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Impacts of Forest Management and Timber Harvest Practices on Karst Critical Zone Processes in Tongass National Forest, Alaska

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IMPACTS OF FOREST MANAGEMENT AND TIMBER HARVESTING PRACTICES ON KARST CRITICAL ZONE PROCESSES IN TONGASS NATIONAL FOREST, ALASKA

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By
Anna Gwendolyn Harris

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IMPACTS OF FOREST MANAGEMENT AND TIMBER HARVESTING PRACTICES ON KARST CRITICAL ZONE PROCESSES IN TONGASS NATIONAL FOREST, ALASKA

Date Recommended 10/9/2020

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To women in science.

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Directed by: Patricia Kambesis, Jason Polk, Xingang Fan, and James Baichtal

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This study characterizes the throughfall, hydrogeochemistry, dissolution rates, and carbon sources of two proximate temperate rainforest cave systems within the Tongass National Forest in Southeast Alaska (Tongass). Study sites include: an old-growth forest, characterized by having never been logged (containing Walkabout Cave system); and a previously logged – within thirty years, second-growth forest (containing Zina Cave system). Precipitation data were recorded over a five-month period at 10-minute intervals, to understand the effects of throughfall between the altering old and second-growth canopies. At each major spring for the two cave systems, high-resolution data were collected from June 29 through November 21, 2019. The following parameters were measured: water level, pH, temperature, and specific conductivity (SpC), at 10-minute intervals. Grab samples for cations (Ca^{2+} and Mg^{2+}) and alkalinity (HCO_3^-) were collected to statistically develop a relationship with geochemical parameters and calculate dissolution rates within each cave system at high-resolution. Limestone wafers were deployed in each cave system and both old and second-growth forests to confirm high-resolution dissolution rates. Carbon isotopes were sampled to provide carbon sourcing data related to seasonal and vegetation changes between the different cave systems.

These data show the impacts of land management practices, specifically timber harvest, on the physical characteristics of the study area cave systems. Given the societal

and scientific value of the study area, the scarcity of karst research in the Pacific Northwest, and the co-sponsorship of the US Forest Service, this study is a valuable contribution to a growing body of data with relevant practical applications. The Tongass is home to a dynamic and vulnerable karst ecosystem, characteristic of earth's Critical Zone (CZ), where solar energy, precipitation, and tree canopy interact with biota and rock mass to create processes and contribute to the hydrologic cycle.

Karst in the Tongass is distinct, supporting significant micro and macro regional ecosystems, including pristine well-developed old-growth forest, prodigious salmon streams, and muskeg peat. This critical ecosystem's existence is governed by the nexus of timber harvesting, climate change, and US Forest Service land management practices. While anthropogenic impacts on karst terrains are well-studied, few studies have been conducted regarding the implications of deforestation on karst, and the impact of these practices on the speleogenesis of karst systems, specifically on heavily managed landscapes in a high-latitude, remote, temperate rainforest.

Chapter One: Introduction

Globally, intact temperate rainforest over karst areas is rare, with one quarter of what remains found in the Pacific Northwest in the regions of British Columbia and Southeast Alaska (Grierson 2018). These karst areas in the Pacific Northwest are most comparable to those of karst lands found on Vancouver Island and the Queen Charlotte Islands of British Columbia, Canada, as well as portions of Patagonia (Chile), Tasmania, and the west coast New Zealand's South Island. Logging has forever changed much of these karst areas to their detriment, which is especially apparent in Southeast Alaska. When Harding and Ford (1993) studied a 1907 clearcut over karst on Vancouver Island, nearly a century later it had not recovered, concluding that soil and biodiversity were lost (Harding and Ford 1993). It is no coincidence that out of the total logged land, 66% of forest on karst has been harvested, whereas only 34% on non-karst has been harvested. Well drained, karstified areas, with nutrient rich soil atop bedrock, create a prime environment for large growth forest (Baichtal and Swanson 1996). Timber harvest on karst creates problems both on and below the surface, redistributing soil, changing flow rates, deoxygenating the water, and starving aquatic organisms. Karst is the underlying system that supports the riches of the Tongass: a large growth forest, abundant wildlife, healthy fisheries, and paleontological significance (Baichtal and Swanston 1996).

Karst landscapes exhibit complex hydrology with seasonal factors that are affected by land management practices that affect the nature and very existence of their heterogeneous complex systems. It is necessary to better understand the impact of human activities on karst to define measures for its protection. Previous and current knowledge of land practices is crucial for assessing potential negative impacts on karst systems, particularly timber harvest within the Tongass National Forest. Historically, land management practices failed to consider the interconnectedness of karst and forest; the nutrient rich soils, dense forest canopy, well-developed drainage, and dissected bedrock surfaces that allow tree roots to become wind firm, thereby supporting a healthy temperate rainforest (Baichtal and Swanston 1996).

While human impacts on karst terrains are a well-documented area in karst science, few studies have been conducted regarding the impact of deforestation on karst, specifically in a temperate rainforest. The primary goal of this research is to understand how previous timber harvests and land management practices have impacted karst watersheds through an examination of the hydrogeochemistry and canopy variation of two karst watersheds within the Twin Peaks Mountain Watershed in Staney Creek on Prince of Wales Island (POW) in Southeast Alaska. This study serves as baseline knowledge for other watersheds within coastal karst, temperate rainforest settings as well as a guide to better management practices in karst areas. This research answers the following questions:

- What are the differences in the geochemical response to precipitation events between cave resurgences in old-growth forest and second-growth forest?
- How does hydrogeochemistry and dissolution compare in a previously logged, second-growth cave system and a pristine, old-growth cave system?
- What are the seasonal differences in geochemistry between old-growth and second-growth temperate rainforest cave systems?

Quantitative post-cut timber harvest data, and its measured impacts, can inform effective policy to determine suitable protection for vulnerable landscapes. High-resolution data provides further insight into the impact timber harvest has on forest regrowth, enhancing our understanding of the processes affected by human induced landscape degradation on karst development.

Chapter Two: Literature Review

2.1 Karst Overview

Karst topography can be found at all latitudes and elevations, with rock types containing karst covering approximately 20% of the Earth's land surface (Ford and Williams 2007). Karst terrain develops on soluble bedrock such as limestone, dolomite, marble, and gypsum; under some condition's karst can also form on quartzite. The landscape is characterized by sinking/losing streams, caves, enclosed depressions, and springs (Ford and Williams 2007). The structure of karst aquifers is characterized by a network of highly permeable conduits surrounded by low permeability rock (Doerflinger 1999).

In 1893, Jovan Cvijic laid the theoretical foundation for karst with the publication of "*Das karstphänomen: Versuch einer morphologischen monographie*" [The karst phenomenon: attempt of a morphological monograph], outlining the existence of karst watersheds as separate and unique systems from surrounding surface catchments (Ford and Williams 2007). The three-dimensional structure of a karst landscape can be broken down into three zones: exokarst, epikarst, and endokarst (Figure 2.1) (Pike et al. 2010, Williams 2008). The surficial limestone is defined as epikarst, or the subcutaneous zone, with fissures enlarged by corrosion (the exokarst) that extend down as much as 10 – 30 meters (m) below the surface to the underlying endokarst. The epikarst zone plays a critical role in the overall karst system, allowing water, air, and other materials such as sediment, organic debris, and nutrients to be readily transferred from the surface to the subsurface (Pike et al. 2010; Ford and Williams 2007). From the epikarst, water percolates through the vadose zone until it infiltrates the saturated or phreatic zone. The upper portion of the phreatic zone is the water table. The endokarst describes all deeper components of the underground karst landscape, including speleothems, cave sediments, small cavities, and cave passages (Ford and Williams 2007).

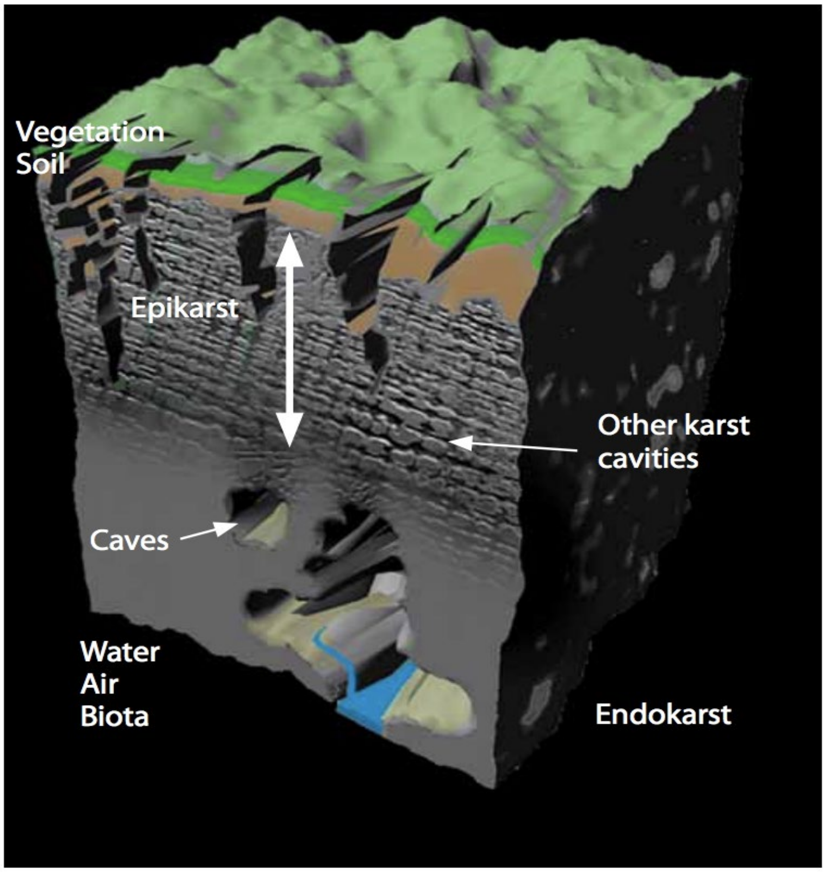


Figure 2.1: The linkage between epikarst and endokarst (Ford and Williams 2007).

Epikarst develops as rainwater mixed with carbon dioxide from air and soil dissolves soluble rocks at or near the surface. Epikarst development typically occurs within 10 m of surface. Cavities in the epikarst tend to be solutionally enlarged near the surface but decrease in size with increased depth. After heavy rains, rapid infiltration and vertical flow encounter resistance as these fissures taper with depth. This percolation should result in a bottleneck effect (Williams 1983). With high rates of precipitation and significant anthropogenic activity, the Tongass karst landscape provides an opportunity to document these changes through study of its hydrogeochemistry.

2.1.2 Temperate Rainforest Karst

Temperate rainforest karst environments exist in Southeast Alaska, USA; British Columbia, Canada; Patagonia, Chile; the South Island of New Zealand, and Tasmania, Australia (Gunn 2004). These areas receive large amounts of precipitation, with the Tongass National Forest in Southeast Alaska receiving a sustained annual precipitation between 1.5 and 6.4 m per year (Gunn 2004). Coastal karst ecosystems in the Pacific Northwest, are often characterized by “large mature trees, diverse plant and animal communities, highly productive aquatic systems, and well-developed subsurface drainage” with extensive underlying cave resources (Griffiths et al. 2005, 3).

These well drained, karstified areas create a prime environment for large growth forest. The western hemlock and Sitka spruce are especially adapted to these karst environments and thrive on the nutrient rich soil atop the bedrock. Additionally, the western hemlock and Sitka spruce can anchor their roots into cracks and fissures in the limestone, allowing them to be windfirm (Baichtal and Swanston 1996). Timber harvesting in karst environments can increase erosion and contribute to sedimentation of sinking streams, as documented on Vancouver Island, British Columbia, and Southeast Alaska, USA (Gunn 2004).

2.2 Tongass National Forest

The combination of high levels of precipitation and pure limestone make for a complex karst landscape in the Tongass (Stowell 2006). Ecologically, the area is unique, because it is one of the few remaining, intact, temperate rainforests, with some of the highest rates of limestone dissolution in the world (Allred 2004). The highly productive ecosystem has adapted to the specific characteristics of the underlying carbonate rocks of high purity and a groundwater system that promotes effective drainage (Gunn 2004). "These characteristics put them among the most dynamic karst terrains on earth, evolving and changing more rapidly and abruptly than karst in more moderate settings" (Bschor 2003, 316).

After a timber harvest, the forest does not regrow back to its previous condition. Old-growth forests are the mature, successional age of forest and generally considered pristine. Structural characteristics used to describe old-growth forests include live trees, number and minimum size of both seral and climax dominants; canopy conditions, commonly including multi-layering; snags, minimum number and specific size; and logs, large (coarse) woody debris (TLMP 2016). Old-growth trees are large, widely spaced, promote additional vegetation growth in the understory, and easy passage and nesting grounds for animals. By contrast, second-growth forests are "trees that cover an area after the removal of the original stand, as by cutting or fire", as defined by the Tongass National Forest Management Plan (TLMP 2016, 7-54). These second-growth forests receive little to no sunlight in the understory, resulting in dense, homogenous tree cover, making animal passage and habitat close to impossible.

Stands, especially large-growth, in low-elevation karst areas are particularly vulnerable to timber harvest due to easier accessibility. Compounding their vulnerability is local data regarding tree regeneration on karst landscapes which indicates few regeneration problems in these low elevation stands, ignoring overall landscape degradation of karst and decreased biodiversity nearly a century after harvest (Harding and Ford 1993). Conversely karst landscapes at higher elevations and steeper sites are characterized by shallower, excessively well-drained soils, smaller trees, and greater regeneration problems (Baichtal and Swanston 1996). Several factors may contribute to regeneration problems: shallow soils with low nutrient availability; excessive drainage of surface and soil waters into subsurface karst systems; removal of much of the shallow soil because of inadequate log suspension; and lastly, continued desiccation of the soil once the protective forest canopy is removed. After the canopy has been removed, high rainfall can rapidly transport soils into the well-developed epikarst (Baichtal and Swanston 1996).

2.2.1 Precipitation and Canopy Throughfall

High rainfall characterizes the Tongass which receives a sustained annual precipitation between 1.5 and 6.4 m per year (Gunn 2004). Precipitation is transferred from the land, soil, and vegetation back into the atmosphere as water vapor by transpiration and evaporation (Figure 2.2), known as evapotranspiration. When the natural vegetation density is disturbed on the surface of a karst system, the effects are seen in the water balance. In New Zealand’s Waitomo region, timber harvest resulted in an increase in runoff and sedimentation in karst systems due to the amount of water reaching the surface that was formerly lost through evapotranspiration processes (Urich 2002). Evapotranspiration can be calculated with the Penman Monteith (PM) equation, which is based on the combination of energy balance and aerodynamics (Howell 2004):

$$\lambda \mathrm{E} = \frac{[\triangle(\mathrm{Rn} - \mathrm{G})] + (\gamma\lambda\mathrm{Ea})}{(\triangle+\gamma)} \qquad \text{(Equation 2.1)}$$

As displayed above, λE is the evaporative latent heat flux, λ is the latent heat of only vaporization, and γ is the partial pressure of water in the air. R_n stands for net irradiance, G is the ground's heat flux, and E_a, and the net vapor transport flux (Howell 2004).

Precipitation, overstory canopy, and canopy conditions, affect throughfall amounts and are dependent upon forest conditions, including tree species, tree density, landscape, soil chemistry, and drainage. Forest canopies are the interconnection between the atmosphere and the biosphere and influence the nature and variability of ecosystems. Mature trees in old-growth forests are more widely distributed than younger trees in second-growth forests that account for the differences in canopy throughfall. Throughfall is the water that falls through the forest canopy contributing to the total water balance of the watershed. Interception rates were utilized to measure the degree to which past management activities, such as timber harvest and roading, influence canopy conditions and throughfall (Prussian 2011). Prussian monitored rainfall and throughfall during 51 storm events over four years to assess the importance of this process in the Tongass, describing the timing of rainfall interception during storms, evaluating its seasonal relevance to the water balance, and assessing potential implications for forest management.

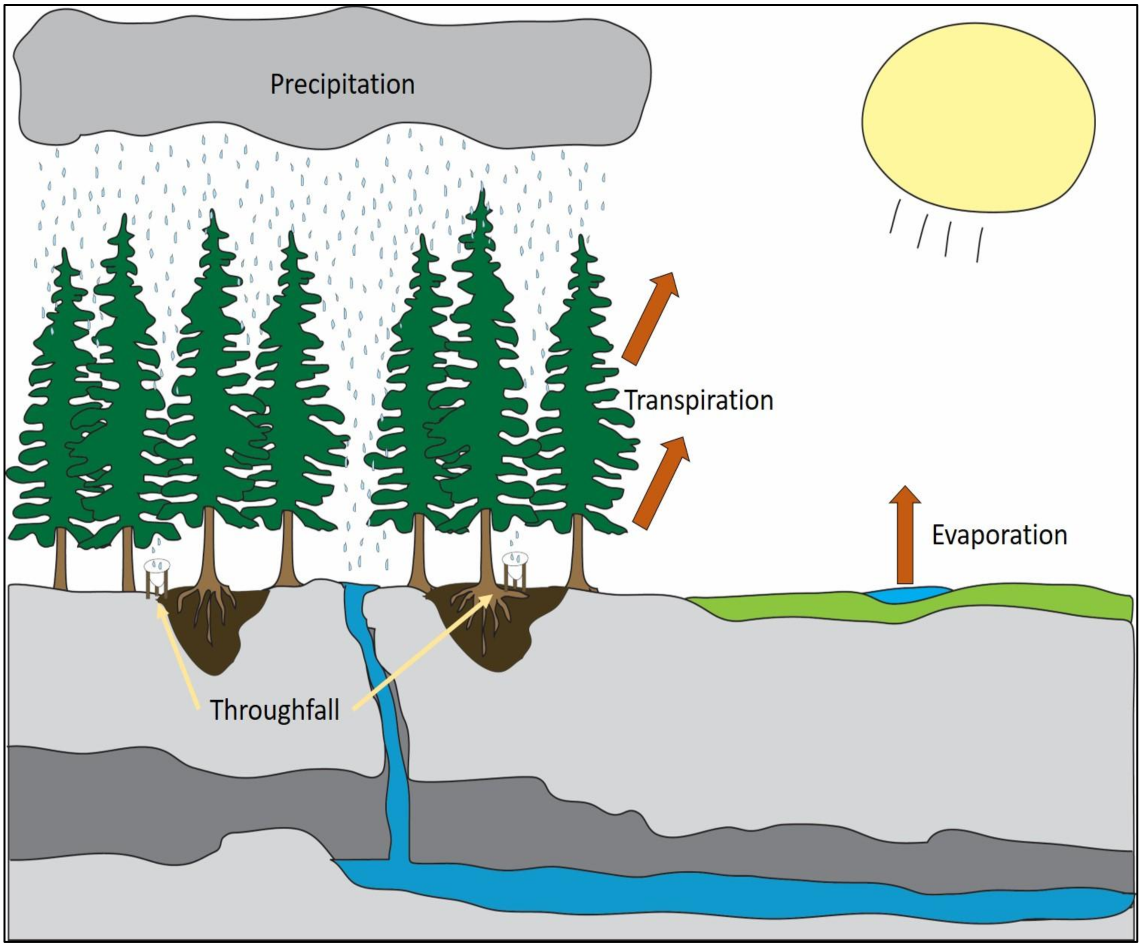


Figure 2.2: The fundamentals of throughfall and evapotranspiration.

2.3 Karst Hydrogeology and Geochemistry

Hydrogeology is the occurrence, distribution, movement, and geological interaction of water in the Earth's crust (Hiscock 2014). The challenges of pollution of surface water and groundwater, the impacts of over-exploitation of water resources, and climate change requires a holistic view of the aquatic landscape, including karst. Without adequate conservation, water resources are at risk for preservation (Di Maggio et al. 2012). In 2001, the US National Research Council recommended the urgency of focusing multidisciplinary studies on Earth's Critical Zone. The CZ is defined as the

> "heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources" (National Research Council 2001, 89).

The CZ is a complex system where solar energy, precipitation, and tree canopy interact with biota and rock mass to create ecosystem processes and contribute to the hydrologic cycle, such as in karst areas. Prior to the 2001, US National Research Council publication on the CZ, the scientific community noted considerable concern for high-latitude ecosystems with regard to climate change, with melting glaciers causing greater impacts on stream ecosystems at high latitudes. Further, the chemistry of waters in remote, high-latitude catchments, such as Southeast Alaska, have received minimal study in comparison to more accessible regions (Wissmar 1997).

Changes in karst waters caused by logging and storm events can be distinguished by multiple geochemical parameters. Temperature, pH, specific conductivity, and stage data are the most frequently analyzed. Carbonate dissolution processes are temperature dependent and thus temperature measurements are crucial. As water temperature increases and decreases, carbon dioxide (CO_2) reacts accordingly, and will dissolve quickly in cooler waters, this reaction will increase the partial pressure on CO_2 (pCO_2). By contrast, during temperature increases, CO_2 is released, resulting in pCO_2 decrease (White 1988a). Water temperature is generally higher in clearcut watersheds vs. forested. However, in the scheme of this study, it is likely that the second-growth forest will have cooler temperatures since limited light will make its way through the second-growth canopy vs. widely spaced old-growth.

The pH of water is the overall concentration and activity of its hydrogen ions (White 1988a; Palmer 2007). pH determines the acidity of water, which correlates to how aggressive it is during dissolution processes. The total amount of dissolved CO_2 will directly affect the pH reading. Water is more acidic [low pH] the higher the amount of dissolved CO_2. Other factors contribute to pH fluctuations such as seasonal changes in vegetation. When water moves through soil it reacts with CO_2, forming carbonic acid (H_2CO_3), which readily dissolves the limestone, making the water more acidic. This process is likely to increase during the spring and summer when vegetation is blooming. In addition, during the winter, pH numbers will be higher than the summer since microbial activity is lower, this translates to less CO_2 in the soil, thus smaller concentrations of H_2CO_3 (White 1988a; Palmer 2007).

Specific Conductivity (SpC) measures the concentration, charge, and movement of dissolved ions in water and is also referred to as the overall electrical conductance (Miller et al. 1988). Like dissolution, SpC is temperature dependent. As temperature increases, dissolution decreases. Colder water can hold on to more CO_2, therefore resulting in more acidic water with higher rates of dissolution (Miller et. al. 1988). A multitude of ions are concentrated in water, however, certain cations such as Ca^{2+} and Mg^{2+} are present in karst waters. These ions will increase in concentration during dissolution, serving as indicator ions in the relationship between SpC and dissolution.

Karst in the Tongass is distinct; it provides the foundation for micro and macro ecosystems in this region. As the epicenter of social, political, and ecological debate in the region for nearly a century, the Tongass contains cultural significance, valuable old-growth timber, abundant wildlife and fish, and mineral deposits (Shaw et al. 2000). Higher rates of Coho salmon productivity have been linked to alkali karst streams versus non-karst streams (Bryant et al. 1998). This complexity makes it important to educate stakeholders about the value of conservation as actions taking place above ground can have negative and irreversible consequences below. Sustainable management of karst, especially as a source of water, will be increasingly important in the future (De Waele 2011).

2.3.1 Carbon Isotopes

It is important to note the ranges of $\delta^{13}C$ that are present in the Earth's soil and atmosphere to better understand the context of $\delta^{13}C$ values from this research. Within soil, CO_2 ranges between -28 and -5‰ and $\delta^{13}C$ ranges in soil are altered by the interchange between CO_2 between the atmosphere and the upper portion of soil. In the atmosphere, CO_2 values are between -9‰ and -7‰, furthermore these values are affected by climate change processes and CO_2 exchange from the ocean (Zhang et al. 2015). Comparing these isotopic concentrations from known sources provides a better understanding of the origin of $\delta^{13}C$ values.

2.4 Groundwater Basins

Groundwater commonly refers to all underground water, although traditionally it only referred to water in the phreatic zone (Palmer 2009). The hydrological cycle can be thought of as a continuous circulation of water on earth, where no water is gained or lost and moves through five major pathways: precipitation, evaporation, runoff, water vapor transport, and water storage (White 1988b). A groundwater basin is defined as the catchment area of water that feeds a spring. Karst groundwater basins are challenging to delineate because the boundaries between drainage divides typically do not follow topographic divides. Delineation of groundwater basins is especially challenging in the Tongass given the topography and geologic structural deformation of the area.

Groundwater flow is three-dimensional so divides can overlap. Water from various elevations can discharge from the same spring and groundwater flow regimes can change quickly as flow rates change, either trickling or flowing rapidly over the topography (Palmer 2009). Karst groundwater drainage divides do not follow typical topographic drainage patterns, such as streams, as observed in non-karst areas. The United States Geological Survey (USGS) has divided the United States into successively smaller and smaller hydrologic units which are categorized into four levels as follows: regions, sub-regions, accounting units, and cataloging units. The units are given unique identifiers, Hydrologic Unit Codes (HUC), based on size from largest to smallest. These codes outline watersheds based on surface drainage and topography. However, karst watersheds do not follow the same characteristics of the basins defined by the USGS HUC which add to the complexity of watershed delineation in karsted areas (United States Department of the Interior 2018).

Recharge plays an important role in karst systems and contributes to fluctuations in the water table. There are two basic types of recharge in karst systems: autogenic and allogenic. Autogenic recharge is precipitation that makes direct contact with karst topography. Allogenic recharge is precipitation that falls on adjacent, insoluble bedrock surfaces accumulating as surface streams that eventually flow into karst features (Palmer 2009, Ford and Williams 2007). The water table in karst environments is not consistent and water levels vary greatly over relatively short time spans. Precipitation rapidly enters the system because of the increased permeability of karst environments. Rapid infiltration of rainfall causes the water table to rise quickly, resulting in large precipitations events called high flow flood events. During these events, karst groundwater can discharge from overflow springs that only activate during these flood events. By contrast, water drains slowly through conduits, cracks, and fissures in the soil during low flow events (Palmer 2009, Ford and Williams 2007).

According to Hiscock (2014), three aquifer characteristics determine whether groundwater resources will be sustainable: vulnerability to pollution under contaminant pressure from the land surface; susceptibility to irreversible degradation from excessive exploitation; and renewability from storage reserves under current and future climate regimes. These characteristics threaten fragile and complex karst systems with interdependencies. Karst watersheds are not as simple to map out as a topographic drainage basin.

2.4.1 Tongass National Forest Groundwater Basins

The majority of karst systems in the Tongass are hydrologically active and have large variations in stream flow. However, the dissolution of soluble bedrock occurs at least four to eight times faster in Southeast Alaska (Allred 2004). In the Tongass, limited dye-tracing demonstrated that karst groundwater systems routinely transport water for more than 1,000 m horizontally to receiving caves, springs, and surface streams (Aley et al. 1993). Caves in this region exhibit tumultuous evidence of storm events and logging, such as increased sedimentation, woody debris from logging operations, and large amounts of other organic materials. The influx of these materials from storm events or land management practices have the potential to plug the karst systems, altering their natural flow regime throughout the hydrogeologic network (Aley et al. 1993).

In order to understand how managed karst systems function, it is important to conduct a hydrologic water balance, which accounts for the greater hydrologic cycle.

Essentially, the change in storage over a period of time should be balanced by both the inputs and outputs within the system. It is assumed that water entering the system will leave the system through evaporation, runoff, and or remain stored underground. This model can be applied in the following equation:

$$P - Q = \triangle S + ET \qquad \text{(Equation 2.2)}$$

As displayed above, P = total precipitation [the average between canopy throughfall and total net precipitation), Q = discharge, △S = total change in storage, and ET = evapotranspiration (Ford and Williams 2007).

2.5 Soil, Sediment, and Timber Harvest

Timber harvesting on karst has led to serious declines in soil depth and fertility worldwide, in some cases culminating in permanent deforestation (Harding and Ford 1993). Tree roots on karst translocate water and nutrients back up into the forest canopy. Much of the forest productivity is tied up in this nutrient cycle; when trees are harvested, the cycle is disrupted. On karst, soils tend to be thin and residual. As the epikarst becomes more developed, the surface-to-subsurface connection increases, as does the likelihood that soil and nutrients can be transported vertically beyond the rooting depth of vegetation and into the conduit systems of the karst drainage. Vertical migration of nutrients and soil becomes possible in areas of heavy rainfall and well-developed subsurface drainage once the forest canopy is removed (Harding and Ford 1993). External impacts usually pose the most serious problems, such as the erosion and deposition of fine sediments within active cave systems. The jointed and fissured nature of the limestone is likely to exacerbate this situation (Watson et al., 1997). This impact can be observed in the Tongass.

In comparison to surface systems, freshwater ecology of cave ecosystems has been poorly studied (Gunn et. al. 2000). Even fewer studies regarding sedimentation rates in relation to timber harvest on karst systems in the Tongass have been conducted. Cesium 137 (^{137}Cs) in soils is not naturally occurring but is a byproduct of open-air nuclear testing that started in 1954, thus making it an excellent indicator of recent sedimentation. A study that measured recent sedimentation rates in Kentucky and Southeast Alaska (Curry 2003), found that these rates, specifically in Southeast Alaska, could be correlated to timber harvest on karst features, providing a glimpse of what logging does to these terrains.

In Curry's 2003 study, seven sites were selected on Prince of Wales Island to conduct sediment sampling: three caves, one sinkhole, two old-growth areas, and one clearcut plot of forest. At the top of the three caves and sinkhole soil layers, high amounts of ^{137}Cs were detected and the amount tapered out towards the bottommost layer of the profile. These four features were all downstream of major clearcuts from the 60's and 70's - affirming that timber harvest could indeed be causing an increase in sedimentation rates. Although, this is most likely a function of hydrologic disturbance from logging. The clearcut ^{137}Cs rates were not completed during this study. The author notes that this study should be continued, as well as a total karst inventory and alternative timber harvest methods considered.

2.6 Karst Management in Southeast Alaska

Following World War II, timber harvest rapidly increased in the Tongass National Forest. The timber industry benefited economically, but the ecology of the region, particularly karst regions, began to decline. Karst areas tend to have a higher density of old-growth, resulting in being targeted for harvest. Timber harvest on these landscapes results in sedimentation in karst systems, stream degradation, and loss of fish habitat, among other factors (Bolle 1989; U.S. Forest Service 1974). Increasing exploitation of nonrenewable karst resources results in severe environmental impact in the Alaskan ecosystem. “Alaskans, particularly the state’s political leaders, have persistently fought environmental protection and regulation in the state while at the same time embracing virtually any economic development project that holds the promise of jobs and alternative contributions to the state’s economy” (Haycox 2016, 2). To protect these areas with prudent resource management policies, it is critical to study and understand the area’s dynamic nature. Studies must bridge the disconnect between karst science, karst management, and interested stakeholders (Urich 2002).

In the United States, there was a rise in new legislation as a result of the environmental movement, including the Forest and Rangeland Renewable Resources Act of 1974 (RPA), the National Forest Management Act of 1976 (NFMA) and the National Environmental Policy Act of 1970 (NEPA) (Kaiser 2006, Kovarik 2007). As part of NFMA, National Forests were required to develop a total "forest management plan" outlining best practices for the protection of all resources during management activities.

The passage of the Cave Resource Protection Act of 1988 (FCRPA) should have been a landmark for environmental protection and regulation "to secure, protect, and preserve significant caves on Federal lands for the perpetual use, enjoyment, and benefit of all people." However, the FCRPA provided only minimal protection for karst and cave features, especially in areas that had already seen environmental degradation (Durbin 1999). It was not until nearly a decade later that public awareness began to spread through the work of dedicated volunteer cavers through the Tongass Cave Project and the publication of the “Karst Landscapes and Associated Resources Assessment” (Baichtal and Swanston 1996; Durbin 1999). By 1993, it was estimated “that two-thirds of the commercial forest land on known karst landscapes on Prince of Wales Island had been harvested” (Baichtal and Swanston 1996).

The first Tongass Land Management Plan (TLMP) was introduced in 1979, revised in 1993, and passed four years later. The 1997 Tongass Land Management Plan addressed karst and cave resources, identifying these landscapes as an “emphasis area” (Baichtal 2003) based on Aley et al.’s 1993 recommendations to continue research in Southeast Alaska’s karst, including the addition of the Karst and Cave Resource Significance Assessment. The TLMP has continued to evolve with the most recent version being published in 2016, and subsequently amended in August of 2020. The current amendment reflects a renewed focus on young-growth timber harvest and the need for karst vulnerability assessments in decision making.

As a consequence of its emphasis on karst, land management in the Tongass has relied on strategies that include “risk assessment” or “vulnerability mapping” (Baichtal 1997). Areas in the Tongass are identified as having low, moderate, and high vulnerability. This vulnerability assessment strategy has been difficult to implement due to unclear directions, limited experience of personnel, and differing interpretations of what constitutes a score (Baichtal 2003). Vulnerability is generally linked to accessibility of the aquifer; the shallower and more readily recharged, the more vulnerable (Hiscock 2014). Similarly, on Vancouver Island, there has been a shift in land management practices from a focus primarily on caves, to a strategy encompassing both endo and exokarst elements (Griffiths et al. 2005).

Another milestone in karst management was the adoption of the 2004 Forest and Range Practices Act (FRPA). The goal of FRPA is to reduce the complexity of legislation and regulation while relying on a science-based approach to the management of karst (Griffiths et al. 2005). FRPA recognizes four fundamental environmental components to be managed: air, land, water, and biota. This results-based regulatory regime focuses on the following five elements:

- Focuses on protecting the integrity of karst systems, including individual surface karst features, caves, and the broader karst landscape.
- Independence of scale (for example, micro-relief karst features, such as karren exposures, are managed along with larger scale components such as complex cave systems).
- Not all karst features need to be found or known in order to manage the karst system.
- Subsurface karst resources are to be managed through appropriate forest practices applied on the surface, utilizing a total karst catchment approach.
- Contributing non-karst portions of delineated karst catchment areas should also be considered (Griffiths et al. 2005).

The recognition of managing karst ecosystems through results-based science assessment that is not overly complicated is a recent development (Griffiths et al. 2005, Shaw et al. 2000). In coordination with other land managers in coastal temperate rainforests, these tools can continue to be revised, applied, and compared. Much has changed in the four decades since the TLMP was first written. Considering new information regarding local anthropogenic impacts, as well as global climate change on vulnerable, non-renewable resources, the value of continued review of sustainable management plans cannot be overstated.

Chapter 3: Study Area

3.1 Prince of Wales Island

The study area is located in Southeast Alaska's Tongass National Forest on northwest Prince of Wales Island (POW) and is only accessible by boat or plane (Figure 3.1). The Tongass National Forest is the largest forest in the National Forest system, covering 16.7 million acres. It is also the largest intact temperate rainforest in the world (US Forest Service 2016). Southeast Alaska extends across 800 kilometers (km) from Icy Bay southward to the international Canadian border at Dixon Entrance. More than 1,000 named islands of the Alexander Archipelago extend along the coastline (Cook and MacDonald 2013), with POW being the southernmost island in the Archipelago. A system of seaways connects the many islands and is known as the Inside Passage. The island is densely forested with Sitka spruce, western hemlock, and western red and yellow cedar. The region is sparsely settled, with an estimated 74,280 people living in more than 30 towns and villages located in and around the Forest as of 2014. The communities of Southeast Alaska depend on the Tongass National Forest in various ways, including employment in wood products, commercial fishing and fish processing, recreation, tourism, and mining and mineral development (US Forest Service 2016). The primary industries on POW are tourism, fisheries, and timber harvest, the last two, of which, are directly linked to the productive karst systems (Heaton et al. 2003).

The karst and cave features are significant for several reasons, including the following resources: mineralogical, paleontological, cultural, and biological. The pure carbonate rocks along the north Pacific coastal temperate rainforest originated as marine reef and lagoon deposits during the Silurian period, 438 to 408 million years ago (Aley et al. 1993). These rocks are part of what is now recognized as the Alexander Terrane, one of five subcontinental blocks of rock that combine to form the panhandle of Southeast Alaska. The Alexander Terrane is geologically diverse and considered exotic. The karst formations are found in bands of Silurian and Devonian limestones that formed somewhere near present-day Chile as reefs surrounding volcanic island arcs (Aley et al. 1993). The intra-island and mountain-block-scale faults define individual karst landscape boundaries. The caves, sinkholes, and other karst feature are localized along sets of small to intermediate scale fracture, joints, and faults (Aley et al. 1993).

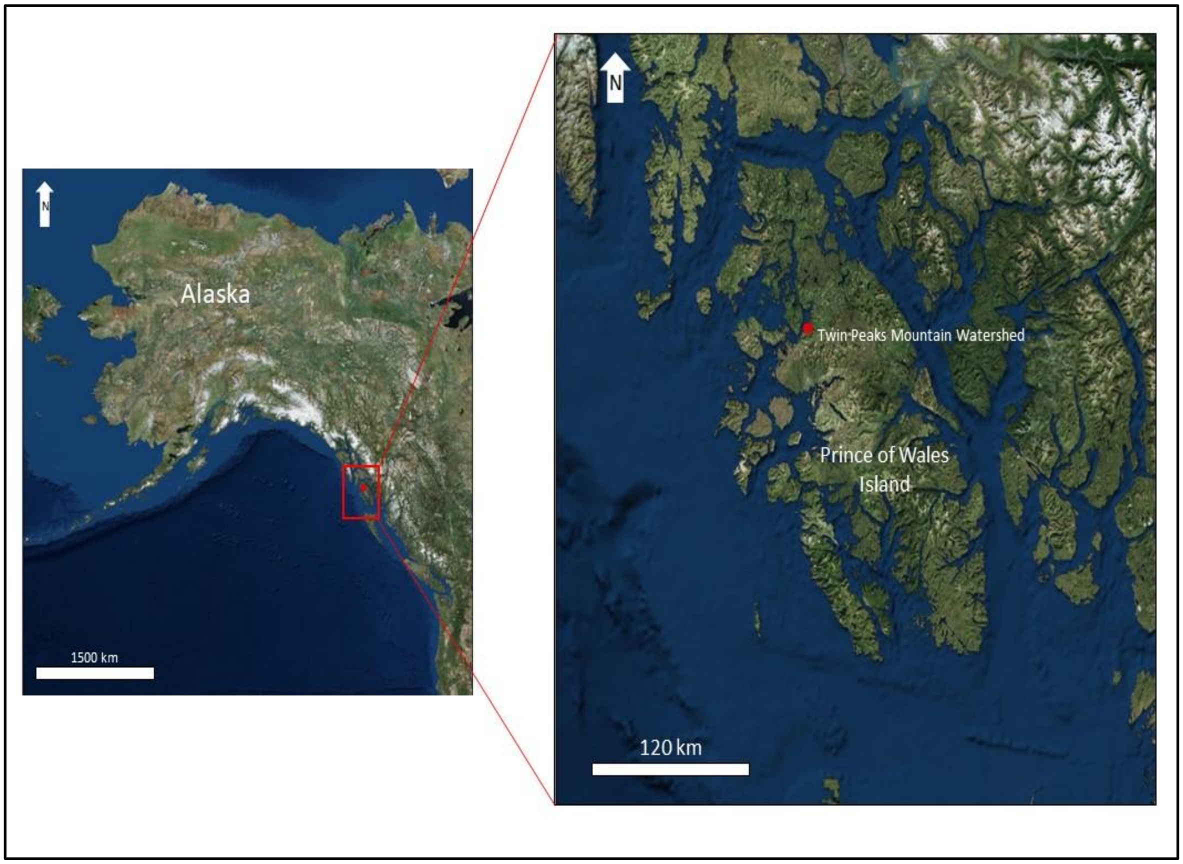


Figure 3.1: Map of the study area on Prince of Wales Island in context to the state of Alaska.

3.2 Geology

According to Baichtal and Swanston (1996), karst on POW is controlled by six main factors: (1) the purity of the carbonate bedrock, (2) the structural components of the bedrock that define zones of weakness along which groundwater is directed to form solution cavities and channels, (3) occurrence of igneous intrusions that may block subsurface flows and alter the carbonates by contact metamorphism, (4) proximity of the carbonates to highly acidic drainage from muskegs, (5) modification of surface topography and drainage by glacial activity, and (6) precipitation and temperature.

The hydrology in this landscape is highly dynamic and subject to extreme variations in flow, especially during the rainy season. Rainfall varies greatly, ranging from annual average precipitation of 1.5 m to more than 6.4 m per year (US Forest Service 2016). The highest flows occur during the fall rainy season, or during winter and early spring, when heavy rains fall on wet snowpack. Higher locations (above 1,000 m in altitude) are often glaciated. Increased changes in temperature, due to climate change, are predicted by the end of the 21st century, altering geomorphic and hydrologic processes in watersheds and stream channels. Changes in temperature and precipitation will have significant consequences (IPCC 2018).

3.3 Paleontological Resources

With a bedrock of Paleozoic limestone, the weathering and dissolution has created a karst terrain. Many caves have been damaged by slash and sedimentation and some entrances have been buried by the building of logging roads. A diverse fauna of fishes, birds, and mammals has been identified spanning the past 50,000 years. Not much research has been done into the area’s paleoarchaeology prior to 1990, due to the belief that Ice Age glaciers covered most of the northwest coast. This changed however, when in 1990 cavers from the Tongass Cave Project began discovering vertebrate fossil deposits. Within the study area, El Capitan Cave is Alaska's largest known cave with nearly 4 km of mapped passageways. Here, late Pleistocene remains of a caribou and brown bear have been recovered (Heaton et al. 2003). Nearby, in Shuká Káa (formally known as On Your Knees Cave) the remains of a ~10,000-year-old human and the remains of mammals from over 57,000 thousand years to the present (Heaton and Grady, 2003) suggest the possibility of costal refugia and the possibility of aboriginal people migrating along coastal waterways. Lesnek et al. (2018 and 2020) demonstrate that deglaciation began as early as 17.0 ka (kilo annum, thousand calendar years ago). They conclude that "an open and ecologically viable pathway through southeastern Alaska was available after 17 ka ago, which may have been traversed by early humans as they colonized the Americas".

3.4 Biological Resources

The Tongass supports abundant fish and wildlife, including all five species of Pacific salmon, brown (grizzly) bears, black bears, wolves, Sitka black-tailed deer, bald eagles, ravens, northern goshawks, and marbled murrelets. The karst landscape influences productivity of its aquatic habitats through its carbonate buffering capacity and carbon input dissolved from the limestone bedrock. This has significant downstream effects on the aquatic food chain and biotic community. Preliminary studies suggest that aquatic habitats associated with karst landscapes may be eight to ten times more productive than adjacent, nonkarst-dominated aquatic habitats (Bryant et al. 1998).

3.5 Study Area Cave Systems

Site locations were carefully chosen on two karst systems to capture varying canopy densities across the landscape. Selected sites included an undisturbed, old-growth forest, and a previously harvested, second-growth forest (which included 25-35 year-old regeneration), and a cleared forested area in a sub-alpine muskeg. All sites were in the Twin Peaks Mountain Watershed within an eight-kilometer radius of the Staney Creek drainage on Prince of Wales Island, Alaska.

3.5.1 Walkabout Cave

Walkabout Cave, formed in the Silurian-aged Heceta Limestone, is in an old-growth forest, on the edge of a muskeg in the sub-alpine. This muskeg drains into Walkabout cave and is composed of calcareous glacial till. The muskeg drainage basin is bounded to the north by a late Pleistocene glacial moraine. Currently, the total surveyed length of the cave is 210.2 m, with a vertical extent of 16.4 m (Figure 3.2). The Heceta Limestone is highly fossiliferous and in Walkabout Cave there is an abundance of coral fossils. This cave is unique and well known for its formations, including soda straws, stalactites, stalagmites, helictites, opaque draperies, and the tallest rimstone dams recorded in Alaska at 40 cm.

A stream flowing from the adjacent muskeg directly enters int Walkabout's entrance at the main insurgence point located 410 m above sea level. When the cave was discovered in 1999, the stream flowed directly into the cave entrance, which was walkable at the time. Since then, the entrance has collapsed, requiring a tight squeeze to enter the cave. The stream has been pirated by two small pits that have formed about 15 m in front of the cave entrance; however, during high flow events, water will flood the area and flow into the cave through the entrance. The main resurgence point for Walkabout Cave is located roughly 120 m down slope from the insurgence at 290 m of elevation. It is assumed that the resurgence is the end of the Walkabout Cave system. The resurgence has no air space and is the onset of a fish-bearing stream that flows to the Pacific Ocean.

3.5.2 Zina Cave

Located in the second-growth forest, Zina Cave is one of the larger, more extensive karst systems in the Tongass. Currently, the total surveyed length is 1,763.3 m and the vertical extent is 119.4 m (Figure 3.3). It is also formed in the fossiliferous Heceta Limestone; however, the bottom of the cave is mudstone, and the main stream passage flows down dip of the geology. When Zina Cave was mapped by the Glacier Grotto cavers made that observation that it could be one of the older caves in Southeast Alaska. This observation is based on the walking-sized phreatic passages in the upper portion of the cave and the 45 m pit that leads to the active stream system. There are many igneous dikes along the active stream system that act as resistant barriers to the downcutting vadose streams, resulting in a terminal sump. The main resurgence of Zina Cave is the baseflow, which was monitored in this study. It is located 292 m down slope from the main cave entrance at approximately 85 m above sea level along a main logging road.

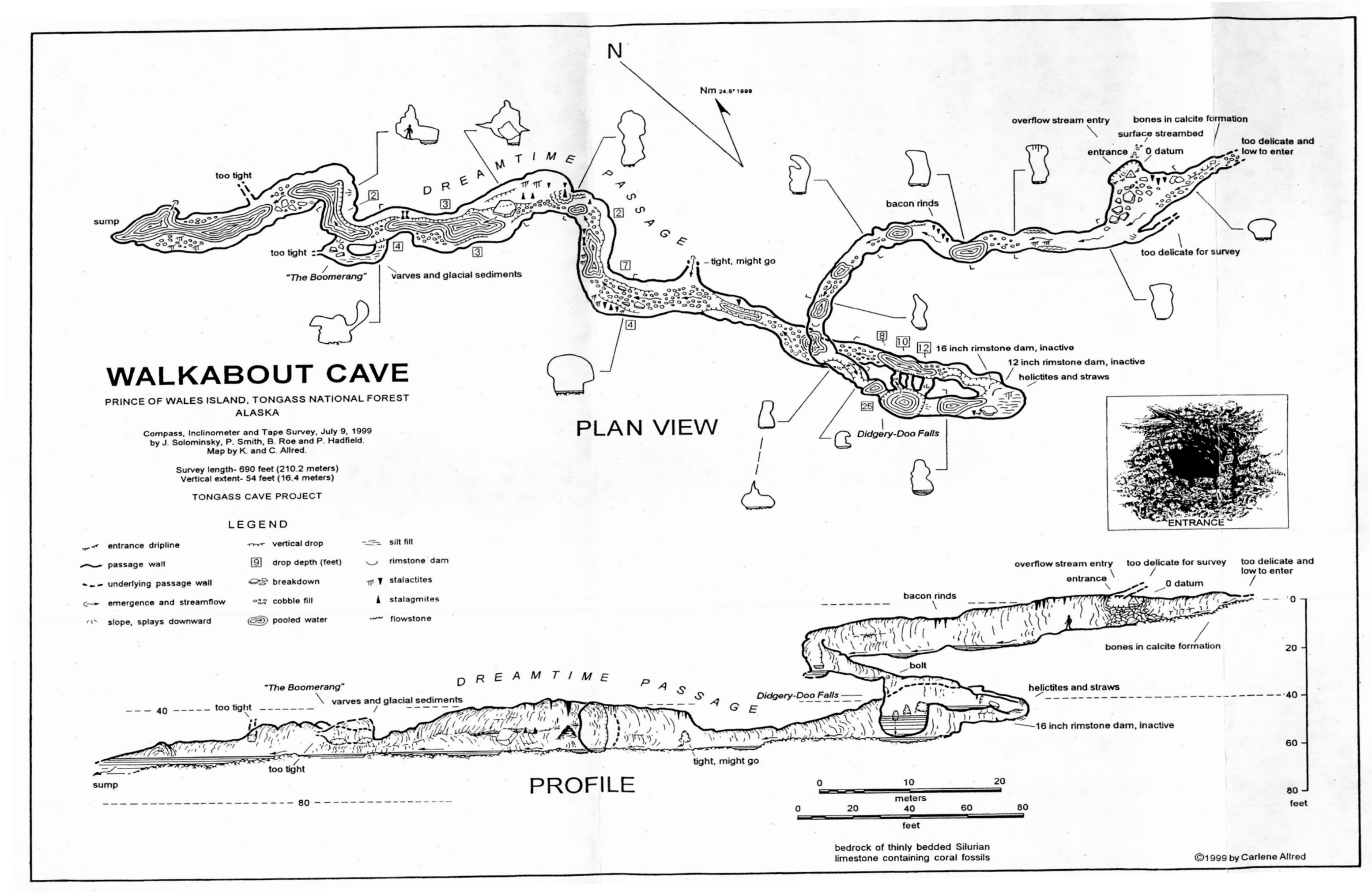


Figure 3.2: Walkabout Cave map. This cave is in the old-growth study area. Two stilling wells were installed: one at the insurgence, located in the cave entrance just past the breakdown and another at the main resurgence.

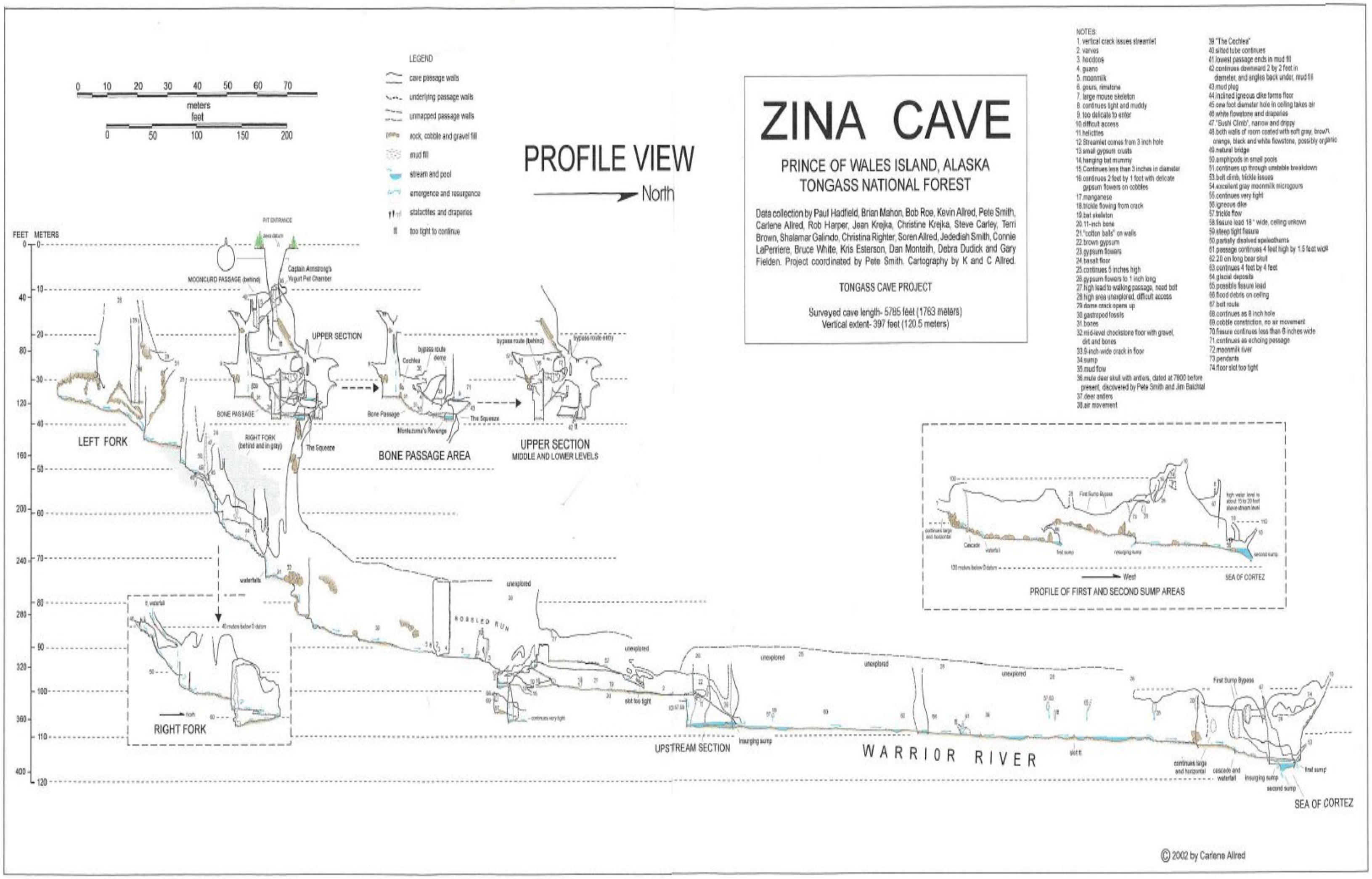


Figure 3.3: Zina Cave map. This cave is in the second-growth study area. The baseflow is the main resurgence from this cave and where a stilling well was installed.

Chapter 4: Methods

The study took place over a five-month period, between June 29th and November 21st, 2019, Julian Dates (JD) 180-325. Multiparameter water quality sondes, pressure transducers, rain gauges, and a weather station were installed. Grab samples for cations (Ca^{2+} and Mg^{2+}) and alkalinity (HCO_3^-) were collected to statistically develop a relationship with geochemical parameters and to calculate dissolution rates within the systems at high-resolution. Grab samples for carbon isotopes were also taken to provide data regarding carbon influx related to seasonal and vegetation changes.

Rain gauges were installed in August, under the two different canopies; one in the old-growth, where Walkabout Cave is located, and one under the second-growth, where Zina Cave is found. The rain gauge data were used to understand throughfall rates in the different canopy settings. Additionally, a weather station was installed in the sub-alpine muskeg adjacent to Walkabout Cave. The station recorded net precipitation and barometric pressure, which is necessary for understanding throughfall and climatic influences on the karst systems. These data further provided insight into the climatic dynamics regarding the relationship between throughfall, recharge, geochemical response, and dissolution rates.

4.1 Site Selection

The two main sites in the Twin Peaks Mountain Watershed were chosen based on their varying canopy densities (Figure 4.1), including old-growth and second-growth forest, both over karstic basins. Walkabout Cave was chosen as the old-growth site and Zina Cave was chosen as the second-growth site. The third site, adjacent to Walkabout

Cave, was the muskeg with no canopy cover and served as the location for the weather station where overall precipitation was recorded. Since the muskeg has no canopy cover, this site was the control site for precipitation data gathered in the old and second-growth sites. Once equipment was installed at the study sites, they were visited bi-weekly for maintenance and to download and collect data.

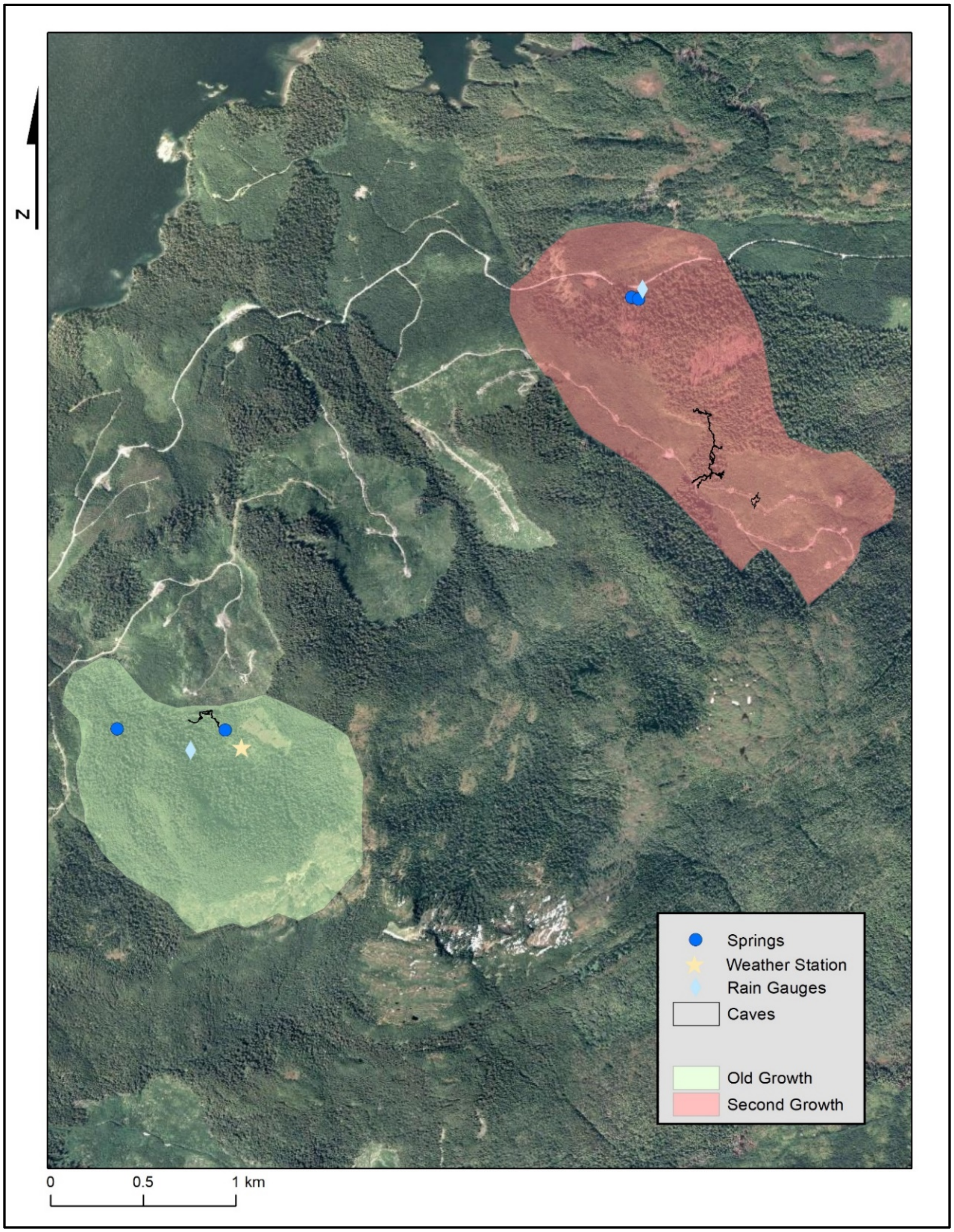


Figure 4.1: The monitored study sites on Twin Peaks Mountain. The springs (blue) are where multiparameter water sondes and pressure transducers were installed. Note the different canopies between the two sites (old and second-growth). The blue diamonds signify where rain gauges were installed to measure precipitation values between the different canopies. The yellow star was where net precipitation was recorded in the open muskeg (control site). The distance between Walkabout and Zina Cave entrances is 3 kilometers.

4.2 Precipitation and Canopy Throughfall

Rainfall data were measured in 10-minute intervals with Davis AeroCone rain collectors and HOBO Micro Stations at all three sites. At the muskeg site, overall precipitation and barometric pressure were recorded, to aid understanding of variations in throughfall and weather patterns. The rain gauges were battery powered and collected up to 150 centimeters (cm) of rainfall at 12.7 cm per hour with a resolution of 0.2 millimeters (mm) per one second of time. The lithium battery had an average lifespan of one-year, obviating replacement within the period of this study (five-months). Initial factory calibration for these devices was conducted prior to primary data collection in June 2019. The rain gauges recorded rainfall in standard time, which was then converted to Julian Date time during data processing. Rainfall data were retrieved with a HOBO shuttle and downloaded into HOBOware software, then converted into graphs and spreadsheets using Origin Pro software.

The rain gauges were installed under both the old and second-growth canopies to accurately account for the variance in the openness between canopies and total throughfall (Figure 4.2). Prior to installation, a vegetation inventory was conducted, and canopy openness determined by taking hemispherical, fisheye angle photographs above each rain gauge in the old-growth and second-growth forest study sites. Canopy openness is the percentage of open sky that is visible from below a forest canopy. The photographs were further examined with Gap Light Analyzer 2.0 (GLA) software, which used the forest canopy structure and the gaps between light transmissions to calculate the percentage of openness. The percentage generated from the software does not account for the influence of topography on the canopy structure; it only calculates the gap space between vegetation (GLA Manual 1999, Frazer et al. 1999). Additionally, the sites required some degree of protection to safeguard the equipment from animals (Prussian 2011).

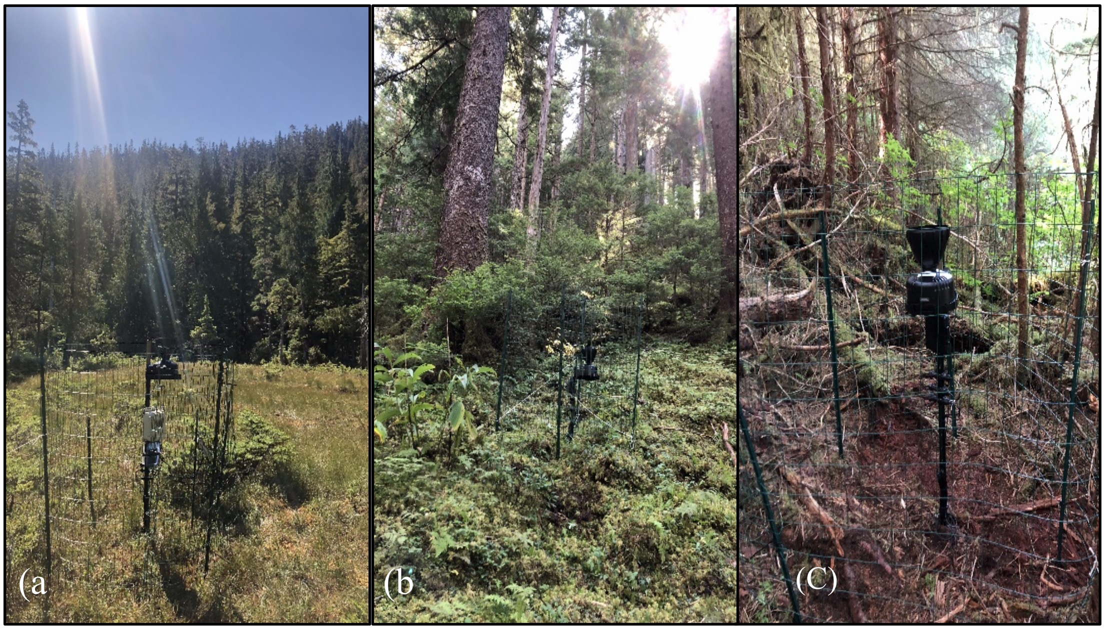


Figure 4.2: (a) Sub-alpine weather station, (b) old-growth rain gauge station, and (c) second-growth rain gauge station.

4.3 Geochemistry and Water Quality

YSI 6920 multiparameter water quality sondes and Onset HOBO U20 pressure transducers were installed at each spring in polyvinyl chloride (PVC) stilling wells (Figure 4.3). At the old-growth site, one sonde was installed at a point of insurgence inside of Walkabout Cave, located in the main entrance; the other sonde was installed at the main resurgence of Walkabout Cave. At the second-growth site, one sonde was installed at the Zina Cave baseflow spring (Figure 4.4). These sondes measured pH, temperature, and SpC at 10-minute intervals for the duration of the study. The probes were calibrated monthly to ensure accuracy. High-resolution stage and temperature data were also recorded at 10-minute intervals with HOBO U20 pressure transducers adjacent to the sondes in the stilling wells. An Oaklon PCTSTestr 50 was used to collect pH, SpC, and temperature data at each site during site visits. The Oaklon tester was calibrated before each field day to ensure quality measurements were being conducted. Due to high water conditions, spot and grab samples were occasionally not collected at the regular sites but were collected in proximity.

Water grab samples for cations (Ca^{2+} and Mg^{2+}), alkalinity (HCO_3^-), and carbon isotopes were collected bi-weekly at each site. These data were used to statistically develop a relationship with geochemical parameters and to calculate high-resolution dissolution rates. All the samples were filtered using a syringe and 0.45μm filter paper to remove any organic materials that may alter the geochemistry (Wilde et al. 2004). Cations were collected in 60 milliliter (mL) plastic bottles and preserved using 7 drops (~0.5 mL) of nitric acid (HNO_3). Carbon isotope samples for $\delta^{13}C$ values were collected in 40 mL plastic vials. All samples were sealed tightly with parafilm to prevent outgassing through the sealed lids. These samples were stored and refrigerated at approximately 4 degrees Celsius (°C) pending lab analysis.

Due to the remote location of the sites, cation samples were shipped to Western Kentucky University's HydroAnalytical Lab at the end of the study in November 2019. The HydroAnalytical Lab determined cation concentrations by using inductively coupled plasma emission spectroscopy (ICP-ES). Carbon isotope samples were also shipped elsewhere and were analyzed using the Thermo GasBench II interface with the Thermo Finnigan DELTA^{plus} XP isotope ratio mass spectrometer at the University of Kentucky's Stable Isotope Geochemistry Laboratory. Additionally, all the alkalinity measurements were conducted in-situ at the study sites using the full range ThermoScientific Orion total alkalinity test.

Precut and weighed limestone wafers were used to confirm dissolution rates. The limestone wafers were placed in each monitored spring, at each rain gauge, and the weather station at 10 cm of depth. The wafers were installed at the beginning of the study in June 2019 and remained in place for the duration until November 2019. When the wafers were collected at the end of November, they were placed in the oven at 104 °C for three days to remove excess water and organics. Following, they were placed in the desiccator for 30 minutes to slowly bring the wafers to room temperature before being weighed. To ensure accuracy the scale was calibrated beforehand. Each wafer was weighed to determine overall loss, which was then used to assess and confirm dissolution rates in grams per year. Dissolution in grams per year was calculated by taking the weight difference in grams at each site and multiplying that value by the ratio days in a year (365 days) to days deployed.

Figure 4.3: Stilling wells at the following study sites: (a) Walkabout Cave insurgence, (b) Walkabout Cave resurgence, and (c) Zina Cave baseflow.

Figure 4.4: Two springs resurging from Zina Cave in the second-growth forest. On the left is the overflow (which only activates during high flow events), and the right is the monitored baseflow.

4.4 Data Processing and Analysis

The entirety of the data collected were compiled and processed in Excel, Hoboware software, and Origin Pro. Water levels were measured with a meter stick at bi-weekly visits and at the initial deployment of instruments, these measurements were used as references for data processing. To calculate high-resolution water level, barometric data were removed from the total pressure data, which was recorded by the pressure transducers, to reduce noise and compute the most accurate data. The hydrochemical data collected from the sondes were corrected for calibration drift based on the *USGS's Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting* in conjunction with calibration values and grab sample data from the handheld Oaklon PCTSTestr 50 (Wagner et al. 2006). Time series analyses and graphs were utilized to understand and identify the correlation between precipitation, throughfall, geochemical properties, dissolution, and carbon isotopes. These variables provide insight into the interconnectedness of karst, climate, forest, and the effects of timber harvest on these ecosystems.

Dissolution in terms of wall retreat for the cave study sites was calculated using the Palmer equation (Palmer 1991):

$$S = \frac{31.56k(1-SIcal)n}{Pr} \qquad \text{(Equation 4.1)}$$

In this equation, S is the rate of wall retreat and *k* is a temperature dependent rate constant, *n* is the reaction order, and *P*r represents the density of limestone. High-resolution estimated dissolution values were calculated and graphed to better understand

and characterize the effects of precipitation, canopy openness, and seasonal trends on dissolution rates within the study site caves.

Chapter 5: Results and Discussion

Five variables were selected to test whether potential differences could be associated with variations between old-growth and second-growth: canopy throughfall and openness; precipitation in Southeast Alaska; seasonal precipitation events; two systems; geochemistry; and carbonate dissolution. The following discussion addresses seasonal differences in the Tongass, including the role of canopy thickness and precipitation in a temperate rainforest. The results and discussion include an analysis between Walkabout and Zina Cave systems and their geochemical responses in relation to precipitation events that took place in the study area from June to November 2019. Furthermore, this section will provide insight into dissolution rates and seasonal carbon isotope data. Data collection for this research was conducted from June 29th through November 21st of 2019 (JD 180-325).

5.1 Canopy Throughfall

In old-growth forests like Walkabout, the greater canopy openness allows for a more substantial amount of throughfall and sunlight to reach the forest floor, resulting in a diverse understory better suited for wildlife and overall ecosystem health. In contrast, second-growth forests like Zina experience less throughfall due to the density of trees and the thickness of their canopy, resulting in diminished diversity, which affects wildlife and the overall health of the ecosystem.

The ecosystems, including the well-developed western hemlock and Sitka spruce forests, are part of an ecological unit, growing along valley floors and on top of almost pure carbonate bedrock that formed as a result of differential solution of rocks by acidic groundwater. The acidic groundwater is a direct product of abundant precipitation and passage of the water through organic-rich forest soils (Baichtal and Swanston 1996). The productivity of the forest is in direct association with its world class karst landscape (Aley et al. 1993). Influencing variables seem to be the nutrient rich soils, well-developed subsurface drainage, and dissected bedrock surfaces that allow tree roots to hold fast and become somewhat more windfirm (Baichtal and Swanston 1996). This study was limited to water chemistry and canopy openness, which are only some of the many conditions that affect these forests. Other variables that may affect forest ecosystems include tree species, topography, drainage, and management activities related to timber harvest and recreation.

Similarly, the percentage of canopy openness was calculated to better understand the relationship between throughfall and forest management practices. In the old-growth forest, where Walkabout Cave is located, the canopy is more open, consists of larger trees (mature coastal Sitka spruce, western hemlock, red cedar, and yellow cedar) and has a denser understory. In comparison, the Zina Cave site has a predominance of Sitka spruce and western hemlock. Based on fisheye photographs (Figure 5.1) at the rain gauge sites and the GLA results, Walkabout's old-growth canopy has an openness of 55%; 45% of the sky is obstructed by the canopy (Table 5.1). Zina's second-growth canopy has an openness of 18%; 82% of the sky is obstructed by the canopy (Table 5.1). A rain gauge was set up at each of the cave sites, and one in an open muskeg next to Walkabout Cave. The open muskeg rain gauge served as the study control site for precipitation data in having no canopy and accounted for overall precipitation for both the old and second-growth sites. Precipitation values from the entirety of the study confirmed that the

Walkabout Cave old-growth site is more open than the Zina Cave second-growth site and ultimately received more throughfall (Figure 5.3).

These results agree with previous research, indicating that past management activities, such as timber harvest and roading, influence canopy conditions (Prussian 2011). Prussian's research indicates three issues to be addressed for effective forest management. Firstly, size, density, productivity, and canopy characteristics of old-growth and second-growth forests vary considerably. Variation in these forest attributes may exceed differences associated with age of forest. Secondly, present use of open sky measurements and/or throughfall collection devices may not adequately describe patterns of overstory interception. Lastly, relevant measures of forest overstory need to be made to compare between forest types (Prussian 2011). These factors are all relevant in determining the impacts of land use change on the sensitive karst ecosystems of the Tongass, particularly in relation to cave development as discussed herein.

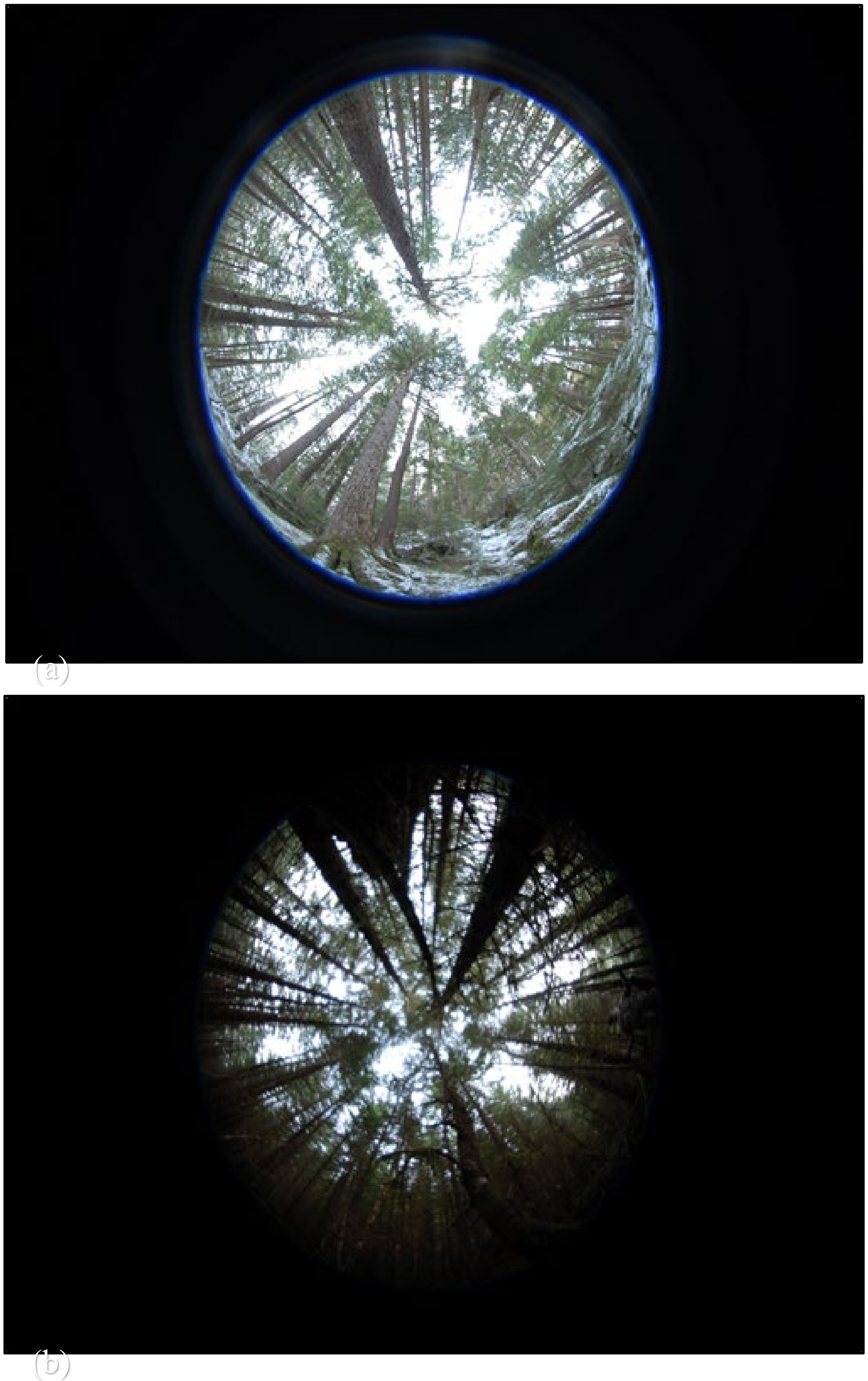


Figure 5.1: Pictured above are the two varying canopies, the photographs were taken looking up, with a fisheye lens directly above the rain gauge locations. These photos help characterize the differences between vegetation density of old-growth (a) and second-growth (b).

5.2 Temperate Rainforest Precipitation

The Tongass rainforest is temperate and maritime and precipitation is abundant; it may exceed 635 cm in a year at some higher altitudes and annual runoff ranges from about 152 - 508 cm a year (Aley et al. 1993). The Tongass rainy season typically begins in July; however, the summer of 2019 rainy season began later (NOAA 2020). For the purpose of this study, September 17th (JD 260) was designated as the start of the rainy season. According to the Annual 2019 National Oceanic and Atmospheric Association's (NOAA) National Climate Report, this delayed start may indicate a trend toward greater volatility in precipitation due to changing climates. Figure 5.2 illustrates the below average precipitation rates on Prince of Wales for 2019. If this trend continues, this may cause long-term changes in the temperate rainforest environment and the geochemistry of karst waters. It is important to note that the precipitation data in conjunction with the geochemical data varies depending on annual climate fluctuations. Thus, the results of this study are influenced by summer drought conditions until precipitation increased during the fall season.

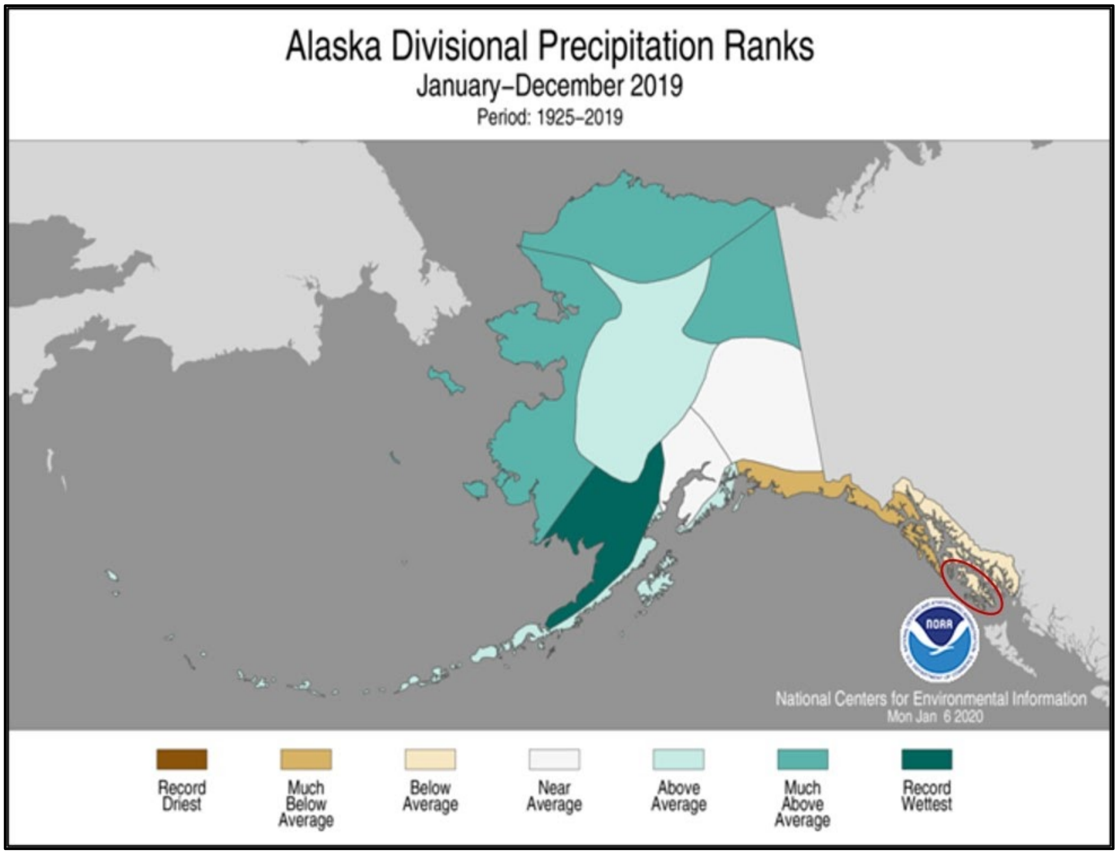


Figure 5.2: This graphic displays Alaska precipitation averages that were received across the state during 2019. The period (1925-2019) accounts for the range of time NOAA has been collecting these data. The red oval is the study area location, Prince of Wales Island. Precipitation varied by region, and was below average throughout Southeast Alaska, including Prince of Wales Island. The summer and fall months displayed extreme drought conditions for much of Southeast Alaska until heavy precipitation in October remediated drought conditions.

Measurements at the field locations indicated a greater response to rain intensity, for example, during storms (precipitation events), than to overall precipitation. As predicted, each canopy site received significantly different amounts of throughfall, as measured by rain gauges installed under each of the two canopies (Figure 5.3). The rain gauge installed in the open muskeg (control site) received a total of 836 mm, which is nearly 150% as much precipitation as the old-growth site, which received a total of 598 mm (Table 5.1). The second-growth site received a total of 266 mm, less than 50% of the old-growth total (Table 5.1). It should be noted that the second-growth microstation site experienced intermittent battery shortage due to a faulty probe that was repaired on October 23rd (JD 296). These intermittent battery shortages resulted in the rain gauge not recording precipitation totals to the microstation; however, accounting for these instances, the second-growth precipitation totals were only slightly lower than they would have been if the probe had not been defective.

During the summer dry season, August through mid-September, the muskeg rain gauge received 220 mm of precipitation, the old-growth received 162 mm, and the second-growth site received 33 mm (Table 5.1). Thus, the rainy season is defined as when precipitation remains more consistent and when most of the precipitation fell during this study. Fogs and mists add an additional, but indeterminate quantity, of water. Table 5.1 and Figure 5.3 summarize the parameters of dry season precipitation, the effects of precipitation variables on old-growth vs. second-growth are consistent with previous findings with density of second-growth canopy impeding infiltration (Stednick 1996).

Based on the recorded precipitation values, the second-growth forest's canopy interception limits sub surface flows, particularly where karst systems have developed adjacent and beneath harvested areas. Additionally, it is possible that sedimentation and slash from prior timber harvest activities have washed into karst features, which will alter the ecology of the karst system by affecting the water chemistry and flow paths (Aley et al. 1993). Previously harvested, thickly regenerated forests (second-growth) result in increased interception rates, thus resulting in less water moving through the karst systems (Prussian 2011). Without natural flow rates in these karst systems, slash and debris will remain in place and will not be pushed out. Subsequently, decreased water flow downstream from these karst areas will result in a reduction of fish, since karst streams contribute to healthy fish habitat, especially for salmon spawning productivity (Bryant et. al 1998; Wissmar et al., 1997).

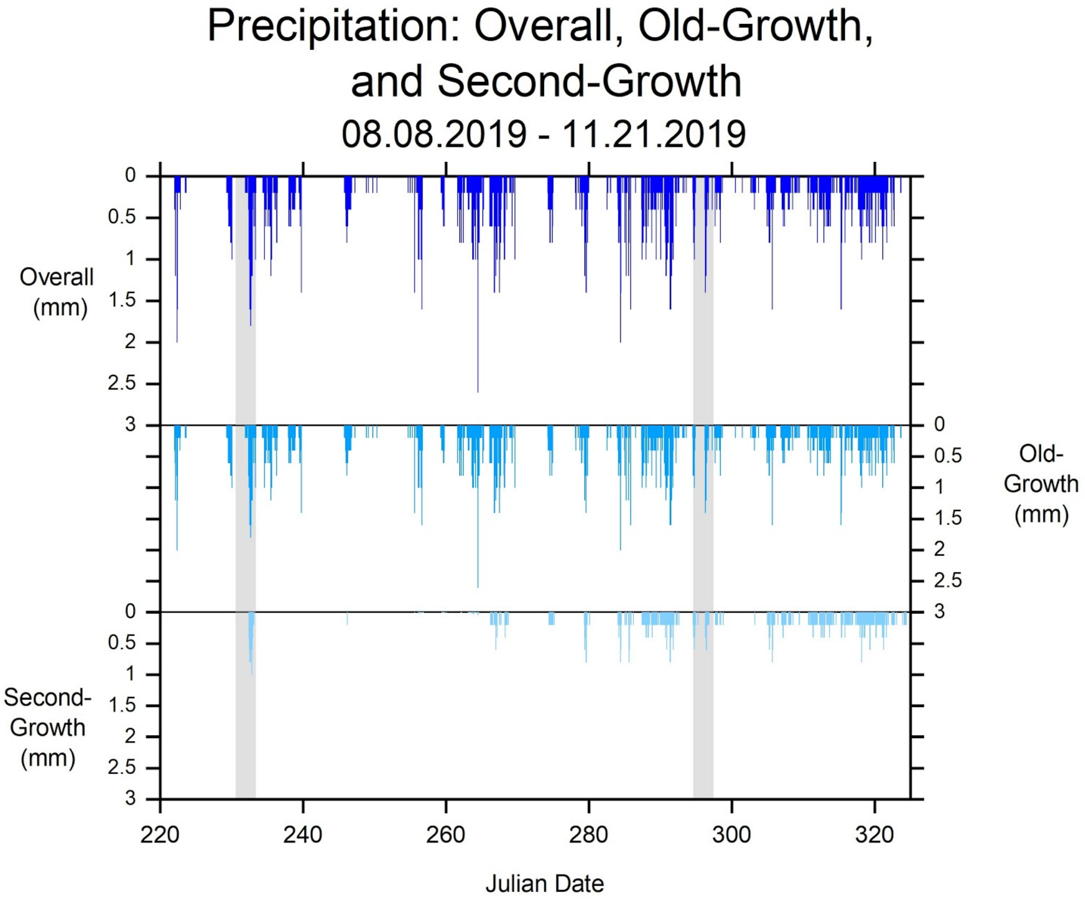


Figure 5.3: Precipitation totals for all three sites. Overall: Muskeg site. Old-growth: Walkabout Cave site. Second-growth: Zina Cave site. The rain gauges were not installed until August 2019. The vertical gray bars indicate the two precipitation events that informed the results of this study.

Site	Dry/Summer (mm)	Rainy/Fall (mm)	Total (mm)	Canopy Openness (%)
Muskeg (Overall)	220	616	836	100
Old-Growth (Walkabout)	162	436	598	55
Second-Growth (Zina)	33	233	266	18

Table 5.1: Seasonal precipitation values and percentage of canopy openness for all the sites for the duration of the study.

5.3 Walkabout and Zina Cave Systems

5.3.1 Walkabout Cave

The Walkabout Cave system provides a good example of the influence of local geology on geochemistry (Figures 5.4 and 5.5). Of particular interest is the calcareous till blanket, where the majority of the water pools before it insurges into Walkabout. Normally muskeg waters in this region have extremely low pH, with acidity largely contributing to rapid cave formation in adjacent carbonate areas (Groves and Hendrikson 2011); however, at Walkabout Cave the muskeg water is buffered through calcareous till prior to the insurgence, resulting in neutral waters (average pH of 7.5) entering the cave. Water at the resurgence was slightly more acidic (average pH of 7.2) than the insurgence. According to Groves and Hendrickson (2011), this phenomenon is not typical in Southeast Alaska based on previous studies. Lower pH numbers at the resurgence can be attributed to other inputs of high CO_2 water into the cave, downstream of the insurgence. In a typical karst system, during the summer months, greater CO_2 inputs will cause pH to decrease. This is due to water infiltrating the soil, thus reacting with CO_2 that has been produced by microbial activity attributed to vegetation growth (Yang et al. 2015); however, this was not an observed trend in the studied temperate rainforest systems.

Precipitation events caused the water level in the system to increase initially; however, there is not an extreme water level increase or decrease from the summer to fall season. On average, the insurgence water level was 0.24 m, and the resurgence was 1.17 m. This may indicate that residence time is a factor in the water accumulating as it moves through the system; however, the resurgence is 120 m lower than the insurgence, which is approximately 410 m above sea level. The subtle seasonal water level response is likely due to the temperate rainforest environment’s consistent moisture conditions and vegetation.

Temperature response for both the insurgence and resurgence was also similar. Temperature increases during precipitation events were due to warmer water quickly entering and flowing through the system. With or without precipitation, the cave water temperature changes were diurnal, based on outside temperature fluctuations from night and day. Overall, the average temperature for the entire system was 7.1 °C.

These similarities in the geochemistry between the insurgence and resurgence may be attributed to the lack of storage in the system and the small size of Walkabout Cave, unlike the Zina Cave system. SpC and pH behave similarly at the insurgence and resurgence, with dilution occurring during rain events. The SpC values at the insurgence had an average of 80.5 μS/cm and the resurgence average was 106.8 μS/cm. Higher average SpC values at the resurgence are due to slightly increased dissolution occurring. As meteoric water (lower SpC) moves from the insurgence to the resurgence through the cave system, it is interacting with the rock longer and becoming more buffered from calcite dissolution.

The topography of the Walkabout area is steep; however, Walkabout Cave itself only has 16 m of vertical extent. During defined precipitation events water flows through Walkabout Cave quickly, alternately during base level water conditions, water flow is not as rapid due to the low gradient of the cave system. The distance from the insurgence to resurgence is roughly 0.6 km downhill, leaving little time for chemical changes to occur; this exhibits a conduit flow regime. Unlike diffuse flow springs, conduit flow is defined by turbulent flow, resulting in chaotic, non-parallel flow, and consequently producing eddies. The mainstream passage in Walkabout had multiple carved pools in the bedrock from rocks continuously weathering in circular patterns from eddies. In conduit flow systems, precipitation rapidly affects the flow, traveling quickly through solutionally enlarged openings, and affecting the geochemical properties in the water (Ford and Williams 2007).

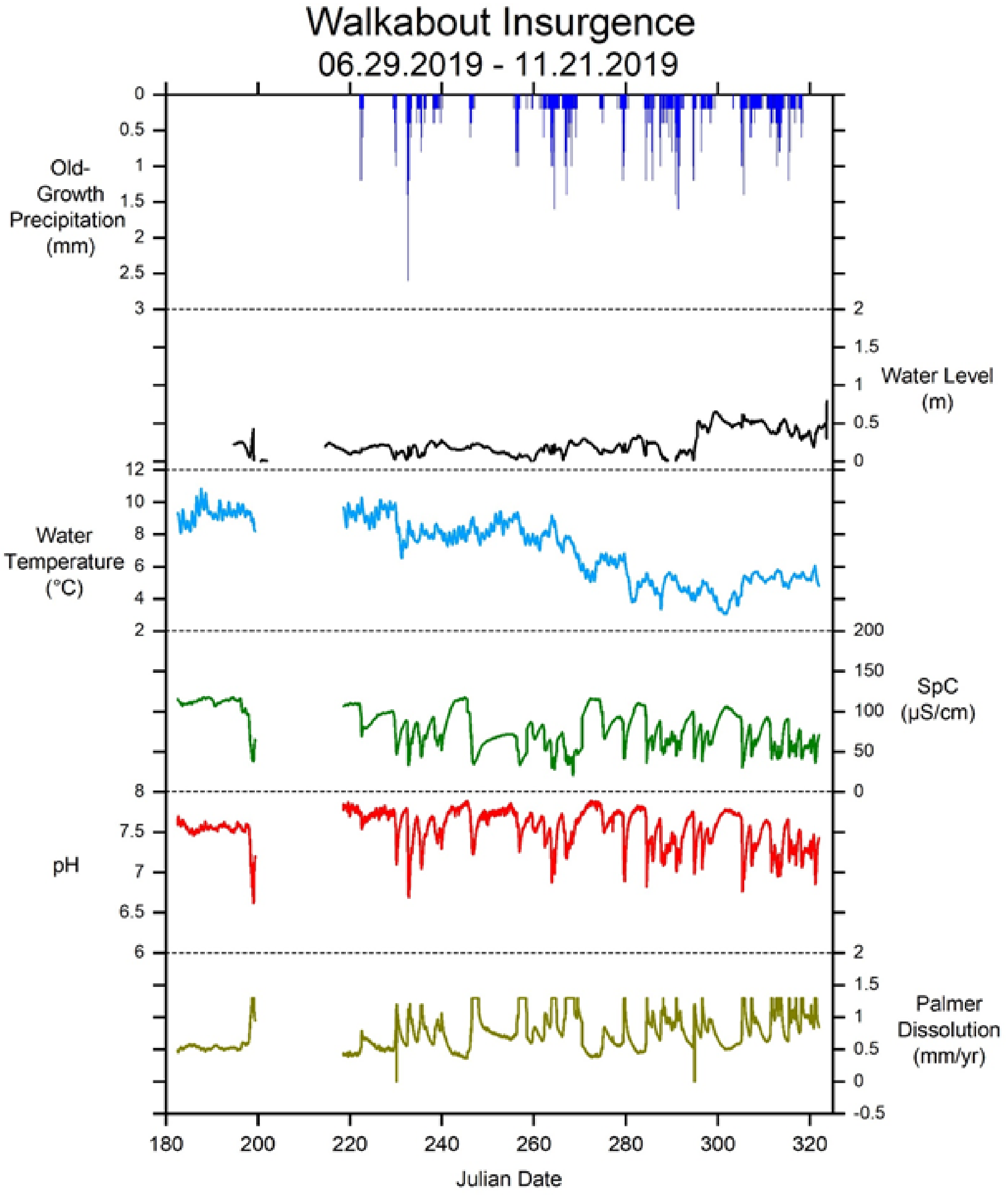


Figure 5.4: Walkabout insurgence geochemical and dissolution rate graph for the duration of the study. Gap indicates equipment failure.

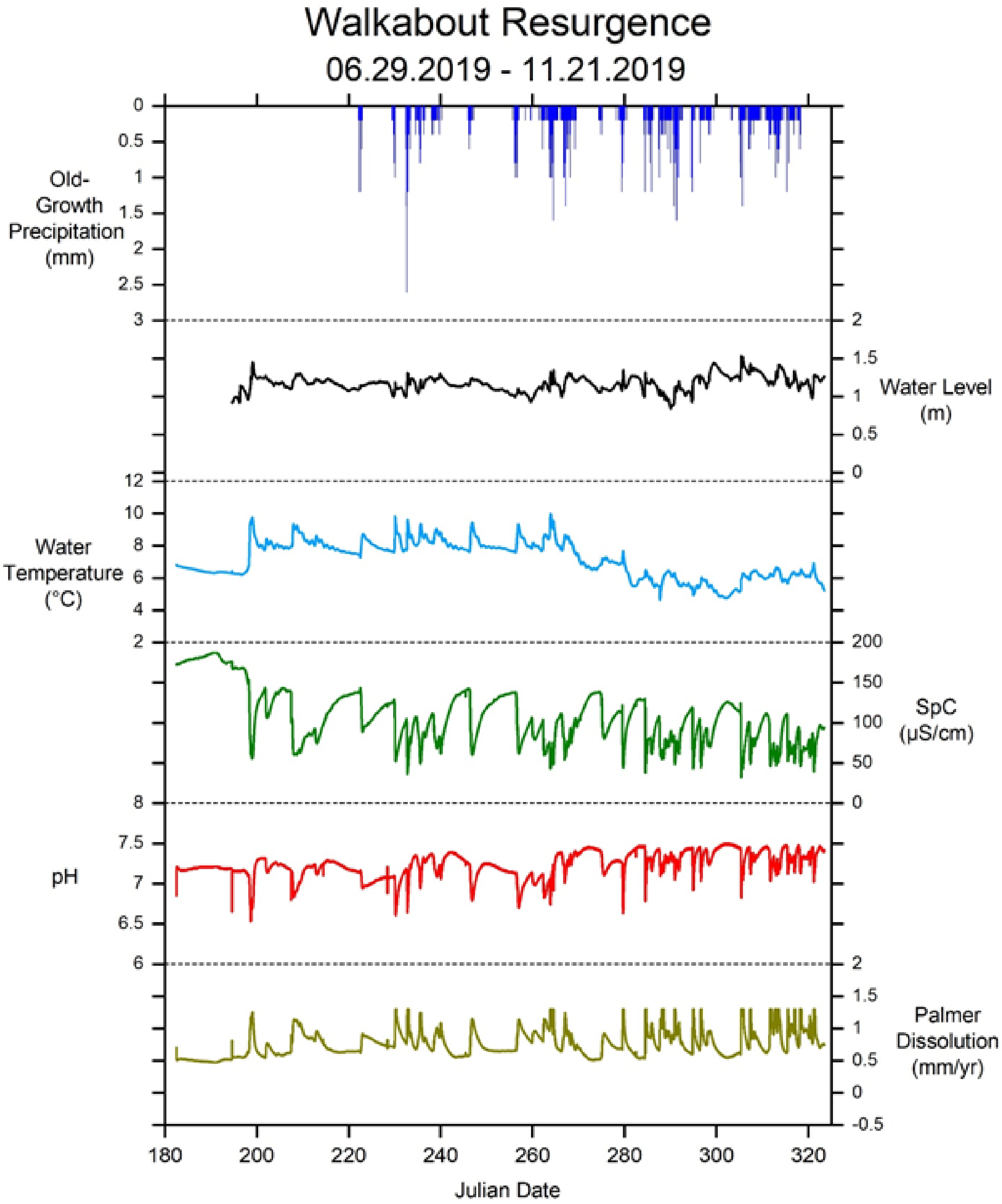


Figure 5.5: Walkabout resurgence geochemical and dissolution rate graph for the duration of the study.

5.3.2 Zina Cave

The Zina Cave baseflow, the main resurgence spring from the cave, shows different long-term geochemical responses than the Walkabout system. Intense precipitation events would cause the baseflow water level to increase subtly. The baseflow water level remained consistent during the study and diurnal temperature fluctuations were not as pronounced as they were at Walkabout Cave. Since the Zina Cave system has an overflow spring adjacent to the baseflow, once the baseflow hits a threshold in water level, the overflow would activate during precipitation events. For much of the summer, the overflow was dry until the fall/rainy season began. The baseflow water level never exceeded 1 m and had an average level of 0.58 m. Geochemically, the Zina baseflow had an average pH of 8, SpC of 183 μS/cm, and temperature of 5.7 °C (Figure 5.6).

The lack of pronounced responses may be attributed to longer water/rock time interaction that occurs in Zina due to its larger size. The main entrance to the Cave is located 377 m above sea level and the baseflow is at 85 m of elevation. From the entrance to the baseflow, the distance is roughly 1.16 km downslope. In terms of water movement from entrance to resurgence, Zina water travels an additional 0.5 km than Walkabout Cave. Additionally, Zina, unlike Walkabout, has more storage, which is flushed through the system during precipitation events. This is demonstrated as rapid increases in pH following defined precipitation events. Tongass forest geologist, Jim Baichtal, conducted a tracer dye test in the Zina Cave system, which confirmed that the water moves from input to output (Zina baseflow) in less than 24 hours. So, while water geochemistry in the

Zina Cave system may exhibit longer rock/time interaction than Walkabout Cave, the water is still moving relatively quickly.

The Zina system likely displays a combination of diffuse and conduit flow. The cave has a mainstream passage, where conduit flow likely occurs; however, there is probably more diffuse flow lower in the system as the geochemical parameters exhibit diffuse flow characteristics at the baseflow. However, there is a main sump at 120 m of depth, it is likely that water backs up at this point in the cave, therefore the water remains in full contact with the bedrock for almost 0.5 km, this could produce similar geochemical conditions to diffuse flow. In contrast to Walkabout, the water resurging at the Zina baseflow is more geochemically buffered; it does not respond as rapidly as the Walkabout system to precipitation events. Water temperature, water level, and geochemical parameters were more consistent over time and they responded slowly to precipitation events in comparison.

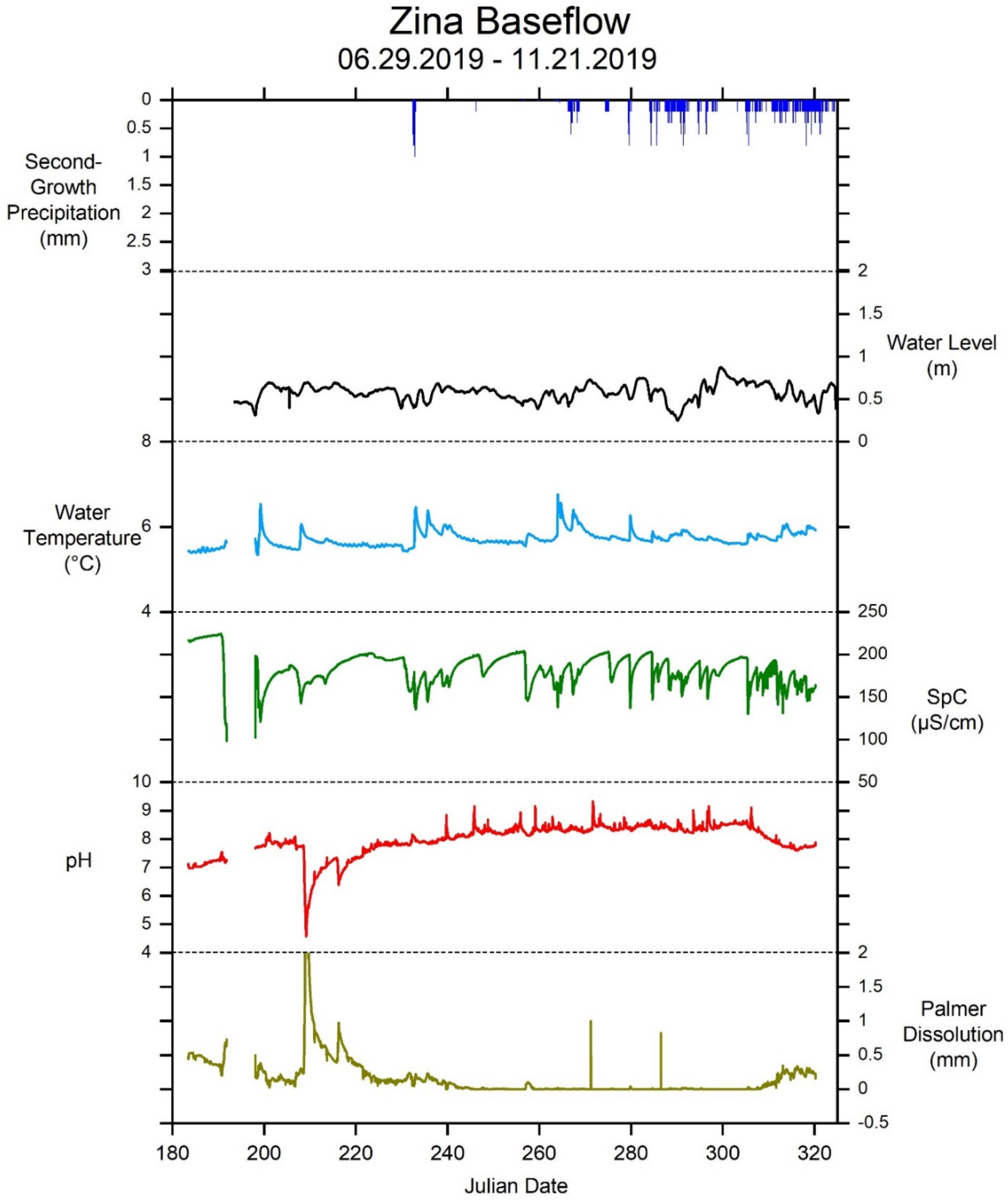


Figure 5.6: Zina baseflow geochemical and dissolution rate graph for the duration of the study.

5.4 Precipitation Events and Geochemical Responses

Precipitation events in each of the study area's watersheds can be correlated, although the intensity of throughfall varies depending on the forest canopy cover. Two precipitation events and their corresponding geochemical responses are detailed in Tables 5.2 and 5.3. Although it might stand to reason that rainy season precipitation events would be significant enough to produce higher precipitation values in the second-growth forest, this is not the case. Precipitation values remain consistent, percentage-wise, across monitored seasons, as previously noted, with canopy cover continuing to provide a significant rain barrier (Table 5.1 and Figure 5.3).

Local topography on Prince of Wales Island plays a large role in orographic storm distribution and runoff patterns given the influence of subsurface flow paths. The geomorphology of karst in this area has developed from the dissolution of limestone and marble bedrock, characterized by grikes, caves, insurgence and resurgence streams, and extensive areas where runoff does not exist on the land surface (Prussian 2007). Instead, streams and runoff infiltrate into the subsurface environment (insurgence) and may reappear kilometers away (resurgence). With annual precipitation in Southeast Alaska ranging from 254 to 508 cm, and average annual air temperatures around 7.2 °C, the climate is ideal for carbonate dissolution (Prussian 2007). For purposes of this study, storms were defined as precipitation events. Additionally, rainwater in Southeast Alaska is slightly acidic, ranging from 5.5-6.5.

The first precipitation event that was studied occurred during the dry, summer season on August 20th (JD 232). Out of all the studied events, this one in particular had the highest accumulated precipitation, 10-minute averages, and 10-minute maximums for all three sites compared to the fall, rainy season event. Precipitation was the most intense during JD 232 and 233. From JD 231-234 it rained 68.2 mm overall, according to the muskeg site. The old-growth rain gauge, where Walkabout Cave is located, recorded a total of 61 mm; the second-growth site, Zina Cave, recorded 33.2 mm during the event. The highest intensity of rainfall was recorded at the old-growth site at 2.6 mm per 10-minutes (Table 5.2), 0.8 mm more than the muskeg site. This variance could be attributed to location difference or from canopy drip, which is common in coniferous forests. However, the muskeg precipitation average remained the highest at 0.18 mm/10-minutes, with the old-growth average at 0.14 mm/10-minutes, and the second-growth average at 0.08 mm/10-minutes. These values were expected since the muskeg has no canopy interference.

Site	**Total (mm)**	**Average (mm/10-minutes)**	**Max (mm/10-minutes)**
Muskeg (Overall)	68.2	0.18	1.8
Old-Growth (Walkabout)	61.0	0.14	2.6
Second-Growth (Zina)	33.2	0.08	1.0

Table 5.2: Precipitation Event, August 20th (JD 232). Results are from August 19-22 (JD 231-234).

The precipitation event on August 20th (JD 232), was studied as a summer precipitation event, also referred to as the dry season. Walkabout and Zina are different cave systems yet have some similarities in geochemical responses from increased precipitation during the summer. Temperature response for both Walkabout and Zina increased as warmer stormwater flowed through the systems. At Walkabout, approximately 22 hours after the start of the precipitation event, the water temperature at the insurgence increased from 7.2 to 8.7 °C. The resurgence temperature increased slightly more over this time from 7.7 to 9.6 °C. Temperature increase also occurred at the Zina baseflow, but was less intense, and had a slightly delayed response time than Walkabout. Over the course of 24 hours, the Zina baseflow water temperature increased from 5.5 to 6.4 °C. The temperature increase observed at the Zina baseflow from this event was distinct, other intense rain events did not always result in a temperature increase at the baseflow.

SpC and pH values decrease in both the insurgence and resurgence in Walkabout, whereas at the Zina baseflow those parameters increased before decreasing. The decrease in SpC and pH in all the systems is attributed to the input of rainwater, which dilutes the water initially at each of these sites. Walkabout resurgence SpC values had a slightly more intense response than the insurgence. Neither the insurgence or the resurgence shows a pulse of storage water, which is seen in the SpC and pH values at the Zina baseflow. The pH response at the insurgence increases and decreases more dramatically than the resurgence due to water flowing in from the adjacent muskeg. Due to the buffering of water in the muskeg from calcareous till, the pH of the water is around 7.5 until an intense rain event flushes more acidic water into the system from the muskeg (Figure 5.7).

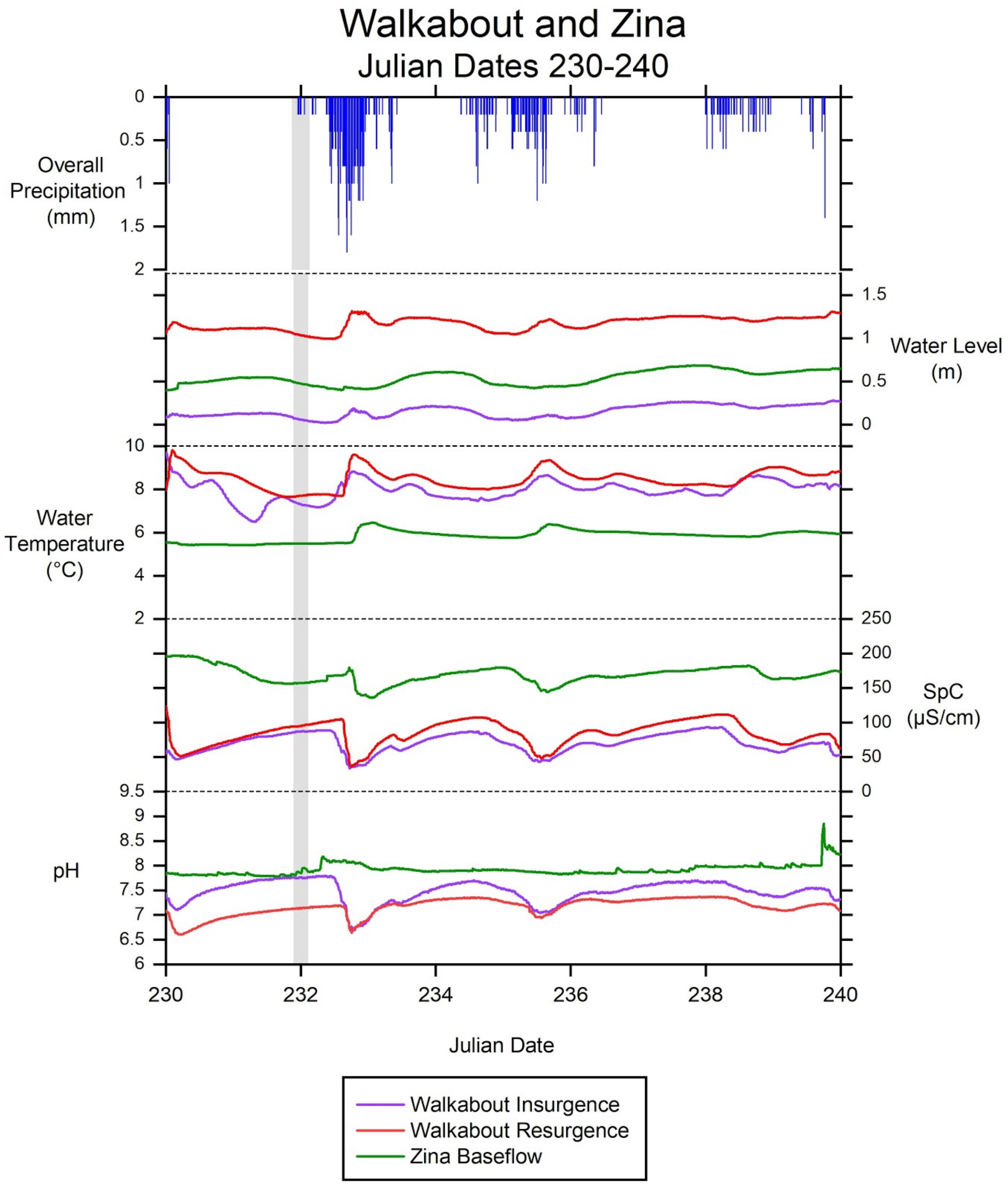


Figure 5.7: Above, the geochemical responses of all three study sites during the precipitation event that began on August 20th, JD 232 (grey vertical bar). The graph covers a 10-day duration from August 18-28 (JD 230-240).

The precipitation event that occurred on October 23rd (JD 296) was during the rainy season in the fall. Precipitation data from JD 294-298 was assessed to understand precipitation averages and intensity during the event (Table 5.3). Overall, the event resulted in 43.2 mm of rainfall. The old-growth site received 33.4 mm of precipitation and the second-growth site received 19 mm of precipitation. This event was not as intense as the previously studied summer event on JD 232. The 10-minute precipitation average at the muskeg site was 0.07 mm and the old-growth 10-min average was 0.06 mm, twice as much as the second-growth average, which was 0.03 mm/10-minutes. This precipitation event encompasses the nature of precipitation during the rainy season in Southeast Alaska and is not defined by intense spurts of rain, but rather consistent rainfall during the season.

Site	**Total (mm)**	**Average (mm/10-minutes)**	**Max (mm/10-minutes)**
Muskeg (Overall)	43.2	0.07	1.4
Old-Growth (Walkabout)	33.4	0.06	1.2
Second-Growth (Zina)	19	0.03	0.6

Table 5.3: Precipitation Event, October 23rd (JD 296). Results are from October (JD 294-298).

Geochemically, the responses during the event on JD 296 at Walkabout and Zina were not extremely different from their summer precipitation responses; however, with temperatures being cooler due to the fall weather, the influx of rainwater caused a small decrease in water temperature at Walkabout's insurgence and resurgence. In contrast, the water temperature at Zina's baseflow did not respond to increased precipitation and has reached an equilibrium, remaining at nearly 6 °C with no diurnal changes (Figure 5.8). SpC and pH values respond like they did during the precipitation event on JD 232. The parameters decreased as diluted rainwater moved through the system, with no evidence of storage water moving through Walkabout at the onset of increased rain. Similarly, SpC at Zina's baseflow also decreased due to diluted rainwater. There was a small increase in pH values, which was likely a pulse of storage water, followed by a subtle decrease. These observations indicate the response to rainwater making its way through the system after it flushes out storage water at Zina (Figure 5.8).

Overall, the differences in seasonal geochemical response based on precipitation events between the sites from summer to fall were minimal. At Walkabout, during the dry/summer season from June through mid-September, the average pH at the insurgence was 7.6 and 7.5 during the fall/rainy months from mid-September through November (Figure 5.9). At the resurgence, the summer pH average was 7.2 and 7.3 during the fall (Figure 5.9). At Zina baseflow, the summer pH average was 7.7 and 8.3 during the fall (Figure 5.9). Compared to Walkabout Cave, Zina Cave experienced a more obvious seasonal trend in pH values. The change is not as drastic due to the temperate rainforest environment; microbial activity between the months of June and November did not vary greatly in contributing CO_2 to the soil, which would be observed in pH values decreasing during summer months and increasing during the winter months. The minimal change could also be due to the time constraint of the study. It is likely that the chemistry of water, particularly the pH, would show a greater response difference between the winter and spring seasons when microbial activity is increasing after a dormant winter period.

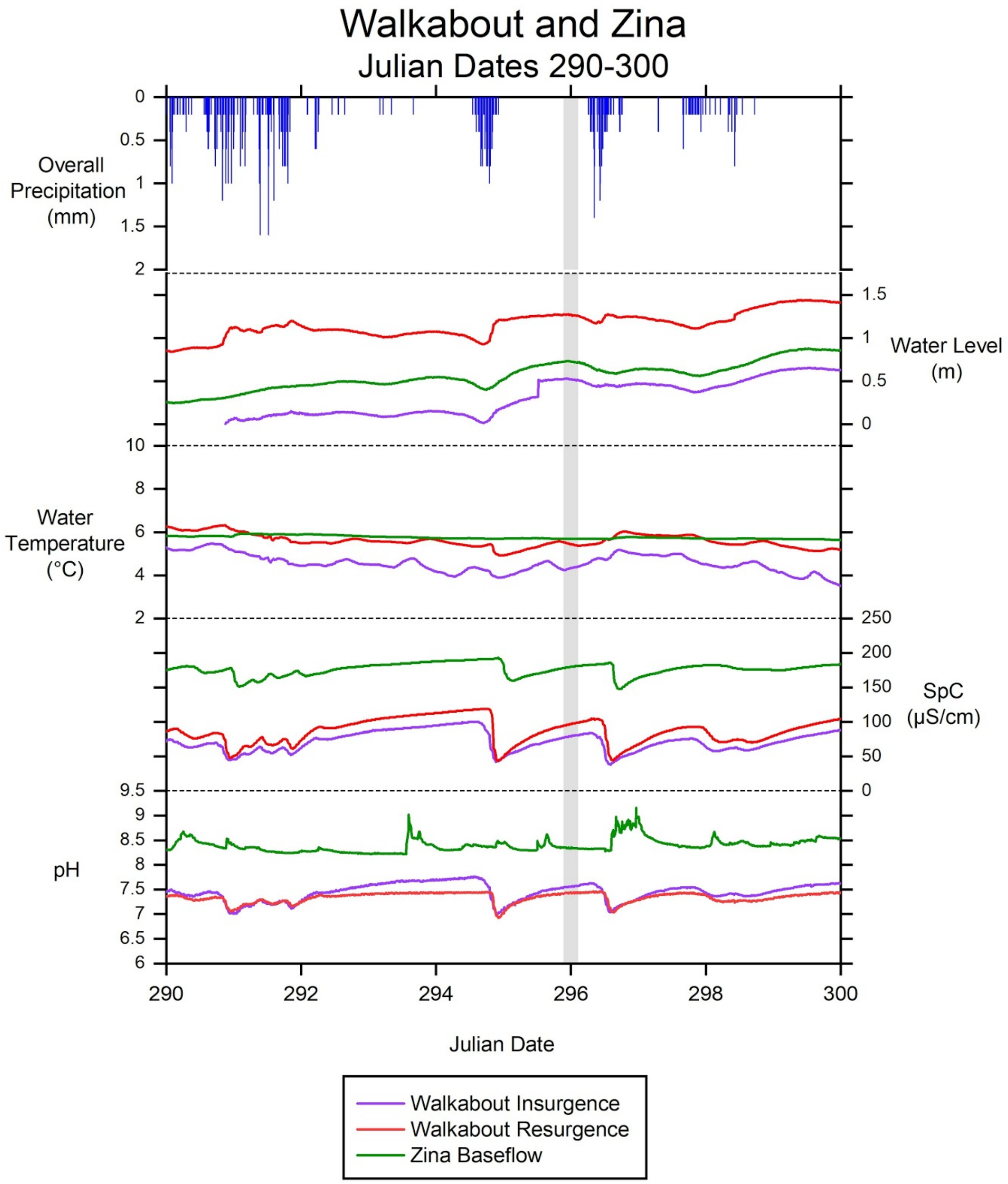


Figure 5.8: Above, the geochemical responses of all three study sites during the precipitation event that began on October 23rd, JD 296 (grey vertical bar). While it may appear that there was no precipitation on 296, this is because the event began later in the day. The graph covers a 10-day duration from October 17-27 (JD 290-300).

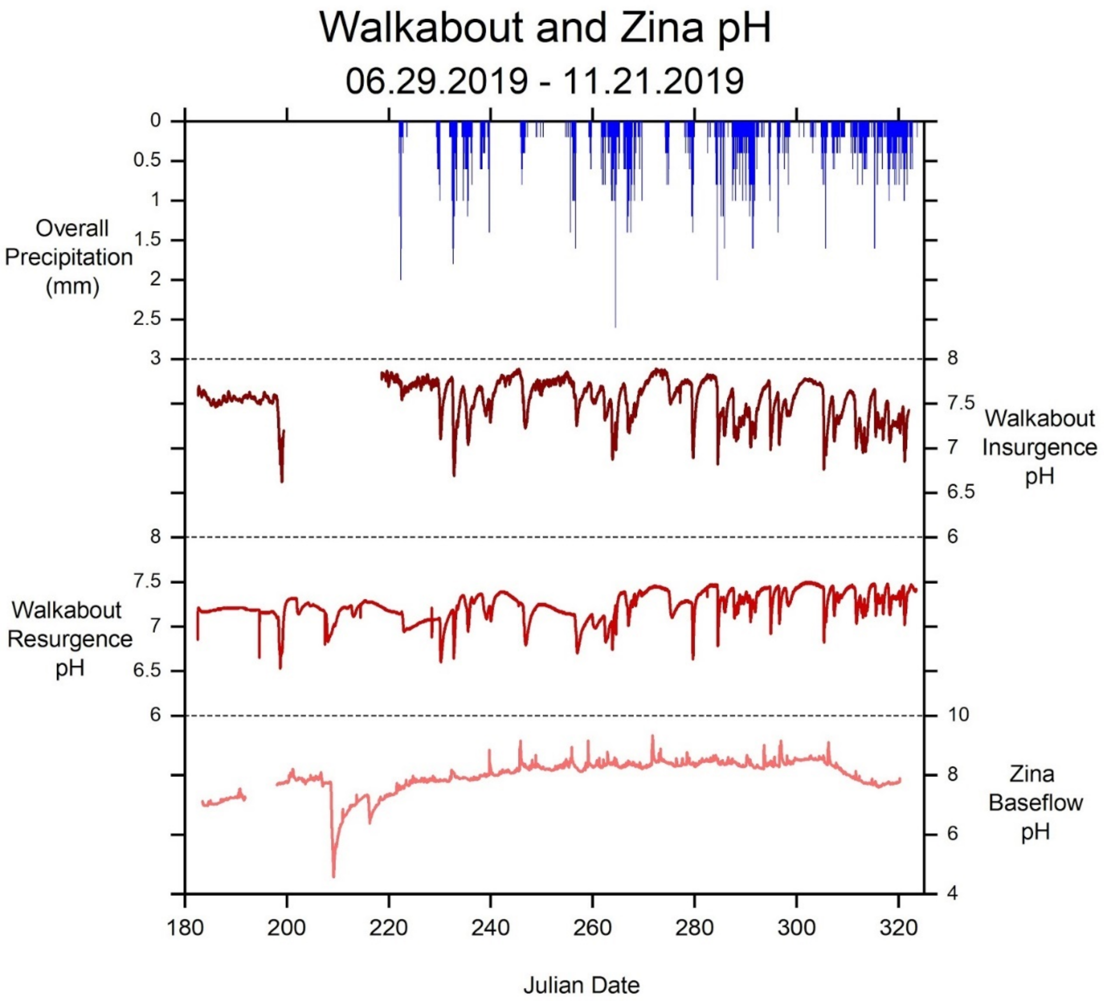


Figure 5.9: pH values for all three sites for the duration of the study. Note the different scales between Walkabout and Zina.

5.5 Estimation of Dissolution Rates

The Palmer dissolution equation was applied to both cave systems to calculate wall retreat in mm/year (yr) in 10-minute intervals for the duration of the study. The calculated dissolution rates over the five-month study period only account for that time period and do not represent total dissolution that occurred for the entire year of 2019. These averages are estimations to help understand the effects of land management, seasonal changes, and precipitation events on dissolution rates.

The estimated average dissolution rate was 0.75 mm/yr at Walkabout insurgence (Figure 5.4), 0.76 mm/yr at Walkabout resurgence (Figure 5.5), and 0.17 mm/yr at Zina baseflow (Figure 5.6). Little variation in dissolution rates between Walkabout insurgence and resurgence shows that water flowing through Walkabout Cave does not change much as it flows through the cave system. Dissolution rates at the resurgence are slightly higher than the insurgence due to other inputs along the cave's flow path or in the area between the sump and resurgence; however, given the closeness of these values between the insurgence and resurgence, it is assumed that they are the same within instrumental error. Especially since additional water enters the system beyond the insurgence from other inputs, altering water level and flow regime. Dissolution at Zina baseflow is about 20% that of dissolution at Walkabout.

Lower dissolution rates at Zina baseflow may be due to the larger size of the Zina karst system. Due to the spatial distribution of Zina Cave and the Zina baseflow resurgence, waters discharging were buffered compared to waters discharging at the Walkabout resurgence. While the rate of dissolution appears to be less at the Zina baseflow compared to Walkabout Cave, the volume of water flow is assumed to be much greater in Zina Cave; this factor will offset the concentration of dissolved calcite. Additionally, the canopy is denser in the Zina karst basin (second-growth forest) compared to the Walkabout karst basin (old-growth forest), where the canopy is more open. Canopy that is more dense limits the amount of throughfall, infiltration, and ultimately, vegetation growth in the understory. Therefore, these conditions limit the amount of aggressive water (containing dissolved CO_2) into the Zina karst system. This relationship can be observed in seasonal pH averages. At Walkabout Cave, pH values hardly responded to seasonal change, while Zina Cave average pH increased by 0.5 from summer to fall. This can be explained by the lack of vegetation and CO_2 in the second-growth forest soil and the transition into the rainy season; causing an influx of water to move through the system. Additionally, discharge data would be useful to calculate more precise dissolution rates based on different flow regimes to better understand how these dynamics are related.

In addition to calculating high-resolution dissolution rates for both systems, pre-cut limestone wafers were utilized to confirm these rates by examining the differences in weight over the duration of the study. At both the Walkabout insurgence and resurgence, three wafers were placed adjacent to the stilling well and positioned in a manner to remain completely submerged in the water. Cumulatively, the wafers at Walkabout insurgence weighed 40.50 grams (g) and were submerged for 106 days. The wafers at Walkabout resurgence weighed 37.12 g and were submerged for 111 days. After collection, the wafers were dried and reweighed. Over this period, the wafers at Walkabout insurgence lost 1.0 g of mass, resulting in an estimated dissolution rate of 3.43 grams per year (g/yr). The wafers at Walkabout resurgence lost 1.16 g of mass, resulting in an estimated dissolution rate of 3.82 g/yr. The three wafers at the Zina baseflow did not dissolve, but instead, gained mass due to the saturation of the water. At the beginning of the study, the wafers collectively weighed 39.88 g. After 113 days of immersion in the spring waters, they weighed an additional 0.05 g. Thus, the estimated precipitation rate at Zina baseflow was +0.16 g/yr (Table 5.4).

As expected, greater dissolution was seen in the old-growth site, whereas the second-growth, with less water getting to the soil and mixing with CO_2, had lower dissolution. Prodigious precipitation along with very acidic soil contributes to some of the highest dissolution rates documented. It is important to note that canopy is not the only variable in these differences, dissolution rates vary considerably in limestone and marble, corrasion, soil cover type, and soil depth. Previous research indicates dissolution rates are greater in clearcuts than old-growth forests (Allred 2004).

At the weather station and at the old-growth and second-growth microstations, three wafers were buried at 10 cm of depth into the top layer of soil adjacent to the rain gauges. At the weather station, located in the muskeg, they weighed 37.63 g. After 105 days in the acidic peat, they weighed 36.48 g for a total of 1.15 g loss in mass. These values resulted in a dissolution rate of 4.01 g/yr. The buried wafers at the old-growth microstation were deployed for 105 days, initially weighing 38.21 g, and losing an overall mass of 0.32 g, resulting in 1.10 g/yr of dissolution. At the Zina microstation, the wafers weighed 38.22 g in the beginning, and after 106 days in the soil they lost 0.14 g of mass. These values resulted in a slightly lower dissolution rate than the old-growth forest at 0.47 g/yr (Table 5.4). If the wafers had been left in place for a longer period, these rates would present more robust data to confirm the dynamics and differences between dissolution rates and their locations.

Site	Days Deployed	Total Weight (g)	Weight Difference (g)	Dissolution (g/yr)
Walkabout Insurgence	106	40.50	1.0	3.43
Walkabout Resurgence	111	37.12	1.16	3.82
Zina Baseflow	113	39.88	+ 0.05	+0.16
Weather Station (Muskeg)	105	37.63	1.15	4.01
Old-Growth (Walkabout)	105	38.21	0.32	1.10
Second-Growth (Zina)	106	38.22	0.14	0.47

Table 5.4: Limestone wafer dissolution rates in grams per year at each study site for the duration of the study.

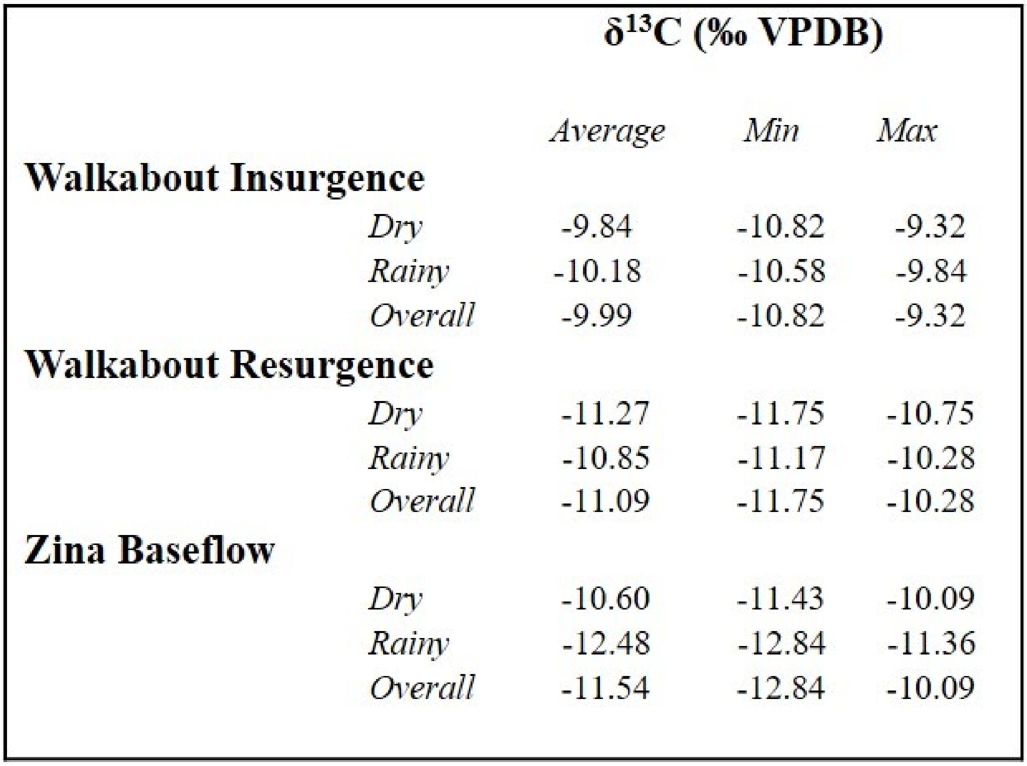
5.6 Carbon Isotopes

Stable carbon isotopes can be beneficial for understanding the source and seasonal fluctuations of carbon in water. The ratio of ^{13}Carbon in a sample of water provides insight into carbonate dissolution, carbon sourcing, and other inorganic processes that occur in recharge water, particularly when utilized in conjunction with other geochemical parameters. For this study, carbon isotope samples were collected bi-weekly at all three sites for the duration of the study, from June to November 2019.

According to the $\delta^{13}C$ values, overall, Walkabout insurgence has a less negative average than the resurgence, suggesting that the insurgence receives more carbon from carbonate dissolution (Table 5.5) (Figure 5.10). Walkabout resurgence values are more negative, indicating inputs of soil CO_2 between the insurgence and resurgence.

Walkabout insurgence and resurgence values are more distinct from one another in the dry season and start to converge in the rainy season. This trend is likely due to increased discharge and the mobilization of soil CO_2 during the rainy season. These findings are indicative of the weather patterns from this particular summer and fall season of 2019.

Water from Zina baseflow has a noticeable change in $\delta^{13}C$ values at the onset of the rainy season. Values become more negative (Table 5.5) (Figure 5.11), indicating more infiltration of rain waters into nearby soil, resulting in a flushing of soil CO_2 into the karst system. An important factor is vegetation growth, which is more abundant during the summer/dry season, when precipitation and infiltration rates are lower. Additionally, more soil CO_2 is mobilized during the onset of the rainy season. The Walkabout $\delta^{13}C$ values trend toward equilibrium during the rainy season, but Zina values continue to be low, suggesting a larger reservoir of soil CO_2 in the Zina system. These data suggest that seasonal changes in precipitation is the major contributing factor to variability in $\delta^{13}C$ values, however soil and vegetation differences within the two systems also contribute to fluctuations. This displays a shift towards a soil source as winter approaches, increased infiltration and an overall influx of water are the main drivers in this shift. However, it does not necessarily relate to a definite change in the geochemistry of the water since this is relatively small scale. Similar to the geochemical findings, the short duration of the study, and the temperate rainforest environment resulted in moderate change in seasonal trends from the summer to fall season of 2019.



		δ¹³C (‰ VPDB)		
		Average	*Min*	*Max*
Walkabout Insurgence				
	Dry	-9.84	-10.82	-9.32
	Rainy	-10.18	-10.58	-9.84
	Overall	-9.99	-10.82	-9.32
Walkabout Resurgence				
	Dry	-11.27	-11.75	-10.75
	Rainy	-10.85	-11.17	-10.28
	Overall	-11.09	-11.75	-10.28
Zina Baseflow				
	Dry	-10.60	-11.43	-10.09
	Rainy	-12.48	-12.84	-11.36
	Overall	-11.54	-12.84	-10.09

Table 5.5: Basic statistics for seasonal δ^{13}C values for
June through November 2019.

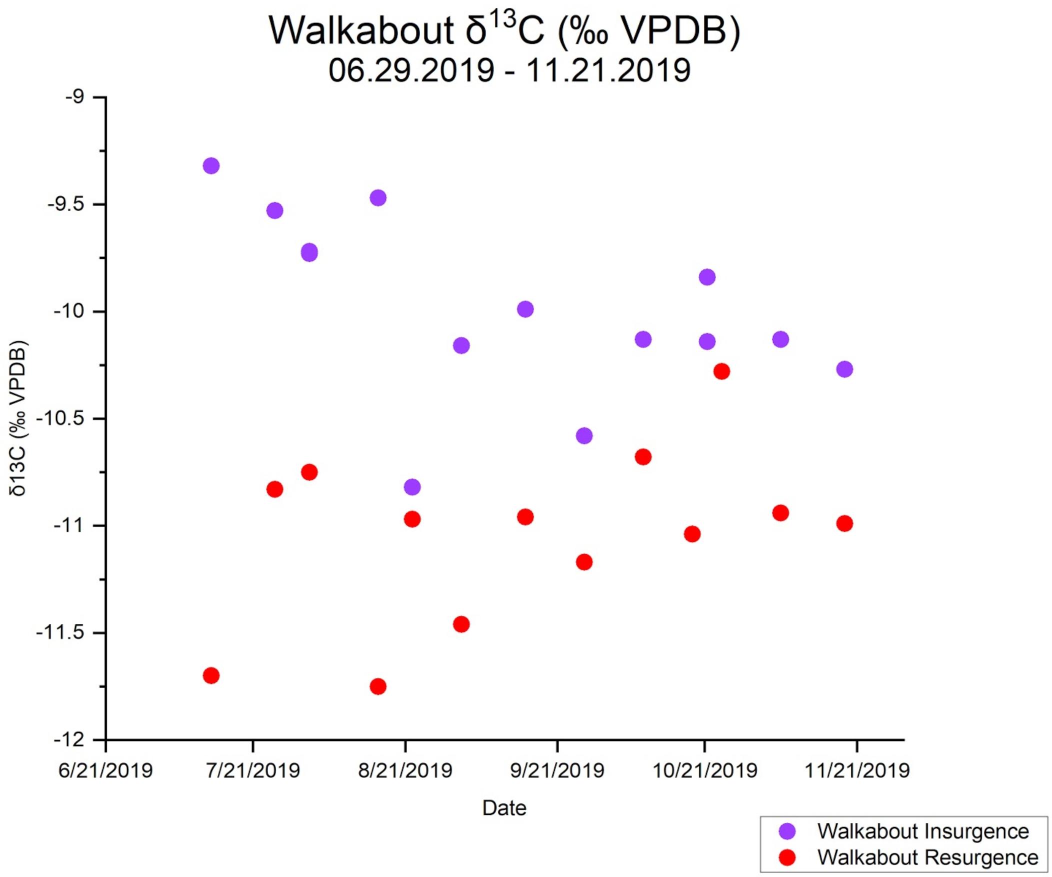


Figure 5.10: δ^{13}C values for Walkabout insurgence (purple) and resurgence (red) for June through November 2019.

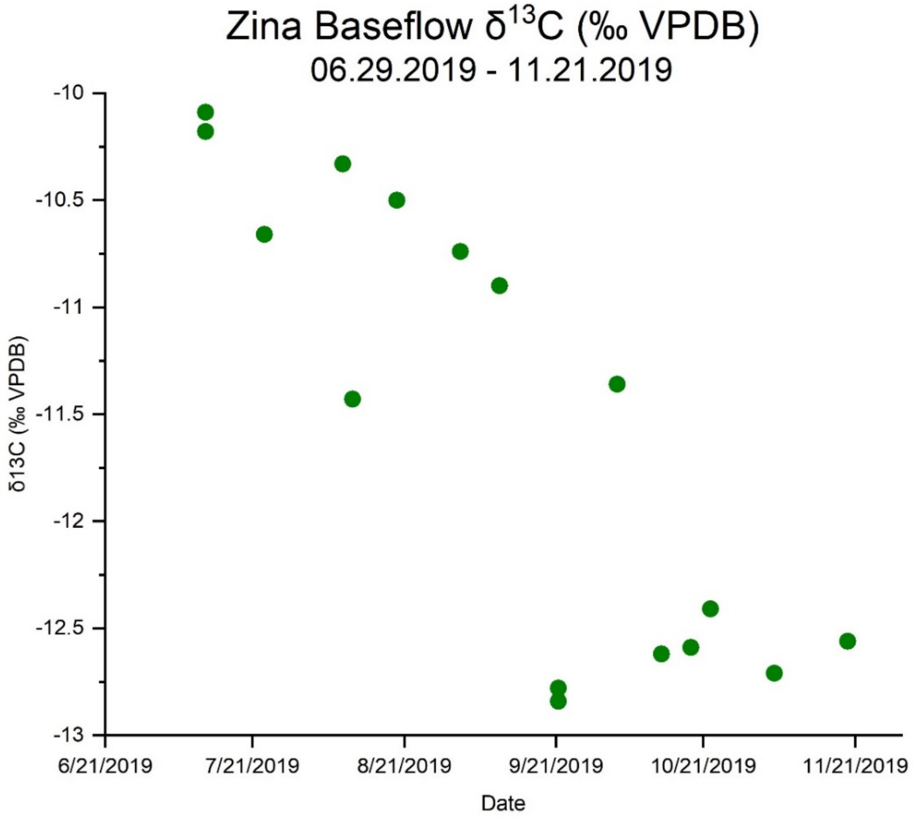


Figure 5.11: Zina baseflow δ^{13}C values for June through November 2019.

5.7 Processes Influencing Speleogenesis in the Tongass

In the Tongass, speleogenesis is influenced by land management practices, particularly timber harvest. An untouched forest in the Tongass is considered to be old-growth. Old-growth forests are characterized by spread out, open tree growth that allows for sunlight and precipitation to make its way to the forest floor, resulting in a healthy, rich understory. Alternatively, second-growth forests are the successional growth of trees after harvest, and are characterized by dense, sometimes impenetrable tree growth. The lack of canopy openness in second-growth forests results in less throughfall and little to no vegetation in the understory. It is assumed that karst systems in old-growth forests display natural karst processes while karst in second-growth is directly impacted by anthropogenic timber harvest practices.

Through the analysis of carbon sourcing and carbonate dissolution kinetics in two separate cave systems, the influence of timber harvest is apparent. CO_2 transport rates in the epikarst zone are often driven by hydrogeochemical responses, which influences carbonate dissolution and conduit formation (Jackson and Polk 2019). Based on precipitation rates, geochemical variation, dissolution rates, and $\delta^{13}C$ values between the old-growth (Walkabout Cave) and second-growth (Zina Cave), it is evident that these variables can affect speleogenesis processes. While the findings from this study are subtle, they require long term monitoring to back up results.

5.7.1 Canopy Cover, Seasonality Influences, and Dissolution

Canopy cover influences both vegetation growth in the understory, as well as throughfall rates, thus directly impacting the production of aggressive water capable of calcite dissolution in cave systems in the Tongass. Canopy cover, precipitation rates, and dissolution between the old-growth and second-growth sites varied considerably during the summer and fall seasons of 2019. At the old-growth forest site, canopy openness was 55%, total precipitation was 598 mm, and Walkabout Cave had an estimated dissolution rate of 0.75 mm/yr. At the second-growth site, canopy openness was 18%, total precipitation was 266 mm, and Zina Cave had a dissolution rate 0.17 mm/yr. Though, it is assumed that soils in the second-growth forest have higher concentrations of CO_2 due to denser vegetation and the lack of throughfall, thus mobilization of soil CO_2, cause waters discharging at Zina baseflow to not be as aggressive as waters at Walkabout.

Conversely, more canopy openness allows for more throughfall, thus increased mobilization of soil CO_2 in the Walkabout system.

Research on karst indicates vegetation productivity directly relates to seasonal changes in soil CO_2 (Breecker et al., Jackson and Polk, 2019). Due to the temperate nature of the Tongass, there is not a clear transition to dormancy regarding vegetation. The undergrowth does die-off during the winter, but the coniferous trees do not go dormant. Therefore, CO_2 production in the Tongass National Forest does not follow the same trends as humid subtropical karst systems. Geochemical data show little change as the seasons transition; however, carbon isotopes show that soil CO_2 becomes more mobilized during the rainy season. Seasonal CO_2 mobilization is controlled by precipitation rates and intensity, rather than seasonal vegetation changes.

At Walkabout, where the canopy is more open, the pH on average changed very little from summer to fall. Similarly, $\delta^{13}C$ values decreased in the fall at Walkabout, resulting in more soil CO_2 contributing to carbon in the system, however, $\delta^{13}C$ values at Zina were more negative than Walkabout in the fall, thus there is a greater reservoir of soil CO_2 in the second-growth basin. Mobilization of soil CO_2 in Zina increases during the rainy season as more precipitation can infiltrate into the soils. At Zina, the pH of the baseflow water decreased as fall/winter approached in conjunction with decreasing $\delta^{13}C$ values, which further indicates a mobilization of soil CO_2 in the rainy season. While more CO_2 may be present in the Zina Cave system during the summer to fall transition, this can be directly correlated to more intense precipitation events that penetrate the second-growth canopy more so than in summer months. This observed relationship is not necessarily related to vegetation growth vs. dormancy but related to seasonal precipitation shifts and the amount of throughfall and soil moisture conditions. These observations are useful in further understanding CO_2 transport into caves, which is not widely studied (Breecker et al. 2012).

High-resolution hydrogeochemical data from multiple data loggers and isotope analysis from collected water samples reflected processes that indicate significant contribution to bedrock dissolution. With respect to CO_2-budgets and seasonal variations, research indicates that in-situ site conditions are important variables (Hélie, Hillaire-Marcel, and Rondeau 2002), as evidenced by differing forest data from Walkabout and Zina regardless of proximity. Some factors contributing to estimated dissolution rates are seasonal and local geologic landforms (muskegs), CO_2 supply, seasonal shifts in precipitation and flow regimes, intensity of duration of precipitation events, and throughfall.

By further understanding the multitude of variables that contribute to dissolution dynamics under different flow regimes (not studied in this study), climatic processes, local geology, and land use that contribute to this, a more holistic perspective of past and future speleogenesis in the Tongass can be acquired. The results of this study indicate site-specific responses with respect to both geochemical and $\delta^{13}C$ changes, regardless of karst landscape similarities and proximity. The results indicate that further comparative analyses between old-growth and second-growth landscapes is needed to delineate the impact of land use and seasonality on geochemistry and carbon sourcing during karst processes.

Chapter 6: Conclusions

Prince of Wales Island is a remote study area, where precipitation is prodigious and the karst ecosystems face encroachment from unsustainable activities, such as timber harvest. This study shows that, in the case of two cave systems, measurable differences in canopy cover, throughfall rates, and carbonate dissolution exist between old-growth and second-growth forests. The results of this study add to the body of research addressing the growing need for sustainable development practices and for better understanding and management of complex karst systems (Guo and Lin 2016).

The major factors that differentiate the two forest settings include canopy cover, throughfall, land-management practices, and local geology. Additionally, seasonal fluctuations were found to show moderate change, due to the temperate rainforest environment. Precipitation data from this study provided a more thorough and holistic understanding on how precipitation affects karst systems regarding canopy density and throughfall. The relationship between canopy density and throughfall influences how karst systems respond and evolve regarding geochemical response, recharge, flow regimes, and dissolution rates, particularly between old- and second-growth forests. The muskeg (control site) accounted for the most precipitation since it had no canopy interference. The old-growth site received 72% of the total precipitation compared to the open-muskeg, and the second-growth site received 32% of the total precipitation compared to the open-muskeg.

At Walkabout Cave, pH values at the insurgence were expected to be acidic due to the proximity of the muskeg, however the calcareous till blanket buffered the waters before entering the insurgence. Due to additional inputs between Walkabout insurgence and resurgence, pH values were slightly more acidic at the resurgence. Overall, there was not extreme geochemical differences between the Walkabout insurgence and resurgence. Alternately, the Zina Cave baseflow waters were buffered in comparison to Walkabout Cave. Rapid precipitation response in the old-growth forest, in contrast to the second-growth forest, highlighted differences in canopy openness. Estimated dissolution rates resulted in more dissolution occurring at Walkabout Cave than Zina Cave.

Based on high-resolution geochemical data, Walkabout insurgence and resurgence had an estimated dissolution rate of 0.75 mm/yr, Zina baseflow dissolution was 20% of that, at 0.17 mm/yr. Some factors that contribute to the concentration of dissolved calcite is the volume of water (assumed to be greater at Zina) and canopy density. Since second-growth canopy is denser, this limits the amount of throughfall, infiltration, and vegetation growth in the understory. Ultimately, these conditions limit the amount of aggressive water (containing dissolved CO_2) into the Zina Cave system.

Similarly, the major contributing factor to variability in $\delta^{13}C$ values was seasonal changes in precipitation. However, it is important to note that soil and vegetation differences within the two systems also contribute to fluctuations. This displays a shift towards a soil source as winter approaches, increased infiltration and an overall influx of water are the main drivers in these seasonal $\delta^{13}C$ shifts. At Walkabout, the insurgence received more carbon from carbonate dissolution than the resurgence based on $\delta^{13}C$ values. Whereas the resurgence received more CO_2 from additional inputs of soil based on the more negative $\delta^{13}C$ values. Zina baseflow $\delta^{13}C$ values had a more noticeable change at the onset of the rainy season due to the flushing of soil CO_2 into the cave system, this trend continued for the duration of the study, suggesting a larger reservoir of soil CO_2 in the Zina Cave system. These findings in conjunction with the geochemical data confirm that the moderate seasonal change in the temperate rainforest environment and the time constraint of the study resulted in a subtle seasonal trend from the summer to fall in 2019.

Key elements of the Tongass National Forest Land Management Plan for karst focus on its open nature and its ability to transport water, nutrients, soil, debris, and pollutants into underlying hydrologic systems. Results from this study reinforce the need for continued focus on karst protection given the evidence of throughfall variation in relation to management and changes in dissolution rates. This data points to the threats posed by unsustainable economic and industrial activities, such as timber harvest, on karst leading to the degradation of its environmental value and the quality of a unique non-renewable natural resource. It would be beneficial for future studies to obtain data from several different input areas into the karst system, especially at Walkabout Cave. Collecting additional long-term longitudinal precipitation data [e.g., summer and winter] to confirm these findings, especially given current annual fluctuations in climate, seasonal variations, and overall precipitation trends could provide further valuable insights. Lastly, enhancing understanding of the processes affected by human induced landscape degradation on karst development is critical as the planet moves toward a future facing unmitigated environmental threats of historic proportion.

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