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Storm Response and Water Balance of Temperate Rainforest Karst Watersheds: Tongass National Forest, Alaska

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A Thesis
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Master of Science

By
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I dedicate this work to my parents.
This thesis is a first step towards understanding the complex relationships between timber harvest and all components of karst systems in the temperate rainforest environment. In beginning to characterize and develop water budgets for these karst systems, this work provides an initial building block for a paired catchment study using Canyon Block and Windgate Watersheds, which could potentially be set aside as research natural areas in the Tongass National Forest. It is hoped that in the future, this data combined with further research will provide a solid foundation for defining an Estimated Clear Cut Allowance on karst areas, limiting impact on this fragile and unique resource.

Chapter 1 provides an introduction to the relationship between timber harvest and karst management on the Tongass, and an introduction to this project. Chapter 2 is a brief description of the geography and geomorphology of southeast Alaska, Prince of Wales Island, and the two study watersheds. Chapter 3 outlines the methodology and analysis. Chapter 4 gives the results in the form of a brief description, graphs and charts. Chapter 5 provides a discussion of the implications of these results and a conclusion.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>i</td>
</tr>
<tr>
<td>PREFACE</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>vii</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1. BACKGROUND AND RATIONALE</td>
<td>3</td>
</tr>
<tr>
<td>Temperate Rainforest Karst and Timber Harvest</td>
<td>3</td>
</tr>
<tr>
<td>Managing Karst as a Resource in southeast Alaska</td>
<td>4</td>
</tr>
<tr>
<td>Experimental Catchment Projects</td>
<td>8</td>
</tr>
<tr>
<td>High Resolution Karst Studies</td>
<td>10</td>
</tr>
<tr>
<td>2. DESCRIPTION OF STUDY AREAS</td>
<td>14</td>
</tr>
<tr>
<td>Southeast Alaska and Prince of Wales Island</td>
<td>14</td>
</tr>
<tr>
<td>Geology</td>
<td>18</td>
</tr>
<tr>
<td>The Study Watersheds</td>
<td>21</td>
</tr>
<tr>
<td>3. METHODS AND MATERIALS</td>
<td>23</td>
</tr>
<tr>
<td>Hydrogeologic Inventory and Watershed Delineation</td>
<td>23</td>
</tr>
<tr>
<td>Dye Trace</td>
<td>24</td>
</tr>
<tr>
<td>Precipitation</td>
<td>30</td>
</tr>
<tr>
<td>Discharge</td>
<td>35</td>
</tr>
<tr>
<td>Hydrograph Recession, Baseflow Separation, and Water Balance</td>
<td>38</td>
</tr>
<tr>
<td>4. RESULTS</td>
<td>41</td>
</tr>
<tr>
<td>Storms</td>
<td>41</td>
</tr>
<tr>
<td>Hydrograph Analysis</td>
<td>45</td>
</tr>
<tr>
<td>Water Balance</td>
<td>51</td>
</tr>
<tr>
<td>5. DISCUSSION AND CONCLUSIONS</td>
<td>55</td>
</tr>
<tr>
<td>Aquifer Analysis</td>
<td>55</td>
</tr>
<tr>
<td>Delineation Assessment</td>
<td>58</td>
</tr>
<tr>
<td>Conclusions</td>
<td>59</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1 – Summary of Storms in Canyon Block,
  October 4th – November 4th 2006.................................................................41
Table 2 – Summary of Storms in Windgate,
  October 4th – November 4th 2006.................................................................42
LIST OF FIGURES

Figure 1 - Southeast Alaska and the Tongass National Forest ........................................... 15
Figure 2 - Canyon Block Watershed .................................................................................. 16
Figure 3 - Windgate Watershed ......................................................................................... 16
Figure 4 - Prince of Wales Island ....................................................................................... 16
Figure 5 - Areas of Carbonate Bedrock in Southeast Alaska ............................................. 20
Figure 6 - Canyon Block Dye Results ................................................................................ 27
Figure 7 - Windgate Dye Trace Results .............................................................................. 28
Figure 8 - Gauge Locations in Canyon Block Watershed .................................................. 33
Figure 9 - Gauge Locations in Windgate Watershed ........................................................... 34
Figure 10 - Stage vs. discharge rating curve for Canyon Block Watershed ...................... 37
Figure 11 - Stage vs. discharge rating curve for Windgate Watershed ............................... 37
Figure 12 - Precipitation in Canyon Block vs. Windgate, Oct. 3rd – Nov. 3rd 2006 .......... 43
Figure 13 - Precipitation, discharge, specific conductivity, and spring temperature in Canyon Block, October 3rd – November 3rd ........................................ 44
Figure 14 - Precipitation, discharge, specific conductivity, and spring temperature in Windgate, October 3rd – November 3rd ................................... 46
Figure 15 - Canyon Block #1: precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 4th – 9th ..................... 47
Figure 16 - Windgate #1: precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 4th – 9th .......................... 48
Figure 17 - Storm recession limb linear fit for Canyon Block ............................................ 49
Figure 18 - Storm recession limb linear fit for Windgate ...................................................... 49
Figure 19 - Canyon Block #2: Precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 11th – 15th ......................... 49
Figure 20 - Windgate #2: Precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 11th – 15th ........................... 50
Figure 21 - Storm recession limb linear fit for Canyon Block for storm #2 ....................... 51
Figure 22 - Storm recession limb linear fit for Windgate for storm #2 ............................... 52
Figure 23 - Baseflow separation for the study period in Canyon Block ............................ 53
Figure 24 - Baseflow separation for the study period in Windgate .................................... 54
ABSTRACT

The Tongass National Forest in southeast Alaska contains 2,176 square kilometers of karst. As part of the evolving Tongass Land Management Plan, research into the function of karst systems is crucial in understanding how forest management affects not only karst areas but also surrounding ecosystems. Dye trace and water balance results in two watersheds on the north end of Prince of Wales Island demonstrate the difficulty in containing the effects of management, as water can enter karst catchments from unknown sources at different flow regimes. A dye trace was conducted in Windgate and Canyon Block watersheds. Two sinking streams were traced to one resurgence spring in Canyon Block, and four sinking streams were traced to one resurgence spring in Windgate. Water balance data calculated for the entire study period and individual storm events suggests that Windgate has been sufficiently delineated. Data from the study period and storm event water balance calculations for Canyon Block suggest that at high flow discharge is pirated into Canyon Block from another system. High resolution monitoring in each catchment show that there is no significant delay between the increase in discharge and the arrival of direct runoff, as evidenced by the
quick decrease in specific conductance. This could result in a quick transmission of sediment and contaminants through the karst system into downstream salmon habitat.

KEYWORDS: karst, dye trace, high resolution spring monitoring, water balance
GEOGRAPHIC DEFINITIONS: United States of America, Alaska, Tongass National Forest, Prince of Wales Island, Thorne Bay Ranger District
CHAPTER I
BACKGROUND AND RATIONALE

Temperate Rainforest Karst and Timber Harvest

Temperate rainforest karst is a unique ecosystem, existing primarily in Patagonia, Chile; Vancouver and Queen Charlotte Islands, Canada; Tasmania; South Island of New Zealand; and southeast Alaska, USA. Extremely high levels of precipitation; steep hydraulic gradients; massive old growth tree volume and diverse communities of plants and animals characterize these karst regions (Aley et al. 1993, Beedle 1997, Baichtal 2003). “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” (Baichtal 2003). Only a small number of studies represent temperate rainforest karst regions in karst research, and government and private agencies manage for multiple uses such as timber harvest, agriculture, and mining in these distinctive areas.

In the United States, timber resources were harvested at an increasing rate after World War II due to the mechanization of logging systems and increasing need. “Between 1945 and 1969, the annual allowable harvest officially rose from 40 million board feet to 200 million” (Bolle 1989). In Southeast Alaska, this increase in allowable harvest created a favorable environment for the establishment of the pulp industry. The Tongass National Forest awarded four 50-year timber sales over the next 20 years in support of the pulp industry, totaling in a proposed 23 billion board feet (U.S. Forest Service 1974).

Due to the productivity of their old growth forests, karst regions were some of the
most heavily harvested portions of the temperate rainforest during this period. “It appears that high timber yields per acre and accessibility have led to a highly disproportional amount of timber harvest on karstlands in the [Ketchikan Area]” (Aley et al. 1993). Over 386 km$^2$ of timber were harvested in karst areas on Prince of Wales Island, Alaska alone during the 20$^{th}$ century (Baichtal 2006). The United States Forest Service by charter was a multiple use agency; however during this period timber production became the focus, and clear cutting became the dominant method.

**Managing Karst as a Resource in Southeast Alaska**

The importance of karst areas as separate subsurface hydrologic systems was recognized during the early part of the 20$^{th}$ century. Jovan Cvijić’s work is a major contribution to karst hydrology, beginning with his 1893 publication “*Das Karstphänomen*”. This work outlined the existence of karst watersheds as separate and unique systems from surrounding surface catchments (Ford 2007). Drawing from the works of Grund (1903, 1914) and Katzer (1909), Cvijić 1918 defined three distinct zones of subsurface water movement, which today are the subcutaneous, vadose, and phreatic (Sanders 1921, Ford 2007). By the 1920s, karst landscapes were recognized as complex subsurface flow conduits in various stages of a process of erosion, drawn from the geomorphic cycle described by W. M. Davis (1899).

After 1930 and until the 1960s, investigations in karst hydrogeology were primarily focused on speleogenesis through water flow and dissolution geochemistry (Meinzer 1923, Davis 1930, Thrailkill 1968). Early analysis of spring hydrographs in relation to specific recharge events was conducted to understand the nature of karst subsurface flow (Ashton 1966, Shuster and White 1971, Knisel 1972, Williams 1977).
The inception of modern environmental policy concerning multiple use and a whole ecosystem approach to natural resource management occurred in the 1960s and 70s. During this period, researchers made great progress in karst studies through the advancement of tracer studies, chemical and hydrological methods, and cave exploration (White 2002). Stakeholders, scientists, and resource managers began to recognize the environmental problems that human civilization presented to karst aquifers. Advances in technology together with this growing awareness led to studies concerning problems such as accessibility to water resources, sinkhole collapse in urban areas, and groundwater contamination (Stringfield and LeGrand 1969, LaMoreaux 1991, Urich 2002). Most notably, storm pulses were connected to a dramatic decrease in water quality through the transport of agricultural and urban pollutants (Crawford 1982, Hallberg et al. 1985).

In the United States, several Acts resulted from this environmental movement, including the Multiple Use Sustained Act of 1960 (MUSYA), the Forest and Rangeland Renewable Resources Act of 1974 (RPA), the National Forest Management Act of 1976 (NFMA)(as a direct result of the Bitterroot controversy) and the National Environmental Policy Act of 1970 (NEPA) (Kaiser 2006). As part of NFMA, National Forests were required to develop a total “forest management plan” outlining how in the future they would consider options to best protect all resources during management activities. The Tongass Land Management Plan (TLMP) was introduced in 1979. In 1993, due to ever evolving environmental concerns, the Forest Service began the process of revising the 1979 TLMP.

The Federal Cave Resources Protection Act of 1988 evolved from rising concerns due to environmental studies in karst aquifers. It required that significant caves be taken
into consideration during any management action on federal lands. In southeast Alaska, exploration and research made possible by the advances in the 1970s demonstrated the significance of caves in that region. The caves were found to be rich in paleontological and cultural resources (Carlson 1993, Dixon et al. 1997). Researchers found through inventories that the caves were used by a number of mammal species, birds and as critical roosting and hibernating habitat for five species of bats (Baichtal and Swanston 1996).

Invertebrate collections from over three hundred cave and resurgence sites yielded at least five troglobitic and forty troglophilic invertebrate species, three of these newly discovered (Carlson 1994 and 1996). El Capitan Pit, the deepest limestone pit in the United States, was mapped at 182.39 meters, and El Capitan Cave, the longest cave in Alaska was mapped at approximately 3.22 kilometers (Lewis 1997). As a result, the Forest Service included the Karst and Cave Resource Significance Assessment of 1993 as part of the TLMP revision process.

This Assessment documented that not just caves, but also the karst systems of southeast Alaska were significant, and noted them to have a beneficial relationship with not only timber but also Coho salmon (*Oncorhynchus kisutch*) fisheries – two of the most important industries in the region. (The link between Coho salmon fisheries and alkali karst waters was confirmed in Bryant et al. 1998.) Timber harvest practices on the Tongass were thought to have negatively affected karst, timber, and fisheries resources through increased sedimentation in caves, dense restocking of forests on karstlands, and increased logging debris in runoff from karst watersheds (Aley et al. 1993). The panel charged the Forest Service with integrating management of karstlands into general land management including inventories of karst features, recharge area delineations,
vulnerability mapping, maintenance of high productivity fisheries in karst streams, and
supporting future karst research (Aley et al. 1993).

The 1997 TLMP incorporated a karst management strategy in accordance with
Aley et al.’s recommendations in 1993, including integration of continuing research in
southeast Alaska’s karst. The management strategy had four phases: “identification of
potential karst lands, inventory of the karst resources, delineation of the karst hydrologic
system(s) and catchment area(s), and assessment of the vulnerability of the karst terrain
to the proposed management activity” (Baichtal 1997). Approximately 1,870 km² of
carbonate bedrock were located in lands administered by the U.S. Forest Service in the
Tongass National Forest. Due to fractures in the rock, high annual precipitation, and
adjacent acidic peatlands, karst had developed in nearly all areas of carbonate bedrock.
The highest concentrations of solution caves in Alaska were found in the Ketchikan area,
on the north end of Prince of Wales Island.

In the 21st Century, the Tongass again began to revise the forest management
plan, and changes to the karst management strategy were developed. The karst
management strategy had been implemented on two timber projects in highly developed
karst areas (Lab Bay and Heceta Sawfly Salvage) with mixed results. Local stakeholders
documented concerns with the implementation of 1997’s karst standards and guidelines,
specifically in regards to the Heceta Sawfly Salvage Sale (Lewis 1997). The Forest
Geologist commented that, “due to the limited experience level of resource specialists
field checking the proposed harvest units it was possible that the karst management
strategy had not been fully implemented in [the Heceta Sawfly Sale]” (Baichtal 1997),
unlike the Lab Bay Project. In 2002, a panel was contracted by the Forest Service to
assess the implementation of the Karst Standards and Guidelines established in the 1997 TMLP and to analyze proposed changes.

The Karst Review Panel found that generally the implementation of Karst Standards and Guidelines had ensured a high level of protection for karst resources; however they recommended a higher level of training for karst specialists and identified some revisions to the proposed changes (Griffiths et al. 2002). The Karst Review Panel’s largest contribution was their recommendation for assessing autogenic (karst) recharge areas. As opposed to the highly ordered pattern of surface drainage, the complex subsurface hydrology of karst systems demands multifaceted considerations when conducting a karst watershed assessment (White 1988). Griffiths et al. 2002 identified this limitation and could not “recommend a single catchment area strategy to cover the array of catchment combinations”, recognizing the distinctiveness of each karst system and recommending that it be treated as a system, not a series of individual features.

Experimental Catchment Projects

Experimental paired or individual catchment studies are the chief quantitative format for studying the effects of afforestation and deforestation on water yield changes in watersheds (Hibbert 1967, Bosch and Hewlett 1982, Hornbeck et al. 1993, Stednick 1996, Sahin and Hall 1996, Brown et al. 2005). These studies are generally accomplished through comparing measured parameters of a hydrologic water budget pre and post management, or between one control catchment and one catchment that has been managed. Results from comparing all studies show that in general, deforestation on a scale greater than 20 percent of the watershed area increases water yields; afforestation decreases water yields (Brown et al. 2005). The results, however, are highly variable
depending upon several site-specific variables such as geographical location, catchment size, timber harvest methods, soils, and geology (Harr and McCorison 1979, Hibbert 1967).

Timber harvest effects in the Pacific Northwest area have been studied through experimental catchment studies by several authors, most notably those affiliated with the H.J. Andrews Experimental Forest in Oregon (Harr and McCorison 1979, Rothacher 1965 and 1970, Rothacher et al. 1967, Jones 2000, Jones and Post 2004). In southeast Alaska, these studies have focused on precipitation and effects of logging on surface streams and fisheries habitat. Two paired catchment studies occurred in southeast Alaska, which occurred from 1949 through 1978, and determined that after timber harvest there was an increase in large woody debris in Maybeso Creek (James 1956, Bryant 1980).

Work done in karst regions during the last twenty years has found that timber harvest can lead to soil erosion and permanent deforestation through vertical migration of nutrients into subsurface passages (Harding and Ford 1993, Kiernan 1993, Lichon 1993). In temperate rainforest karst, experimental catchments studies occurred on Vancouver Island, British Columbia, Canada (Harding and Ford 1993); the Waitomo area of New Zealand (Gunn 1978); and Tasmania (Kiernan 1988, 1989, and 1993). Gunn 1978 found that timber harvest in the Waitomo area of New Zealand increased runoff by the amount previously lost through evapotranspiration and subsequently increased sedimentation into dolines and karst systems (Urich 2002). No work has been done to quantify these effects in karst areas of southeast Alaska.
**High Resolution Karst Studies**

The advances in technology and science during the late 20th century have focused work in karst aquifers on “quantifying the conceptual model” (White 2002). Tracing in aquifers progressed from visual qualitative observation to quantitative methods allowing for the measurement of flow dynamics and storage aquifers using artificial and environmental tracers paired with automatic water samplers (Thrailkill 1991, Meiman et al. 2001, White 2002, Einsiedl 2005). The development of computer data loggers has allowed for great developments in karst geochemistry and hydrogeology (Groves and Howard 1994a/b, Liu et al. 2004a/b, Despain 2005, Groves and Meiman 2005).

Specifically, researchers utilizing high-resolution analysis of spring hydro and chemographs are working to characterize subsurface flow pathways in karst aquifers. Thrailkill *et al.* (1982) analyzed dye trace and water chemistry data in south central Kentucky to establish differences between deep conduit and shallow recharged springs. In 1988 Hess and White used continuous measurements of temperature, conductivity, and stage combined with precipitation to demonstrate a relationship between storm pulses and changes in conductivity and temperature in south central Kentucky karst. In 1996 Meiman and Ryan combined continuous measurements of temperature, conductivity, stage, and rainfall with a quantitative dye trace in order to demonstrate the benefit of high frequency, flow dependent sampling at karst springs for characterization of water quality.

Since 1996, conceptual models have been developed through high resolution spring monitoring. Desmarais and Rojstaczer (2002) used physical and chemical responses of springs to storm events to characterize groundwater flow in karst aquifers.
Several authors have used multifractal analysis in developing spring flow simulation models (Labat et al. 2002, Majone et al. 2006). None of this work has been conducted in temperate rainforest karst, or with the intention of modeling karst watershed response to timber harvest management.

With the development of high-resolution data loggers, study on remote karst sites such as those in temperate rainforest karst is increasingly feasible. High-resolution data also creates opportunities for expansion of previous studies. White (2002) lists several of these studies, including the calculation of a high-resolution quantitative water budget in a karst aquifer. Additionally, integrating these studies with natural resource management in karst regions becomes vital as global populations increase and resources are consumed. In 2002, the Karst Review Panel on the Tongass National Forest identified several areas of possible future study, similar to the recommendations of Aley et al. in 1993 and Baichtal in 1997. Aley et al. recommended that the Forest Service should identify and set aside "one or two high quality, but minimally impacted, areas for possible designation as a Research Natural Area" especially in low to middle elevation high vulnerability karst (1993). Baichtal suggested research into the complexity of karst hydrologic systems and their interactions with timber harvest (1996). Along those lines, Griffiths et al. suggested future study into the interaction between the forest and the karst system (2002).

In southeast Alaska, a comprehensive dye trace project beginning in 2003 is working to delineate the significant karst area of Prince of Wales, Tuxecan, and Kosciusko Islands (Prussian and Baichtal 2003). To date, however, no high-resolution characterization of a karst aquifer in southeast Alaska has occurred. The effects of timber harvest in southeast Alaska on karst watersheds have only been evaluated qualitatively,
based on observations of increased sedimentation and dissolution of formations (Allred 1993).

This thesis project collects baseline data consisting of high resolution spring discharge, specific conductivity, temperature, and precipitation and evaluates two small low to middle elevation high vulnerability karst watersheds for future use in a comprehensive experimental catchment study for the Tongass National Forest. If the response of the two catchments to storm events demonstrates that both systems have developed similar flow characteristics such as well developed conduit flow and storage properties, then the responses of each to changes in surface vegetation through timber harvest can be compared in future work. It is important to define base level conditions before the surface vegetation is partially or totally removed, so the changes in hydrology of the catchments can be related specifically to this process.

The study also includes analysis of storm-period-water balances. The water balances estimated for each watershed provide a basis for evaluating the appropriateness of the delineation of the two catchments. If the two watersheds are delineated appropriately, then there should be no gain in water over the entire study period. Defining each watershed appropriately is integral in developing the future paired catchment study. If the watersheds are not defined appropriately, changes in the hydrology of each could be caused by allogenic factors, instead of the autogenic factor of forest removal imposed on the watershed.

Urich states that there is a "gap between the science of karst and the practice of karst management" (2002). Ultimately it is hoped that what is learned from this study and future related projects would help bridge the gap between karst science and karst management.
managers - furthering understanding of the complex and fragile relationships between surface and subsurface of temperate karst ecosystems.
CHAPTER II
DESCRIPTION OF STUDY AREAS

Southeast Alaska and Prince of Wales Island

The Tongass National Forest (Figure 1) is the largest forest in the National Forest System, encompassing over 6.9 million hectares covering the islands of the Alexander Archipelago and the narrow band of mainland from Dixon Entrance to Icy Bay (USDA Forest Service 1991). The vegetation of southeast Alaska is a temperate rainforest, with average temperatures ranging from 1 to 9° C. Precipitation is frequent, occurring on approximately 220 days during the year with June the driest and October the wettest month on average. Rainfall is variable, tending to increase dramatically with increases in elevation, and averaging from 660 mm to 5,588 mm per year (U.S. Forest Service 1974, Aley et al. 1993). The two study watersheds, Canyon Block (Figure 2) and Windgate (Figure 3), are located on the north end of Prince of Wales Island (Figure 4) the southernmost main island in the Alexander Archipelago.

Prince of Wales Island is the largest island in the Alexander Archipelago at approximately 7,174 km$^2$, and the third largest island in the United States of America. Elevation ranges from sea level along the coastline to 1,218 meters at the highest point. Precipitation levels fall into the higher range for southeast Alaska, averaging approximately 4,064 mm annually. The island has the largest road system in southeast Alaska and the largest town on the island consists of 1,175 residents. The two main economic forces in southeast Alaska are the fisheries and timber industries, both of which are linked to the productivity of the karst ecosystem.
Figure 1 – Southeast Alaska and the Tongass National Forest (USDA Forest Service)
Figure 2 - Canyon Block Watershed

Figure 3 - Windgate Watershed

Figure 4 - Prince of Wales Island, AK. The boxes in the upper right hand corner show the approximate locations of southeast Alaska and Prince of Wales Island in relation to the entire state of Alaska.
The forests on Prince of Wales Island consist of western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), Alaskan yellowcedar (*Chamaecyparis nootkatensis*), and shore pine (*Pinus contorta*). Understory species consist of Devil’s Club (*Opopanax horridus*), Skunk Cabbage (*Lysichiton americanus*), Alaska blueberry (*Vaccinium alaskaense*), and Red Huckleberry (*Vaccinium parvifolium*). A variety of ferns and mosses are found on Prince of Wales, including the Green Spleenwort (*Asplenium trichomanes-ramosum*), a calciphile fern found only in areas of carbonate rock or limey soils. High elevations consist mainly of Sitka spruce, Alaskan yellowcedar and western hemlock gradually thinning into alpine muskeg or wetland areas. Shore pine is generally only found in muskegs. Western redcedar is typically found in lower elevations, between sea level and 305 meters.

Large Fauna on the island consist of Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) and black bear (*Ursus americanus*). The island is home to the Alexander Archipelago wolf (*Canis lupus ligoni*), a federally endangered species. The island is also the only known location for the Prince of Wales flying squirrel (*Glaucomys sabrinus griseifrons*). Aquatic life is prolific in the waters around Prince of Wales Island, including: Coho “Silver” (*Oncorhynchus Kisutch*), Pink “Humpback” (*Oncorhynchus gorbuscha*), Sockeye “Red” (*Oncorhynchus Nerka*), and Chum “Dog” (*Oncorhynchus keta*) Salmon. A variety of fish are found in the freshwater lakes and streams on the island, including: Cutthroat trout (*Oncorhynchus clarkii clarkia*), Rainbow/ Steelhead (*Oncorhynchus Mykiss*), and Dolly Varden (*Salvelinus Confluentus*).
Geology

Prince of Wales Island is part of the Alexander terrane, a large crustal fragment with a depositional history ranging from the late Precambrian to the Early Jurassic (Soja 1991). The Alexander terrane is partially composed of fossiliferous and largely undeformed or unmetamorphosed interbedded massive carbonate breccias of the Heceta Formation (Baichtal 2006). The Heceta Formation represents collapsed island shelves as well as reef and shallow water limestones originating in the Northern Hemisphere during the Silurian period (408 – 438 mya) (Aley et al. 1993; Soja and Antoshkina 1997; Freitas et al. 1998).

This terrane collided obliquely with the landmass of North America and accreted onto the continental margin during the middle Jurassic to Late Cretaceous time (Coney et al. 1980). The process of accretion resulted in fragmentation and smearing of sections of the terrane northward, while other portions remained in place (Aley et al. 1993). As a result, areas of carbonate exist on the Tongass from the Chilkat Peninsula in the north to Prince of Wales Island in the south (Figure 5). The Heceta Formation is overlain by the early Devonian aged Karheen Formation, which is characterized by conglomerate and sandstone clasts in a calcareous matrix (Baichtal 2006).

Prince of Wales Island contains approximately 1,813 km² of karst (Baichtal 2006). These karst areas are concentrated on the north end of the island and surrounding smaller islands, where over 500 caves have been mapped. Karst formed to some extent on Prince of Wales prior to the Wisconsin glacial advance 21,000 to 14,000 years ago. This period of glaciation caused scouring, passage collapse, and sediment fill in karst systems, as well as leaving thick glacial till deposits and razing epikarst development at
lower elevations.

The intense development of karst on the Tongass National Forest is controlled by several factors including the high percentage of calcium carbonate (CaCO$_3$) in the limestone of southeast Alaska – averaged at 97.65 percent (Mass et al. 1992). In addition, faults and fractures resulting from the northward movements of the Alexander Terrane are dominated by northwesterly trending strike-slip faults and second order intersecting north-trending strike-slip faults, which define karst conduit formation (Gehrels and Berg 1992, Aley et al. 1993, Baichtal and Swanston 1996).
Southeast Alaska Karstlands

British Columbia
Canada

Chichagof Island

Baranof Island

Prince of Wales Island

SE Total Karst 217,555 hectares (537,588 acres)
Tongass Karst 186,963 hectares (461,994 acres)
Tongass Harvested Karst 38,639 hectares (95,479 acres)
Tongass Karst Harvested before 1960 5,664 hectares (13,996 acres)

Figure 5 – Areas of Carbonate Bedrock in Southeast Alaska
(USDA Forest Service)
The Study Watersheds

Canyon Block (Figure 3) and Windgate (Figure 4) watersheds are karst watersheds, underlain by carbonate bedrock in which subsurface drainage developed through dissolution. These blocks of karst are isolated, surrounded by non-carbonate rock. In the 1991 and 1992, both watersheds were evaluated for timber sale. These two watersheds were discovered to have open insurgences, caves, and a high density of sinkholes – classifying them as high vulnerability karst according to management guidelines from TLMP. Consequently, these watersheds were removed from harvest consideration at the recommendation of the Forest Geologist – the first two watersheds ever reserved from a timber sale based on karst resource evaluations. The units around each watershed were clear cut in the late 1990s.

Canyon Block watershed encompasses approximately 13.7 hectares (.14 km²), ranges in elevation from 134 to 244 meters, and has a northern exposure. It is comprised of approximately 95 percent un-harvested old growth conifer forest of Sitka spruce, western hemlock, western red and Alaskan yellowcedar and five percent forested wetlands. The geology consists of massive algal and fossiliferous Silurian Heceta Limestone over thrust by Ordovician-Silurian andesitic and volcanic Luck Creek Breccias (Baichtal, 2006). No bedding is apparent in the limestone. The sub alpine and alpine portions of the watershed are underlain by the Luck Creek Breccias.

There are two main cave systems in the watershed, Red Canyon at 290 m and White canyon at 43 m. The entrances to each cave are at the limestone / breccia contact. Red Canyon cave is used by bats as is evidenced from bat droppings present in the upper part of the cave, and deer bones were found in the back of the cave. Speleothems include
pink flowstone, moonmilk, lion’s tail formations, stalactites and stalagmites. Forest Service employees mapped these caves in July of 1992 using standard compass, clinometer and tape. The spring surfaces at the contact between the Heceta Limestone and the over thrust Luck Creek Breccias.

Windgate watershed encompasses approximately 60.6 hectares (0.61 km$^2$), ranges in elevation from 244 to 397 meters, and has a southwestern exposure. It is comprised of approximately 60 percent forested wetlands and 40 percent un-harvested old growth conifer forest of Sitka spruce, western hemlock, western red and Alaskan yellowcedar. The geology of the watershed consists of well-bedded, fossiliferous Silurian Heceta limestone lying conformably on mudstones and sandstones of the Staney Creek Formation and overlain by Devonian Karheen conglomerates and mudstones. The limestone strikes east west, and dips to the north at approximately 20 degrees (Baichtal 2006). The sub alpine and alpine portions of the watershed are underlain by the Karheen formation.

Four main caves are located within the catchment, Field Of Bees Cave with a length of 58 m, Pete’s Moss Cave at 193 m, Cuff Cave at 12 m, and Windgate Cave at 596 m. The Tongass Cave Project mapped these caves in 1993. These caves have all been nominated as significant caves, citing evidence of bat usage and abundant speleothems. Windgate spring surfaces at the conformable contact between the underlying Staney Creek Formation and the overlying Heceta Limestone.
Hydrogeologic Inventory and Watershed Delineation

A hydrogeologic inventory was conducted in the Canyon Block and Windgate Cave watersheds in order to delineate each catchment. Preliminary inventory work had already established the presence of the karst watersheds; however no exhaustive inventory had previously been conducted (Woods 1990, Fritzke 1992). In fluvial (surface) catchments, topography can be used to delineate groundwater flow; however in karst (subsurface) catchments flow is often autonomous of topography. (White 1988, Aley et al. 1993, Groves 2007) Karst areas in the Tongass frequently have fluvial (allogenic) and karst (autogenic) drainage components. This is the case in the two study watersheds. Because of the two types of drainage, three main methods of delineation were used: inventory of karst features (sinking streams, sinkholes, swallets, springs) and surface fluvial systems; survey of the cave streams in each watershed; and groundwater flow tracing with fluorescent dyes (Groves 2007).

1993 USDA Forest Service Orthophotographs and contour maps were used to identify surface streams, sinkholes, lineaments and geologic contacts in the study watersheds. Extensive surface inventories were conducted during June of 2006 to pinpoint feature locations using a Garmin 76CSX Global Positioning Satellite (GPS) unit. Surface streams were followed from insurgence (sink) points up to the drainage divide in order to evaluate the total catchment area. The geologic contact between the carbonate and non-carbonate rock units was walked to locate insurgence and resurgence points.
Additional features not identified through photo and map interpretation were also located and recorded during the surface inventory phase. These data were integrated into the project Geographic Information System (GIS) (ArcView version 9.2) with the orthophotographs and contour maps.

The caves in each catchment were mapped using standard Suunto compass, clinometer and nylon tape in US feet by the Tongass Cave Project in 1991. The data from the survey was entered into Fountainware Compass version 5.05, a program used to generate a line plot from data. The line plots were then georeferenced in the project GIS using GPS locations obtained for the entrance of each cave. Once the karst features, subsurface and surface streams were identified and mapped, fluorescent dye tracing was conducted in order to confirm the delineation of each catchment.

**Dye Trace**

While it is possible to delineate subsurface streams through cave survey, the complexity of subsurface flow is not discernible where cave passages do not allow human passage. Dye tracing with fluorescent dyes is a useful method for obtaining information on internal connections between the insurgence of allogenic water into karst catchments and the resurgence springs where cave mapping is not possible (White, 1988). A dye trace was conducted in the Canyon Block and Windgate watersheds using standards developed by the Center for Cave and Karst Studies (CCKS) and Ozark Underground Laboratories (OUL).

Materials were provided by CCKS and included activated charcoal packet samples, glass vials, and fluorescent dyes. The activated charcoal in the sample packets continuously absorbs and accumulates all dye types used in this study (Aley 2002).
Gloves and protective clothing were used when handling all samples and during dye injection to prevent cross contamination. Collected samples were transported and shipped in coolers to maintain a constant temperature. CCKS staff analyzed all samples using a spectrofluorophotometer.

Locations for sampling and dye injection were chosen utilizing the GIS database constructed for each catchment. Packets were placed not only in streams that appeared to be the main resurgence for each catchment, but also in nearby streams that could potentially be connected by subsurface flow. Where necessary, packets were placed at more than one site in those streams when midstream spring resurgence was suspect through sudden increases of flow volume. Site locations were chosen to ensure the samples remained underwater and accessible during all flow levels, and two packets were placed at each site in case of packet loss. All insurgence points in each catchment were marked as dye injection points.

Two insurgence points were selected in the Canyon Block watershed, and four sample locations were selected downstream from the insurgence points (Figure 6). Background water and packet samples were taken June 8th to June 14th, 2006. When the background sample packets were removed, they were replaced with new packets. Two pounds of Rhodamine WT dye were injected into the insurgence above Red Canyon Cave and two pounds of Fluorescein dye were injected into White Canyon Cave in the Canyon Block on June 18th, 2006. Streams in the watershed were at high flow during injection, and the overflow spring was active. During the first week following the injection, flow decreased until the overflow spring became dry. Packets were changed approximately once a week, for a sampling period of three weeks.
The main pulse of dye came through the catchment during the first week of sampling. Packets located at the overflow resurgence and downstream from the confluence of the resurgence and the surface stream tested positive for dye, with the stream at > 10,000 ppb (parts per billion) and the overflow spring at approximately 800 ppb (Figure 7). Packets located above the confluence of the overflow spring and the stream did not test positive for either dye.
Figure 6 – Canyon Block Dye Trace Results
Figure 7 – Windgate Dye Trace Results
Four insurgence points were chosen in Windgate watershed, and nine sample locations were selected in various streams downstream from the catchment – including what was considered to be the main resurgence (Figure 7). Background water and packet samples were taken during the last week of July 2006. When the background samples were collected, they were replaced with new packets. One pound of Rhodamine WT was injected into the north insurgence; two pounds of Sulforhodamine B were injected into Field of Bees Cave, one pound of Fluorescein was injected in the Pete’s Moss insurgence and finally one pound of Eosine was injected into Windgate Cave. Water samples were taken 24 hours after dye injection at the suggestion of the Forest Geologist. Due to the closeness of the dyes on the spectrum, the lab at CCKS conducted a spectrum separation and to pick out each separate dye during analysis.

Streams were at high flow during injection, and saw a gradual decline in discharge over the first week of sampling. During water sampling, the trace results were visual at the main resurgence spring. The results from the water samples confirmed the visual trace. Only packets at the resurgence stream tested positive for any of the four dyes. (Figure 7).
Precipitation

Rainfall data were measured with Onset RG2 data logging rain gauges equipped with HOBO H7 event data loggers. The rain gauges have a resolution of 0.01 inch of precipitation and 0.5 seconds of time, and each rain gauge was calibrated to an accuracy of one percent for precipitation and ± 1 minute per week before field installation. During field placement, rain gauges were leveled using an engineer's level and elevated on PVC pipes to eliminate splash. All rain gauges were launched on Julian day 224 (August 12th) and the final download was on Julian day 312 (November 8th), for a data collection period of 87 days. The period of time from Julian Day 224 through Julian Day 276 (October 3rd) was considered a calibration period during which time the placement and general ability of the gauges and loggers was tested. The focus of the study was on October, the month with the highest average precipitation in the Tongass National Forest.

There were seven rain gauges positioned in each catchment (Figures 8 and 9). Five were placed under the old growth canopy and measured throughfall. The remaining two were placed in open areas to avoid canopy effect and measure gross precipitation. The rain gauges were downloaded approximately once a week. During download, the clock on each HOBO H7 event logger was reset to the current time. One gross precipitation gauge in each catchment was not placed in the field until mid-September. One of the net precipitation gauges in the Canyon Block suffered from electrical problems with the HOBO, which were irresolvable through various repair efforts. Any efforts made were undone when the gauge was attacked in late October by a black bear. This gauge offers only a brief period of data collection during the beginning of the month of October.

Rainfall data were downloaded from the gauges with a HOBO Shuttle in the
format of a number of events or “tips” per time period. In the case of a RG2 rain gauge, one event equals .01 inch of precipitation, which was later converted into millimeters in a Sigma Plot spreadsheet. The HOBO Shuttle was uploaded to the computer using HOBO Boxcar software, designed by Onset Computers. Once on the computer, the data required further processing through a macro developed in Microsoft Excel, developed by Onset in order to parse out the events into a uniform time interval. The data was then transferred to Sigma Plot software.

Once in Sigma Plot, the rainfall data were evaluated for specific storm periods. Storms were defined by this study as rainfall events greater than 5 mm proceeded by a 12-hour period with zero to .508 mm precipitation and followed by a 12-hour period of zero to .508 mm precipitation, based on response rates and storms observed in other catchments on Prince of Wales Island (Prussian 2006). When analyzing storm data, the spatial distribution of the precipitation must be considered. This involves finding an “Equivalent Uniform Depth” (EUD) for the whole of each watershed. Because the throughfall gauges in the Canyon Block watershed represent a relatively dense, uniformly spaced network, a simple arithmetic average was employed to compute EUD (Serrano, 56).

The Canyon Block watershed represents an area of complete old growth canopy, with little to no open areas of muskeg. Windgate, however, contains a large portion of open partially forested muskeg in the higher elevations. While there are five throughfall gauges, there are only two gauges located in these open areas. Thus, rain gauges in this catchment were averaged in a manner that took into consideration the great difference in gauge density and area between the old growth and muskeg portions of the watershed.
(Serrano, 56). The EUD for the forested and muskeg areas of Windgate were calculated using the same simple arithmetic average applied in Canyon Block. These two values were weighted by the proportional area of forest and muskeg within the watershed (calculated in ArcGIS) to obtain a single EUD for Windgate watershed.
Figure 8 – Gauge Locations in the Canyon Block Watershed
Figure 9 – Gauge Locations in Windgate Watershed
Discharge

Stage data were collected using one Campbell Scientific CR10X datalogger with a CS420 – L Druck Pressure Transducer located in the resurgence of each catchment (Figures 8 and 9). The CS420 – L has an accuracy of ± 0.1% FSR. The CS420 – L was submersed in the resurgence stream of each catchment; in a stable location where all discharge was collected at high and low flow with no flow separation due to cobbles or debris. A large PVC tube was affixed securely around the probe in order to alleviate disturbance by fauna and debris. Both data loggers were installed on Julian Day 224 (August 12th) and taken offline on Julian Day 312 (November 8th), for a data collection period of 88 days. The study focus is on the data collected from Julian Day 276 (October 3rd) through Julian Day 307 (November 3rd), throughout the month of October. The data logger’s program was written to collect continuous data with two-minute resolution. Data were downloaded every week and uploaded to the main computer with a Palm Pilot IIIxe utilizing PConnect software designed by Campbell Scientific, Inc. The downloaded data were viewed using PC208 software, also designed by Campbell Scientific, Inc.

Stage data were used to estimate discharge based on a measured relation between stage height and discharge. Estimates of discharge at several different flow levels were obtained using the sudden injection method with sodium chloride (Salt Slug) (Groves 2007). The Campbell CS10X data logger was also equipped with the CS547A specific conductance/ temperature sensor, and set with a second program written to record conductivity every two seconds. The CS547A has an accuracy of ± 5% of reading 0.44 to 7 mS cm\(^{-1}\) and ± 10% of reading 0.005 to 0.44 mS cm\(^{-1}\). To record the change of conductivity as the salt slug passed the sensor, the first program was turned off, and this
second program activated. The conductivity prior to injection was noted. The salt slug consisted of a solution of stream water and common table salt mixed in a bucket to achieve conductivity greater than that of the stream. The volume and conductivity were recorded.

Approximately 20 meters upstream of the sensors, the mixture was injected into the stream at a steady, even pace and the spike in conductivity was measured by the probe and recorded by the data logger. The salt slug data were then downloaded off of the data logger and uploaded on to the computer using the Palm Pilot IIIxe. Using the View function of PC208, the salt slugs were trimmed from the main portion of the data and saved as separate files for analysis. These data were then processed using a transform in Sigma Plot written by Joe Meiman of the National Park Service. The discharge measurement derived through this process was then related to the stage height in Sigma Plot, and a scatter plot graph was developed. From this rating curve, a quadratic equation was fit to the data points in Sigma Plot with an \( r^2 \) value of 0.90 for Windgate (Figure 10) and 0.96 for Canyon Block (Figure 11).
Figure 10 – Stage vs. discharge rating curve for Canyon Block Watershed

Figure 11 – Stage vs. discharge rating curve for Windgate watershed
From this rating curve, discharge values were calculated from the measured stage record and a continuous hydrograph was produced. In addition to analyzing the precipitation data for storms, the streamflow hydrograph must be analyzed to pinpoint the exact times when the storm runoff moves through the stream. This is done by locating inflection points in the streamflow hydrograph, which is described below (Serrano, 236).

**Hydrograph Recession, Baseflow Separation, and Water Balance**

The shape of the recession curve on a hydrograph is useful for characterizing stormflow, groundwater flow, and storage in karst aquifers. The equation used for defining this relationship is:

\[ Q_t = Q_o e^{-kt} \]  \hspace{1cm} (2)

where \( Q_t \) = discharge \([L \cdot T^{-1}]\) at \( t \) units of time after \( Q_o \), \( Q_o \) = discharge \([L \cdot T^{-1}]\) value in the recession limb, \( t \) = time \([T]\) after \( Q_o \), \( e \) = the base of the Napierian logarithms, and \( k \) = the regression coefficient typical of flow component \([T^{-1}]\) (White 1988, Ford and Williams 1989, Serrano 1997). This equation can be fit to portions of the recession limb as a straight line on a semi-logarithmic graph. Three lines were fit to the recession limb of two storms each in Canyon Block and Windgate on a semi-logarithmic graph using a piecewise three-segment regression equation. Inflection points were the intersections of these fitted lines. The \( r^2 \) value for each fit in all storms was 0.99. It is possible for any number of lines to fit the recession curve, however the final intersection or inflection point represents the end of storm flow and beginning of baseflow. Baseflow separation was derived through connecting the point just before the rising limb of the hydrograph.
with the final inflection point on the recession limb located through fitting lines to the recession limb of each storm as described above.

Each portion of the curve represented by a straight line has a value of $k$. Serrano 1997 demonstrates using equation (2) that taking the logarithms and rearranging the equation to solve for $k$ by defining $t_1 = 1$ $[T^{-1}]$ gives:

$$k = \frac{t}{\ln Q_o - \ln Q_t} \quad (3).$$

The values of $k$ for the quick flow response are used to characterize and compare the response of Canyon Block and Windgate to individual storms.

A hydrologic water balance or budget represents the larger hydrologic cycle on earth – the change in storage over time is balanced by the inputs and the outputs into a system. This paradigm is applied in watersheds for an annual or storm budget. All inputs and outputs of water for the system can be represented in an equation. In this study, the water balance equation is used to obtain quantitative data concerning the change in storage and evapotranspiration on a storm basis and over the entire study period:

$$P - Q = \Delta S + ET \quad (1).$$

Where $P =$ total precipitation (precipitation measured under the canopy averaged with precipitation measured in the open) $[L^3T^{-1}]$, $ET =$ evapotranspiration $[L^3T^{-1}]$, $Q =$ discharge $[L^3T^{-1}]$, and $\Delta S =$ change in storage $[L^3T^{-1}]$. Values for $P$ were measured directly. Storms were defined in each catchment for rainfall based on the values
described above and for discharge through the location of inflection points on the hydrograph, also described above and evaluated for $ET$ and $AS$ using equation 1. The water balance was also estimated for the entire study period, during which time $AS$ is assumed to be zero citing a constant base level.
Storms

Average precipitation values for weather stations on Prince of Wales Island during the month of October range from 247.14 mm to 289.81 mm (NOAA 2006). Values for Canyon Block fall within this range, however values for Windgate are slightly higher than the NOAA average. From the third of October to the third of November, there was approximately 258.28 mm of total precipitation in the Canyon Block watershed and 439.90 mm of total precipitation in Windgate watershed. Average spring discharge for the period in Canyon Block was .052 m$^3$/s; in Windgate it was .17 m$^3$/s. Five measurable storms were recorded in Canyon Block watershed and six were recorded in Windgate watershed during the month of October. Tables one and two display relevant values about each storm.

Table 1 – Summary of Storms in Canyon Block, October 4$^{th}$ – November 3$^{rd}$

<table>
<thead>
<tr>
<th>Storm #</th>
<th>Start of Storm (Julian Day 2006)</th>
<th>Type$^a$</th>
<th>Total Rainfall (mm)</th>
<th>Duration (hours)</th>
<th>Time of Return to Base Level (Hours)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>277.04</td>
<td>b</td>
<td>36.49</td>
<td>64</td>
<td>118</td>
</tr>
<tr>
<td>2</td>
<td>284.452</td>
<td>p</td>
<td>62.69</td>
<td>56</td>
<td>133.7</td>
</tr>
<tr>
<td>3</td>
<td>290.57</td>
<td>b</td>
<td>45.55</td>
<td>48</td>
<td>(1)</td>
</tr>
<tr>
<td>4</td>
<td>293.26</td>
<td>p</td>
<td>123.13</td>
<td>155</td>
<td>(1)</td>
</tr>
<tr>
<td>5</td>
<td>303.69</td>
<td>b</td>
<td>14.73</td>
<td>48</td>
<td>(1)</td>
</tr>
</tbody>
</table>

$^a$ - b: bimodal storm (2 storm peaks), p: polymodal storm (multiple storm peaks)

$^b$ - 1: recession interrupted by next storm
Table 2 – Summary of Storms in Windgate, October 4th – November 4th

<table>
<thead>
<tr>
<th>Storm #</th>
<th>Start of Storm (Julian Day 2006)</th>
<th>Type*</th>
<th>Total Rainfall (mm)</th>
<th>Duration (hours)</th>
<th>Time of Return to Base Level (Hours)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>276.65</td>
<td>s</td>
<td>55.96</td>
<td>70</td>
<td>62.2</td>
</tr>
<tr>
<td>2</td>
<td>284.58</td>
<td>s</td>
<td>57.94</td>
<td>96</td>
<td>116.6</td>
</tr>
<tr>
<td>3</td>
<td>290.54</td>
<td>p</td>
<td>42.67</td>
<td>50</td>
<td>(I)</td>
</tr>
<tr>
<td>4</td>
<td>293.68</td>
<td>b</td>
<td>184.29</td>
<td>86</td>
<td>(I)</td>
</tr>
<tr>
<td>5</td>
<td>297.85</td>
<td>b</td>
<td>68.23</td>
<td>45</td>
<td>(I)</td>
</tr>
<tr>
<td>6</td>
<td>303.71</td>
<td>b</td>
<td>30.78</td>
<td>55</td>
<td>(I)</td>
</tr>
</tbody>
</table>

* - b: bimodal storm (2 storm peaks), p: polymodal storm (multiple storm peaks), s: single peak/ sharp response
b - I: recession interrupted by next storm

Although the local topography of Prince of Wales Island often plays a large role in storm distribution, storms can be correlated between the two watersheds, with the exceptions of storm four in Canyon Block and storm five in Windgate. Storm four in Canyon Block appears to be the same as the combination of storms four and five in Windgate, however in Windgate there was a distinct twelve-hour period with no precipitation separating the two storms (Figure 12). This seems to suggest that storm five in Windgate is an isolated occurrence, however it is an artifact of the method used to define storms. Storm four in Canyon Block is most likely the same event as storms four and five in Windgate. Storms arrive first in Canyon Block and begin roughly four hours later in Windgate, with the exception of storm number three, which began in Windgate 38 minutes before it arrived in the Canyon Block (Figure 12).

The observed precipitation patterns during the month tend to be of long duration storms with an average overall intensity, generally peaking in intensity twice during each storm. In Canyon Block, storms one, three and five are all bimodal peak storms. Storm
two shows three peaks and storm four shows four peaks. In Windgate, storms three, four, five and six are bimodal peak storms.

![Graph showing precipitation in Canyon Block vs. Windgate, Oct. 3rd – Nov. 3rd 2006, numbers 1 – 6 represents storms in each catchment.](image)

Figure 12 – Precipitation in Canyon Block vs. Windgate, Oct. 3rd – Nov. 3rd 2006, numbers 1 – 6 represents storms in each catchment.

Storm one only has one sharp peak, and storm two shows three peaks. On average, storm duration in Canyon Block was 74.2 hours, and in Windgate 67 hours. The largest storm in each catchment is storm four, with 123.92 mm of precipitation in Canyon Block and 184.29 mm of precipitation in Windgate, averaging out over 155 hours in Canyon Block and 86 hours in Windgate.
The outflow springs at Canyon Block and Windgate demonstrated a significant response in discharge, conductivity, and temperature for each storm event described above (Figures 13 and 14). The trends in precipitation are reflected in the discharge response. For all storms measured in both catchments, each peak of precipitation is correlated with a resultant peak in discharge, even during bimodal and polymodal storms. The spring response to storm events is rapid in both watersheds, which is visible in the

![Graph showing precipitation, discharge, specific conductivity, and spring temperature in Canyon Block, October 3rd - November 3rd.](image)

Figure 13 – Precipitation, discharge, specific conductivity, and spring temperature in Canyon Block, October 3rd – November 3rd.

sharp increase in the rising limb of each hydrograph (Figures 13 and 14). The recession limb of the hydrograph is slightly more gradual than the rising limb as precipitation flows from the catchment. Storms typically occurred about 12 hours apart during the month. For the larger volume storms such as three, four and Windgate storm five, this short
period did not allow enough time for recovery of the spring discharge to pre-storm baseflow levels. Therefore, baseline values were defined by the period of zero rainfall at the beginning of October and November during which time discharge receded to the lowest recorded value during the study period. For Canyon Block, the base level for spring discharge was thus defined as .01 m³/s (Figure 13); for Windgate the value was defined as .065 m³/s (Figure 14).

Following each storm, conductivity displayed an inverse relationship to discharge--as discharge increases conductivity exhibits a drop in value. Conductivity remains at an approximately constant level until the storm water enters the catchment.

![Graph of precipitation, discharge, specific conductivity, and spring temperature in Windgate, October 3rd - November 3rd.](image)

*Figure 14 – Precipitation, discharge, specific conductivity, and spring temperature in Windgate, October 3rd – November 3rd.*

Once a storm ended, specific conductivity typically displayed a lag time during the recession leg of the hydrograph when it recovers back to its prestorm value as the
precipitation from the storm leaves the catchment. In the spring at Canyon Block, the maximum, pre-storm value is .11 mS (Figure 13) and the Windgate spring the value is .22 mS (Figure 14). At both springs during storms two, three, and four, (and five, in Windgate) subsequent storms caused the conductivity to drop again before the prestorm levels could be reached.

Spring temperatures exhibited a positive correlation to discharge in both catchments. As discharge increases the temperature of the water increases in an analogous fashion (Figure 13 and 14). As the storm pulse moves out of the karst system, the temperature drops to close to the previous levels, matching the recession trend of the discharge curve. The seasonal effects of changing air temperatures are visible in the decline in spring temperature values towards the end of the study period, as the air temperatures gradually drop towards the end of the month. Daily high temperatures on Prince of Wales Island for the beginning of October are 18 ° C and drop to approximately −3 ° C at the end of the month (NOAA 2006). As the cooler weather moves in, flow pulses tend to be associated with water temperature decreases instead of increases

**Hydrograph Analysis**

The best storms to utilize in studying the karst aquifer are those with sharp input pulses of recharge into the aquifer provided by intense, short duration storms (White 1988, Hess and White 1988). The ideal storm would have little to no antecedent or post storm rainfall. Due to the character of the temperate rainforest though, storms of this nature are rare, especially during the rainy season of September through November. Storm one in each catchment closely approximated these conditions. Storm two is less
intense but provides a greater volume of rainfall than storm one and a definable recession period as opposed to later storms that are immediately interrupted by subsequent events.

During storm one, Canyon Block experienced a period of intense rainfall from 12:44 to 18:02 on October 4 (Julian Day 277, Figure 15). The total precipitation volume for this storm was 8333 m$^3$. The maximum rate of precipitation occurred during an eight minute period during the storm, from 15:48 to 15:56 on October 4th, averaging .62 m$^3$/s. This eight-minute period represented the peak of the storm. The main portion of the discharge pulse reached the spring approximately 20 minutes after the peak of the rainfall, at 16:16. The total storm runoff volume was 7,213 m$^3$ after baseflow separation. Three distinct rates of recession ($k$) were evident in the recession limb of the hydrograph (Figure 17).

![Figure 15 - Canyon Block #1: precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 4$^{th}$ - 9$^{th}$.](image-url)
Figure 16 – Windgate #1: precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 4th–9th.

The second inflection point represents the end of storm runoff. The $k$ values for the quickflow portion of the recession limb are $k_1 = 5.41$ and $k_2 = 4.63$.

Storm one in Windgate exhibited a period of intense rainfall from 14:00 to 19:00, October 4th (Day 277, Figure 16). The total precipitation volume for the storm period was 29590 m$^3$, with the maximum rate of precipitation, 3.45 m$^3$/s, having occurred during a two-minute period from 16:14 to 16:16. The main portion of the discharge pulse reached the spring approximately three hours after the peak of the rainfall, at 19:04. The total storm runoff volume was 20638 m$^3$ after baseflow separation. Three distinct recession rates were visible in the recession limb of the hydrograph (Figure 18). The second inflection point represents the end of storm runoff. The $k$ values for the quickflow portion of the recession limb are $k_1 = 2.39$ and $k_2 = 3.35$. 
Figures 17 and 18 – Storm recession limb linear fit for Canyon Block (Figure 17) and Windgate (Figure 18) for Storm #1.

Figure 19 – Canyon Block #2: Precipitation, discharge with baseflow separation, specific conductivity and spring temperature, October 11th – 15th.
Storm two in the Canyon Block consisted of a period of rainfall from 10:54 on October 11 (Julian Day 284) to 19:00 October 15 (Day 288) (Figure 19). Total precipitation volume for this storm was 14307 m$^3$. Storm two was a polymodal storm, with no distinct central peak of precipitation. The average precipitation rate over the entire period was .038 m$^3$/s. The total storm runoff volume was 21586 m$^3$ after baseflow separation. Three distinct rates of recession ($k$) were evident in the recession limb of the hydrograph (Figure 21). The second inflection point represents the end of storm runoff. The $k$ values for the quick flow portion of the recession limb are $k_1 = 7.93$ and $k_2 = 16.26$.

Figure 20 - Windgate #2: Precipitation, Discharge with baseflow separation, Specific Conductivity and Spring Temperature, October 11$^{th}$ – 15$^{th}$. 
The precipitation for storm two in Windgate occurs from 13:58 October 11 (Day 284) to 17:44 on October 15 (Day 288) (Figure 20). The total precipitation volume for the storm period was 30636 m³. This storm was a polymodal storm with no distinct main peak of precipitation, but the average overall precipitation rate was .085 m³/s. The total storm runoff volume was 15350 m³ after baseflow separation. Three distinct recession rates were visible in the recession limb of the hydrograph (Figure 22). The second inflection point represents the end of storm runoff. The $k$ values for the quick flow portion of the recession limb are $k_1 = 5.59$ and $k_2 = 16.97$.

**Canyon Block**

**Windgate**

![Graphs showing storm recession limb linear fit for Canyon Block (Figure 21) and Windgate (Figure 22) for storm #2.](image)

**Figures 21 and 22** - Storm recession limb linear fit for Canyon Block (Figure 21) and Windgate (Figure 22) for storm #2.
Figure 23 – Baseflow separation for the study period in Canyon Block.

**Water Balance**

Storm 1 in Canyon Block had a volume of 7,213 m$^3$ of storm runoff and 8,333 m$^3$ of precipitation. Subtracting discharge from precipitation yields a net gain of 1,120 m$^3$ to the catchment through storage and evapotranspiration. Storm two in Canyon Block had a volume of 21,586 m$^3$ of spring discharge and 14,307 m$^3$ of precipitation. The water balance calculation yields a net loss of water over the storm period of 7,279 m$^3$. There was a total volume of 140,180 m$^3$ of discharge over the study period, October 3$^{rd}$ to November 3$^{rd}$. The base flow level of .01 m$^3$/s was used to connect a line of baseflow separation on the hydrograph of the study period (Figure 23). After baseflow separation,
the total storm runoff was 107,979 m\(^3\) compared with the total volume of precipitation for
the period of 66,195 m\(^3\). The calculated water balance for Canyon Block using these
values results in a net loss of water over the study period of 41,783 m\(^3\).

Storm 1 in Windgate had a total of 20,638 m\(^3\) spring discharge and 29,591 m\(^3\)
precipitation. Subtracting these values leads to a net gain of 8,953 m\(^3\) to
evapotranspiration and storage. For storm two, Windgate had a total volume of spring
discharge of 15,350 m\(^3\) and precipitation of 30,636 m\(^3\). The water balance calculation
leads to a net gain of 15,286 to evapotranspiration and storage. There was a total volume
of 461,411 m\(^3\) of discharge over the entire study period. The base flow level of .065
m\(^3\)/s was used to connect the baseflow separation line on the hydrograph of the study
period (Figure 24). After baseflow separation, the total storm runoff for the period of
292,799 m\(^3\) was compared with total volume of 296,619 m\(^3\) for precipitation. The water
balance calculation yields a small net gain over the study period of 3,820 m\(^3\) to
evapotranspiration (ET) and storage (S).
Figure 24 – Baseflow separation for the study period in Windgate.
 CHAPTER V
DISCUSSION AND CONCLUSIONS

Aquifer Analysis

Observed hydrographs indicate that both Canyon Block and Windgate contain allogenic and autogenic recharge properties with well-developed conduit systems. Evidence supporting this observation is the flashy response of both watersheds to all storm events during the study period. In addition, each spring returns relatively quickly to pre-storm baseflow levels unless interrupted by a subsequent storm event. Windgate's peak and recovery times are longer than those reported for Canyon Block, but this is expected due to the larger catchment area of Windgate. Windgate is 60.6 hectares, as compared to Canyon Block, which is 22.8 hectares.

Hydrographs and calculated lag times for specific conductivity and spring temperature indicated that both aquifers contain only a small amount of storage in diffuse passages or pore spaces. The behavior of these catchments shows somewhat typical hydrology and geochemistry characteristic of many karst aquifers. In general, as water enters a karst catchment it comes into contact with limestone, which is composed mainly of the mineral calcite in the form of calcium carbonate (CaCO₃). Atmospheric and surface water is typically under saturated with respect to calcium (White 1988, Ford and Williams 1989). As rain and surface water (H₂O) travel through the karst aquifer, natural carbonic acid (HCO₃⁻) in the water dissolves limestone, approaching saturation with respect to the mineral calcite (CaCO₃) as it approaches the discharge spring. Three
forward reactions, that vary depending on the pH and temperature of the water and the availability of \( (\text{Ca}^{2+}) \), in limestone drive calcite dissolution are:

\[
\begin{align*}
\text{CaCO}_3 + H^+ & \Leftrightarrow \text{Ca}^{2+} + HCO_3^- & (4) \\
\text{CaCO}_3 + H_2CO_3^- & \Leftrightarrow \text{Ca}^{2+} + 2HCO_3^- & (5) \\
\text{CaCO}_3 + H_2O & \Leftrightarrow \text{Ca}^{2+} + HCO_3^- + OH^- & (6)
\end{align*}
\]

(Plummer et al. 1978, White 1988, Ford and Williams 1989). The double arrows indicate that these processes can occur in both directions – if the process is moving to the right, dissolution of calcite occurs, to the left, calcite precipitation. In most karst systems, the amount of \( \text{CaCO}_3 \) dissolved increases and the water approaches saturation the longer it remains in the system (assuming favorable conditions for dissolution, not precipitation) (White 1988, Ford and Williams 1989). In studies, the dissolved content of \( \text{CaCO}_3 \), which in combination with magnesium is often referred to as the “hardness” of the water, has been linearly linked to the specific conductivity (Hess and White 1988, White 1988, Ford and Williams 1989, Desmarais and Rojstaczer 2002). In addition, the temperature of precipitation and surface water often reflects the atmospheric temperature. Water that has spent sufficient time in the karst system often reflects the temperature of groundwater.

As water from a storm event enters and moves through the karst system, discharge and velocity increase, decreasing the residence time of the water in the conduits. During the sharpest impulse of water, in Canyon Block discharge increased from \( 0.005 \text{ m}^3/\text{s} \) to \( 0.36 \text{ m}^3/\text{s} \) and in Windgate discharge increased from \( 0.065 \text{ m}^3/\text{s} \) to \( 1.45 \text{ m}^3/\text{s} \) at storm peak. This meteoric input water is characterized by a lower conductivity and higher
temperature than water that has become equilibrated with aquifer temperatures. In a karst watershed with storage in pore spaces and the aquifer itself, the initial storm pulse increases hydraulic head and forces the water in storage out at the spring. This can result in a brief, initial increase in conductivity and decrease in temperature as water with an increased CaCO₃ content leaves the catchment as the front end of the storm pulse, enriched in relatively high conductivity, pre-storm diffuse storage water is transmitted through the system (Hess and White 1988).

For storm events in Canyon Block and Windgate, no initial increase in specific conductivity or temperature is evident. Values in these two catchments continue to recover from the previous period of storm dilution until new meteoric water enters the system, at which time values begin to change to their respective minimum or maximum (Figures 14 and 15). Hess and White 1988 reported that the peak of the discharge at the spring typically occurs before the peak in conductivity in conduit and diffuse flow systems. In Canyon Block during the storm one, conductivity actually fell to its minimum before the peak of discharge – suggesting that during dry antecedent conditions, there is little water stored in the karst aquifer. During more gradual storms such as storm 2, this lag time is longer as there is no sharp pulse or main period of input. However, during the study period, for each peak in discharge, there is an almost simultaneous drop in conductivity and increase in temperature – suggesting that the amount of water in the aquifer does not significantly increase.
Delineation Assessment

The calculation of the study period water budget for Windgate suggests that this study has appropriately delineated the watershed. This is supported by the small loss of water in the budget over the period, during which time the catchment is making the transition from the dry season of summer to the wet season of fall. Storage of water in regolith and vegetation generally increase from “dry” to wet. Correlation evidence is found in the water budget for storms one and two in Windgate, both of which show a net loss to evapotranspiration and storage. It is possible that the catchment is losing water to piratization, however there are no karst blocks nearby and all local streams and springs were tested negative for connection to the karst watershed through the dye trace.

The calculation of the study period water budget for Canyon Block suggests that this study has not appropriately delineated the watershed. Evidence for this suggestion is the loss of water over the study period, during which time the catchment should be increasing the amount of water in storage as it transitioned from the “dry” summer season to the wet fall season. Additionally, the surplus in the budget indicates that more water is leaving the system then entered in the first place – a violation of the rule of the conservation of mass. The water budget calculated for storm two correlates with this suggestion, as there is a surplus of water as the product of the calculation. However, the budget for storm one indicates a net loss. Assuming that all calculations are correct, this indicates that at low flow, the catchment is conservative, however at high flow water is piratized into the catchment from another karst system. This is a possibility, as additional karst systems are located in reasonable proximity to Canyon Block.
Conclusions

Canyon Block and Windgate both show autogenic and allogenic recharge with well-developed conduit systems. Little storage exists in the pore spaces or aquifer, however it is indicated through the water budgets that storage exists in the vegetation and regolith. Both catchments were covered in ice during the Wisconsin glacial advance, resulting in a thick mantle of glacial till, and qualitative observations show during wet conditions that many pools of standing water occur on the surface in each catchment. It is possible that that storage in the regolith of these catchments is high. Future work studying regolith storage capacity as a variable in the water balance would contribute greatly to understanding the movement of water through these karst catchments.

Precipitation events between the two catchments appear to be positively correlated, however this study only represents one month of autumn and variation in meteorological patterns is greater across an annual time scale. Based on characteristics of the individual watersheds, these two watersheds could be utilized in a paired catchment study. Windgate has been defined satisfactorily and is a conservative catchment, however Canyon Block gains water during high flow storm events. Before a paired catchment study can occur, more work must be done to understand the flow patterns of Canyon Block, including additional work in delineating other possible recharge areas. This would include additional hydrogeologic inventory, with additional reconnaissance of karst features covering a larger area and dye trace analyzing these features in reference to the Canyon Block system at both high and low flow levels.

In undertaking an experimental catchment study, many measurements must be taken which have a certain percentage of error and estimation. As mentioned previously,
meteorological conditions change dramatically from year to year. Future work should include measurement of discharge and precipitation year round for the construction of an annual water budget for these catchments over the course of several years. Through this calculation, annual patterns in discharge for a variety of conditions can be analyzed.

This is the first study attempting to calculate a water balance in a temperate rainforest karst environment, and it takes into consideration data for high flow volumes during the wettest season of the year. There are other, more detailed observations that could be helpful to better understand water budgeting. For example, integration of stemflow into the water budget through the use of stemflow collars and a detailed stand exam would allow for a greater understanding of how throughfall and ultimately evaporation and transpiration work in the system. The use of fog harps would be beneficial to quantify the input of water to the catchment through fog and stratal drip.

The quick response and flashy nature of these two karst systems, as well as the outcome of each water balance has implications for timber management in karst catchments on the Tongass National Forest. If karst catchments in the Tongass that have been glacially modified hold the majority of storage in the regolith and vegetation, it could be suggested that timber harvest activities would increase the amount and rate of water moving through these karst systems at high flow. This increase would occur through decreased interception (more water reaching the ground), decreased storage space in the canopy (tree removal), and the increase in sediment movement through the removal of trees and brush from the forest floor. In addition, the karst system could be more sensitive to smaller storm events. The amount of increase in discharge and sensitivity would be dependant on the percentage of the catchment that was harvested.
An increase in the amount of water moving through the karst system at high flow would have impacts on the economic benefits of karst waters. It has been shown that salmon prefer the high alkalinity streams emanating from karst areas (Bryant et al. 1998). The primary chemical processes which result in geochemical differences between karst and non-karst streams occurs in the process of equation (4), (5), and (6). This process is sensitive in respect to dissolved ions, temperature, and pH, with a major impact in the buffering of carbonic acid within rainfall and in some catchments, highly acidic water with organic acids flowing from alpine muskeg areas. An increase in the flow rate of water moving through the system due to a greater influx of water is indicative of an overall lowering of stream temperature during storm periods and could cause an overall decrease in the alkalinity of the stream by lowering contact times between the through flowing water and the limestone of the aquifer framework.

Studies contributing to further understanding of the processes in temperature rainforest karst watersheds benefit not only the Forest Service and local stakeholders who depend on the fisheries industry in Southeast Alaska, but also karst science as a whole. Southeast Alaskan karst is unique in that it is coniferous temperate rainforest karst, which only exists in areas of British Columbia, Canada and Southeast Alaska (Aley et al. 1993). Globally, dense population and agricultural use have already impacted many karst regions. Timber harvest management in the past, in certain areas, has impacted Tongass karst. Currently, 20.7% of the karst on the Tongass National Forest has been harvested (Baichtal 2006). The remaining 78.3% has had no direct human impacts, and presents a great opportunity for continued study, as well as a great responsibility for karst managers.
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