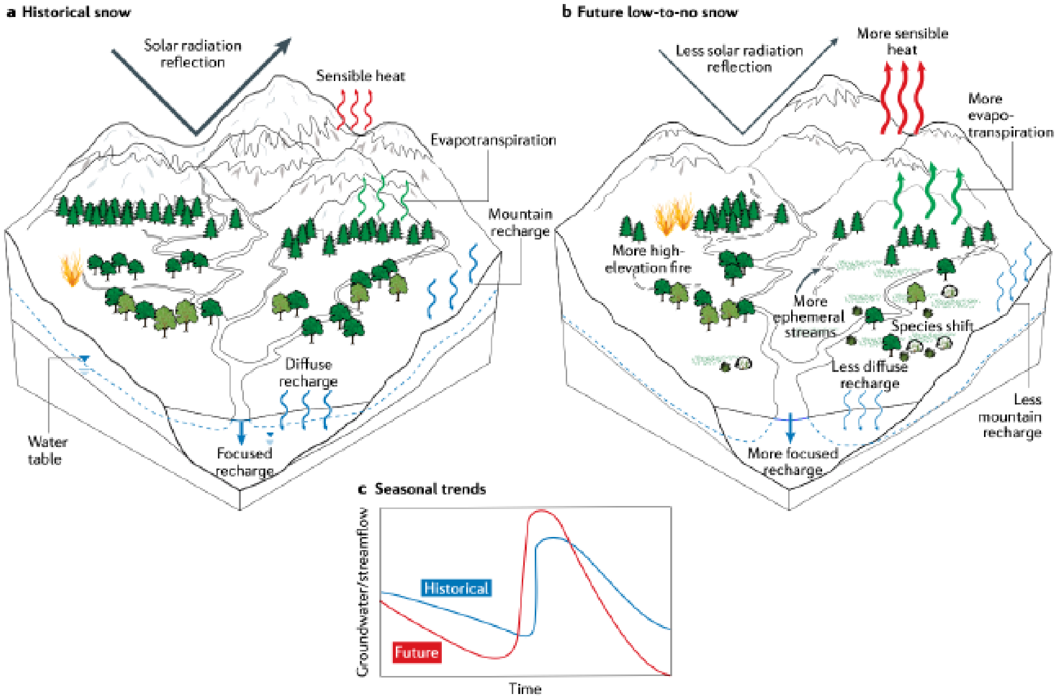


Figure 2: *Schematic illustrating the hydrologic processes that have historically occurred in mountain regions and how climate change may affect them. Retrieved from Siirila-Woodburn et al. (2021).*

In summary, various regions across the globe have shown trends in the changing precipitation phase and amount due to climate change, overall indicating a negative impact on the mountain regions.

1.6 Knowledge gaps

Various studies on mountain groundwater have only focused on specific mountainous regions. For example, a decrease in summer groundwater levels between

1976 and 1999 was observed in British Columbia, Canada (Allen et al. 2014). While in some parts of Arizona, their groundwater level trends declined from 1990 to 2008 (Tillman & Leake, 2010) with additional predictions of lower seasonal mountain system recharge for the years 2050–2099 (Ajami et al., 2012). In another study, Manning et al. (2012) reported that groundwater age increased from 1997-2010 in a watershed in the Sierra Nevada Mountains of California, United States, which indicated that the rates of recharge may be declining in response to declining snowpack.

Despite a number of observational studies projecting declining groundwater levels, it is challenging to verify these predictions and identify actual trends in mountains because there aren't many observation wells located in mountainous regions.

1.7 Study introduction and summary approach

This project aims to address the limited spatial and temporal extents of observational studies surrounding groundwater resources in mountainous regions and enhance our understanding of long-term trends across geographical boundaries. Furthermore, I aim to address the change in the dominant type of precipitation and its consequences on the recharge cycles of groundwater.

My research questions are:

1. Does snowmelt or rainfall precipitation dominate mountain groundwater recharge across mountain regions of Canada and the US?
2. Are snow-dominated mountain groundwater systems changing differently than rain-dominated systems over time?
3. Are confined and un-confined mountain aquifers changing differently over time?
4. Will a shift towards less snow and more rain impact this groundwater recharge, due to climate change?

This study will investigate the above questions using groundwater well data collected from publicly available groundwater databases across Canada and the United States with approximately 30-year-long records on average and filtered based on certain criteria set by Samways (2023). The final dataset includes 171 observation wells that will be further categorized based on the hydrologic regime (rain versus snow-dominated) using average annual air temperature as the threshold. We will use non-parametric statistical tests on each group (snow/rain/high temperature dominated) of wells to identify differences between the temporal trends in groundwater level. Additionally, we will identify whether the well depth and aquifer type influence the groundwater level trends of each group. This analysis will help to clarify why mountain groundwater wells in North America exhibit a range of temporal trends in their response to changing climatic conditions.

Chapter 2: Methods

2.1 Data filtering

Data on groundwater levels for mountain areas across Canada and the United States was gathered from publicly accessible groundwater databases by Samways (2023). These databases included the Yukon Observation Well Network (Government of Yukon, 2022), the Manitoba HYDATA database (HYDATA, 2022), the British Columbia Provincial Groundwater Observation Well Network (PGOWN) (Province of British Columbia, 2022), the Alberta Groundwater Observation Well Network (GOWN) (Government of Alberta, 2022) and the United States Geological Survey (USGS) Groundwater database (U.S. Geological Survey, 2022).

The observation well data was then filtered based on the availability of data that meets the filtering criteria (i.e., non-probabilistic sampling). Samways (2023) filtered the well data based on location within a mountain region, proximity to surface water bodies, and record length and percentage of missing data using R (R Core Team, 2023) and ArcGIS Pro (Esri Inc., 2023) as illustrated in Figure 3.

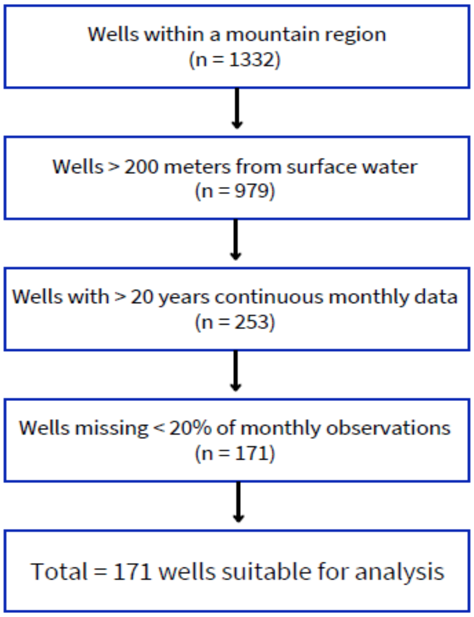


Figure 3*: Criteria for filtering out the well data provided by Samways (2023).*

Additionally, Samways (2023) determined the mean annual temperature of each well from WorldClim 2 (Fick & Hijmans, 2017), and the long-term trends in temperature at each well location were calculated using data from the Climatic Research Unit gridded Time Series (CRU TS) dataset (Harris et al., 2020). Sen's slope (Sen, 1968) was used to define trends, which were then computed in R on raster data layers covering the years 1991–2021.

2.2 Categorizing snow vs rain dominated wells.

To categorize whether each groundwater well is dominated by rain or snowmelt, we looked at the monthly groundwater hydrograph to identify characteristic patterns illustrated in Figure 1. The hydrographs differ based on the timing of peak recharge; snowmelt-dominated wells see peak groundwater recharge in late spring and early summer while rainfall-dominated wells generally see a peak in late summer and early winter.

As the dataset includes a wide range of water table depths and ranges, we first needed to standardize our dataset to compare the hydrographs produced at each well against one another. We chose a temporal range between 2015 to 2020 as a representative period of recent conditions. We then standardized the monthly record of groundwater level to zero mean and unit variance. The results were further averaged across the five years to create a seasonal cycle comparable among the various wells.

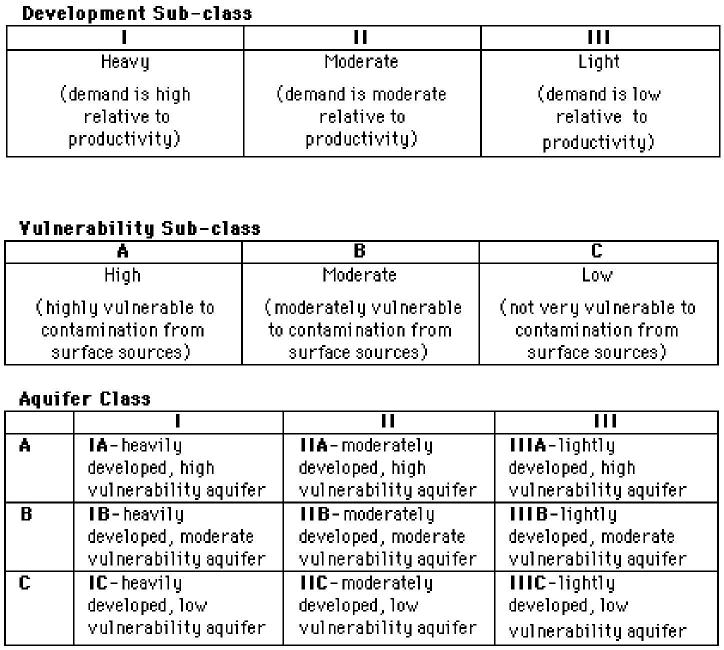
The above dataset was used to produce hydrographs using R studio (R Core Team, 2024) and the ggplot2 package (Wickham H., 2016). The wells were then categorized into snowmelt and rainfall regimes using various temperature thresholds. Temperature thresholds were selected by trial and error such that they accurately grouped the wells according to hydrograph shape. To visually represent the geographical distribution of the dominant hydrological regime of each well, we have used ArcGIS Pro (Esri Inc., 2024) to produce a map of the associated wells across our study area.

2.3 Characteristics of groundwater wells

The observation well depth and the aquifer type (confined vs unconfined) data were collected for each well location. Well depth and aquifer type were tested as potential explanatory variables that influence the temporal changes in groundwater levels. The groundwater depth and aquifer type for the US wells were collected from the National Ground-Water Monitoring Network (USGS, 2024). This database included an indication of confined, unconfined, or mixed for most observation wells in this study. The Alberta Groundwater Observation Well Network (GOWN) (Government of Alberta, 2023) also included an indication of confined or unconfined wells.

The British Columbia well database (PGOWN) (Province of British Columbia, 2024) did not indicate confined or unconfined aquifers but instead used an aquifer classification system based on aquifer vulnerability defined in Table 1 (Kreye et al., 1994).

***Table 1:** Classification system of aquifer types for British Columbia groundwater wells (From Kreye et al. (1994))*



Development Sub-class

I	II	III
Heavy (demand is high relative to productivity)	Moderate (demand is moderate relative to productivity)	Light (demand is low relative to productivity)

Vulnerability Sub-class

A	B	C
High (highly vulnerable to contamination from surface sources)	Moderate (moderately vulnerable to contamination from surface sources)	Low (not very vulnerable to contamination from surface sources)

Aquifer Class

	I	II	III
A	**IA**-heavily developed, high vulnerability aquifer	**IIA**-moderately developed, high vulnerability aquifer	**IIIA**-lightly developed, high vulnerability aquifer
B	**IB**-heavily developed, moderate vulnerability aquifer	**IIB**-moderately developed, moderate vulnerability aquifer	**IIIB**-lightly developed, moderate vulnerability aquifer
C	**IC**-heavily developed, low vulnerability aquifer	**IIC**-moderately developed, low vulnerability aquifer	**IIIC**-lightly developed, low vulnerability aquifer

The vulnerability sub-class from Kreye et al. (1994) reflects the vulnerability of an aquifer to contamination, with (A) being highly vulnerable and (C) being low vulnerability. Kreye et al (1994) notes that vulnerability to contamination is related to the lithology, with unconfined sand and gravel aquifers thought to be most susceptible to contamination. We therefore assume that wells in the A class are unconfined, wells with the B class are mixed and wells with the C class are confined including all levels respectively.

2.4 Groundwater trends and statistical analysis

The groundwater level trend analysis for each well was produced by Samways (2023) using R (R Core Team, 2023), and the associated packages ‘dplyr’ (Wickham et al., 2020), ‘lubridate’ (Grolemund & Wickham, 2011), and ‘zoo’ package (Zeileis & Grothendieck, 2005). Then, the Mann-Kendall statistical test and Sen’s slope (Sen, 1968) were calculated to determine the magnitude, direction, and statistical significance of groundwater level trends for each well.

To further analyze my dataset, I conducted a non-parametric Kruskal-Walli's test to measure the statistically significant differences in the central tendencies of groundwater level trends in different well subsets: (a) groundwater level trends in snowmelt- versus rainfall-dominated wells, (b) groundwater level trends in confined versus unconfined aquifers.

The exploratory analysis of relationships between groundwater trends and well depth was conducted using Spearman's rank correlation coefficient (ρ) to characterize the monotonic associations between groundwater trend magnitude and well depth. This operation was undertaken in R studio (R Core Team, 2024) to obtain the statistical results.

2.5 Intra-annual changes in groundwater levels

Changes in mountain groundwater systems can include intra-annual changes, even when no overall long-term trend can be detected (Nygren et al., 2020). For each well, we plotted the monthly hydrograph with a line representing each year in the record using R studio (R Core Team, 2024) and the ggplot2 package (Wickham H., 2016). These plots allow visualization of changing monthly patterns in the groundwater levels across a wider temporal range.

Chapter 3: Results

3.1 Hydrologic regime classification

The dataset comprises records from 171 wells, documenting groundwater levels on the first day of each month with a maximum record length from 1937 to 2022. Figure 4. illustrates the geographical distribution of these wells across Canada and the US. To determine the current hydrologic regime, we further filtered the dataset to include only wells with complete datasets between 2015 and 2020, which yielded 134 wells. The mean annual air temperatures for the remaining wells ranged from 1.8 to 20.7 degrees Celsius.

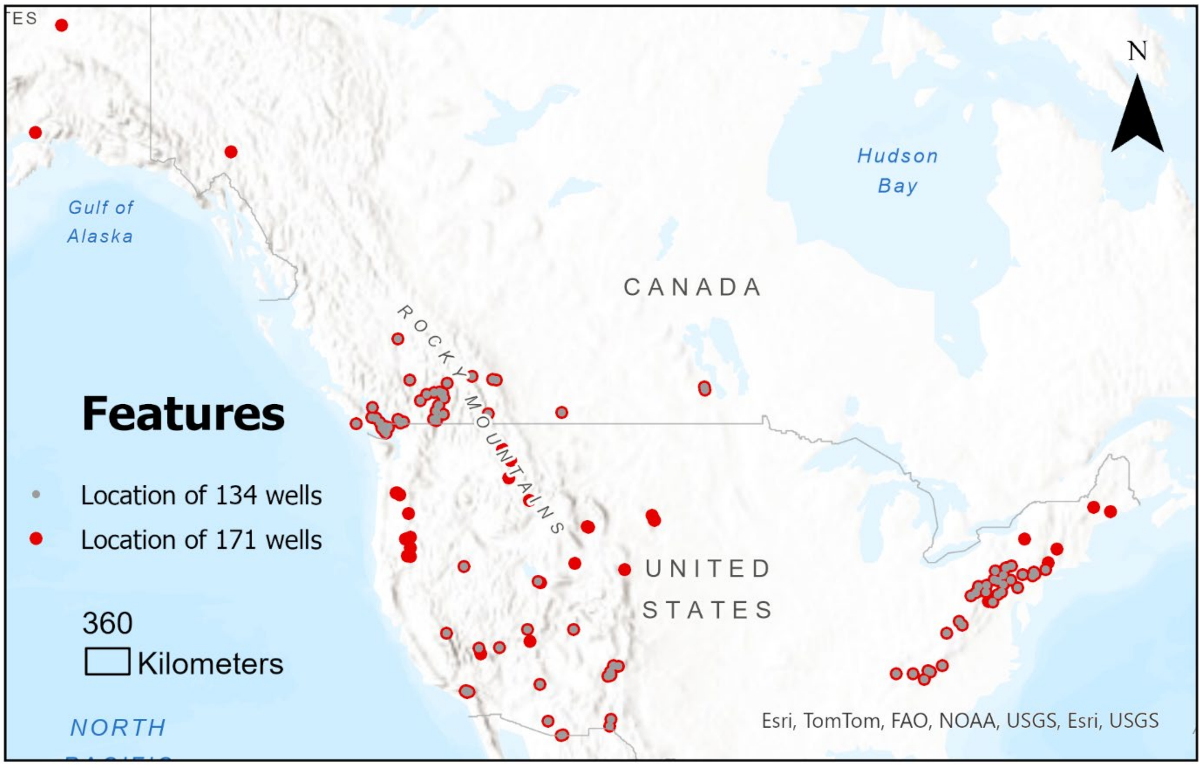


***Figure 4:** Locations of 171 wells (red circles) across Canada and the United States along with 134 wells (grey circles overlapping the red circles) that were selected for further analysis.*

We categorized the hydrologic regime for each well based on mean annual air temperature. Threshold air temperature values were established by trial and error to define the three categories: snow-dominated (nival), rain-dominated (pluvial), and high-temperature rain-dominated. The temperature thresholds were chosen to maximize the similarity between the shapes of the normalized monthly groundwater hydrographs (Figures 5-7) as outlined in research done by Allen et al. (2014).

The temperature range of 1.5 to 8.5 °C was chosen for snow-dominated wells. Figure 5 shows the normalized hydrographs for the 27 wells that were classified as snow-dominated. These wells show a recharge peak between late spring and early summer.

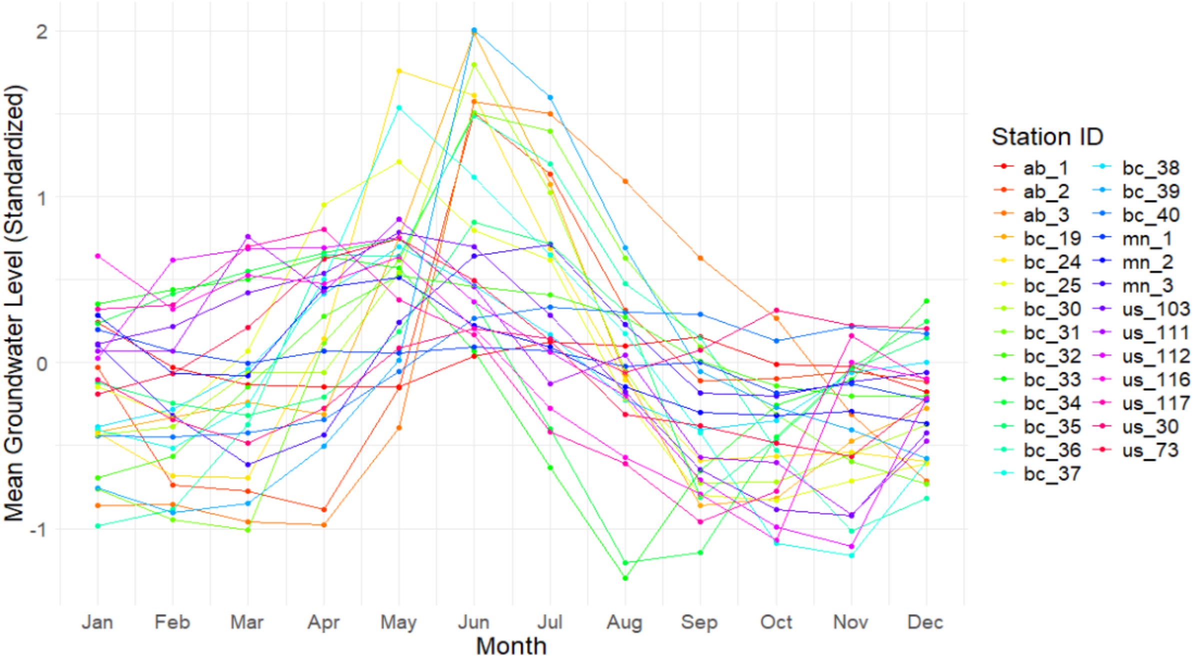


***Figure 5**: Standardized monthly hydrographs of snow-dominated (1.5-8.5ºC) groundwater observation wells (lines and symbols) averaged over 2015–2020-year period.*

Figure 6 illustrates the normalized hydrographs of the 57 wells that were classified as rain-dominated between the temperature range of 8.5 and 13ºC, with the recharge peak in early spring and minimum level in the late summer.

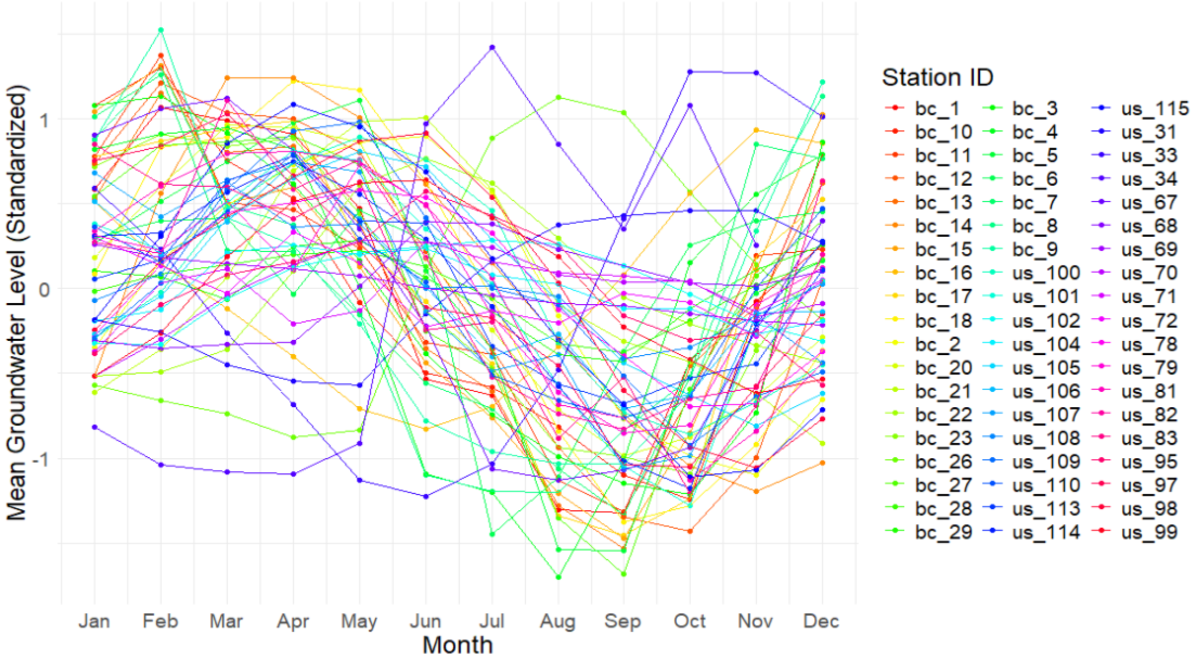


***Figure 6**: Standardized monthly hydrographs of rain-dominated (8.5-13ºC) groundwater observation wells (lines and symbols) averaged over 2015–2020-year period.*

Figure 7 illustrates the 50 wells that were considered high-temperature rain-dominated regime wells between the temperature range of 13 and 21º C. These wells did not exhibit the hydrograph shape of a rain-dominated well but were at higher temperatures and therefore were unlikely to be snow-influenced. The hydrographs generally show a slight recharge peak in early spring and a minimum level in the late summer. However, the groundwater level is mostly constant throughout the year as the hydrograph is concentrated around the mean.

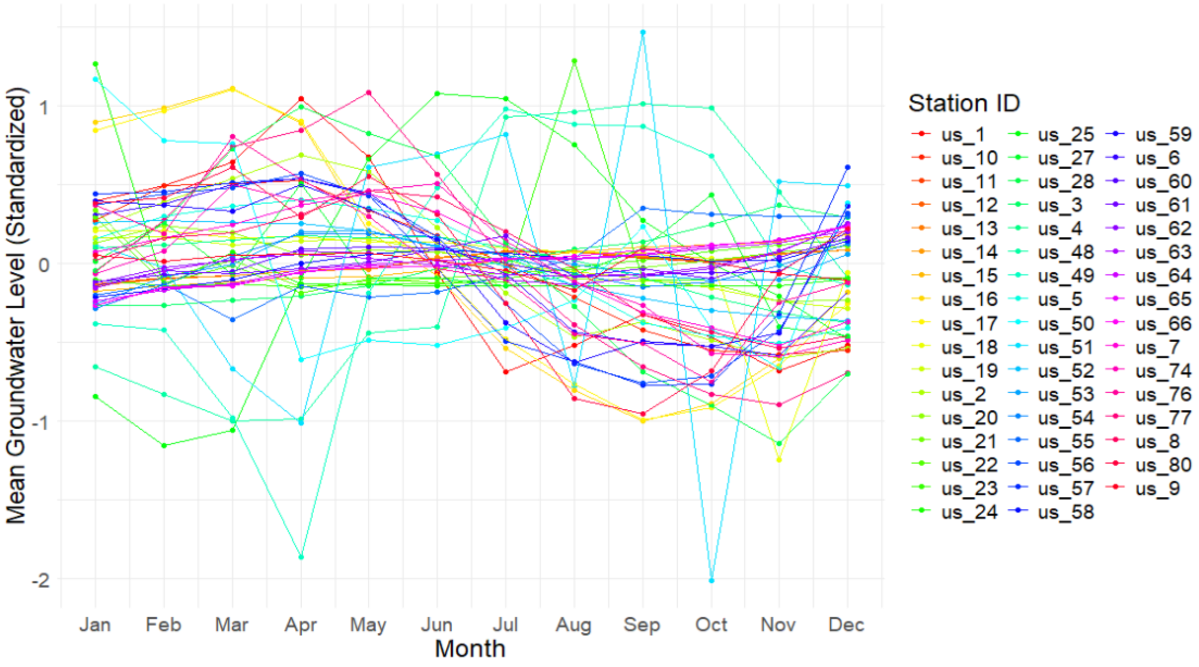


Figure 7: *Standardized monthly hydrographs of rain-dominated (13-21°C) groundwater observation wells (lines and symbols) averaged over 2015–2020-year period.*

The snow-dominated wells are located inland and mostly concentrated around the Canadian Rocky Mountains and the northern Appalachian Mountain regions (Figure 8). The rain-dominated wells are located on the west and east coasts of Canada and the US and are mostly concentrated around the Coast Mountains and the central Appalachian Mountain regions with a few rain-dominated wells in the American Rocky Mountains. Lastly, the high-temperature rain-dominated wells are in the arid American Southwest and the southern end of the Appalachians.

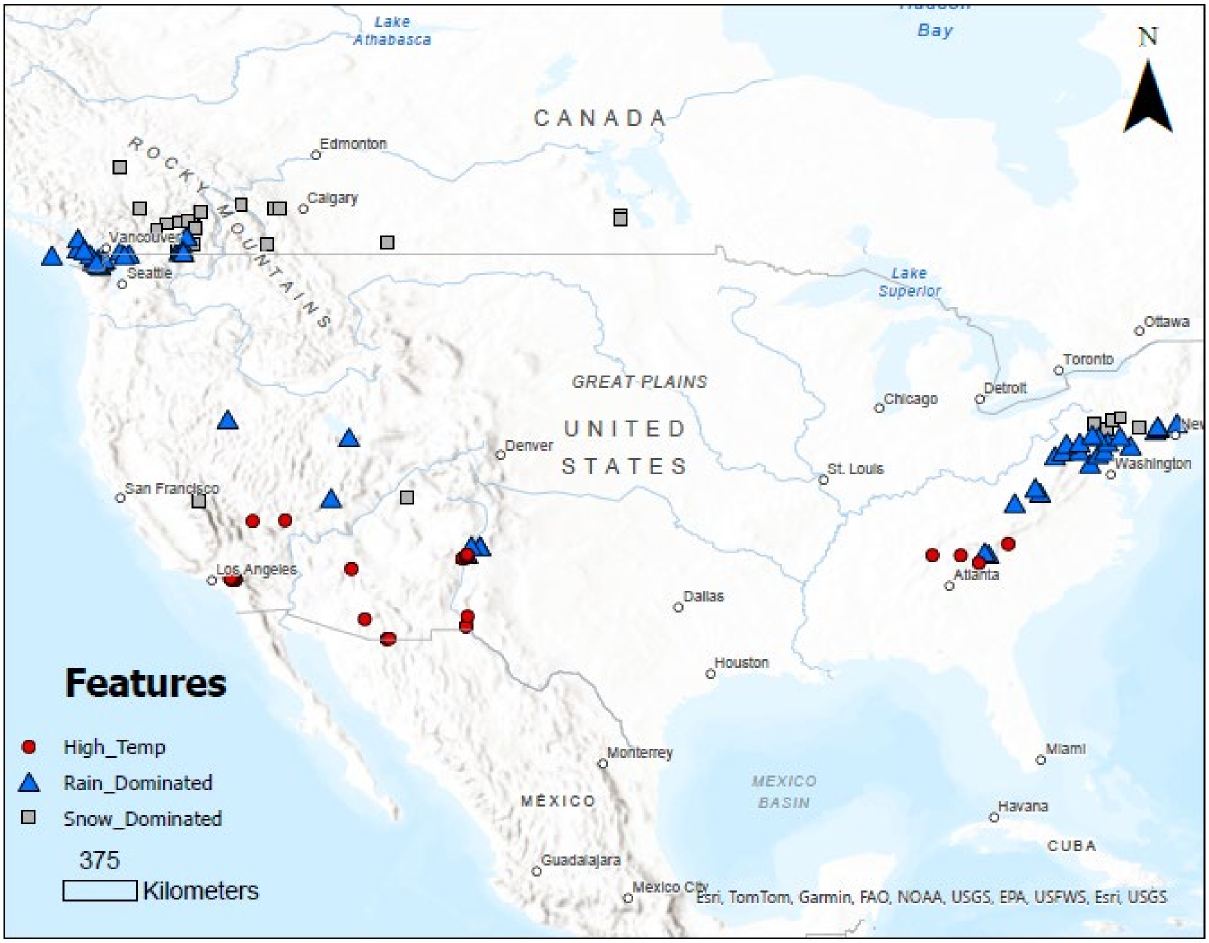


Figure 8: *The location of 134 wells categorized by the hydrologic regime, with grey squares indicating snow-dominated wells, blue triangles indicating rain-dominated wells and red circles indicating high-temperature wells.*

3.2 Statistical analysis results

3.2.1 Statistical analysis based on hydrologic regime.

The Kruskal-Walli's test indicates a non-significant difference (p = 0.1687) between the groundwater level trends observed for the three hydrologic regimes, snow-dominated, rain-dominated, and high-temperature rain-dominated wells, accompanied by a boxplot in Figure 9. Overall, the median across the three categories is similar, and the largest interquartile range is observed for high-temperature rain-dominated wells, with more negative groundwater level trends than the rain-dominated and snow-dominated wells.

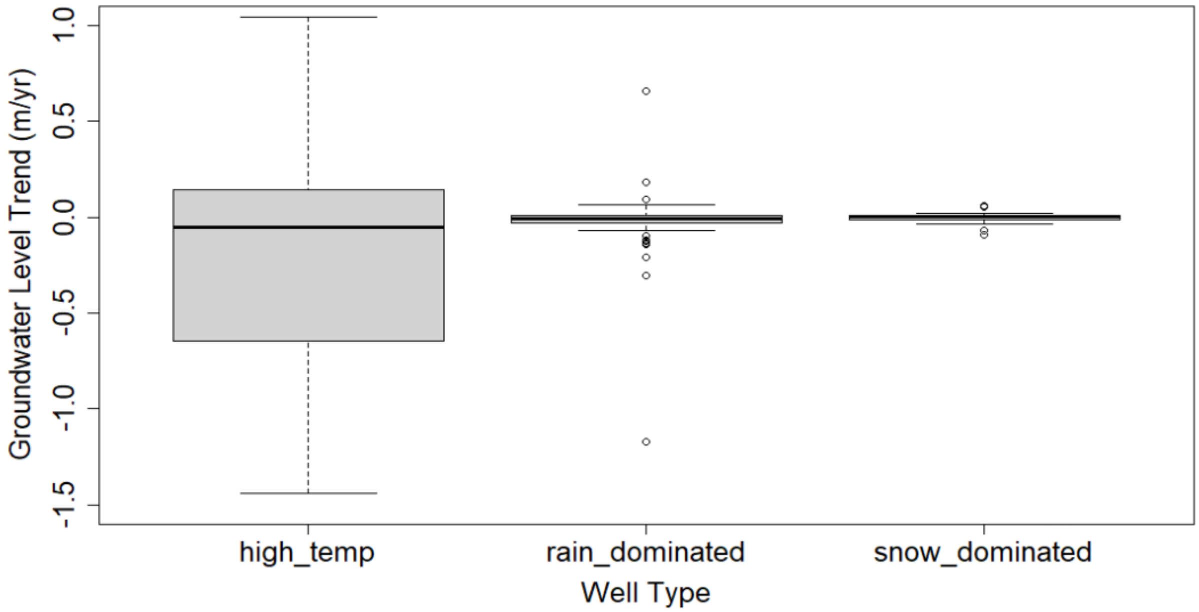


Figure 9: *Boxplots for the groundwater level trend (m/yr) against the three well type categories; snow-dominated, rain-dominated, and high temperature rain-dominated wells.*

Comparing just the snow-dominated versus rain-dominated wells, we found that the Kruskal-Walli's test indicates an even lower level of significance difference (p = 0.3406). Figure 10 shows the boxplot for the two categories, with similar medians. The rain-dominated wells have a larger interquartile range and more negative groundwater level trends than the snow-dominated wells.

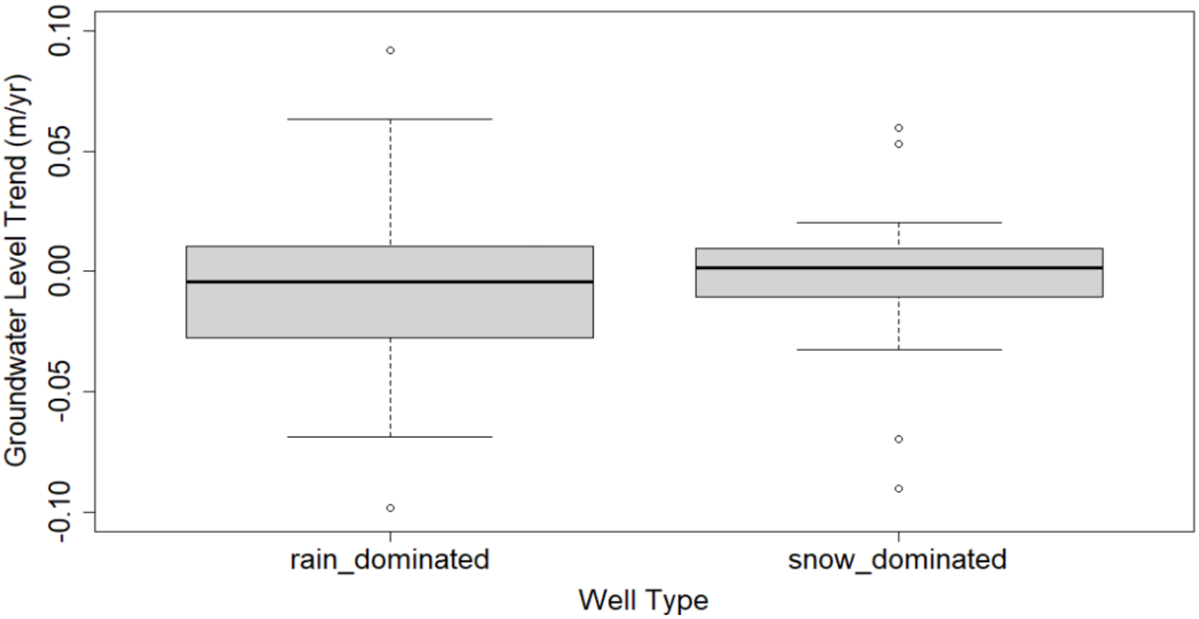


Figure 10: *The boxplots for the groundwater level trend (m/yr) against the two well type categories; snow-dominated and rain-dominated wells.*

3.2.2 Statistical analysis based on aquifer type.

Aquifer type (confined, unconfined, or mixed) was available for 141 wells (82% of the dataset), with 36 wells (21%) identified as confined aquifers, 27 wells (16%) identified as mixed and most of the wells, 78 in total (45%), were classified as unconfined aquifers. Thirty wells (18%) lacked a definitive classification in the database records.

The Kruskal-Walli's test was employed to assess the significance of differences among the three aquifer types—confined, unconfined, and mixed—while excluding missing data from the analysis. The results revealed a statistically significant difference ($p = 0.0182 < 0.05$) in the trends observed between the three aquifer types. The boxplots in Figure 11 show the groundwater level trend distributions of the three aquifer types, with the medians somewhat similar across the three categories. The mixed aquifer type also has a much larger interquartile range and is skewed toward positive groundwater level trends. The unconfined aquifer type has more outliers than other aquifer types.

Further, we have employed the Kruskal-Wallis test on the confined and unconfined aquifer types only, and the results revealed a non-significant difference (p = 0.2509 > 0.05). We have created a boxplot for confined and unconfined categories only, Figure 12, which indicates that the confined aquifer has more negative groundwater level trends than the unconfined aquifer type.

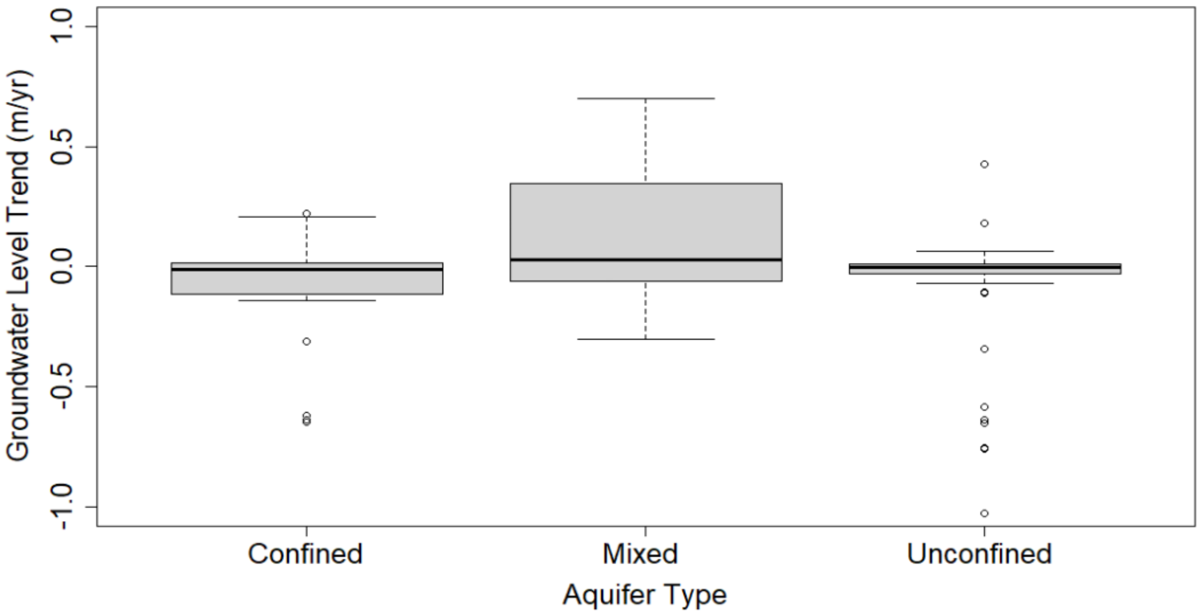


Figure 11: *Boxplots for groundwater level trend (m/yr) against the three aquifer types; confined, mixed, and unconfined aquifers.*

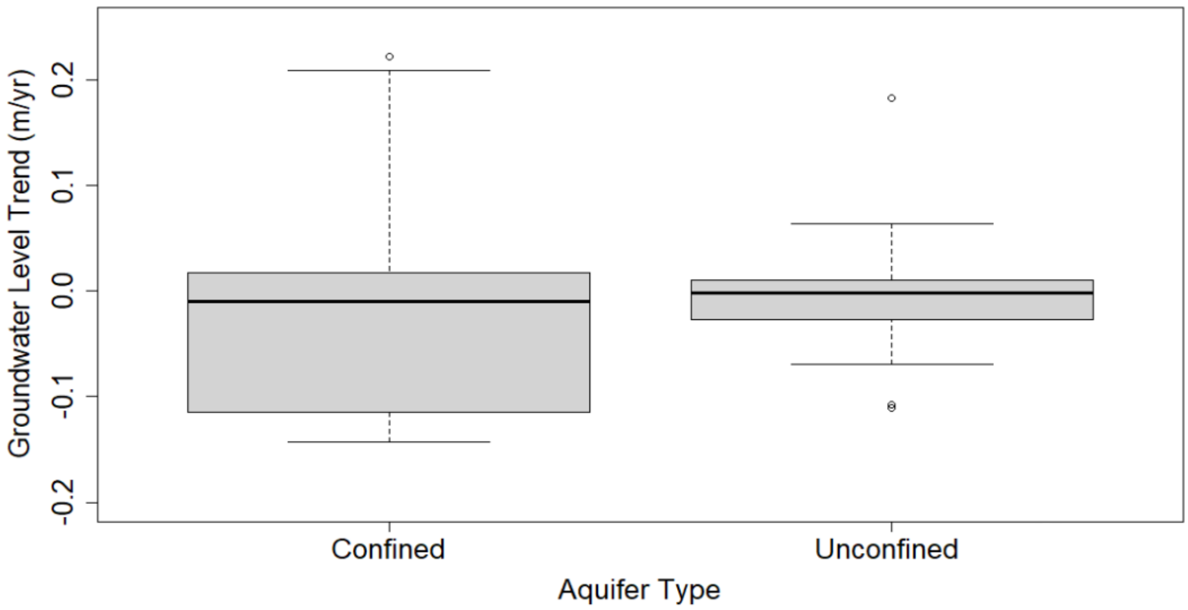


Figure 12: *Boxplots for the groundwater level trend (m/yr) against the two aquifer types; confined and unconfined aquifers.*

3.2.3 Statistical analysis based on well depth.

The Spearman correlation analysis for well depth and the groundwater level trends indicated a weak negative correlation of $\rho = -0.01089$, which is not statistically significant ($p<0.05$). Figure 13 illustrates the relationship between well depth and groundwater level trend with a scatter plot. At shallower depths, the groundwater level trend is generally close to zero, and as the well depth increases, the groundwater level trends start to disperse both positively and negatively.

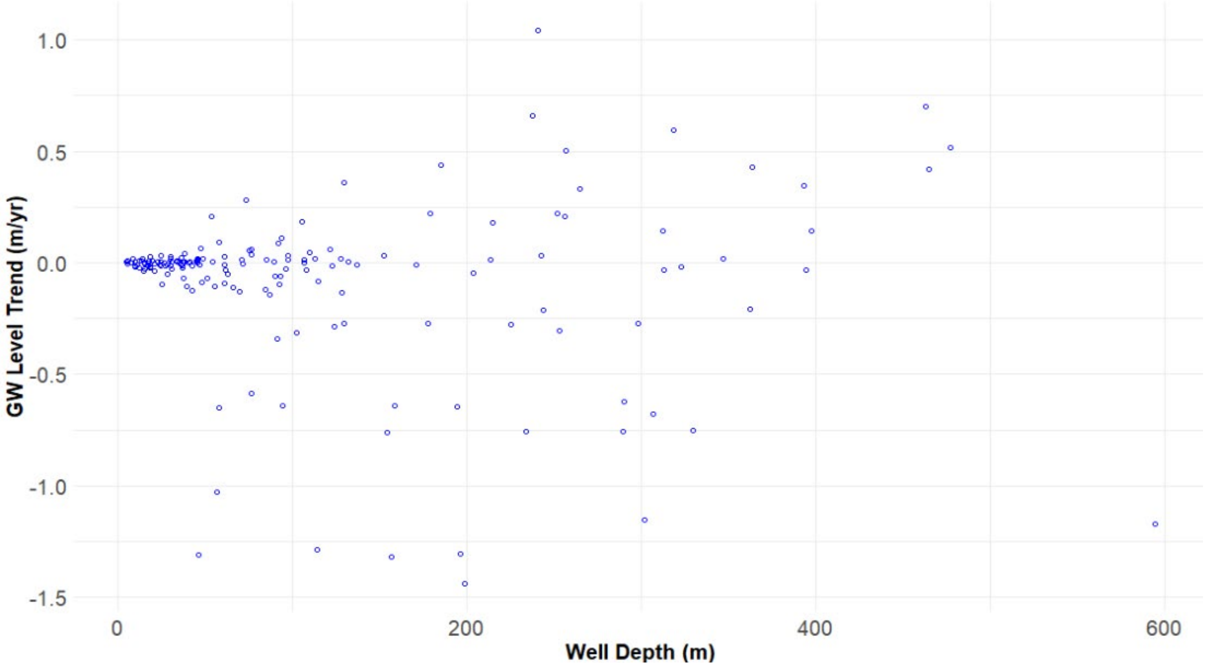


Figure 13: *Scatter plot for groundwater level trends (m/yr) against the well depth (m) for the 171 wells (open blue circle).*

3.3 Intra-annual changes in groundwater levels

We have also produced hydrographs for 171 wells to illustrate the variability of the intra-annual changes in groundwater levels of each well throughout their specific time range. Although the overall long-term trends are available for each well, only some of these indicated a clear intra-annual change. Figure 14 shows a declining groundwater level from 1976 to 2020, while Figure 15 indicates that the peaks in groundwater level recharge during late spring are shifting towards late summer and is decreasing over time between 1987-2015.

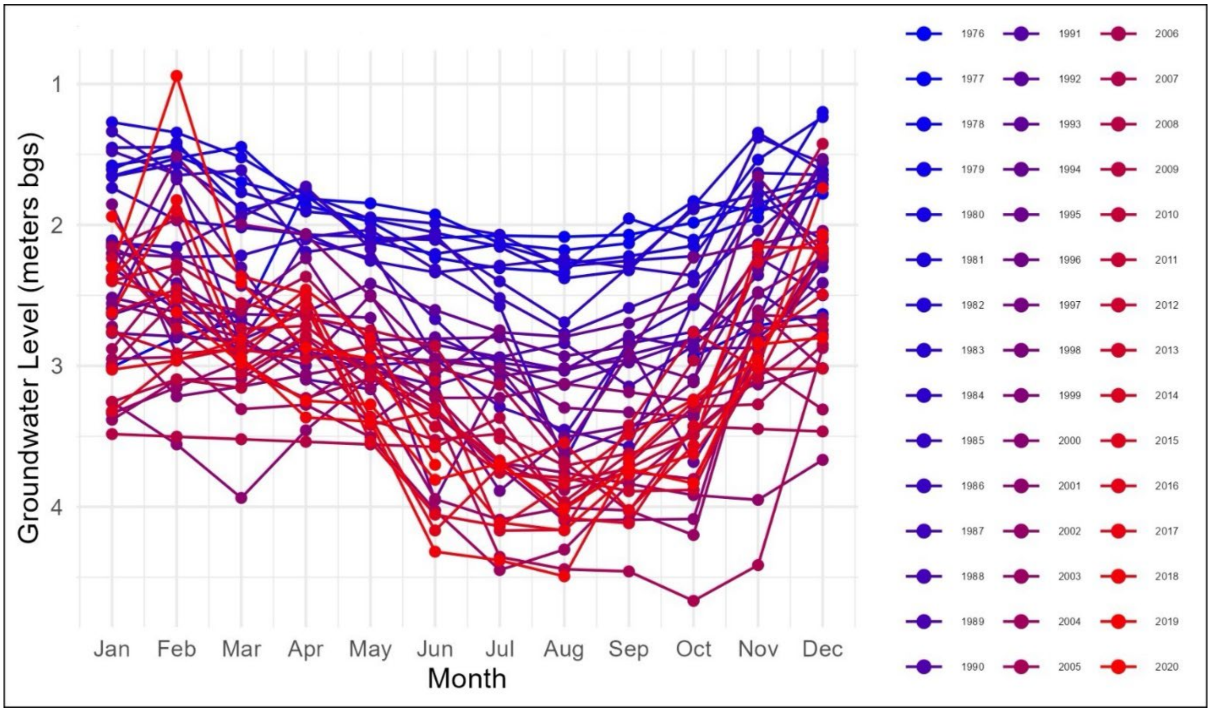


Figure 14: *Scatter plot for a well in British Columbia (ID: BC_8) with groundwater level in meters below ground. Each circle is a groundwater level during the specific month and the blue scatter line are older years and red are recent years.*

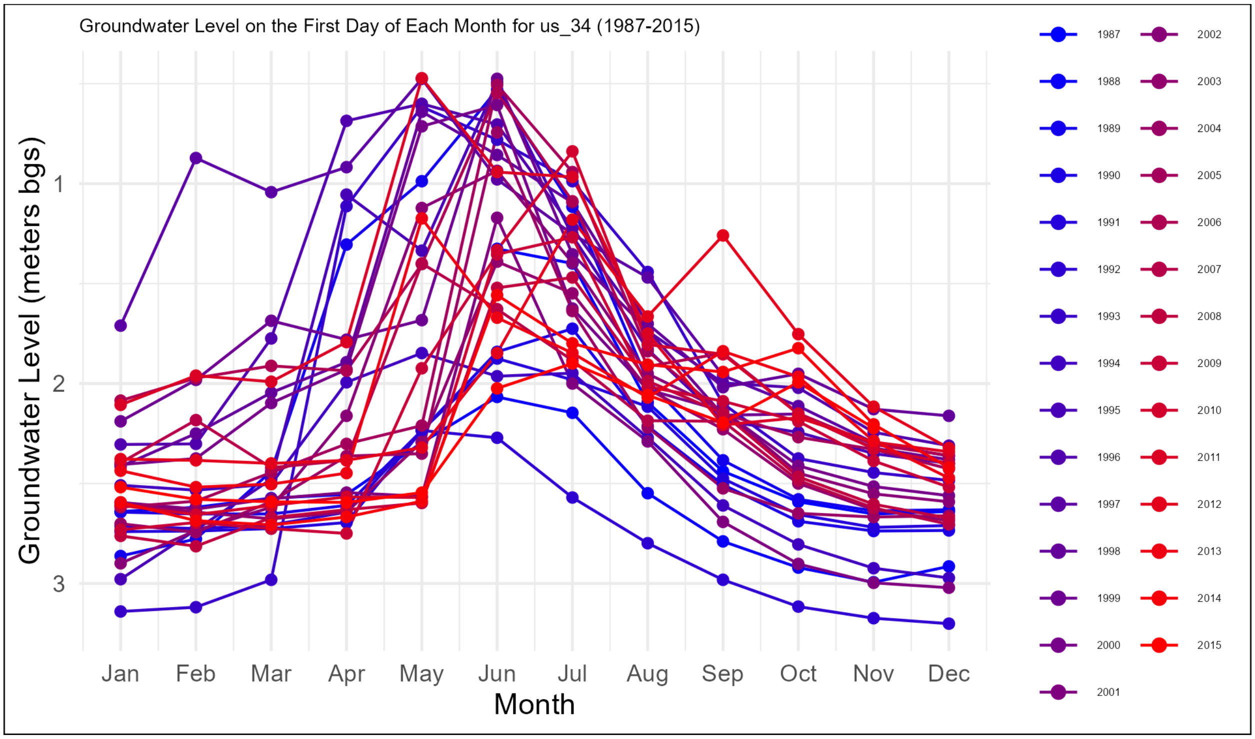


Figure 15: *Scatter plot for a well in the United States (ID: US_34) with groundwater level in meters below ground. Each circle is a groundwater level during the specific month and the blue colours are older years and red are recent years.*

Chapter 4: Discussion

4.1 Factors influencing groundwater level trends.

In our investigation, we delved into the factors that could potentially influence the magnitude and direction of mountain groundwater level trends. We used Kruskal-Wallis tests, correlation coefficient analyses, and box plots to investigate the influence of hydrologic regime, aquifer type, and well depth.

4.1.1 Groundwater level trends against hydrologic regime

Our analysis revealed the presence of three distinct hydrograph types—snow-dominated, rain-dominated, and high-temperature rain-dominated—across Canada and the United States. The seasonal hydrograph patterns observed in snow-dominated and rain-dominated groundwater wells are consistent with previous research conducted by Allen et al. (2014) from 1976 to 1999, which identified similar seasonal hydrograph patterns for snow-dominated and rain-dominated regions, respectively. This consistency highlights that the temperature range we selected for hydrograph classification serves as a suitable parameter for categorizing our dataset.

The spatial distribution of the three hydrograph classifications provides valuable insights into the geographic variability of groundwater dynamics. Snow-dominated wells tend to cluster around the Canadian Rocky Mountains and the northern Appalachian ranges, reflecting the influence of snowmelt and seasonal snow accumulation on groundwater recharge in these regions. Conversely, rain-dominated wells are predominantly concentrated along the Coast Mountains and central Appalachians. These findings are consistent with Allen et al. (2014) where the Vancouver Island wells were observed to be rain-dominated regimes. The high-temperature rain-dominated wells, are situated along the south and southwest areas of the United States, extending into subtropical regions characterized by warmer temperatures. For example, the average annual temperature that was reported in Arizona is 68°F (18.3°C), and it is characterized as an arid to semiarid climate. The average annual rainfall exceeds the average annual snowfall rate, with fluctuating periods of precipitation during a summer monsoon period and a winter frontal storm period (Pool D.R. et al., 2010). Thus, due to the differences in the climatic conditions between the rain-dominated and high-temperature rain-dominated hydrological regime, this can lead to the difference in the hydrography shape between the hydrological regime as seen in Figure 6 and 7.

Our results indicated an insignificant difference (p=0.1687) in terms of how the snow-dominated, rain-dominated, and high-temperature rain-dominated mountain groundwater systems have changed over the recent decades. This suggests that the dominant type of precipitation phase does not exert a significant influence on groundwater behaviour within our dataset. Although insignificant, the boxplot revealed that high-temperature wells exhibited less positive and more negative groundwater level changes, particularly evident across mountainous regions of the United States, where most of the high-temperature rain-dominated wells are located. However, we observed that in some of the wells, there were an intro-annual change in groundwater levels and an overall change in the seasonal patterns of groundwater level recharge (Figures 14 and 15).

Furthermore, the difference between snow- and rain-dominated wells was also insignificant (0.3406), further supporting the conclusion of non-significant differences between these categories. The median trend values for both snow- and rain-dominated wells were nearly identical (Figure 10). However, a noteworthy observation emerged from the boxplot comparison—rain-dominated wells exhibited more negative groundwater level trends, indicative of a decrease in groundwater recharge over time.

Our results conflict with some previous studies which suggest less snow will result in less groundwater recharge. A modelling study conducted by Sultana and Coulibaly

(2011) emphasized how reduced snow storage also results in reduced yearly groundwater recharge, even when total annual precipitation rises. Given that the infiltration capacity varies with rainfall intensity, this may be connected to the variations in the length and intensity of precipitation events (Fu et al., 2019).

A study conducted between two-year periods suggested that more recent years saw prolonged periods of rain-related rising hydraulic heads in the winter and dropping hydraulic heads linked to high evapotranspiration in the spring. As a result, the main recharge process is transitioning from spring snowmelt to winter rain. Moreover, shorter snowmelt periods and longer periods of high evapotranspiration rates are known to cause fluctuation in the hydrologic head. Thus, the change is driven by higher temperature and not the precipitation changes (Nygren et al., 2020).

Overall, Samways (2023) indicated that there is a general negative trend in groundwater level trends across Canadian and US mountain regions. However, the dominant type of precipitation that recharges the groundwater level does not play a role in the trends of groundwater levels. Thus, the insignificance between precipitation type and groundwater trends could be attributed to the varying infiltration process of groundwater recharge, snowmelt periods, and the external factors such as evapotranspiration rates which were not considered in our study.

4.2.1 Groundwater level trends against the aquifer type

Our results revealed a statistically significant difference (p = 0. 0182) in groundwater trends among the three aquifer types—confined, unconfined, and mixed—indicating that aquifer type indeed plays a role in how mountain groundwater systems are changing. The median trend for confined aquifers was slightly negative, unconfined was near zero and mixed was positive. The mixed aquifer type also had a larger interquartile range than the other types, indicating more variability.

The reasons behind the differing aquifer-type response to climatic change are not obvious. However, two possibilities include (1) relation to the signal-to-noise ratio of long-term trends versus shorter-term fluctuations. As the confined aquifers are less connected to the surface, the short-term fluctuations in recharge may not be detected, however, over longer time frames, the fluctuations could be more prominent, and thus, the negative groundwater level trends can be detected over time. As the unconfined aquifer is closer to the surface, the groundwater level will undergo more rapid fluctuations in response to recharge (a noisier hydrograph) in which the overall change of groundwater level trend over time would not be significantly detected. Alternatively (2), a small change in recharge/discharge may result in a larger change in hydraulic head in a confined aquifer compared to an unconfined aquifer given their differing storage capacities (Dingman, 2015).

Furthermore, one would expect the mixed-type aquifer to fall somewhere between the confined and unconfined types, which was not the case in our results. This may suggest that the mixed aquifer type exhibits unique groundwater dynamics compared to the confined and unconfined aquifer type. However, it could also be influenced by potentially inconsistent definitions of mixed aquifer types across jurisdictions.

Aquifer type generally serves as an additional control factor that can influence the groundwater level trend, in addition to the other climatic, anthropogenic, and physiographic settings that were identified by Samways (2023).

4.2.2 Groundwater level trends against the well depth

The Spearman correlation coefficient indicates a weak negative correlation ($\rho = -0.01089$) between groundwater level trend and well depth which is not statistically significant. Therefore, well depth does not influence the observed groundwater level trends. However, the scatter plot in Figure 13 reveals a pattern whereby shallower wells exhibit less variability in groundwater level trend, and deeper wells display a more dispersed range of both positive and negative trends associated with good depth.

This observed relationship, although weak, may have a similar explanation to the difference between confined and unconfined aquifers since shallower wells are more likely to be unconfined. Shallow wells, being closer to the surface, are more susceptible to short-term fluctuations in precipitation and sensitive to temperature rise (Hare et al., 2021). As a result, we often observe oscillations in groundwater levels, with shallower wells reflecting these changes more prominently. Conversely, discharge from deeper groundwater sources is more seasonally stable, and in comparison, to shallower wells, deeper wells often have deeper water levels (Burns et al., 1998; Hare et al., 2021). The slower movement of groundwater within deeper aquifers contributes to this phenomenon, with recharge processes occurring over longer timeframes. Consequently, we observe a greater consistency in groundwater level trends among deeper wells, as they are less susceptible to immediate fluctuations in surface conditions. However, these results contrast previous studies which indicate that shallower wells will be more sensitive to changes in groundwater recharge due to their proximity to the surface (Benz et al. 2017, Kløve et al. 2014).

This depth-dependent variability in groundwater level recharge underscores the importance of considering temporal and spatial scales in hydrogeological analyses. Shallow wells may provide valuable insights into short-term fluctuations and local hydrological dynamics, while deeper wells offer a broader perspective on long-term trends and aquifer behaviour. By incorporating data from wells of varying depths, researchers can obtain a more comprehensive understanding of groundwater dynamics and improve predictive models for water resource management and conservation efforts.

4.3 Limitations of the study

In discussing the limitations of our study, it is important to address several key factors that may have influenced our findings. Firstly, our choice of temporal range in categorizing the hydrologic regime, spanning from 2015 to 2020, excluded a substantial portion (22%) of our dataset which includes several wells with colder annual air temperature and warmer annual temperature. This exclusion may have led to a reduction in statistical power as our sample size was reduced for certain areas, like the colder regions.

Secondly, the lack of available data on aquifer types for some of the wells in our dataset poses a significant limitation. Specifically, the definition of mixed aquifer type in varying literature and our assumption of aquifer type for wells in British Columbia and Manitoba. This limitation underscores the importance of comprehensive data collection and documentation in hydrogeological studies since consistent definition and data collection will allow researchers to reduce biases in data collection.

Thirdly, a limitation in the spatial distribution of observation wells within mountainous regions. Despite efforts to include a representative sample of wells across varied terrain, we encountered challenges in obtaining data from mountainous settings at higher slopes, elevations, and in glacierized environments. This lack of observation wells in such challenging environments may have introduced biases in our analysis, as groundwater dynamics within those mountain regions could differ considerably from our snow-dominated hydrograph regimes.

In addressing these limitations, future research endeavors should prioritize expanding the temporal and spatial scope of observation wells, particularly in rugged mountainous environments. Additionally, efforts to improve data availability and documentation, particularly regarding aquifer characteristics, will enhance the robustness and reliability of future hydrogeological analyses. By addressing these limitations, research can advance our understanding of groundwater dynamics and put measures on more effective water resource management.

Chapter 5: Conclusion

5.1 Summary

This study has suggested some of the factors that could potentially affect the long-term groundwater levels across mountain regions in Canada and the United States. Generally, the non-significance of the precipitation phase on the groundwater level trend indicates that the shift towards more rain and less snow as a consequence of climate change does not have a prominent effect on the groundwater recharge magnitude.

This research has presented some external variables that could influence the groundwater level trends in mountain regions such as aquifer type and well depth. The overall dataset indicated a statistically significant result with the aquifer type, confined showing a high proportion of negative groundwater level trends while the mixed aquifer type indicated a more positive groundwater level trend. Additionally, the relationship between well depth and the groundwater level trends revealed a non-statistically significant correlation result, which indicated that well depth does not correspond with the negative or positive groundwater recharge over time. Given the consequence of changing climate, it is important to understand the changing mechanisms in groundwater recharge and storage in mountain regions and its contribution to the downstream water resources.

5.2 Future research

An important area of focus should be the installation of observational wells in a wider variety of mountainous environments in the future and providing an ongoing high-quality and long-term data collection from the various well sites. Additionally, more observational wells could be in colder climatic regions such as Alaska and the Yukon as there aren't many long-term public observation wells and these areas could provide us more insights into the cold climatic hydrological regimes.

Moreover, more detailed and consistent observations of geological characteristics should be considered as this will provide a consistent definition of the aquifer types, specifically the mixed aquifers. This will aid in understanding how and if various confining layers influence the groundwater recharge on a broader scale.

Generally, this research will provide important insights into how various factors can influence our groundwater systems and thus ensure that we can manage our groundwater more sustainably against the potential effects of our changing climate.

References

Ajami, H., Meixner, T., Dominguez, F., Hogan, J., & Maddock, T. (2012). Seasonalizing mountain system recharge in semi-arid basins – climate change impacts. *Groundwater, 50*(4), 585–597.

Allen, D. M., Stahl, K., Whitfield, P. H., & Moore, R. D. (2014). Trends in groundwater levels in British Columbia. *Canadian Water Resources Journal, 39*(1), 15–31. Alley, W. M., Healy, R. W., LeBaugh, J. W., & Reilly, T. E. (2002). Flow and storage in groundwater systems. *Science, 296*(5575), 1985-1990.

Allen, D. M., Whitfield, P. H., & Werner, A. T. (2010). Groundwater level responses in temperate mountainous terrain: regime classification, and linkages to climate and streamflow. *Hydrological Processes*, *24*(23), 3392–3412. https://doi.org/10.1002/hyp.7757

Alley, W. M., Healy, R. W., LeBaugh, J. W., & Reilly, T. E. (2002). Flow and storage in groundwater systems. *Science, 296*(5575), 1985-1990.

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). https://doi.org/10.1029/2005wr004387

Barackman, M. L., & Brusseau, M. L. (2002). GROUNDWATER SAMPLING. In *Elsevier eBooks* (pp. 121–139). https://doi.org/10.1016/b978-012064477-3/50010-2

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066), 303–309. https://doi.org/10.1038/nature04141

Benz, S. A., Bayer, P., & Blum, P. (2017). Global patterns of shallow groundwater temperatures. *Environmental Research Letters*, *12*(3), 034005. https://doi.org/10.1088/1748-9326/aa5fb0

Bresciani, É., Cranswick, R. H., Banks, E., Batlle-Aguilar, J., Cook, P. G., & Batelaan, O. (2018). Using hydraulic head, chloride and electrical conductivity data to distinguish between mountain-front and mountain-block recharge to basin aquifers. *Hydrology and Earth System Sciences*, *22*(2), 1629–1648. https://doi.org/10.5194/hess-22-1629-2018

Burns, D. A., Murdoch, P. S., Lawrence, G. B., & Michel, R. L. (1998). Effect of groundwater springs on NO3− concentrations during summer in Catskill Mountain streams. *Water Resources Research*, *34*(8), 1987–1996. https://doi.org/10.1029/98wr01282

Chen, Z., Hartmann, A., Wagener, T., & Goldscheider, N. (2018). Dynamics of water fluxes and storages in an Alpine karst catchment under current and potential future climate conditions. *Hydrology and Earth System Sciences, 22*(7), 3807–3823.

Cochand, F., Therrien, R., & Lemieux, J. (2018). Integrated hydrological modeling of climate change impacts in a Snow-Influenced catchment. *Groundwater*, *57*(1), 3–20. https://doi.org/10.1111/gwat.12848

Cochand, M., Christe, P., Ornstein, P., & Hunkeler, D. (2019). Groundwater storage in high alpine catchments and its contribution to streamflow. *Water Resources Research*, *55*(4), 2613–2630. https://doi.org/10.1029/2018wr022989

Condon, L. E., Atchley, A. L., & Maxwell, R. M. (2020). Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nature communications, 11*(1), 873.

De Vries, J., & Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal, 10(1), 5–17. https://doi.org/10.1007/s10040-001-0171-7

Dingman, S. L. (2015). *Physical Hydrology: Third Edition*. Waveland Press.

Esri Inc. (2024). ArcGIS Pro (Version 2.6.2). Esri Inc. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Fick, S.E., & Hijmans, R. J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology, 37*(12): 4302-4315.

Fort, M. (2015). Impact of climate change on mountain environment dynamics. Journal of Alpine Research | Revue De Géographie Alpine, 103–2. https://doi.org/10.4000/rga.2877

Fu, G., Crosbie, R., Barron, O., Charles, S. P., Dawes, W., Shi, X., Van Niel, T., & Li, C. (2019). Attributing variations of temporal and spatial groundwater recharge: A statistical analysis of climatic and non-climatic factors. *Journal of Hydrology*, *568*, 816–834. https://doi.org/10.1016/j.jhydrol.2018.11.022

Goulden, M. L., & Bales, R. C. (2014). Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. Proceedings of the National Academy of Sciences of the United States of America, 111(39), 14071–14075. https://doi.org/10.1073/pnas.1319316111 groundwater systems. Science, 296(5575), 1985-1990.

Government of Alberta. (2022). GOWN. Retrieved from http://environment.alberta.ca/apps/GOWN/

Government of Yukon. (2022). Yukon Observation Well Network. Water Resources Branch.

Grolemund, G. & Wickham, H. (2011). Dates and times made easy with lubridate. Journal of Statistical Software, 40(3), 1-25. URL http://www.jstatsoft.org/v40/i03/

Haidu, I., & Nistor, M. (2020). Long-term effect of climate change on groundwater recharge in the Grand Est region of France. *Meteorological Applications, 27*(1).

Halloran, L. J. S., Millwater, J., Hunkeler, D., & Arnoux, M. (2023). Climate change impacts on groundwater discharge-dependent streamflow in an alpine headwater catchment. *Science of the Total Environment*, *902*, 166009. https://doi.org/10.1016/j.scitotenv.2023.166009

Hammond, J. C., Harpold, A. A., Weiss, S., & Kampf, S. K. (2019). Partitioning snowmelt and rainfall in the critical zone: effects of climate type and soil properties. *Hydrology and Earth System Sciences*, *23*(9), 3553–3570. https://doi.org/10.5194/hess-23-3553-2019

Hare, D. K., Helton, A. M., Johnson, Z. C., Lane, J. W., & Briggs, M. A. (2021). Continental-scale analysis of shallow and deep groundwater contributions to streams. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-21651-0

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data, 7*, 109.

Hartmann, A. (2022). The hydrology of groundwater systems - from recharge to discharge. In Elsevier eBooks (pp. 324–330). https://doi.org/10.1016/b978-0-12-819166-8.00097-9

Hayashi, M. (2019). Alpine Hydrogeology: The critical role of groundwater in sourcing the headwaters of the world. *Groundwater*, *58*(4), 498–510. https://doi.org/10.1111/gwat.12965

Hayashi, M. (2019). Alpine Hydrogeology: The critical role of groundwater in sourcing the headwaters of the world. *Groundwater*, *58*(4), 498–510. https://doi.org/10.1111/gwat.12965

Hayashi, M. (2020). Alpine hydrogeology: the critical role of groundwater in sourcing the headwaters of the world. *Groundwater, 58*(4), 498–510.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, S., Molau, U., Morin, S., Orlove, B., & Steltzer, H. (2019). High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson- Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

Hughes, A., Mansour, M., Ward, R., Kieboom, N., Allen, S., Seccombe, D., Charlton, M., & Prudhomme, C. (2021). The impact of climate change on groundwater recharge: National-scale assessment for the British mainland. Journal of Hydrology, 598, 126336. https://doi.org/10.1016/j.jhydrol.2021.126336

HYDATA. (2022). Province of Manitoba, Groundwater Management.

Immerzeel, W. W., Lutz, A., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S. B., Brumby, S. P., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U. K., Kargel, J. S., Koppes, M., Kraaijenbrink, P., Kulkarni, A. V., Mayewski, P. A., . . . Baillie, J. (2019). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Käser, D., & Hunkeler, D. (2016). Contribution of alluvial groundwater to the outflow of mountainous catchments. Water Resources Research, 52(2), 680–697. https://doi.org/10.1002/2014wr016730

Klöve, B., Ala-aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., Rossi, P. M., Uvo, C. B., Velasco, E. M. L., & Pulido-Velázquez, M. (2014). Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology*, *518*, 250–266. https://doi.org/10.1016/j.jhydrol.2013.06.037

Kløve, B., Ala-aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., Rossi, P. M., Uvo, C. B., Velasco, E. M. L., & Pulido-Velázquez, M. (2014). Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology (Amsterdam)*, *518*, 250–266. https://doi.org/10.1016/j.jhydrol.2013.06.037

Knight, J. (2022). Scientists' warning of the impacts of climate change on mountains. *PeerJ*, *10*, e14253. https://doi.org/10.7717/peerj.14253

Knight, J., & Harrison, S. (2023). The sensitivity and evolutionary trajectory of the mountain cryosphere: Implications for mountain geomorphic systems and hazards. Land Degradation & Development, 34(9), 2464–2482. https://doi.org/10.1002/ldr.4630

Kreye, R., Ronneseth K., and Wei, M., 1994. An Aquifer Classification System for Ground Water Management in British Columbia. In Proceedings, 6th National Drinking Water Conference, Victoria, B.C

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*, 997-1014.

Manning, A. H., Clark, J. F., Diaz, S. H., Rademacher, L. K., Earman, S., & Plummer, L. N. (2012). Evolution of groundwater age in a mountain watershed over a period of thirteen years. *Journal of Hydrology*, 460, 13–28. doi:10.1016/j.jhydrol.2012.06.030

Manning, A. H., Solomon, D. K., & Thiros, S. A. (2005). $^3H/^3He$ age data in assessing the susceptibility of wells to contamination. *Groundwater*, *43*(3), 353–367. https://doi.org/10.1111/j.1745-6584.2005.0028.x

Markovich, K. H., Manning, A. H., Condon, L. E., & McIntosh, J. C. (2019). Mountain-block recharge: A review of current understanding. *Water Resources Research, 55*, 8278–8304. https://doi.org/10.1029/2019wr025676

Martínez-Cob, A. (1996). Multivariate geostatistical analysis of evapotranspiration and precipitation in mountainous terrain. *Journal of Hydrology, 174*(1-2), 19-35.

McGlynn, B. L., McDonnel, J. J., & Brammer, D. D. (2002). A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. Journal of Hydrology, 257, 1–4), 1–26. https://doi.org/10.1016/S0022-1694(01)00559-5

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society, 86*(1), 39-50.

Neidhardt, H., & Shao, W. (2023). Impact of climate change-induced warming on groundwater temperatures and quality. *Applied Water Science*, *13*(12). https://doi.org/10.1007/s13201-023-02039-5

Nistor, M. (2020). Groundwater vulnerability in the Piedmont region under climate change. *Atmosphere, 11*(8), 779.

Nygren, M., Giese, M., Kløve, B., Haaf, E., Rossi, P. M., & Barthel, R. (2020). Changes in seasonality of groundwater level fluctuations in a temperate-cold climate transition zone. *Journal of Hydrology. X*, *8*, 100062. https://doi.org/10.1016/j.hydroa.2020.100062

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science, 313*(5790), 1068-1072.

Ombadi, M., Risser, M. D., Rhoades, A. M., & Varadharajan, C. (2023). A warming-induced reduction in snow fraction amplifies rainfall extremes. *Nature*, *619*(7969), 305–310. https://doi.org/10.1038/s41586-023-06092-7

Pepin, N. C., & Lundquist, J. D. (2008). Temperature trends at high elevations: Patterns across the globe. Geophysical Research Letters, 35(14), L14701. https://doi.org/10.1029/2008GL034026

Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hasmi, M. Z., Liu, X. D., Miller, J. R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöner, W., Severskiy, I., Shahgedanova, M., Wang, M. B., Williamson, S. N., & Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. *Nature Climate Change, 5(*5), 424–430.

Pisani, B., Samper, J., & Marques, J. E. (2019). Climate change impact on groundwater resources of a hard rock mountain region (Serra da Estrela, Central Portugal). *Sustainable Water Resources Management, 5*(1), 289–304.

Poeter, E. (2020, August 21). *6.3 Groundwater in permafrost settings*. Pressbooks. https://books.gw-project.org/groundwater-in-our-water-cycle/chapter/groundwater-in-permafrost-settings/

Pool, D.R., Blasch, K.W., Callegary, J.B., Leake, S.A., and Graser, L.F., 2011, Regional groundwater-flow model of the Redwall-Muav, Coconino, and alluvial basin aquifer systems of northern and central Arizona: U.S. Geological Survey Scientific Investigations Report 2010-5180, v. 1.1, 101 p.

Province of British Columbia. (2022). PGOWN. Retrieved from https://www2.gov.bc.ca/gov/content?id=B03D0994BB5C4F98B6F7D4FD8610C836

R Core Team. (2024). R: A language and environment for statistical computing. R 73 Foundation for Statistical Computing, Vienna, Austria. https://www.R-project. org/.

Räisänen, J. (2023). Changes in March mean snow water equivalent since the mid-20th century and the contributing factors in reanalyses and CMIP6 climate models. *The Cryosphere*, *17*(5), 1913–1934. https://doi.org/10.5194/tc-17-1913-2023

Rhoades, A. M., Ullrich, P. A., & Zarzycki, C. M. (2017). Projecting 21st century snowpack trends in western USA mountains using variable-resolution CESM. *Climate Dynamics*, *50*(1–2), 261–288. https://doi.org/10.1007/s00382-017-3606-0

Rhoujjati, N., Brahim, Y. A., Hanich, L., Rhoujjati, A., Rafik, A., Ouatiki, H., Chehbouni, A., & Bouchaou, L. (2023). Snowpack and groundwater recharge in the Atlas mountains: New evidence and key drivers. *Journal of Hydrology: Regional Studies*, *49*, 101520. https://doi.org/10.1016/j.ejrh.2023.101520

Samways, J. R., (2023). LONG-TERM TRENDS IN MOUNTAIN GROUNDWATER LEVELS IN CANADA AND THE UNITED STATES

Scherrer, S. C., Ceppi, P., Croci-Maspoli, M., & Appenzeller, C. (2012). Snow-albedo feedback and Swiss spring temperature trends. Theoretical and Applied Climatology, 110(4), 509–516. https://doi.org/10.1007/s00704-012-0712-0

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., Nico, P. S., Feldman, D. R., Jones, A. D., Collins, W. D., & Kaatz, L. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Somers, L. D., & McKenzie, J. M. (2020). A review of groundwater in high mountain environments. *WIREs Water, 7*(6).

Somers, L. D., McKenzie, J. M., Mark, B. G., Lagos, P., Ng, G. C., Wickert, A. D., Yarleque, C., Baraër, M., & Silva, Y. (2019). Groundwater buffers decreasing glacier melt in an Andean Watershed—but not forever. *Geophysical Research Letters, 46*(22), 13016–13026.

Sultana, Z., & Coulibaly, P. (2010). Distributed modelling of future changes in hydrological processes of Spencer Creek watershed. *Hydrological Processes*, *25*(8), 1254–1270. https://doi.org/10.1002/hyp.7891

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 & technology, 41*(21), 7424-7429.

Tillman, F. D., & Leake, S. A. (2010). Trends in groundwater levels in wells in the active management areas of Arizona, USA. *Hydrogeology Journal, 18*, 1515-1524.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1), 123–138. https://doi.org/10.3354/cr00953

U.S. Geological Survey. (2022). National Water Information System data available on the World Wide Web, accessed October 11, 2022, from https://waterdata.usgs.gov/nwis/gw

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., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., & Woods, R. (2011). Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences, 15*(2), 471–504.

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).

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, *3*(11), 917–928. https://doi.org/10.1038/s41893-020-0559-9

Wang, H., Xiang, L., Steffen, H., Wu, P., Jiang, L., Shen, Q., Li, Z., & Hayashi, M. (2022). GRACE-based estimates of groundwater variations over North America from 2002 to 2017. *Geodesy and Geodynamics, 13*(1), 11-23.

Weiler, M., McDonnell, J. J., Tromp-van Meerveld, I., & Uchida, T. (2005). Subsurface stormflow. Encyclopedia of Hydrological Sciences, 1–14. Hoboken, NJ: John Wiley & Sons. https://doi.org/10.1002/0470848944.hsa119

Wickham, H., François, R., Henry, L., & Müller, K. (2020). dplyr: A Grammar of Data Manipulation. R package version 1.0.2. https://CRAN.R-project.org/package=dplyr

Zeileis, A. & Grothendieck, G. (2005). zoo: S3 Infrastructure for Regular and Irregular Time Series. *Journal of Statistical Software, 14*(6), 1-27. doi:10.18637/jss.v014.i06

Zhu, S., Ptak, M., Choiński, A., & Wu, S. (2020). Exploring and quantifying the impact of climate change on surface water temperature of a high mountain lake in Central Europe. *Environmental monitoring and assessment, 192*, 1-11