Final Report

# An Assessment of the Potential for Using Water and Chloride Budgets to Estimate Groundwater Recharge in Granitic, Mountain Environments

Submitted to:

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Prepared By

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## 1. Introduction

This report summarizes the work performed by Boise State University as part of a subcontract awarded by the Idaho Department of Environmental Quality entitled *An Assessment of the Potential for Using Water and Chloride Budgets to Estimate Groundwater Recharge in Granitic, Mountain Environments.* The motivation for the study is to assist the Idaho DEQ in assessing the potential impacts of land use changes on groundwater resources. Specifically, DEQ is interested in assessing potential impacts of land use changes on groundwater quality. The magnitude of groundwater recharge in mountainous granitic environments is critical to making predictions about changes in water quality. Numerous methods exist for estimating regional groundwater recharge. However, many approaches are limited to specific conditions that are difficult to meet in mountain environments. Groundwater recharge in mountain environments is difficult to measure directly because shallow soils overlying fractured bedrock create complex flow paths. Further, there is generally a paucity of groundwater wells and supporting data in these regions of interest. The chloride mass balance (CMB) approach is a simple reconnaissance method that is commonly applied to provide rough estimates of groundwater recharge in semi-arid and arid regions. The utility of the CMB approach, particularly the inexpensive reconnaissance versions of the method, is unknown for small mountainous watersheds.

The purpose of this project was to evaluate the potential for using the CMB approach to evaluate groundwater recharge in watersheds of the Idaho Batholith. Specific objectives of the project were 1) determine the state-of-the-science on techniques for quantifying rates of groundwater recharge in granitic, mountainous environments, 2) assess the potential for using data from nearby watersheds to estimate groundwater recharge, and 3) conduct a pilot study in the Dry Creek watershed near Boise, Idaho.

The report is organized as follows: Following this introduction, Section II puts the problem of estimating localized groundwater recharge in mountains in the context of current literature. Section III contains an overview of methods to estimate bedrock infiltration (defined in section II) with an emphasis on water and chloride budgets. Section IV contains our findings related to the specific objectives stated above. Section V contains a summary and recommendations.

In addition to this final report, funding for this project contributed to the completion of one peer-reviewed manuscript (McNamara et al., 2005), provided data for another manuscript that is currently in preparation, and partially supported one graduate student.

## 2. Definitions and Scope of Work

Research on the topic of this project is generally found in the literature category of mountain front recharge (MFR), which is defined as the contribution of mountainous regions to the recharge of aquifers in adjacent basins (Figure 1). This large scale problem involves several processes including surface runoff from mountains to the valley floor via streams, subsurface discharge through soils and streambeds, and subsurface contributions to valley aquifers from adjacent bedrock. This last process, called mountain block

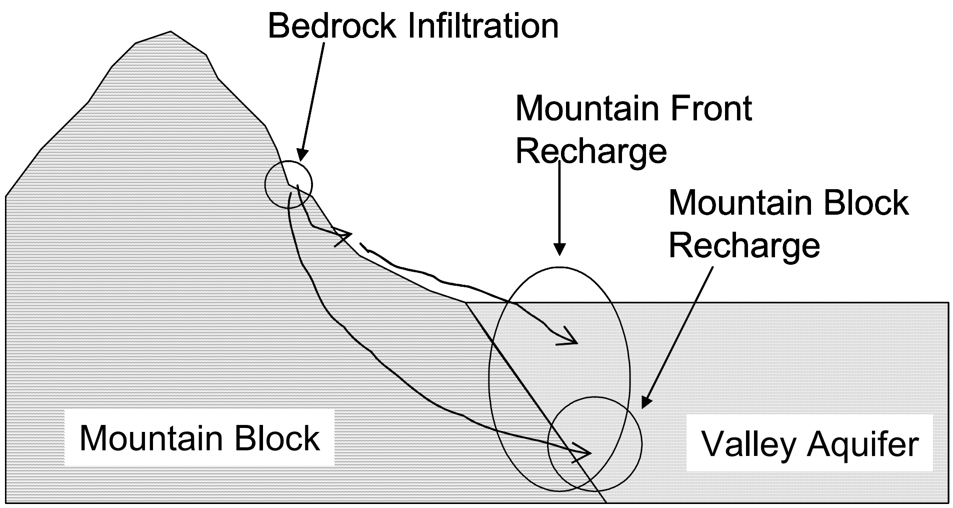


Figure 1: Schematic illustrating relationships between bedrock infiltration, mountain-block recharge, and mountain-front recharge.

recharge (MBR), occurs via subsurface fractures and fissures. Most MFR and MBR studies take a valley-centric perspective and are primarily concerned with assessing quantities of water entering the valley aquifers. However, this current project is concerned with the other end of the flow path at the local recharge source.

Land managers that are charged with assessing impacts of land use on groundwater recharge are not concerned with the down-valley problems of quantifying subsurface discharge into valley bottom aquifers, but are interested in site-specific recharge at the other end of the flow paths in the mountains. How much of the annual precipitation over relatively small areas enters the bedrock fracture system? From this upstream perspective, it can not be said if water that enters the bedrock fracture system, henceforth called bedrock infiltration (BI), travels through the mountain block to the lower basin or re-enters streams high up in the mountains. Regardless, the starting point for MBR is BI, and it is this localized process that is of immediate concern for land managers. What happens between bedrock infiltration and mountain front recharge is a field of research that is ripe for future investigations, but is well beyond the scope of this project. For this reason this report avoids the terms mountain block recharge and mountain front recharge in favor of the term bedrock infiltration to refer the precipitation that is lost to the bedrock subsurface within a study area of interest.

Methods to assess bedrock infiltration are not well developed. Instead, methods designed for assessing deep infiltration in soils must be modified to account for the complexities of mountain landscapes. Infiltration is generally a one-dimensional process wherein water moves from the surface into the subsurface. Estimating groundwater recharge through infiltration is typically a problem of determining when vertically moving subsurface water travels beyond the evaporative demands of the climate and vegetation. Bedrock infiltration is complicated by the fact that the surface of interest is typically hidden by a thin but complicated soil layer. For bedrock infiltration to occur, infiltrating water must survive passage through this layer while being subject to evapotranspiration and lateral throughflow to streams. Once water reaches the soil/bedrock interface it will move down slope until a fracture with sufficient conductivity is encountered. In arid and semi-arid regions dry soil can prohibit water from reaching the soil/bedrock interface for much of the year. Infrequent summer rainfall must first wet near surface soils to field capacity, but evapotranspiration typically removes this water. McNamara et al. (2005) showed that in a semi-arid watershed near Boise Idaho hillslope soils must wet to depth before they can contribute appreciable runoff to streams (Figure 2). This is also true for bedrock infiltration. Hence, the problem of estimating bedrock infiltration involves complex interactions between topography, soil moisture dynamics, climate, and bedrock geology.

## 3. Methods to Estimate Bedrock Infiltration

Several recent reviews have been written summarizing methods to estimate one-dimensional groundwater recharge (i.e. Allison et al. 1994; Gee and Hillel, 1998; Flint et al., 2002; Grismer et al., 2000; and Scanlon et al., 2002). de Silva (2004) lists the techniques as (a) lysimeter method, (b) soil water budget models, (c) water table fluctuation method, (d) watershed water balance method, (e) numerical modeling of the unsaturated zone, (f) zero flux plane method, (g) Darcy method, (h) tritium profiling method and (i) chloride profiling method (Lerner et al., 1990; de Silva, 1998; Scanlon et al., 2002). de Silva (2004) further states that all but the watershed water balance method are point estimates and that the watershed method is the least valid because of many problems associated with two dimensional flow. However, point methods are based on the idea that once vertically infiltrating water overcomes near surface evaporative demands, water continues downward as piston flow to become groundwater recharge. The problem then is simply to estimate the rate at which that water moves. However, the piston flow model is not applicable where thin sloping soils overly fractured bedrock. This report takes the opposite view of de Silva (2004) that watershed based approaches to estimate bedrock infiltration are more applicable than point based approaches in mountainous terrain. Consequently, we limit further discussion to using watershed water and solute budgets to estimating bedrock infiltration.

### 3.a. Water Budget

The water budget equation is based on conservation of mass which dictates that the difference between the rate that water enters a region ($Q_{in}$) and the rate that water exits that region ($Q_{out}$) over a period of time ($\Delta t$) must match of change in the volume of water stored ($\Delta S$) in the region during that period of time.

$$Q_{in} - Q_{out} = \frac{\Delta S}{\Delta t} \qquad (1)$$

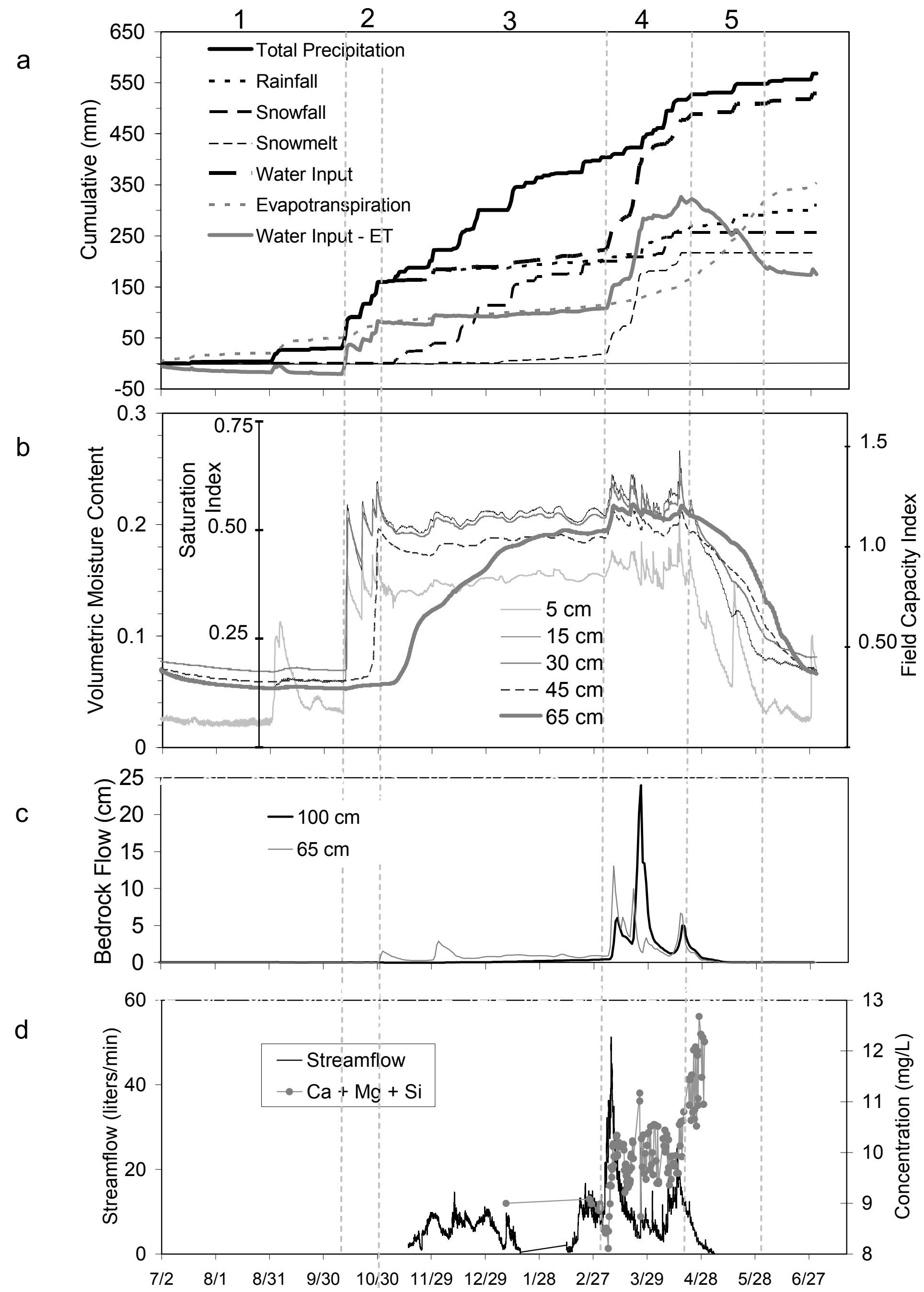


Figure 2. Timing of events during the 2001 water year a) at the land—atmosphere interface, b) in the soil column, c) at soil/bedrock interface modeled by SHAW, and d) in the stream. The numbers across the top and the gray vertical line refer to the characteristic moisture periods described by McNamara et al. (2005).

Expansion of the terms in Equation 1 will vary with the spatial and temporal scales of the applications, but the basic physical concept is true for all scales over all periods of time. For example, the water budget equation can be applied to the near-subsurface in agricultural lands to evaluate water losses to deep infiltration from irrigation, or to evaluate how precipitation is partitioned between evapotranspiration, streamflow, and groundwater recharge in small to large watersheds. In both of these cases, the vertical movement of water to the deep subsurface, or groundwater recharge, is typically calculated as a residual with all other components being measured or modeled.

For a watershed bounded by topographic highs and a surface water outlet, inflow terms include precipitation (P) and groundwater ($GW_{in}$). Outflow terms can include evapotranspiration (ET), surface runoff (R), and losses to groundwater ($GW_{out}$). Storage (S) can take place in the vegetation canopy ($S_{can}$), snow ($S_{snow}$), surface water ponding ($S_{pond}$), and soil moisture ($S_{soil}$).). Incorporating these terms into Equation 1 results in

$$(P+ GW_{in})\,\Delta t = (ET + GW_{out} + R + \Delta S_{can} + \Delta S_{snow} + \Delta S_{soil} + \Delta S_{pond})\Delta t \qquad (2)$$

All components are given as rates so that a mass balance is produced when integrated of a period of time. Well known hydrologic processes such as overland flow and infiltration are not included at the watershed scale because these processes are simply internal cycling mechanisms that do not bring water into or carry water out of the watershed. Groundwater can also be an internal cycling mechanism if water enters and exits the groundwater system within the boundaries of the watershed. For groundwater recharge investigations, it is therefore important to apply the water budget equation to proper watershed scales that will provide the desired information. Bedrock infiltration only represents water that enters the watershed boundaries from the surface and leaves the watershed boundaries through the subsurface. In this application bedrock infiltration is the difference between $GW_{in}$ and $GW_{out}$

$$BI = GW_{out} - GW_{in} \qquad (3)$$

The difficulty of applying Equation 2 increases as time scales decrease and spatial scales increase. A common application is to evaluate Equation 2 at the annual time scale. In this case the storage terms can be considered 0 (i.e. soils hold essentially no water during the summer, become wet during the winter then return to dry conditions the following summer). For a one year period Equation 2 can then be written as

$$BI = P - ET - R \qquad (4)$$

where the quantities in Equation 4 are annual total volumes. In the remainder of this report the components of the water budget equation refer to annual equivalent depths, which is the volume of water transported by the particular process in a year divided by the watershed area.

The major limitation to applying the water budget approach to any scale is that the accuracy of recharge estimates depends on the accuracy with which the other components are measured or modeled. P and R are easily measured. ET and is not. This is a particular concern in areas where groundwater recharge is a small component of the water budget such as in arid and semi-arid mountain environments where ET and streamflow are high. However, the water budget method provides a rough estimate of potential losses of surface water to groundwater.

An excellent summary of the errors associated with measurements of individual components of the water budget is given in Dingman (2002). Evapotranspiration is the most difficult component to evaluate so the accuracy of the water balance approach depends largely on the accuracy of ET estimations. For example, if ET is 60% of P, and BI is 20% of P, then a 20% uncertainty in the ET estimate leads to a 60% uncertainty in BI (example modified from Wilson and Huade, 2004).

### 3.b Estimating Groundwater Recharge Using Chloride Mass Balance

A key advantage to tracking the mass balance of a conservative solute (i.e. non-reactive) that is carried by water such as chloride is that evapotranspiration can be ignored. Evapotranspiration does not transport chloride so the mass of chloride input to a watershed in a year can be accounted for by the mass that leaves as streamflow and the mass that enters the groundwater system. This is based on several assumptions including 1) there is no storage of chloride in the unsaturated zone, and 2) precipitation is the only source of chloride in the flow system.

The first assumption is easily violated if chloride balances are performed on less than an annual time scale. In arid and semi-arid climates nearly all rainfall that falls during the summer months evaporates, but strands chloride behind in the vadose zone. When fall rain and spring snowmelt travels through the soil, infiltrating water picks up the stranded chloride. Assumption 1 is strictly valid if the amount of stranded chloride during the dry season is approximately the same from year to year. The second assumption can be violated from weathering of geologic formations high in chloride or from anthropogenic activities such as road salting.

Additional assumptions must be made depending on the application. Two general classes of applications include point-based chloride profiling and watershed scale mass balances.

#### 3.b.1 Point-based Chloride Profiling

The chloride mass balance (CMB) approach was first developed as a one-dimensional estimation of point recharge in desert soils (Allison and Hughes, 1978). This application is commonly called chloride profiling and involves calculating the vertical mass flux of chloride then relating mass flux to water flux. The mass of chloride that flows through any region is the product of the flow rate of water ($L^3t^{-1}$), the concentration of chloride in that water ($ML^{-3}$), and the time period of interested (t). The derivation of an annual chloride budget with no annual storage of chloride follows the same logic as the annual water budget discussed above. A one-dimensional annual chloride budget can be written as

$$P*C_p = GR*C_{gr} + R*C_r \tag{5}$$

where P is precipitation, GR is groundwater recharge, and R is surface runoff. C is annual average chloride concentration in precipitation, groundwater, and runoff. A significant advantage the chloride balance over the water balance is that ET is not included in chloride balances because ET does not transport chloride. ET, however, does change chloride concentrations in the subsurface. Typically, chloride concentrations increase with depth to the base of the root zone then remain relatively constant with depth after that (Scanlon et al., 2002). This evaporative concentration can be ignored if $C_{gr}$ is measured well below the affected zone. Solving for groundwater recharge, Equation 5 is written as

$$GR= (P(C_p)- R(C_r))/C_{gr} \tag{6}$$

The chloride profiling method is commonly applied to arid and semi-arid regions with little or no surface runoff and with a clearly defined water table in unconsolidated sediments (Allison and Hughes, 1978). In such environments the problem can be reduced to one dimension and Equation 4 reduces to

$$GR = P\frac{C_p}{C_{gr}} \tag{7}$$

Equation 7 can be used in reconnaissance investigations by obtaining P and $C_p$ from publicly available data sources then sampling deep soil moisture or groundwater to estimate $C_{gr}$. In this way a CMB can be performed quickly without the expense and time commitment of constructing an annual water budget. Precipitation data and chloride concentrations in precipitation are available from the National Atmospheric Deposition Program. Applicable data is available for Idaho locations, i.e. Smiths Ferry station, Valley County, just south of Cascade, elevation 1442 meters and Craters of the Moon station.

### 3.b.2 Watershed Chloride Mass Balance

Equation 7 is difficult to apply in mountainous terrain because of the thin soils and the sloping topography. The thin soils make it essentially impossible to sample $C_{gr}$ directly below the site of interest. The sloping topography creates significant lateral flow, i.e. not piston flow, and surface drainage. Streams are not routinely monitored for chloride concentrations so it is difficult to estimate $C_r$ without conducting a year of monitoring. Dettinger (1989) modified the chloride profiling method for application to several watersheds in Nevada. Subsequent similar studies have by conducted in Nevada by Russell and Minor, 2002 and by Thomas and Albright, 2003. Rather than using $C_{gr}$ in a vertical profile below the sites of interest these studies use springs and wells to obtain regional average groundwater chloride concentrations. This approach provides good estimates of regional groundwater recharge rates, but it integrates large areas. Consequently, the watershed scale CMB approach is best suited to estimate mountain block recharge rather than localized bedrock infiltration.

### 3.b.3 Application of CMB to Bedrock Infiltration in Small Mountain Watersheds

Sections 3.b.1 and 3.b.2 illustrate important problems for applying the CMB approach to estimate groundwater recharge at point and watershed scales. At the point scale it is difficult to sample $C_{gr}$ and the assumption of piston flow is violated. At the watershed scale, however, the difficulties of determining $C_{gr}$ can be overcome if sampling locations are selected carefully to ensure that the $C_{gr}$ represents the local recharge water, called bedrock infiltration. Proximal groundwater wells can be used if they exist. Springs must represent groundwater that has gone through the localized concentrating by evapotranspiration, but does not integrate multiple evapotranspiration regimes. Springs, however, can not exist in the study site of interest or else the watershed is not likely to be a recharge area.

An alternate approach to estimate the chloride concentration in recharge water, $C_{bi}$, is to assume that all rainfall evapotranspires without contributing to recharge so that recharge only comes from melting snow. Further assume that the chloride that is stranded in the prior dry season by evapotranspiration is entirely mobilized by later snowmelt. The concentration in recharge water is therefore the mass of chloride delivered from the atmosphere during the entire year divided by the volume of water that falls as snow during the year. This is equivalent to multiplying the average annual concentration in precipitation by the ratio of annual depth of precipitation to annual depth of snow water equivalent (SWE)

$$C_{bi} = (C_p)*(P/SWE) \tag{8}$$

This approach neglects the effects that evapotranspiration might have on the snowmelt water and assumes that no stranded chloride is transported laterally to streamflow. Both of these additional assumptions are not strictly true, but the violations are likely minor and counter to each other.

Claassen et al. (1986) approached the $C_{bi}$ problem by assuming that the chloride concentration in runoff is equal to the chloride concentration in recharge water. However, they present no data to support this assumption. Dettinger (1989) states that in most watersheds, runoff concentrations tend to be one quarter to one half of groundwater concentrations.

## 4. Status of proposed objectives

### 4.a. Objective 1: Determine the state-of-the-science on techniques for quantifying rates of groundwater recharge in granitic, mountainous environments.

The product of this objective was proposed to be a report for the Idaho Department of Environmental Quality summarizing techniques for estimating localized groundwater recharge, or bedrock infiltration, in granitic, mountainous environments. Significant advances are being made concerning methods to assess MBR such as age-dating with noble gases (Manning, 2002), environmental isotopes (Ofterdinger et al., 2004), and advances in hydroclimatic modeling (Chavez et al. 1994a. and 1994b.) Several excellent summaries have been written about MBR including reviews of estimation methods (e.g. Scanlon and Healy, 2002; Wilson and Guan, 2004). Nearly all techniques summarized in scientific literature, however, are designed to understand either point-scale estimates of groundwater recharge in deep soils or integrated watershed scale contributions to mountain block recharge (large scale subsurface contributions of mountain blocks to valley aquifers). The methods to assess MBR consider only the quantity of water entering the valley aquifers without regard to the spatially variable processes of how water entered the mountain block. The MBR problem is beyond the scope of this investigation as defined in Section 2. It is this author's opinion that watershed water balance and modifications to the watershed chloride mass balance approaches described in Section 3 are the only feasible techniques to estimate bedrock infiltration. Consequently, the summary of water and chloride mass balance approaches serves as the review of pertinent techniques. The work related to this objective, however, has served as a starting point to begin to address larger scale MBR. An MS student at Boise State University, Pamela Antrim, has been working on a summary of MBR as part of her thesis, which will be complete by May 2006.

### 4.b. Objective 2: Assess the potential for using data from nearby watersheds to estimate groundwater recharge.

The US Forest service operated an experimental watershed program for many years in Silver Creek, a tributary of the Middle Fork of the Payette River, which is physically very similar environment to the Cascade, Idaho region. The purpose of this objective was to determine if data from the watershed could be used to gain insight into groundwater recharge in the region.

A chloride mass balance of one sub-watershed in the Silver Creek drainage was published by Clayton (1986). To simplify weathering investigations, the Clayton (1986) study used chloride mass balances to identify watersheds that were "tight", or watersheds that receive no groundwater discharge and lose no water to deep infiltration. Two watersheds were found wherein the mass of chloride that entered each watershed as precipitation (4.6 and 4.7 kg/ha) approximately equaled the mass that left as streamflow (4.8 and 4.9 kg/ha). The greater streamflow loads could be a result of the stranded chloride problem described in Section 3.

That Clayton was able to search for and find tight watersheds suggests that groundwater recharge in mountainous terrain is spatially variable and not consistent within a region. The variability is likely controlled by the fracture density of the underlying geology. Consequently, it is not advisable to transfer recharge estimates from one watershed to another watershed without consideration of the geology. This result has inspired a second MS student at BSU to conduct thesis research on the fracture density in the Idaho Batholith to support groundwater recharge investigations. Ms. Hoffman will begin this research in summer 2005 and will complete her thesis in fall 2006. The objective of her work will be to determine the potential porosity and relative fracture density of granitic bedrock in the Dry Creek watershed. She will map surface expressions of fractures, use remote sensing to detect large scale fracture patterns, and model subsurface fracture distributions with FracMan software (Dershowitz et al., 1996). We are modeling this research after the comprehensive Turkey Creek investigation in Jefferson County, Colorado (Bossong et al., 1996).

## 4.c Objective 3: Dry Creek Pilot Study

The purpose of this objective was to take advantage of existing hydrologic infrastructure in the Dry Creek watershed in the foothills adjacent to Boise, Idaho to test the chloride and water balance approaches for estimating bedrock infiltration in granitic watersheds (Figure 3). Faculty and students in the Department of Geosciences at Boise State University have been conducting hydrologic studies in Dry Creek for approximately four years. Currently, seven stream gauging stations and three weather stations are distributed throughout the 27 $km^2$ watershed. One weather station is located in a 0.012 $km^2$ watershed where we are also monitoring, hillslope overland flow, snow depth, soil moisture in 20 locations, and streamflow. This small watershed, called the Treeline watershed, is the site for this pilot study.

Water and chloride budget investigations should be conducted over time periods that encompass one wet season. The funding period for this subcontract overlapped with the end of one wet season and the beginning of the next. Consequently, we were unable to construct current budgets as part of this grant. We are, however, continuing the sampling program and seeking further funding from other sources to construct budgets at larger scales in the Dry Creek watershed. Fortunately, water samples were collected, but unanalyzed, in previous years as part of other projects. Funds from this subcontract were used to analyze samples from previous years to complete water and chloride budgets for the Treeline watershed for the 2001 water year, and to begin a new sampling program to perform similar analyses at larger scales. Water and chloride budgets for the large watersheds will be completed after a full year of sampling is completed following the spring 2005 snowmelt period.

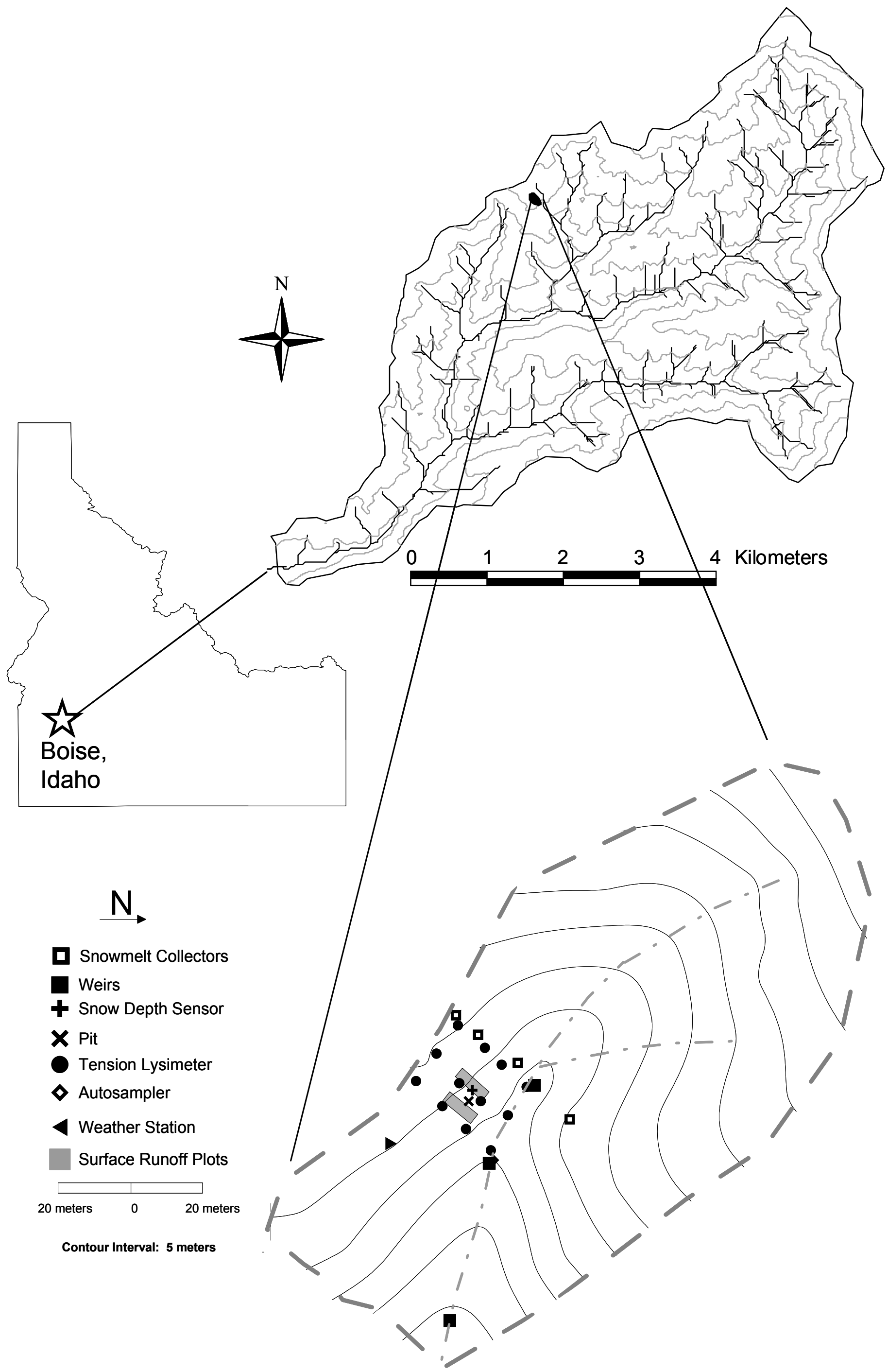


Figure 3. Location of the Dry Creek Experimental Watershed.

The goal of the study is to compare estimations of bedrock infiltration from the Treeline watershed using water and chloride budgets for the 2001 water year. Specific objectives include

1. Quantify the annual bedrock infiltration from the Treeline watershed using a water balance approach (Equation 4),
2. Quantify the mass of chloride lost to bedrock infiltration (Equation 5),
3. Convert the annual chloride loss to bedrock infiltration rates with Equation 6 using different approaches to estimate $C_{bi}$ including

    a. groundwater from a proximal spring
    b. groundwater from a proximal well,
    c. the stranded chloride approach with Equation 8.

**Methods**
Combined rainfall and snowfall, P, was measured in a shielded weighing bucket gauge mounted on a post approximately 1.5 m above the ground surface. P was considered snow when the air temperature was below 0 degrees Celsius. In addition, snow depth was monitored hourly at one point by a sonic depth sensor. Occasional snow surveys are performed to obtain basin-average snow water equivalent. SWE obtained from snow surveys compared favorably to SWE obtained from the weighing bucket gage.

Evapotranspiration (ET) and Soil Moisture: ET was calculated using the Simultaneous Heat and Water (SHAW) model (Flerchinger et al., 1996). SHAW is a comprehensive one dimensional model that simulates moisture fluxes from the atmosphere through the vadose zone. SHAW requires soil texture, vegetation type, air temperature, solar radiation, and wind speed. Soil texture was described as components of sand, silt, and clay from five samples collected from two soil pits excavated to bedrock. Meteorological variables were measured with a Campbell Scientific weather station close to the precipitation station. SHAW simulations were calibrated and verified by comparing simulated to observed soil moisture patterns. Soil moisture was monitored in two vertical profiles 100 cm (pit100) and 65 cm (pit65), 2 m apart and 15 m upslope from the stream channel on the N-facing slope. Moisture content was monitored at 15 minute intervals with Water Content Reflectometers (Campbell Scientific, Logan,UT) at depths of 5 cm, 15 cm, 30 cm, 65 cm, and 100 cm.

Streamflow, R, was monitored at a plywood v-notch weir draining 0.012 $km^2$. Stage in the pond behind each weir was monitored by pressure transducers.

Rain and snow samples were collected to determine chloride concentration in precipitation, $C_p$. Rain was collected during occasional storms using plastic funnels draining in polyethylene bottles. Snowcores were collected periodically throughout the cold season and melted to sample the chemical composition of the snowpack. Snowmelt pans were used to collect snowmelt at the base of the snowpack. Water samples were collected from the stream twice daily using an ISCO automatic sampler during the snowmelt period and approximately weekly during the low flow winter period. The stream does not flow during the summer. All water samples were passed through a 1 micron filter at the time the sample was taken. All water samples were refrigerated before analysis. Chloride analysis was completed by a colormetric method at the Utah State University Analytical Laboratory.

## Results

### *Water Balance*

Bedrock infiltration from water budget calculations (Equation 4) was 71 mm or 13% of annual precipitation (Table 1). Figure 3 shows that SHAW simulates observed soil moisture patterns well suggesting the evapotranspiration estimates are reliable. Bedrock flow, a product of SHAW, in Table 1 is the amount of water that reaches the soil bedrock interface. Once the moisture content at this interface reaches field capacity, additional water becomes available for bedrock infiltration. Figure 2b shows that the deep soils did not reach field capacity (approximately 17%) until April suggesting that the bedrock infiltration can only occur during a brief period of the year. SHAW simulations suggest that 244 mm or 42% of total precipitation reached the soil bedrock interface. This water either travels laterally to the stream or infiltrates the bedrock. The difference between this bedrock flow and streamflow (143 mm) is 101 mm, which provides an upper boundary to potential bedrock infiltration. Actual bedrock infiltration is expected to be less, as our water budget calculations suggest, because some moisture will remain in storage at moisture contents below field capacity.

### *Chloride Balance*

Using annual average chloride concentrations from Table 2 and annual water fluxes from Table 1, the watershed received 4.6 Kg of chloride via precipitation and exported 2.1 Kg of chloride via streamflow suggesting that 56% of the chloride that entered the watershed left via bedrock infiltration. This supports the water budget calculation that the watershed loses water to the underlying bedrock.

**Table 1. Annual and monthly water budget of the Treeline Catchment.**

| | Observations | | Equation 4 Calculations | | SHAW Simulations | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P (mm) | Runoff (mm) | Bedrock Infiltration (mm) | BI/P | Rain (mm) | Snow[2] (mm) | Snowmelt (mm) | ET (mm) | $\Delta S_{soil}$ (mm) | Bedrock Flow (mm) |
| **Total Annual** | **568** | **143** | **71** | **0.13** | **311** | **257** | **217** | **354** | **5** | **244** |
| July-00 | 3 | | | | 3 | 0 | 0 | 17 | -7 | 0 |
| August-00 | 1 | | | | 1 | 0 | 0 | 4 | -2 | 0 |
| September-00 | 26 | | | | 26 | 0 | 0 | 28 | 2 | 0 |
| October-00 | 130 | | | | 130 | 0 | 0 | 29 | 76 | 0 |
| November-00 | 62 | | | | 22 | 40 | 0 | 12 | 10 | 0 |
| December-00 | 78 | | | | 5 | 74 | 2 | 8 | 11 | 0 |
| January-01 | 68 | | | | 8 | 60 | 7 | 8 | 5 | 4 |
| February-01 | 29 | | | | 7 | 22 | 9 | 8 | 2 | 8 |
| March-01 | 53 | | | | 35 | 17 | 164 | 23 | 4 | 167 |
| April-01 | 77 | | | | 33 | 44 | 35 | 54 | -15 | 61 |
| May-01 | 20 | | | | 20 | 0 | 0 | 124 | -57 | 3 |
| 1-Jun | 20 | | | | 20 | 0 | 0 | 41 | -24 | 0 |

**Table 2. Annual average chloride concentrations (mg/L), and Bedrock Inifiltration calculatio**

| | Streamflow | Precipitation | Proximal Groundwater Springs | Proximal Well (Bogus Basin) | Equation 8 |
|---|---|---|---|---|---|
| **Mean** | 0.69 | 0.68 | 1.20 | 1.24 | 1.28 |
| **Min** | 0.29 | 0.29 | na | na | na |
| **Max** | 1.78 | 1.32 | na | na | na |
| **STDEV** | 0.22 | 0.34 | na | na | na |
| **n** | 137 | 14 | 1 | 1 | 1 |
| **BI** | | | **241** | **233** | **226** |
| **BI/p** | | | **0.42** | **0.41** | **0.40** |

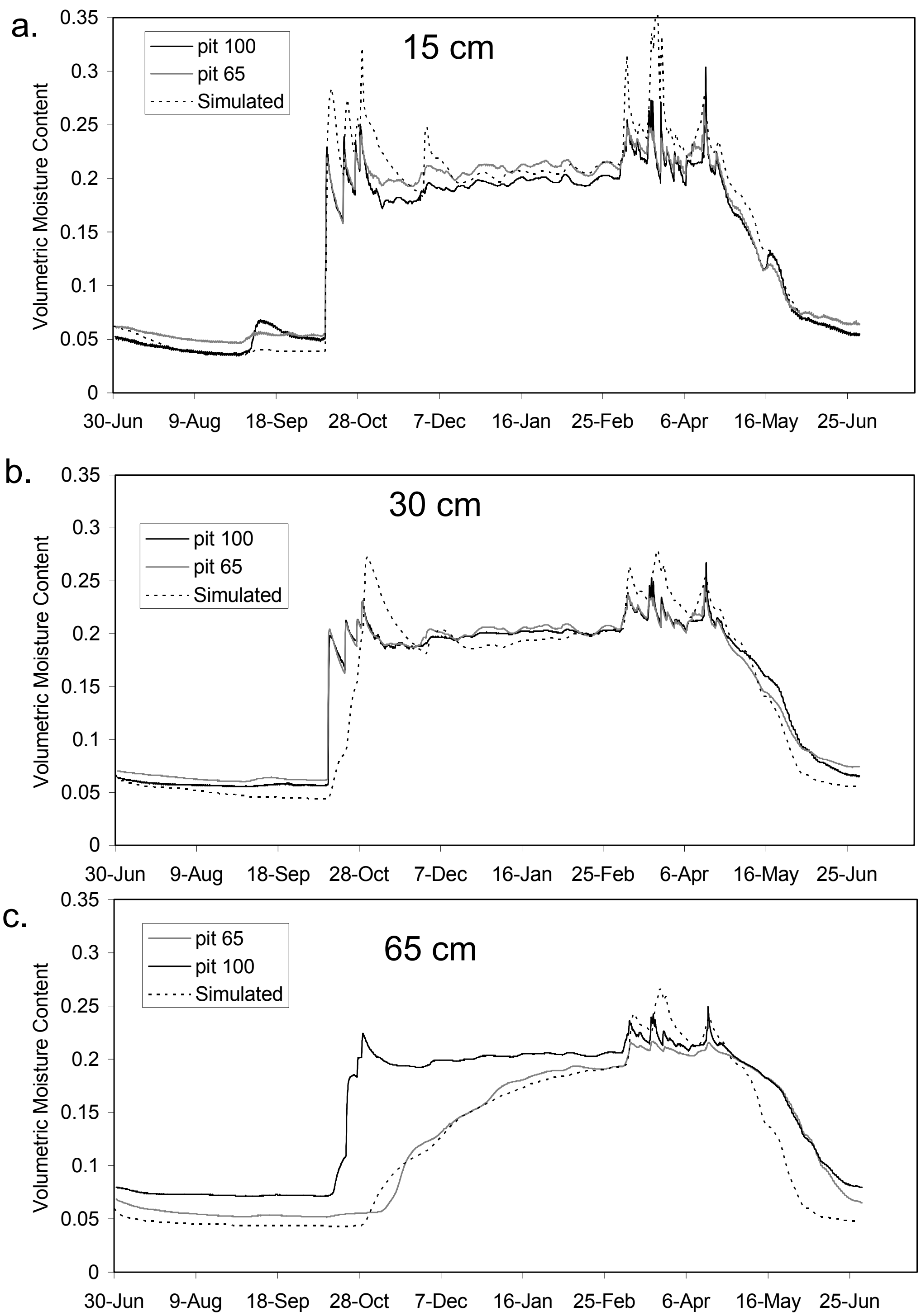


Figure 4. Observed and simulated volumetric moisture content at a) 15, b) 30, and c) 65 cm depth in Pit 65 and Pit 100.

All three approaches to estimate $C_{bi}$ produce strikingly similar bedrock infiltration results near 40% of precipitation. This encouraging result suggests that when wells or springs are not present, the stranded chloride approach can be used to estimate $C_{bi}$.

Differences between the water budget and CMB approaches can be attributed errors in ET and $C_{bi}$ estimations. However, without a full error analysis of both approaches it is difficult to say which approach is more robust. At best, we can say that both approaches suggest that the Treeline watershed loses water to bedrock infiltration and that the magnitude of that loss is somewhere between 10% and 40% of annual precipitation.

Table 3 presents estimations of mountain block recharge from other watersheds in the western USA. Recall, however, bedrock infiltration is different than mountain block recharge. If the entire Boise Front operated like the Treeline Watershed then bedrock infiltration would be similar to mountain block recharge. However, because many watersheds in the Boise Front receive groundwater discharge through springs, mountain block recharge will likely be less than our bedrock infiltration calculations.

Table 3. Reported values of mountain block recharge (MBR) (Taken from Wilson and Guan, 2004).

| **Location** | **Reference** | **Method** | **MBR % of P** | **Annual P** | **Rock type** |
|---|---|---|---|---|---|
| Wasatch Range, Utah | Feth et al. 1966 | Water balance | 22 | 926 | unknown |
| San Juan Mountains, Colorado | Huntley, 1979 | Water balance | 38% | Not reported | High permeability volcanic rock |
| Sangre de Cristo Mountains, Colorado | Huntley, 1979 | Water balance | 14% | Not reported | Shists, gneisses, and granitic intrusives, well cemented sedimentary rocks |
| Santa Catalina Mountains, Arizona | Chavez et al., 1994 | Hydrology model | 0.2% | 280-760 | Layered gneiss with folds |
| Yucca Mountains, Nevada | Flint et al., 2002 | Hydrology model | 2.7% | 170 | Welded and non-welded tuff |

**5. Summary**

The purpose of this project was to assess the potential for using water and chloride mass balances to determine groundwater recharge rates in granitic, mountainous terrain. The three specific objectives asked these questions: First, what techniques are available for estimating groundwater recharge in mountainous terrain. Second, can data from nearby watersheds be used to estimate groundwater recharge in a watershed of interest? Third, what information will a pilot study in the Boise Front provide?

It is the author's opinion that only the chloride and water balance approaches are appropriate to estimate bedrock infiltration at watershed scales. Other techniques such and using environmental isotopes and noble gases are more appropriate for estimating large scale fluxes at discharge locations.

Our data recovery effort from the Silver Creek watershed showed that groundwater recharge in mountainous terrain is highly variable. It is possible to locate "tight" and "leaky" watersheds within a region. Consequently, it is not recommended to translate recharge estimates from one watershed to another without information about the underlying geology.

The Dry Creek pilot study showed that the chloride mass balance approach can be used to estimate localized bedrock infiltration in mountain watersheds. The approach, however, can not determine if bedrock infiltration makes it to the regional groundwater system or simply discharges to a spring or stream down-valley. Further, differences between recharge estimates from water balances and chloride balances suggest that the absolute numbers should be used with caution. At best, we can say that both approaches suggest that the Treeline watershed loses water to bedrock infiltration and that the magnitude of that loss is somewhere between 10% and 40% of annual precipitation. We are continuing our sampling program through other funding sources to further investigate scale issues related to chloride mass balances.

In addition to this report, this project contributed to a journal publication (McNamara et al., 2005), provided data to prepare a second journal publication about the application of the chloride mass balance in thin soils, and launched two masters thesis investigations. Data from this project providing the basis for a proposal that is currently being developed for submission to the USDA National Research Initiative, and a BSU graduate student, Bernadette Hoffman, received a $10,000 fellowship from NASA to investigate the geologic controls on groundwater recharge, a problem that was initiated by this project.

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