GROUNDWATER RECHARGE ESTIMATION
USING CHLORIDE MASS BALANCE
DRY CREEK EXPERIMENTAL WATERSHED

by

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The thesis presented by Pamella Sarah Aishlin entitled Groundwater Recharge Estimation Using Chloride Mass Balance, Dry Creek Experimental Watershed is hereby approved:

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For recognition and encouragement of my interest in science, from its earliest inception through three university degrees, I dedicate this thesis to my mother, Diana Marie Taylor, a truly admirable woman.

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ABSTRACT

Estimates of groundwater recharge conducted via chloride mass balance application at multiple catchment scales within Dry Creek Experimental Watershed delineate both a percentage of annual precipitation partitioned to recharge and spatial variability within the recharge. Inclusion of stream flow discharge in the chloride mass balance equation further qualifies the recharge estimates as net groundwater recharge values representing water available to deeper mountain block groundwater flow paths. The estimate of annual precipitation partitioned to net groundwater recharge for the entire catchment, water year July 2004 through June 2005, is zero to 11%. However, application at multiple catchment scales within Dry Creek Experimental Watershed indicates as much as 22% of annual precipitation being partitioned to net groundwater recharge in higher elevation subcatchments during the same period. Results for the second study year, July 2005 through June 2006, were predominantly assessed as invalid due to mobilization of inter-annually stored unsaturated zone chloride. Spring and stream chloride concentration time-series data applied to hydrograph separation were utilized to determine the timing of unsaturated zone chloride mobilization and concurrent vertical and lateral transport toward bedrock infiltration and stream channels. Additionally, gain/loss analyses conducted using the stream chloride concentration time-series data provide evidence of stream flow loss to groundwater recharge. The contrasting results for water year 2004-2005 versus 2005-2006 emphasize caution necessary in addressing assumptions underlying application of chloride mass balance to recharge estimation and

the need for careful delineation of an appropriate multi-annual period of integration toward an estimate of average annual groundwater recharge.

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INTRODUCTION

As populations increase and development expands within semi-arid basins and on adjacent mountain fronts, local surface and ground water resources are increasingly utilized. In order to accurately address short-term and long-term water management within these communities dependent on mountain block water catch and delivery, detailed understanding of mountain block hydrology and mountain-block recharge rates is needed (Hutchings et al., 2001; Wilson and Guan, 2004). However, recharge estimation in mountain environments is hindered by the difficulty in measuring or modeling evapotranspiration affected by variable soil depth, slope, aspect, vegetation and elevation. Additionally, mountain front water flux pathways are affected by steep slopes, complex ground-water flow paths and sensitivity of surface runoff to precipitation intensity and snowmelt variables, which results in spatial and temporal variability in water flux that is especially difficult to measure or predict. Effects of the above described complexities are exacerbated in arid or semi-arid mountain environments, wherein evapotranspiration occurs at high rates relative to rainfall and recharge is snowmelt-driven. It is emphasized here that the detailed knowledge necessary for short term and long-term water management requires annual or multi-annual recharge estimation and understanding of water flux at the mountain-front catchment scale due to spatial variability in hydrologic parameters, as well as the need to assess catchment scale hydrologic impacts of land-use change over time (Wilson and Guan, 2004).

Methods traditionally applied to delineate catchment scale water flux in mountain environments involve intensive measurement, extrapolation and modeling of physical parameters (Bossong et al., 2001). The cost, time commitment and uncertainty involved in these methods is high relative to environmental tracer methods (Allison et al., 1994; Phillips, 1994), because traditional water balance methods utilize parameters difficult to measure or model, such as evapotranspiration and groundwater flux, while tracer methods utilize parameters which may be directly measured, including precipitation, stream discharge and water chemistry. Therefore, to address cost-effective, reliable methods for estimating net groundwater recharge and delineating catchment scale water flux in arid or semi-arid mountain environments, this study utilizes the chloride ion as an environmental tracer within Dry Creek Experimental Watershed (DCEW) on the Boise Front.

Notable early use of environmental chloride involving measurement of chloride concentrations in stream flow and precipitation was undertaken by Wood (1924), Anderson (1945) and Eriksson (1960). Application progressed from comparison of chloride concentrations in stream flow and precipitation to proposal of ground water recharge estimation utilizing groundwater chloride concentrations. The proposed chloride mass balance (CMB) method involved quantifying the mass of chloride delivered from precipitation to groundwater based on measurement of chloride concentration in precipitation and groundwater, combined with measurement, or estimation, of precipitation received, from which an annual volume of groundwater recharge could be calculated. The method was based on the premise that change in concentration of chloride in the system results from evapotranspiration. Recharge estimation was then conducted and assessed by Eriksson and Khunakasem (1969) in Israel using this method. Since 1969, use of the method has evolved from application at point-value locations underlain by deep vadose zones to application in mountainous terrain. The term “net groundwater recharge” applied in this study denotes recognition of complex water pathways occurring in mountain catchments which include discharge of groundwater to surface water flow within a given catchment.

Primary objectives for this two-year study include net recharge estimation at multiple catchment scales and delineation of time-variable contributions of surface, shallow subsurface and groundwater flow to stream flow. Development of such knowledge is necessary not only to water management in terms of quantity, but also water quality. Specific questions to be answered include: How much of the annual precipitation received is partitioned to net groundwater recharge?, Where and when does this recharge occur? and, What is the timing and magnitude of vadose zone, surface water and groundwater interactions in stream flow?

Study Site

Dry Creek Experimental Watershed is located 6.5 km north of Boise, Idaho within the Boise Front Range in semi-arid southwestern Idaho. Below the Boise Front, the city of Boise hosts a growing population of over 200,000 on a broad valley floor receiving less than 300 mm precipitation annually. While the Boise Front watersheds are considered a likely source of valley groundwater recharge (Hutchings et al., 2001) and development for residential and recreational use continues upward along the Boise Front, hydrologic investigation of these catchments has remained incomplete. Initial steps toward increasing understanding of the Boise Front hydrogeologic system began with installation of a Snotel weather station at the Bogus Basin Ski Resort and two stations established in DCEW in 1999. Annual precipitation values for the station years on record is given in Figure 1, showing annual precipitation over the past seven years to vary from less than 300 mm in lower elevations to over 600 mm in higher elevations, occurring predominantly as rainfall and snowfall during November through May.

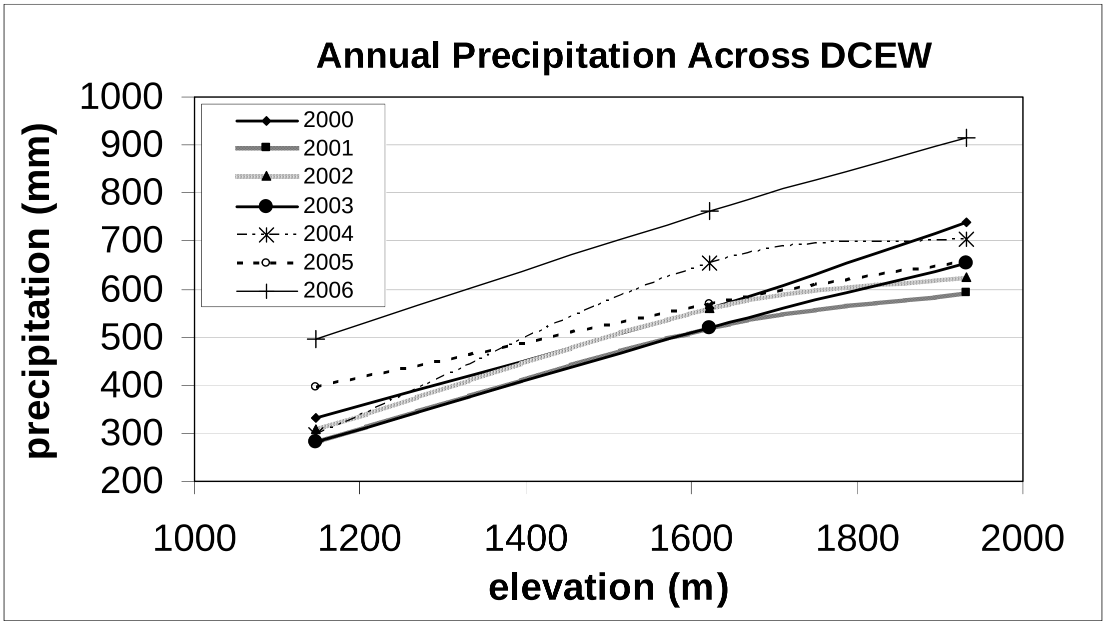


Figure 1. Annual precipitation, DCEW, October water years 2000 to 2006. Data points are from Lower weather station (1146 m), Treeline weather station (1622 m) and Bogus Snotel station (1932 m).

The area encompassed by DCEW is 27.2 km^2 with an elevation range of 1000 m, where Dry Creek intersects Bogus Basin road, to 2200 m at the Boise Front ridge line. Terrain is steep with thin sandy soils and predominant grass and brush groundcover in the lower elevations, contrasted by Ponderosa pine forest in the upper elevations. Underlying bedrock is fractured crystalline rock of the Idaho batholith, predominantly biotite granodiorite wthin the study area (Mitchell and Bennett, 1979). Dry Creek and Shingle Creek provide perennial stream flow in the watershed, while springs and numerous tributaries provide perennial or intermittent flow (Figure 2).

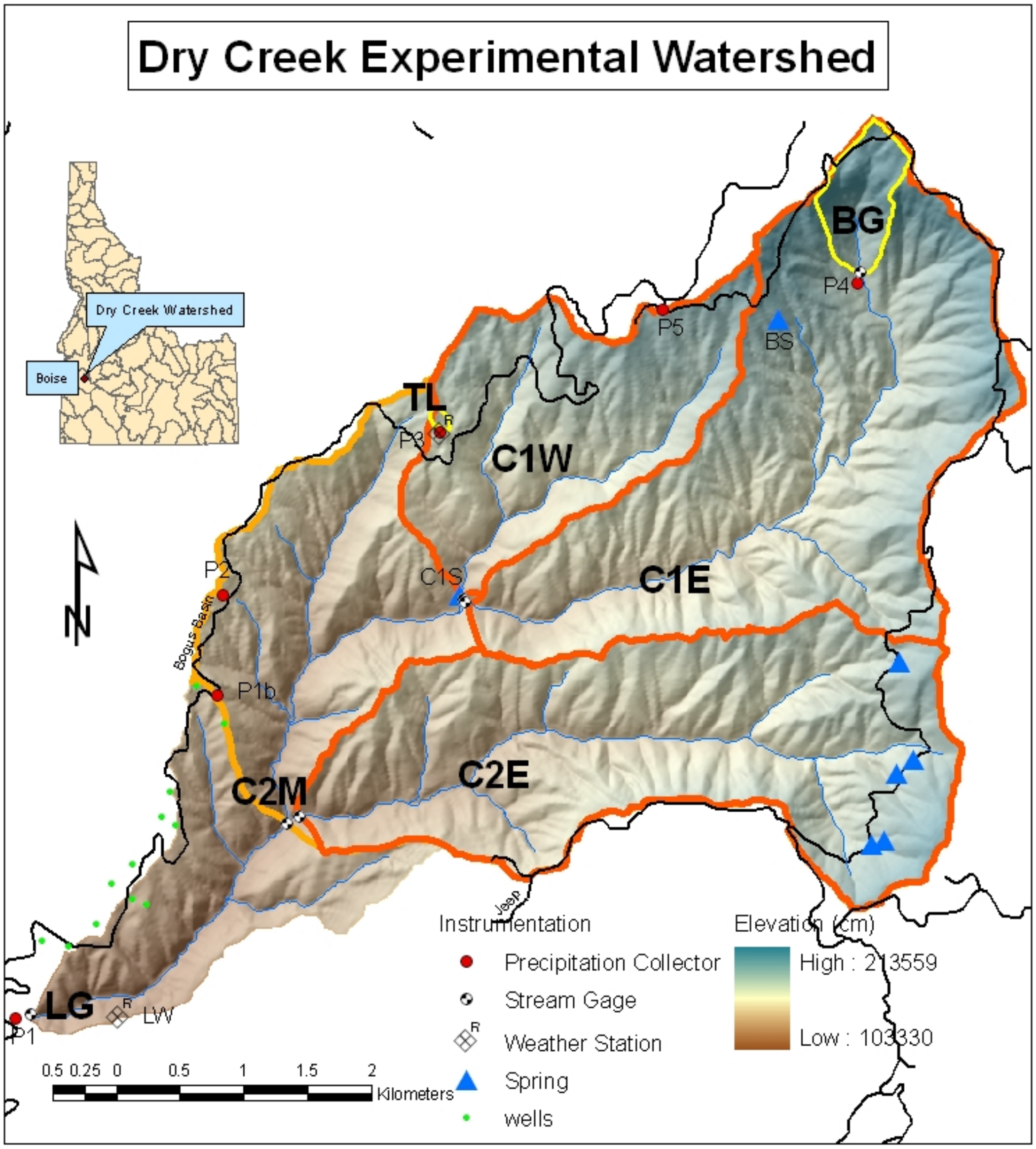


Figure 2. Dry Creek Experimental Watershed. Measurement site instrumentation is shown with study catchments outlined as defined by outlet measurement points LG, C2M, C2E, C1E, C1W, TL and BG.

Dry Creek Watershed has been the focus of numerous hydrologic studies since 1999 as operated by the Watershed Processes Research Group of the Department of Geosciences at Boise State University. Through research group efforts the watershed has been equipped with six stream instrumentation sites in addition to weather station and soil moisture sensors (Figure 2). The sub-catchments to which CMB estimation of net groundwater recharge and analysis of intra-annual water flux will be specifically applied are outlined in Figure 2, identified by outlet instrument designations: TL, BG, C1E, C1W, C2E, C2M and LG.

Literature Review of Environmental Chloride Application to Water Balance and Water Flux Investigations

A traditional water balance approach to estimating ground water recharge for a given catchment incorporates all flux processes, including evapotranspiration and groundwater flow, which are difficult to quantify and, thereby, incorporate significant uncertainty. This is especially notable for applications in arid regions wherein evapotranspiration, which is difficult to measure or model, represents a large portion of the water budget and ground water recharge may be minimal (Phillips, 1994). Conceptually, a water balance equation may be applied to catchment water flux on an annual basis, in which case annual net change in storage, ΔS, represents zero net annual gain or loss of water from soil and groundwater as the additive result of flux parameters

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \pm error \tag{1}$$

wherein, P is precipitation into the catchment, G_{in} and G_{out} represent groundwater flow into and from the catchment, Q is stream flow from the catchment and ET is water lost through evapotranspiration.

Comparison of recharge estimation methods has shown that methods utilizing environmental tracers have been more successful for recharge estimation in arid regions than physical parameter methods (Allison et al., 1994; Phillips, 1994). Natural tracers used for recharge estimation include deuterium, tritium, oxygen-18, bromide, chloride and chloride-36 (Tyler and Walker, 1994; Gee and Hillel, 1988). Of these tracers, chloride has been utilized for mass balance estimation of recharge as simplest, least expensive and most universal (Allison et al., 1994). The use of chloride as a natural tracer in hydrologic investigations arises from its conservative behavior and containment in water moving through a hydrogeologic system under average concentrations. Chloride is applicable to water balance investigations when concentration in system water occurs solely from exclusion during evapotranspiration processes. Entry of chloride to an inland system occurs as wet and dry fall originating from entrainment of the solute above marine surfaces as an aerosol (Hem, 1985). Wet fall input of chloride to the system occurs when chloride ions entrained in the atmosphere are included in rain and snow. Concentrations are greatest near the ocean-land margin and decreasing inland with values ranging from 200 to 0.02 mg/l (Feth, 1981).

Among notable outcomes in environmental chloride tracer studies, Wood (1924) hypothesized a relationship between increase in stream chloride and destruction of native vegetation in Australia, Anderson (1945), also in Australia, observed relationships between catchment ratios of stream discharge to precipitation relative to chloride concentrations, and Eriksson (1960) conducted analyses of stream chloride concentrations relative to atmospheric chloride, from which he hypothesized chloride impingement by vegetation. Also, in his 1960 study, Eriksson presented application of chloride to water budget analyses utilizing relative concentrations of precipitation and groundwater chloride concentrations and proposed the use of chloride concentrations for recharge estimation. This was followed by calculation of recharge rate on the coastal plain of Israel using CMB by Eriksson and Khunakasem (1969).

Beyond the 1969 application, use of environmental chloride as a hydrologic tracer has continued in arid regions characterized by low relief and deep unsaturated zones. In these environments, application has been to determine ground water recharge and assess potential for contaminant transport. For low-relief environments characterized by direct vadose zone flux to groundwater, the CMB method for recharge estimation involves water table or vadose zone-profile measurements of chloride concentration and stated average values for annual precipitation flux and groundwater chloride concentration (Wood, 1999). The CMB equation for such as system, as expressed by Wood (1999) is

$$q = \frac{PCl_p}{Cl_{gw}} \tag{2}$$

where q is ground water recharge flux (L/T), P is average annual precipitation (L/T), Cl_p is average precipitation-weighted chloride concentrations and Cl_{gw} is the average chloride concentration in ground water (M/L^3). For CMB application involving vadose zone profile measurements of chloride rather than measurement at the water table, a core is taken beneath the root zone from which chloride concentrations are measured in pore water and averaged. These methods provide time-averaged estimates of local or point-specific ground water recharge. Locations for which chloride mass balance recharge estimation has been conducted in this manner include the High Plains of Texas (Wood and Sanford, 1995), in New Mexico (Stephens 1993), sites in Australia (Allison et al., 1994; Tyler and Walker, 1994) and sites in the Middle East and Africa (Bazuhair and Wood, 1996; De Vries and Von Hoyer, 1988; Eriksson and Khunakasem, 1969). For systems in which recharged water contains both Holocene and Pleistocene age water, Flint et al. (2002) present additional analyses and calculations.

In contrast, application of CMB to mountainous terrain involves quantifying precipitation and stream flow volume over the course of a year, or multiple years, for a given catchment, as well as measuring chloride concentrations in precipitation, stream water and ground water. Groundwater sampling is typically accomplished at springs and/or wells producing from the saturated zone of the unconfined aquifer. Mountainous locations to which chloride mass balance estimation of recharge has been applied include multiple sites in Nevada (Thomas and Albright, 2003; Zhu et al., 2003; Russell and Minor, 2002; Dettinger, 1989), Montana (Hay,1997) and the San Juan Mountains of Colorado (Claassen et al., 1986).

Application of CMB to studies conducted in Nevada and the Montana study have largely focused on estimating recharge occurring from a given bounding mountain block to an adjoined broad valley-fill aquifer. This relates to the concept of mountain front recharge as presented by Wilson and Guan (2004) which includes infiltration of surface water at the mountain front and deep groundwater flow from the mountain block to the valley aquifer. Dettinger (1989) applied CMB at a reconnaissance level to 15 intermountain basins in Nevada, including the Las Vegas basin, for which groundwater samples were primarily taken from deep wells along the mountain front, precipitation input was based upon regional data and elevation-based interpolation, chloride concentration in precipitation was determined as a temporal and spatial average of region-wide data values. At this reconnaissance level, Dettinger found the CMB estimates to be in fair agreement with Maxey-Eakin and water balance estimates previously applied in Nevada, but cautioned as to the need for reliable, site specific bulk chloride input concentrations because the CMB equation is especially sensitive to this parameter.

The investigation of ground water recharge conducted in Montana by Hay (1997) on the western flank of southern Bridger Range, involves application of the method in a more humid region of the intermountain west in which stream flow from the mountain front is significant. Measurement of chloride concentration in groundwater conducted by Hay utilized groundwater wells screened at different depths across the broad valley floor rather than using springs or mountain front wells. Recharge to the valley aquifer was assumed to occur from stream flow discharging from the mountain front and precipitation occurring directly on the broad valley floor below the mountain front versus assuming recharge to occur at the mountain front through diffuse surface flow or bedrock flow. Therefore, the CMB equation parameter for input includes both precipitation and stream flow. Flow from the several mountain front streams included in the study was monitored weekly at the mountain front and utilized to estimate stream inflow to the basin. Two streams were sampled for chloride concentrations on two consecutive days in July, early in the three-year study period, for use in the CMB calculation. The author states that the streams were just returning to base flow at the time these samples were taken. Chloride concentration in precipitation was taken as an average of mean annual values measured by the National Atmospheric Deposition Program at Clancy, Montana, for the ten years preceding the study. Hay expresses sensitivity in his CMB calculations to values of chloride concentration in groundwater and cautions as to the effects of inter-annual variation in precipitation input and timing of spring snowmelt with suggestion that alternating warm and cool conditions minimize peak discharges and allow maximum infiltration of water into the subsurface.

In contrast to the above described Nevada and Montana studies, Russel and Minor (2002) utilized chloride concentration of groundwater measured from springs of successive elevation within the mountain block to conduct CMB estimates of recharge for broad alluvial or lake sediment filled basins. The elevation-dependent CMB application is based on the concept of variable rates of recharge as a function of elevation within the mountain front. This concept arose from analyses conducted by Russel and Minor that indicated nonlinear correlation of decreasing spring elevation with increased ratios of spring water chloride concentrations to average precipitation chloride concentration, with greater increases in relative spring water chloride concentration occurring at lower elevations. This relationship is interpreted by the authors to indicate that recharge occurs within the mountain block at spatially variable, elevation-dependent rates, with further indication that recharge occurs within a given catchment as a function of various factors including slope, aspect, vegetation and various elevation-dependent factors. From these analyses, the authors produce CMB estimates of mountain block recharge to valley aquifers not as a single calculation for the mountain block as performed by Dettinger, but as elevation-dependent, area-weighted calculations of recharge. Russel and Minor (2002) cite chloride concentration of groundwater measured from springs within the mountain front as being most sensitive to uncertainty, with estimates of mean precipitation being second in sensitivity.

Application of CMB to a specific mountain catchment was undertaken by Claassen et al. (1986). The catchment investigated by Claassen et al. is the northeast-facing 28 km^2 Deep Creek catchment of Snowshoe Mountain, a resurgent dome of Tertiary quartz latite tuff with an elevation range 2600 to 3700 m in south-central Colorado. Three years of CMB integration were involved in this application, with significant inter-annual variability in precipitation input. For this investigation, Claassen et al. applied CMB concurrent with physical measurement of bedrock infiltration.

The chloride mass equation utilized by Claassen et al. is similar in concept to that presented in Equation 2 with added parameters of stream discharge and stream chloride concentration. However, application of the equation differs, because the parameter calculated in this case is annual surface runoff R_s. The equation utilized by Claassen et al. is presented below,

$$[Cl_P]P_g = \lfloor Cl_{Rg} \rfloor R_g + \lfloor Cl_{Rg} \rfloor R_s \qquad (3)$$

where square backets indicate analytical chloride concentrations, P_g is measured precipitation and R_g is measured recharge. In applying CMB to the catchment, the authors utilized temporally weighted averages of chloride concentration in precipitation for each year, based annual precipitation input values on linear elevation-precipitation regression between precipitation measured at one low and one high elevation point within the catchment, and assumed chloride concentration in runoff to equal that in recharged water. Precipitation sampling was conducted at these two points as bulk wet and dry fall via collectors with constricted 25 mm openings designed to reduce evaporation. Collectors were placed both below canopies and outside of vegetative canopies to delineate effects on input chloride concentrations. Volumetric measurement from these collectors was found to be in agreement with rainfall equivalents measured by adjacent standard rain gages. The concentration of chloride in groundwater, [Cl_{Rg}], was determined from water collected in the vadose zone of fractured bedrock for measurement of $R_{g.}$ Chemistry of spring water in the catchment was additionally analyzed and found to be representative of shallow saturated-zone pore water.

Average accuracy for calculation results was presented as within 10% of total precipitation. The authors attributed this error as largely due to net annual change in soil water storage in opposition to assumption of zero net annual storage and subsequently expressed this error as subject to minimization in environments possessing thinner soil cover, higher permeability and greater summer moisture. Error was additionally attributed to inadequate temporal sampling for stream water chloride concentrations. This is particularly notable relative to the authors' finding that chloride concentration determined for recharge water was in agreement with measured baseflow concentrations sampled prior to snowmelt, while variation in stream water chloride concentrations following snowmelt were omitted. This disparity is represented in Claassen et al.'s conceptualized bi-directional chloride routing from storage in the vadose zone to either recharge or runoff (Figure 3), which does not account for temporally-variable contributions to stream flow.

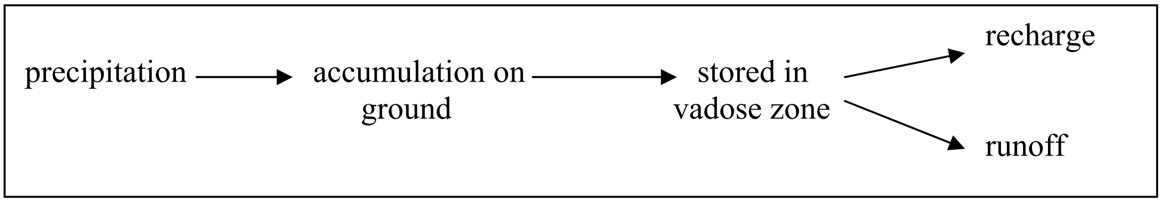


Figure 3. Chloride routing (adapted from Claassen et al. (1986)). Initial and final boundary conditions for above depicted routing are defined as zero chloride storage in the vadose zone.

To address the possibility of extrapolating data for application of CMB to additional catchments for a given time period, Claassen et al. (1986) conducted measurements at an additional high altitude catchment and concluded that low temporal and spatial variability of atmospheric chloride deposition concentrations throughout a region defined by a 200 km radius suggests the feasibility of extrapolating data toward recharge estimation in additional catchments possessing similar characteristics, with only groundwater chloride and applicable surface water concentrations needing to be measured. The authors further expressed applicability of CMB to systems comprised of igneous, metamorphic and non-marine sediments, as well as the usefulness of method as an independent comparison for water budgets obtained by mass and energy-balance methods. However, Claassen et al. state that selection of a period of integration presents a complication in attempting CMB at a basin discharge point and that selection of an annual period of integration requires the assumption that water recharge has the same composition year to year. This assumption was shown by the authors to be incorrect where significant microclimatic variation exists year to year and results in varied recharge concentrations inter-annually.

Case-specific temporal and spatial scales apply to the approaches outlined above, with the application method for environmental chloride as a tracer designed according to the rate and geometry of water flux in the system investigated. Low-relief vadose zone methods and application of CMB to mountain front valley aquifers represent long-term, time-averaged flux estimates from which an annual rate of recharge is extracted by applying an annual precipitation input volume to the CMB equation and its chloride concentration input parameters, while the mountain front and catchment scale investigations, particularly those involving stream discharge, note the necessity of several years of data collection. Noting these differences, it is especially important to determine the temporal scale over which the sampled recharged water has accumulated, because this sampled recharge water is the “pool” from which a single annual rate of recharge is taken. The assumptions for application of CMB require consistency in the parameters over the temporal scale represented by the recharged water, including average annual precipitation, atmospheric chloride input and average rates of recharge, noting that annual recharge rates occur as a function of numerous physical variables within the system, notably timing and volume of precipitation and/or snowmelt. Consistency in the parameters may involve parameters quantified by several years of data collection. Application of CMB to individual catchments within mountainous terrain will produce flux estimates representing average flux over relatively short time-scales, perhaps as brief as decadal or sub-decadal, depending upon ground water flow rates prevalent in the catchment.

Conceptual Hydrologic Model for Dry Creek Experimental Watershed

As indicated by the CMB applications outlined above, valid application of CMB to recharge estimation begins with a conceptual hydrologic model to which the mass balance model is adapted. From the conceptual hydrologic model and subsequent inferred or described chloride routing model, specific definition is given to CMB equation parameters. The conceptual hydrologic model for DCEW applied in this study incorporates the findings of prior hydrogeologic investigations in DCEW, as well as field observation of spring flow, stream flow, bedrock characteristics, soil characteristics and catchment morphology in DCEW. The most intensive investigations in DCEW which contribute to construction of the conceptual hydrologic model are those which have been conducted in the Treeline headwater catchment (Figure 2), for which findings relevant to construction of the conceptual hydrologic model are outlined in the section below, followed by observations and hydrogeologic data for adjacent catchments.

Treeline Site

Intensive studies conducted in the 0.02 km^2 Treeline Site in the northwest portion of DCEW (Figure 2) by McNamara et al. (2004) indicate that bedrock infiltration and stream flow generation via lateral flow occur as a function of soil moisture conditions which, in this semi-arid environment, follow five sub-annual scenarios. These include (1) a summer dry period, (2) a transitional fall wetting period, (3) a winter wet, low-flux period, (4) a spring wet, high-flux period, and (5) a transitional late-spring drying period, with transitions between the scenarios controlled by changes in the water balance as a function of rain, snow, snowmelt and evapotranspiration. Based upon the findings of this

Treeline Site investigation, potential for bedrock infiltration is considered to exist during the winter wet, low-flux period and during the spring wet high-flux period.

The distribution of infiltrating water to bedrock versus lateral flux to stream channels will occur as a function of precipitation/snowmelt rate and various soil and bedrock conditions, including frozen soil horizons, subsurface permeability and hydraulic connection within the hill slope. From hydrometric and chemical analyses conducted for the 2000 snowmelt period, Yenko (2003) concludes that stream discharge at the Treeline Site originates from lateral flux through the soil and along the soil/bedrock interface once saturation and hydraulic connection in the slope are achieved with no contribution from groundwater. In light of this research, stream discharge and precipitation data for 2004-2005 water year at the Treeline Site, shown in Table 1, are noted as indicating net water loss to bedrock infiltration at the stream channel during early snowmelt in January through March. In conjunction with this stream discharge data, stream channel infiltration studies, including a brief tracer test, conducted by MakramMorgosAbdelmasih (in print, 2006) during the 2004-2005 water year indicate in-stream loss to bedrock. Water budget analysis for the Treeline Site by McNamara et al. (2004), utilizing the SHAW model, place evapotranspiration estimates as 72% of precipitation received for water year 2000, from which bedrock infiltration is expected to be slightly less than 28% of the precipitation received, based on observed minimal stream discharge. In contrast, soil moisture studies and application of SHAW model for water year 2003-2004 project 43% loss to bedrock across the catchment (Williams, 2005). Annual precipitation received at the Treeline Site for the above mentioned water years is

561 mm for 1999-2000, 655 mm for 2003-2004 and 569 mm for 2004-2005, with water years defined as beginning October 1.

Table 1. Monthly precipitation/discharge relationships at Treeline Catchment and calculated reach gain/loss, 2004-2005.

2004-2005	**uppr weir (m^3)**	**mid weir (m^3)**	**lwr weir (m^3)**	**uppr status**	**lwr status**	**net**	**weather conditions**	**Pcp (m^3)**	**net Q/P**
Oct-Dec	153	624	209	gain	loss	gain	rain and minimal snowmelt	3792	0.06
Jan	63	181	20	gain	loss	loss	minimal snowmelt	705	0.03
Feb	67	204	20	gain	loss	loss	minimal snowmelt	480	0.04
Mar	34	15	28	loss	gain	loss	rain and snowmelt	1416	0.02
April	259	118	272	loss	gain	gain	Rain	1089	0.25
May 24	449	386	674	loss	gain	gain	Rain		
May 31	65		144			gain	Rain	2024	0.07
Jun	48		66			gain	Rain	773	0.09
Total			**1221**					**10280**	**0.12**

Headwater Catchments with Perennial Stream Flow

In contrast to the above described Treeline Site in which stream flow is typically limited to October through June, additional headwater catchments in DCEW maintain perennial stream flow. It is to be noted that the perennial streams, Dry Creek and Shingle Creek (Figure 2), are fed by numerous springs and seeps. Hydrogeologic investigation conducted by Gates et al. (1994) through aerial photography analyses and field reconnaissance around Shafer Butte adjacent northward to DCEW, revealed similar springs and seeps which follow linear trends to which the authors have attributed possible fracture control where shallow dipping fracture planes intersect slopes. Fracture trace analyses and structural mapping conducted in this same region indicate the granitic rock as “very shattered with through-going fractures” and show three major steeply-dipping, intersecting joint sets at N70˚W, N20˚W and N20˚E (Gates et al., 1994). The authors further characterize the densely fractured nature of the granitic bedrock as capable of providing groundwater storage. Step-drawdown and recovery tests conducted by these authors at Bogus Basin Ski Resort in this same region indicate a hydraulic conductivity in the granitic aquifer to be as high as 5.18 cm/day where the three fracture sets intersect. In addition to these hydrogeologic investigations, tritium sampling and analysis conducted at Bogus Basin Ski Resort exploratory well 3, depth 122 meters, and adjacent spring indicate groundwater age to be 9 to 23 years (Schroeder et al., 1993). Tritium units w/ decay rate extrapolated backward and compared to Salt Lake and Portland tritium concentrations in precipitation are shown for reference in Appendix A.

Based on the above outlined observations at Treeline and adjacent catchments, the conceptual hydrologic model for DCEW includes infiltration of precipitation through thin sandy soil to fractured bedrock, predicted to occur primarily within headwater catchments during winter low-flux and spring snow-melt periods, given hydraulic connection via adequate moisture content through the full soil profile. Steep slopes, however, are considered to facilitate development of lateral throughflow and soil-bedrock interface flow toward stream channels when hydraulic connection develops within hill slopes, while recharge to groundwater may occur within stream channels, particularly at higher elevations. In headwater catchments with springs and seeps, groundwater contributes to stream flow via surface discharge, while subsurface groundwater flow to streams is hypothesized to occur intermittently along Dry Creek at the lower elevations. This is important to consider relative to observation that watersheds of high relief are more likely to loose water by subsurface flow, and that streams draining larger watersheds tend to receive the subsurface outflow of their constituent catchments (Dingman, 2002). The role of evapotranspiration in DCEW is suspected to be dominated by transpiration throughout the growing season, with the greater amount of actual evapotranspiration occurring in the higher elevations where vegetation is dense. This is evident in a comparison of mapped evapotranspiration and MSAVI2 vegetation index for DCEW, Figures 4 and 5. However, the percentage of precipitation being partitioned to evapotranspiration may be greater in lower elevations facilitated by less precipitation and warmer temperatures.

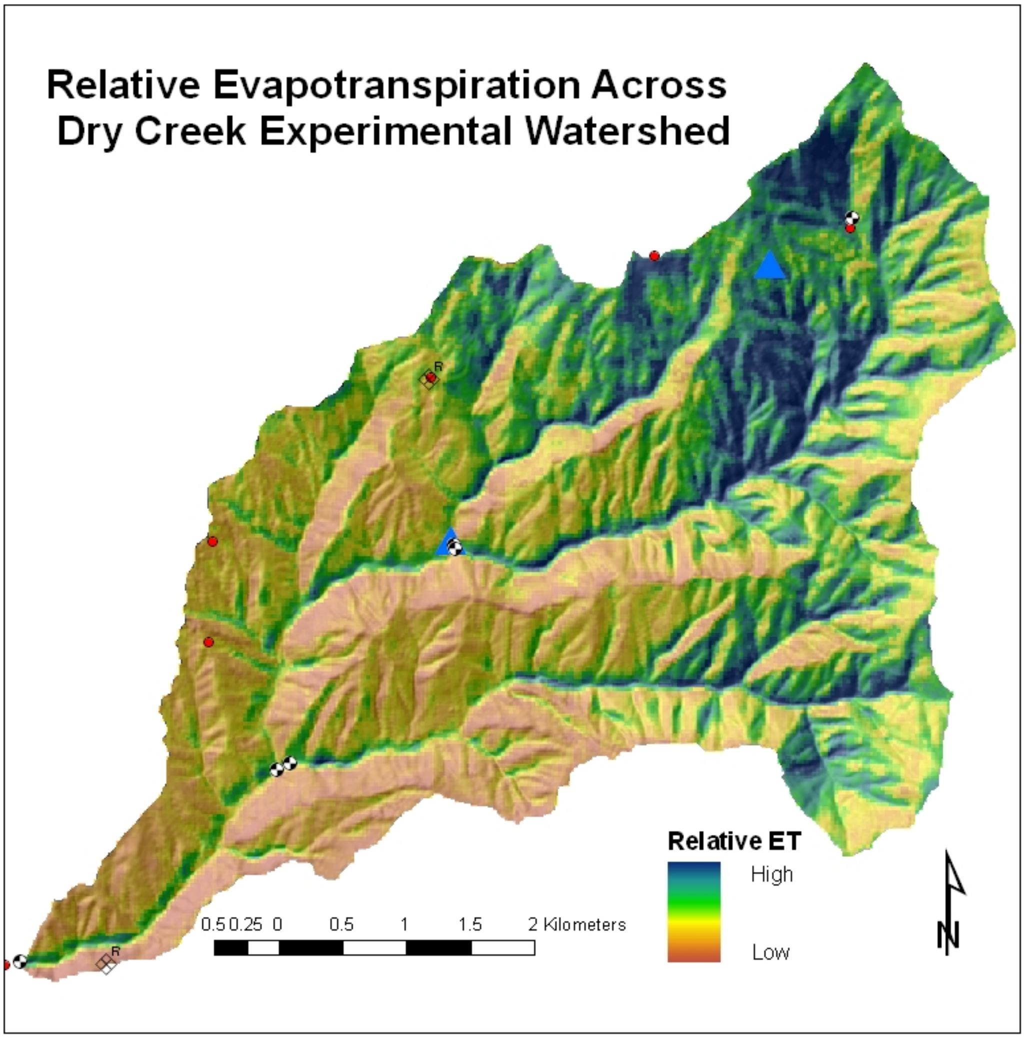


Figure 4. Seasonal evapotranspiration for 2000, March through October (with actual ET values mapped in millimeters).

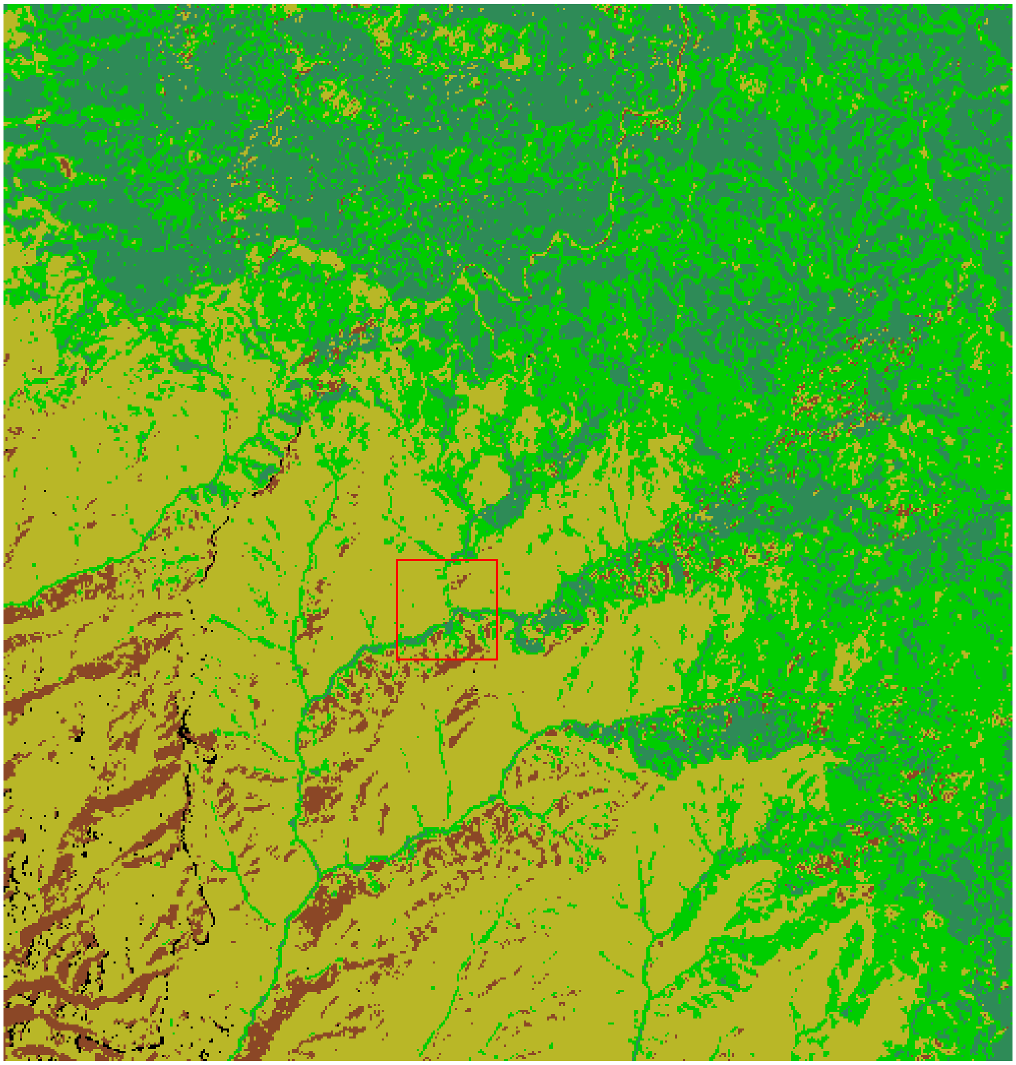


Figure 5. Vegetation map for DCEW and surrounding catchments. Classification input included MSAVI2 vegetation index derived from Landsat data. Rectangle is centered on C1E, C1W and C1S for reference. Key: dark green - conifer forest, bright green - riparian/ slope brush, yellow - grass/shrub, brown - bare ground, black - paved road.

A sketch of the afore-described conceptual model is provided in Figure 6. Key components of this conceptual hydrologic model include multiple water flux pathways. Flux pathways featured are: 1. infiltration of water to bedrock, 2. groundwater discharge to surface runoff via springs and/or baseflow, 3. shallow subsurface flow toward stream channels, 4. bedrock-interface flow to stream channels, 5. stream channel loss to bedrock, and 6. loss of water via evapotranspiration. Terminology depicted for clarification includes bedrock infiltration, groundwater recharge and net groundwater recharge. Net groundwater recharge is defined in this study as water which reaches a depth within the saturated zone of the aquifer, below which no groundwater discharge occurs within the given catchment. In this context, net groundwater recharge may potentially be further routed to stream discharge in larger down-gradient catchments or may be routed as deep mountain block groundwater flow to valley aquifers.

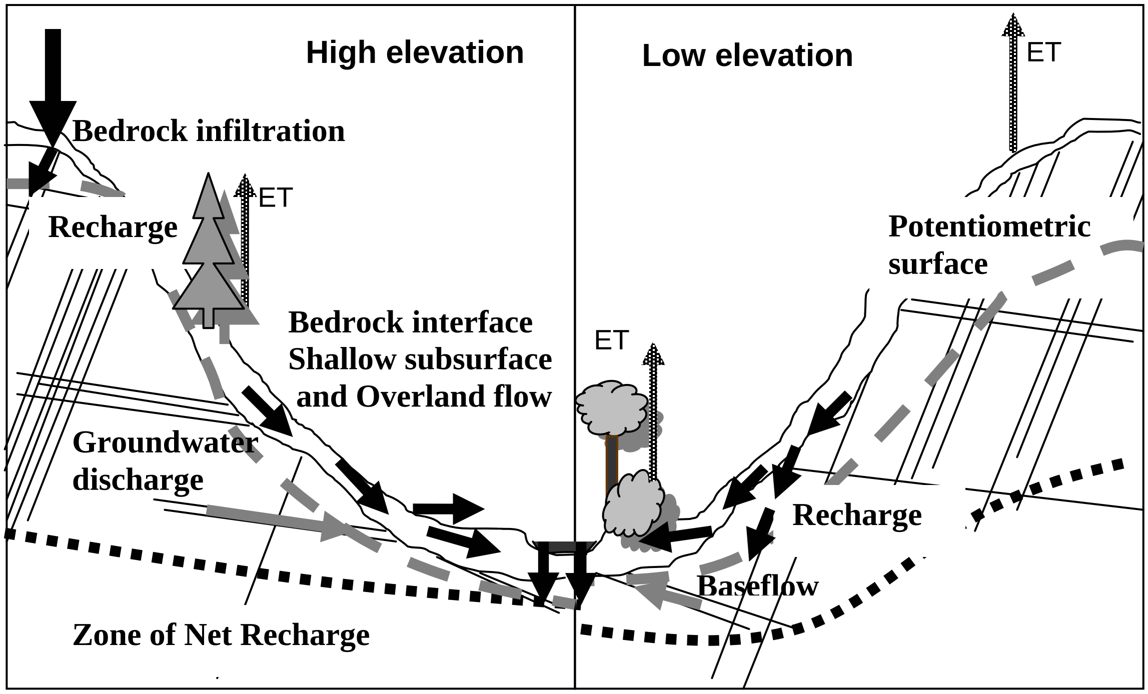


Figure 6. Conceptual hydrologic model for DCEW. Left panel depicts model for elevations above C1W and C1E. Right panel depicts model for lower elevations.

Chloride Mass Balance Application to Dry Creek Experimental Watershed

As cautioned by Claassen et al. (1986), the two-year study period may be inadequate to capture inter-annual variability in recharge, in which case, the study may be continued and guided by discoveries made in the course of the study. In accordance with the conceptual hydrologic model presented in this paper for DCEW, chloride routing is conceptualized as shown in Figure 7. Based on this routing, CMB applied to the entire catchment or a given sub-catchment provides estimation of net groundwater recharge resulting from groundwater recharge occurring in hill slopes and/or stream channels minus subsequent losses from groundwater storage occurring as spring flow or base flow within the catchment which are subsequently discharged from the catchment via stream flow.

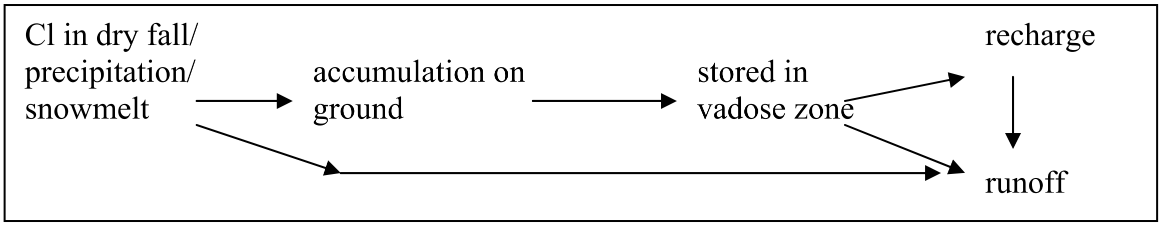


Figure 7. Chloride routing model for DCEW.

Applying the chloride routing model for DCEW to a chloride mass balance in which the input mass of chloride is set equal to the output of mass produces the following equation for calculation of net groundwater recharge volume, R, for the applied number of years in a catchment from which stream discharge occurs

$$R = \frac{(P)(Cl_p) - (Q)(Cl_q)}{Cl_r} \tag{4}$$

where P is precipitation volume received by the study catchment for the annual or multi-annual study period, Cl_p is catchment temporal-spatial volume weighted average bulk chloride concentration of precipitation during the study period, Cl_r is groundwater chloride concentration for the study catchment, Q is total stream discharge from the study catchment during the period of study and Cl_q is temporal volume weighted average of chloride concentration in stream discharge during the study period. Similarity may be noted between this equation and Equation 3 in which the input equals output form of the equation arises from establishing mass balance with chloride received into a catchment set equal to chloride routed to stream discharge and the groundwater reservoir, assuming zero storage of chloride in the unsaturated zone. Accomplishment of this zero storage requires calculation on an annual or multi-annual basis, according to intra-annual and inter-annual variability in soil moisture. Application at the catchment scale requires that groundwater chloride concentrations applied represent the effects of evapotranspiration across the catchment. Optimally, sampling should be conducted on a temporal scale necessary to capture inter-annual variability in groundwater chloride concentrations resulting from inter-annual variability in recharge.

Valid implementation of CMB requires that the system meet various assumptions, including 1) chloride mass flux into the system has not changed over time, 2) bulk wet and dry fall are the only inputs of chloride to the system, 3) chloride is conservative in the system, 4) no external surface water or groundwater input occurs, 5) the system is at steady state and 6) no unmeasured runoff from the system occurs (Wood, 1999; Dettinger, 1989). For this investigation stream discharge is projected to vary intra-annually in composition as derived from variably contributing source components, including throughflow, bedrock interface flow, baseflow, spring flow and surface runoff. Spring, stream and precipitation chloride concentration time-series data from each catchment will be utilized toward delineating temporal and spatial variability in spring and stream flow source contributions. Application of environmental chloride as a tracer to delineate intra-annual water flux via spring and stream chloride concentration time-series data would require the system to meet assumptions 3, 4 and 6 as outlined above.

METHODS

Use of CMB to determine annual net groundwater recharge for a catchment requires a minimum of one year of data collection to best assure zero net chloride storage above the saturated. This study involves two years of data collection for water years July 2004 through June 2006. Study year start/end date was selected to correspond with the start of the dry season/end of the snowmelt and spring rain to best assure the necessary zero net chloride storage in the unsaturated zone. Data collection was conducted as dictated by the parameters shown in Equation 6: annual precipitation volume (P), annual stream discharge (Q) and chloride concentration in precipitation (Cl_p), groundwater (Cl_r), and stream water (Cl_q). The same parameters are utilized in this study to accomplish both hydrograph separation and stream flow gain/loss calculations to address vadose zone, groundwater and surface water interactions in DCEW. Hydrograph separation using end-member chemistry is applied to quantify the volume of stream flow attributable to time-variable stream flow sources. Gain/loss analyses are used to ascertain when groundwater contributions to stream flow occur and when stream flow loss to groundwater occurs along the lower reach of Dry Creek between C1E and LG.

Precipitation (P)

Precipitation data for this study was collected by paired shielded and unshielded precipitation gages at the two DCEW weather stations (Figure 2) and a shielded gage at the Bogus Snotel site. In addition to these weather stations, precipitation collectors were installed at five sites of successive elevation (Figure 2). These collectors were utilized for supplementary precipitation depth measurement in addition to serving as the source of precipitation samples for measurement of chloride concentration in precipitation. Towards calculation of precipitation volume, only shielded precipitation gage data was utilized to provide consistency with the Bogus Snotel site. For intermittent periods during winter 2004-2005, equipment failure at the two DCEW weather stations resulted in data gaps for received precipitation. This data gap was addressed as month sums based on interpolation through linear regression of precipitation depth with elevation using adjacent weather data and precipitation collectors.

Monthly precipitation sums for each of the three weather stations were applied to linear regression with station elevations, from which hypsometric interpolation of precipitation depth across the entire catchment in 100 meter increments for each month. Annual totals of precipitation were determined from the 12 month sums. This process was applied to DCEW and subcatchments of DCEW selected for recharge estimation (Figure 2). The distribution of elevation across DCEW is shown with the hypsometric curve depicted in Figure 8. An isoline method was applied to dry months for which a consistent elevation-precipitation trend was not apparent using elevations zones centered on each precipitation station,. The resultant monthly precipitation depth per elevation/isoline zone were area-weighted and summed for annual precipitation depth, then multiplied by catchment area for monthly volumes of precipitation received.

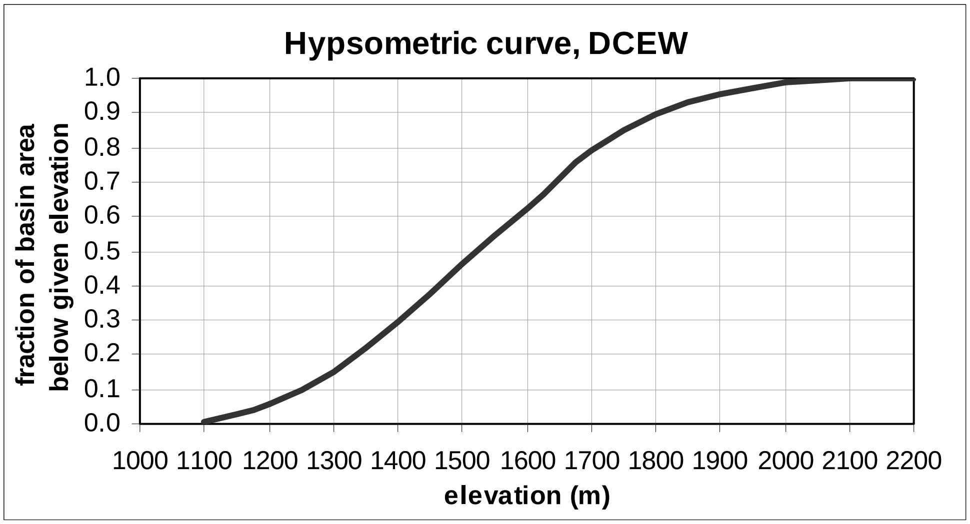


Figure 8. Hypsometric curve for DCEW, showing relative distribution of elevation across the 27 km^2 catchment.

Stream Discharge (Q)

Annual discharge calculation for each catchment outlet was performed from hourly stage measurement. Instrumentation utilized at stream sites for stage measurement includes capacitance rods and pressure transducers, coupled with stream gaging to establish discharge rating curves. For the higher discharge streams, gaging was conducted with a pygmy current meter or large cup current meter as dictated by flow, alternately, a sonic flowmeter was utilized. Dilution gaging with potassium bromide was employed in smaller headwater streams. When stage measurement instrumentation failure contributed to missing data, interpolation of discharge by linear regression with adjacent station data was utilized toward discharge calculation, using months on record for which the station lacking data exhibited parallel discharge patterns with the adjacent station.

The interpolated values were further adjusted according to available physical discharge measurement (Appendix B).

Chloride concentrations ($Cl_{p,}$ $Cl_{q,}$ Cl_r)

Precipitation collectors were measured and sampled promptly following precipitation events. These collectors remained in place between events to provide bulk (combined wet and dry fall) chloride concentration sampling. Collector construction utilized 0.2 m diameter screened funnels attached to graduated collectors which were wrapped in reflective tape to minimize evaporation. Samples were collected immediately following each precipitation event. Snow was sampled as grab samples which were melted under refrigerated conditions for subsequent analysis. Also, snowmelt buckets, one each year, were emplaced beneath snow pack near precipitation collector P5 (Figure 2) as winter snowfall began. These buckets were left undisturbed beneath snowpack, then sampled at completion of snowmelt above the bucket.

Sampling for chloride at spring and stream locations was accomplished on an approximate bi-weekly schedule at each catchment outlet and spring shown in Figure 2, except for the Shingle Creek springs which were sampled only during the late summer. Well water was collected during a pump test in October, 2006 in the easternmost well between C1E and LG (Figure 2). Prior to sampling, bottles were thrice rinsed in water to be sampled, samples were filtered on site and refrigerated until delivered to lab for analysis. Samples were stored in 30 or 60 ml high density propylene. Analysis was conducted by ion chromatography.

Annual average chloride concentrations, Cl_p and Cl_q, to be applied in the CMB equation for recharge estimation were determined as weighted averages for stream precipitation and discharge. For small catchments, annual average chloride concentration, Cl_p, was determined by temporal-volume weighting of monthly or seasonal average chloride concentrations of precipitation to corresponding monthly or seasonal precipitation volumes based on the nearest precipitation collector. This weighting was utilized to address temporal variation in precipitation chloride concentrations, most notably occurring as low-chloride snowmelt in water year 2005-2006. Snowmelt chloride concentration determined from the snowmelt collection bucket placed near precipitation collector P5 was applied to weight snowmelt chloride concentration against monthly water equivalent snowfall values for January through April, water year 2005-2006 for the Bogus catchment and upper elevation precipitation zone. For larger catchments, C1E, C2E, C2M and LG, a secondary area weighting was applied to temporal-volume weighted annual chloride concentration calculation per elevation-precipitation zone. The area weighting is conducted according to attributable fraction of catchment area represented by given included precipitation zone. The precipitation zones were delineated by approximate midpoint distance across increasing elevation between precipitation collectors.

Annual stream chloride concentrations, Cl_q, were calculated from monthly discharge volume-weighted chloride concentrations for each study catchment from sampling conducted at catchment outlets. Additional sampling of surface water was conducted on three separate dates in 2006 across DCEW towards assessment of suspected road salt transport into the study area. The dates were selected for maximum snowmelt runoff following the winter season in which road sand mixed with salt was applied along portions of Bogus Basin road at the west edge of DCEW. Warm temperatures for the needed runoff occurred and were taken advantage of once in February and April of 2006, with sampling focused at the head of all tributaries originating along Bogus Basin road and draining into DCEW. The third sampling day, conducted in May, 2006, targeted tributaries draining to Dry Creek and included many rarely-flowing tributaries, as well as the study catchment outlet points.

Groundwater chloride concentrations, Cl_r, determined from spring flow were not derived as an average of time-series chloride data . Spring flow chloride concentrations were averaged over the last month of the dry season to produce an approximation of chloride concentration in groundwater at each spring location, BS, C1S and Shingle Creek Springs including R1S. For water year 2004-2005, this was derived from late September to early October data, while for water year 2005-2006, August data was utilized due to earlier fall wet-up. The late summer/early fall spring flow is utilized as most representative of groundwater, because downward infiltrating surface water contributions to spring flow are assumed to be at an annual minimum late in the dry season. Groundwater chloride concentration for the BG catchment was taken as chloride concentration in stream flow averaged at the end of the dry season, August to September, 2004-2005, and August to early October, 2005-2006. This approach to groundwater chloride concentration for the BG catchment arises from the spring-fed nature of stream flow in BG which involves numerous springs and seeps persistent during the dry months.

Due to lack of well and spring access to groundwater, derivation of groundwater chloride concentration for the Treeline catchment was accomplished by a "stranded-chloride" snowmelt method. This method is based on the concept that all chloride delivered by dry fall and rainfall is stored in the unsaturated zone until remobilized and transported to stream channel and/or groundwater as a result of spring snowmelt. Thus, the mass of chloride delivered by precipitation (P*Clp) equals the mass of chloride transported through the unsaturated zone by spring snowmelt. Calculation of chloride concentration in groundwater using this method is demonstrated via Equation 5 below.

$$Cl_r = P*Cl_p/S \qquad (5)$$

Where Cl_r is chloride concentration in groundwater, P is the volume of rainfall received in the catchment since the last snowmelt period, Cl_p is average chloride concentration of the received precipitation, and S is the volume of new snowmelt.

Net Recharge Estimation and Calculation of Evapotranspiration

Estimation of the annual or multi-annual volume of precipitation partitioned to net groundwater recharge for a given catchment is conducted using CMB Equation 4, with parameters, P, Q and Cl_x, determined as described above. The calculation is performed for each catchment separately, for each water year. Catchments for which this calculation was conducted include: LG, C2M, C2E, C1E, C1W, BG and TL (Figure 2).

For a given catchment, the annual or multi-annual water budget may be completed by calculating evapotranspiration, ET, as a residual volume

$$ET = P - Q - R \qquad (6)$$

where all parameters are annual or multi-annual volumes. P is precipitation volume received into a given catchment, Q is stream discharge from the catchment and R is the net recharge volume calculated by CMB. Additionally, concentration factor calculations of point value evapotranspiration were conducted using groundwater chloride concentrations via a method similar to that presented by Eriksson (1960), wherein the fraction of precipitation partitioned to evapotranspiration is calculated for point locations at which groundwater chloride concentrations are sampled. The groundwater sample point locations are considered to represent spatially-limited upgradient areas of bedrock infiltration wherein the mass of chloride delivered by precipitation is routed to groundwater storage. Calculation is conducted as

$$ET_f = 1 - (Cl_p / Cl_r) \tag{7}$$

where ET_f represents the fractional portion of precipitation lost to evapotranspiration, Cl_p is chloride concentration in precipitation and Cl_r is chloride concentration in groundwater sampled. The equation is based on precipitation being set as a value of one to represent one hundred percent of all water input and conceptualization of groundwater recharge as occurring as vertical infiltration of evapotranspiration-concentrated water through the unsaturated zone. The fractional amount of precipitation partitioned to groundwater recharge is one minus the fractional portion of precipitation lost to evapotranspiration. This application requires that no surface or shallow subsurface runoff from the source area occurs. This requirement may be inadequately met for areas with steep slopes incurring lateral shallow subsurface transport of soil-zone chloride by which evapotranspiration would be under-estimated with this method.

Hydrograph Separation and Stream Flow Gain/loss Calculations

Hydrograph separation and stream flow gain/loss calculation methods applied toward addressing the questions of vadose zone, groundwater and surface water interactions in DCEW are outlined in this section. Temporal separation of stream flow sources, as monthly volumes, was conducted using stream chloride concentration time-series data, stream discharge data and end-member chloride data, including precipitation time-series data. Groundwater chloride concentration for a given stream reach is assumed to represent both average groundwater chloride concentration contributing to stream flow the annual average concentration of lateral soil-water flux to the stream channel. However, monthly chloride concentrations in lateral soil-water flux to stream channels will likely deviate above and below the annual average (Kauffman et al., 2003), requiring qualification of monthly results. It is expected that the employed hydrograph separations will at least provide temporal indication of lateral flux through the shallow subsurface to the stream channel, particularly at onset when dry season unsaturated zone chloride is first mobilized and transported.

For first order headwater catchments, monthly flow source separation was conducted using steady state mass balance equations for water and a conservative tracer,

$$Q_s Cl_s = Q_p Cl_p + Q_{gs} Cl_{gs} \tag{8}$$

where Q_s is monthly stream discharge volume. Precipitation volume contributing to stream flow in a given month is Q_p. Combined groundwater and/or shallow subsurface flow contributions to stream flow for the same time period is denoted as Q_{gs}. Corresponding chloride concentrations are accordingly represented by Cl_s, Cl_p and Cl_{gs}. Algebraic solution for Q_p and Q_{gs} as percentages of Q_s using Equation 8 are accomplished by equating Q_p as one minus Q_{gs} or vice versa and subsequent substitution into the equation with Q_s equated to one. This method was applied to the Treeline and BG catchments.

Gain/loss calculations include calculation of monthly average chloride concentrations of water gained/lost.

The stream reach along Dry Creek from C1E to LG was assessed for gain/loss of stream flow and chloride mass, as well as stream flow source contributions. Five components to stream flow contribution are identified for this reach, including tributary catchments, C1E, C1W, C2E and spring C1S. Groundwater and/or surface/shallow subsurface flow contributions to stream flow are lumped into the fifth component of stream flow and chloride mass contribution. A steady state mass balance equation for water and a conservative tracer as applied to this analysis is

$$Q_{LG}Cl_{LG} = Q_{C1E}Cl_{C1E} + Q_{C1W}Cl_{C1W} + Q_{C2E}Cl_{C2E} + Q_{C1S}Cl_{C1S} + Q_{gs}Cl_{gs} - Q_{l}Cl_{LG} \qquad (9)$$

where $Q_{xx}Cl_{xx}$ represents monthly or annual chloride mass as measured at the outlet of each respective catchment or point of entry to Dry Creek with the exception of $Q_{gs}Cl_{gs}$ and $Q_{l}Cl_{LG}$. It is important to note that the values Q_{LG} and $Q_{LG}Cl_{LG}$ represent, respectively, stream flow discharged at the outlet and chloride mass discharged at the outlet after the possible occurrence of unmeasured loss of water and chloride mass, represented by Q_{l} and $Q_{l}\,Cl_{LG}$ respectively. This unmeasured loss may occur under net gain and net loss conditions. That is, a gain in stream flow between C1E and LG does not preclude loss to groundwater recharge or evapotranspiration, it only indicates a net gain, wherein $Q_{gs}Cl_{gs}$, which represents the mass of chloride added by groundwater and/or surface/shallow subsurface flow between C1E and LG, is greater than $Q_{l}Cl_{LG}$. A net loss of chloride mass, however, does affirmatively indicate loss of stream flow to groundwater recharge, although more may have been lost than calculated from the known inputs and resultant output at LG .

All values are derived from measurement in this study with the exception of Q_{gs}, Cl_{gs} and Q_l. Due to comparable stream chloride concentrations at C2M and LG, and those at C1E and C2E, with minimal input by C1W and C2S, particularly during the dry months when loss to groundwater recharge is more likely to occur, chloride concentration along the reach from C1E to LG is assigned the value measured at Lower Gage, Cl_{LG}. A net gain in stream flow occurs when Q_{gs} is greater than Q_l, while a net loss occurs when Q_l is greater than Q_{gs}. Net gain or loss in stream flow water and mass, designated as Q_{net} and M_{net}, respectively, is determined through calculation via rearrangement of Equation 9, and representation as follows,

$$Q_{gs}Cl_{gs} - Q_l Cl_{LG} = Q_{LG}Cl_{LG} - Q_{C1E}Cl_{C1E} + Q_{C1W}Cl_{C1W} + Q_{C2E}Cl_{C2E} + Q_{C1S}Cl_{C1S} \quad (10)$$

$$Q_{net} = Q_{gs} - Q_l \quad (11)$$

$$Q_{net} = Q_{LG} - Q_{C1E} + Q_{C1W} + Q_{C2E} + Q_{C1S} \quad (12)$$

$$M_{net} = Q_{gs}Cl_{gs} - Q_l Cl_{LG} \quad (13)$$

$$M_{net} = Q_{LG}Cl_{LG} - Q_{C1E}Cl_{C1E} + Q_{C1W}Cl_{C1W} + Q_{C2E}Cl_{C2E} + Q_{C1S}Cl_{C1S} \quad (14)$$

Calculation of Q_{net} and M_{net} are conducted using Equations 12 and 14, from which hydrologic interpretations are made. For instance, a net loss of both stream discharge and chloride mass would indicate stream flow loss to groundwater recharge, which precludes concurrent groundwater contribution, without necessarily eliminating the possibility of unmeasured shallow subsurface flow contributions to stream flow which were subsequently lost to recharge at the stream channel and unmeasured. A net loss of water or net gain of water, combined with a net gain in chloride mass would indicate stream flow contribution by groundwater and/or shallow subsurface flow.

To approximate Cl_{gs}, on a monthly or annual basis, Cl_{net} is defined, calculated and interpreted as follows, using values of M_{net} and Q_{net}, as defined and derived in Equations 11 through 14,

$$M_{net} = Q_{net} Cl_{net} \tag{15}$$

$$Cl_{net} = \frac{M_{net}}{Q_{net}} \tag{16}$$

$$Cl_{net} = \frac{Q_{gs} Cl_{gs} - Q_l Cl_{LG}}{Q_{gs} - Q_l} \tag{17}$$

where Cl_{net} conceptually represents the chloride concentration of stream flow contributions by groundwater and/or shallow subsurface flow to the stream channel, plus concentrating effects from evapotranspiration in the stream channel. It is to be understood that the term $Q_l Q_{LG,}$ loss of chloride mass at a concentration equal to net chloride concentration in the stream channel does not effect Cl_{net}. Further, by Equation 17, it may be noted that a portion of stream flow loss, Q_l, by evapotranspiration, will effect an increase in Cl_{lnet}. However, in a flowing stream the effect of Q_{net} loss by evapotranspiration is considered to be minimal. Therefore, in making interpretations of hydrologic processes based upon stream flow chloride concentrations, calculated Cl_{net} values may be interpreted as approximations of Cl_{gs}. Calculated values of Cl_{net} may be compared to adjacent groundwater chloride concentration, Cl_r. Values of Cl_{gs} less than Cl_r indicate addition of low chloride surface runoff or low chloride shallow surface water delivery to the stream channel, while values of Cl_{gs} greater than Cl_r would indicate addition of high chloride shallow surface water delivery to the stream channel.

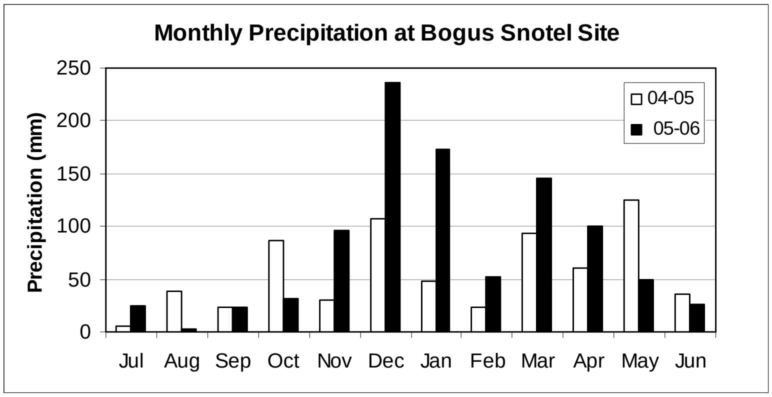
RESULTS

Precipitation (P)

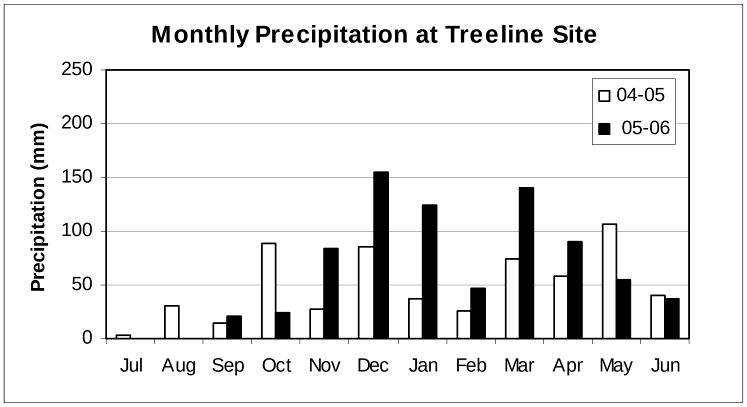
Significant differences occurred in quantity and timing of precipitation received during water year 2004-2005 versus water year 2005-2006. Precipitation received at the Bogus Snotel Station was 42% greater during the second study year compared to the first study year, and 31% and 24% greater at Treeline and Lower Weather stations, respectively (Table 2). During water year 2004-2005, maximum monthly precipitation occurred as rainfall in May, whereas in water year 2005-2006 maximum monthly precipitation occurred as snowfall in December (Figure 9). The 2005-2006 values represent the greatest depth of annual precipitation received during the years on record (Figure 1).

Table 2. Annual precipitation at each weather station, 2004-2005 and 2005-2006.

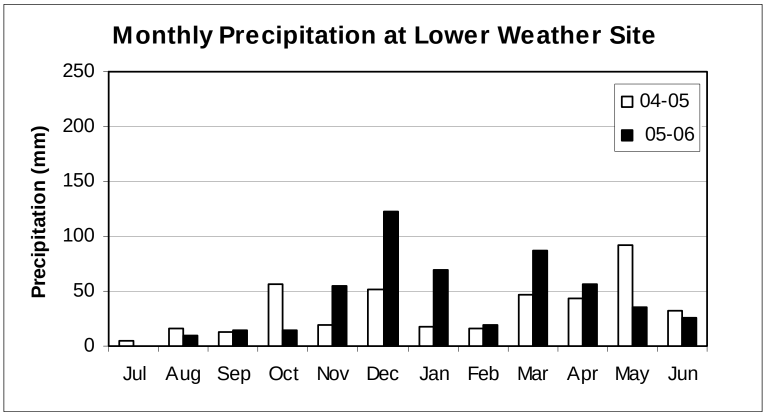
	Lower Weather (mm)	**Treeline (mm)**	**Bogus Snotel (mm)**
2004-2005	411	593	676
2005-2006	510	778	962


Monthly Precipitation at Bogus Snotel Site

a.


Monthly Precipitation at Treeline Site

b.


Monthly Precipitation at Lower Weather Site

c.

Figure 9 a,b,c. Comparison of monthly precipitation at Bogus Snotel Site, Treeline Site and Lower Weather Station for water years 2004-2005 and 2005-2006. Precipitation which occurred during November through March at Bogus Snotel and Treeline sites occurred predominantly as snowfall.

Error in precipitation depth as derived from shielded precipitation gage data at the Lower Weather, Treeline and Bogus Snotel sites and is assessed as systematic error, 6 to 9% low, based upon calculations conducted for actual precipitation using Equation 18 applied to paired shielded and unshielded gage data at the Treeline and Lower Weather sites (Table 3)

$$A = (S^{1.8})*(U^{0.8}) \tag{18}$$

where A is the computed wind-adjusted precipitation, U is the unshielded precipitation measured and S is the shielded precipitation measured. This equation is described by Hanson (2001), based on prior work conducted by W. R. Hamon in the Reynolds Creek Experimental Watershed, southwestern Idaho.

Table 3. Comparison of shielded, unshielded and actual/calculated precipitation for DCEW weather stations, water year 2005-2006.

2005-2006	Shielded (mm)	Unshielded (mm)	Actual (mm)	% Difference Actual vs. Shielded
Treeline	778	699	847	9
Lower w.	405	376	430	6

Annual volume of precipitation was calculated for DCEW (Figure 10) and selected study catchments using the described method of linear regression applied to hypsometric representation of each catchment. Precipitation volume for the Treeline catchment, however, was calculated using only Treeline weather station data, due to size and location of the catchment.

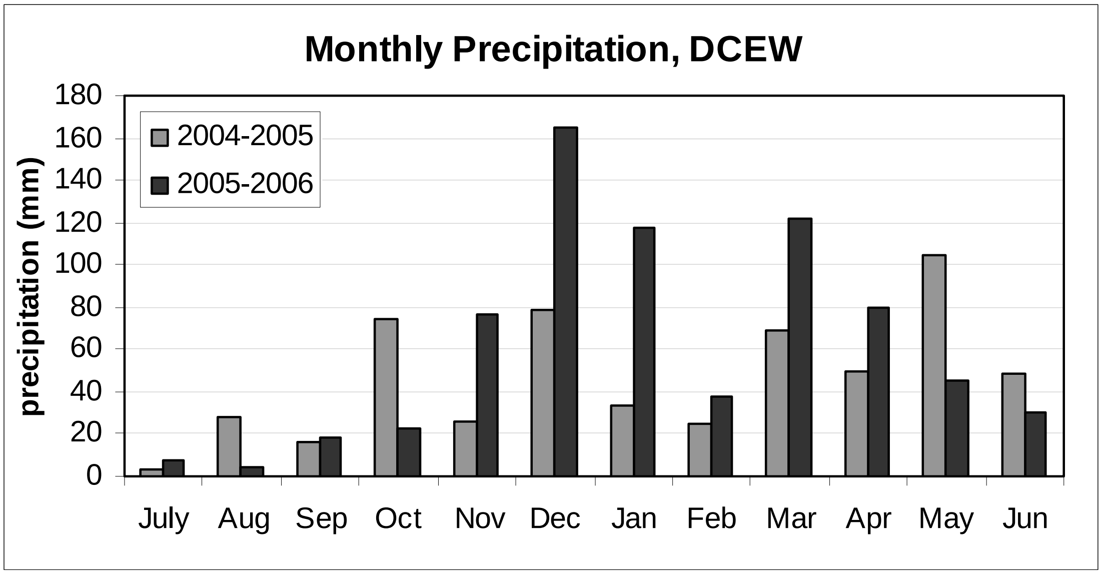
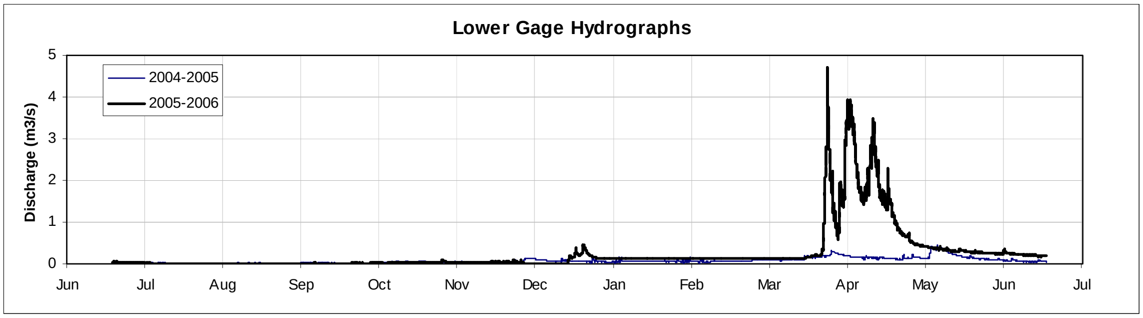


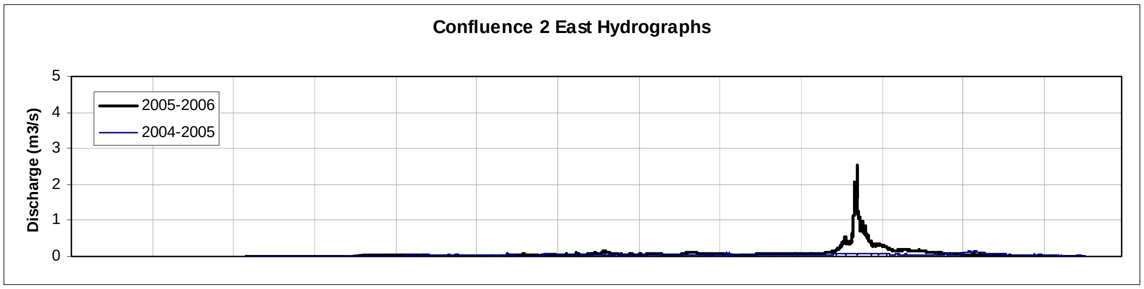
Figure 10. Hypsometric (elevation-dependent, area-weighted) calculated monthly precipitation for DCEW, 2004-2005, 2005-2006.

Stream Discharge (Q)

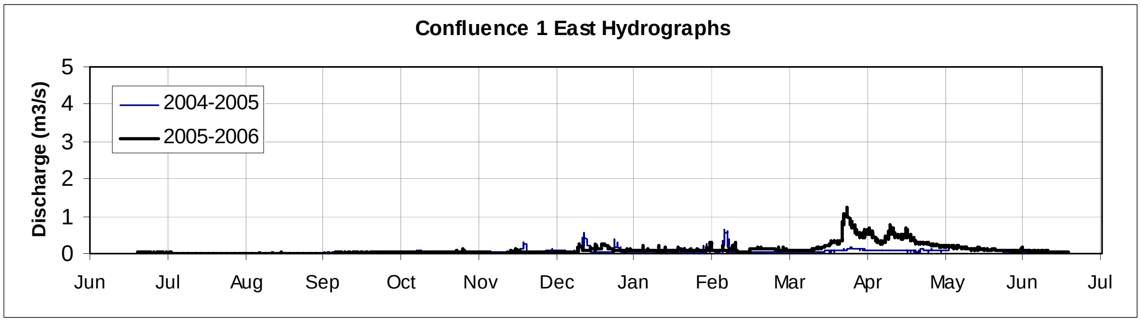
Greater increase occurred in stream discharge between the two study years than observed for precipitation, ranging from a 75% increase in discharge at the Treeline site to a 260% increase in discharge at Lower Gage. Hydrographs are presented in Figures 11a,b,c for three gage sites, C1E, C2E and LG, in which the inter-annual contrast in peak stream discharge is strikingly apparent.



a.



b.



c.

Figure 11 a,b,c. Hydrographs for 2004-2005, 2005-2006, for Lower gage, C2E and C1E.

Qualification of the discharge values requires consideration of error resulting from application of power regression to stage-discharge data, systematic and random gaging error, as well as systematic and random error in stage measurements. Further error in discharge may be attributed to data interpolation conducted for missing data intervals. The stage and discharge measurements, as well as calculated discharge, for C1E are presented for discharge value error assessment, considering minimal data interruption at C1E. As shown in Figure12, the pressure transducer data at C1E displayed less error than the capacitance rod data, and remains within the 10% range of measurement precision for staff gage height values, thus the pressure transducer data was utilized for final calculations of discharge. The rating curve derived for C1E by power regression of stage-discharge data, utilizing pressure transducer stage values, is shown in Figure 13. Maximum -20% systematic discharge gaging error, as determined through comparison with alternate discharge measurements via dilution gaging and flowmeter (pygmy assessed to produce discharge values as much as 20% high), and assessed 10% random error in staff and pressure transducer stage values are also shown in Figure 13. Graphical analysis of Figure 13 provides assessment of maximum error in discharge resulting from application of power regression to stage-discharge data. The resultant assessment is a maximum 5 cfs error in calculated discharge occurring at 24 cfs at maximum discharge, which equates to a 21% maximum error. Error results are similar at the remaining instrumentation sites.

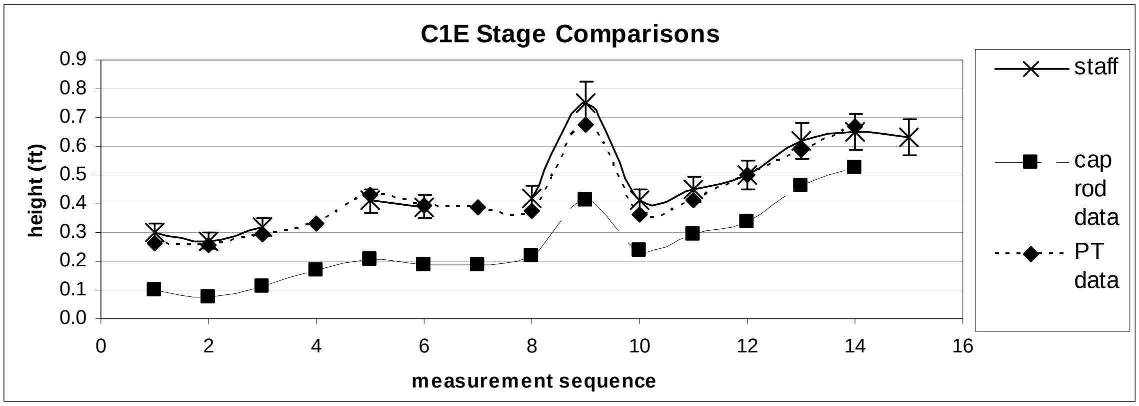


Figure 12. Comparison of staff gage, capacitance rod and pressure transducer data at C1E for multiple dates during water year 2004-2005. Staff values are shown with 10% error for gage precision 0.01 ft.

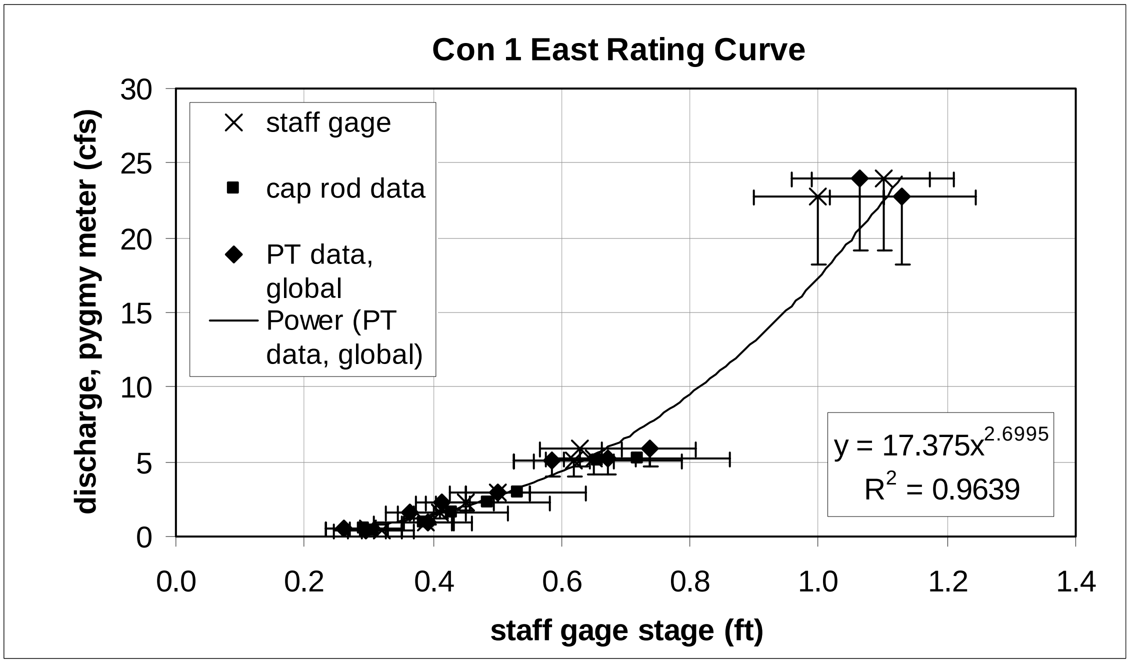


Figure 13. Error assessment for C1E rating curve, error bars represent 21% maximum systematic error in discharge as measured by pygmy meter compared to concurrent lower discharge values derived from gaging with dilution methods and sonic meter, and 10% random error in stage measurements. Rating curve power equation is based on pressure transducer stage values vs. discharge values.

Chloride Concentrations (Cl_p, Cl_q, Cl_r)

An arithmetic average of all bulk precipitation chloride concentrations for the entire two-year study period is 0.545 ppm, standard deviation 0.691 ppm with a maximum of 3.868 ppm (Figure 14). However, as discussed, temporal volume-weighting and area weighting methods were applied to derive annual average Cl_p values per catchment, per year, with resultant annual values for Cl_p ranging from 0.269 ppm to 0.477 ppm. Average chloride concentration for 2005-2006 snowmelt sampled from the snowmelt bucket near precipitation collector P5 was 0.076 ppm. In general, higher chloride concentrations persisted at lower elevations and during the drier months.

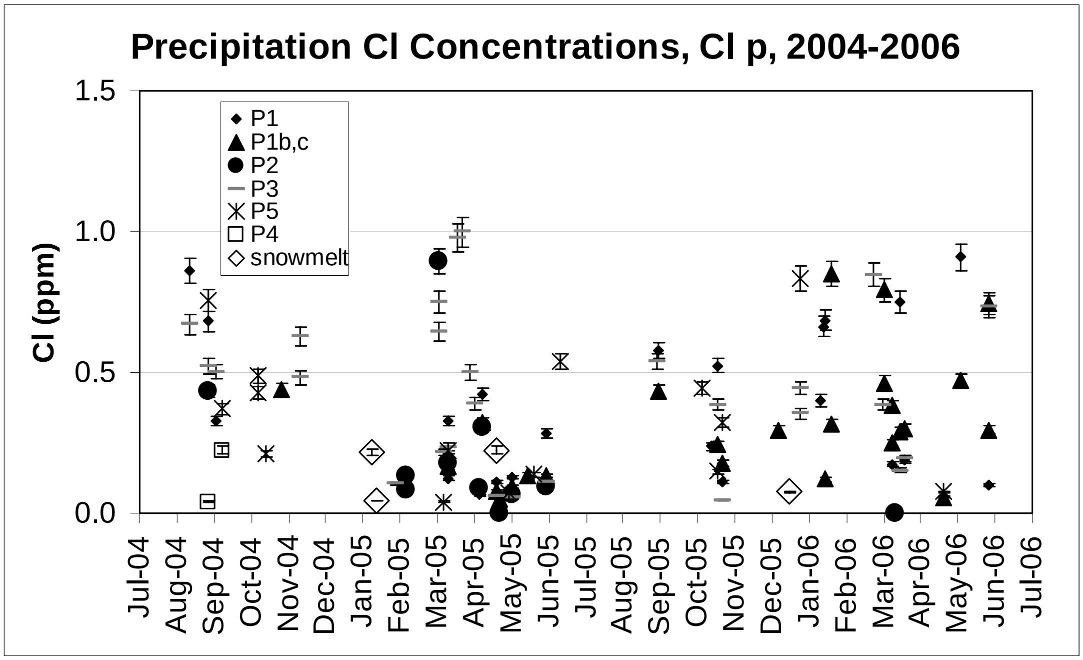
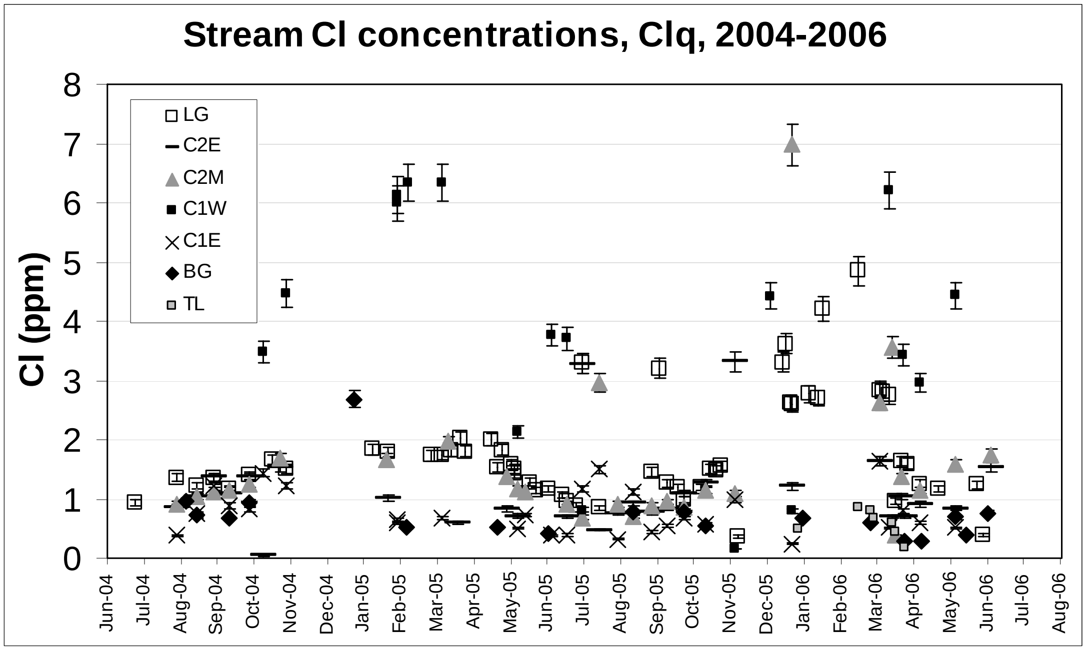
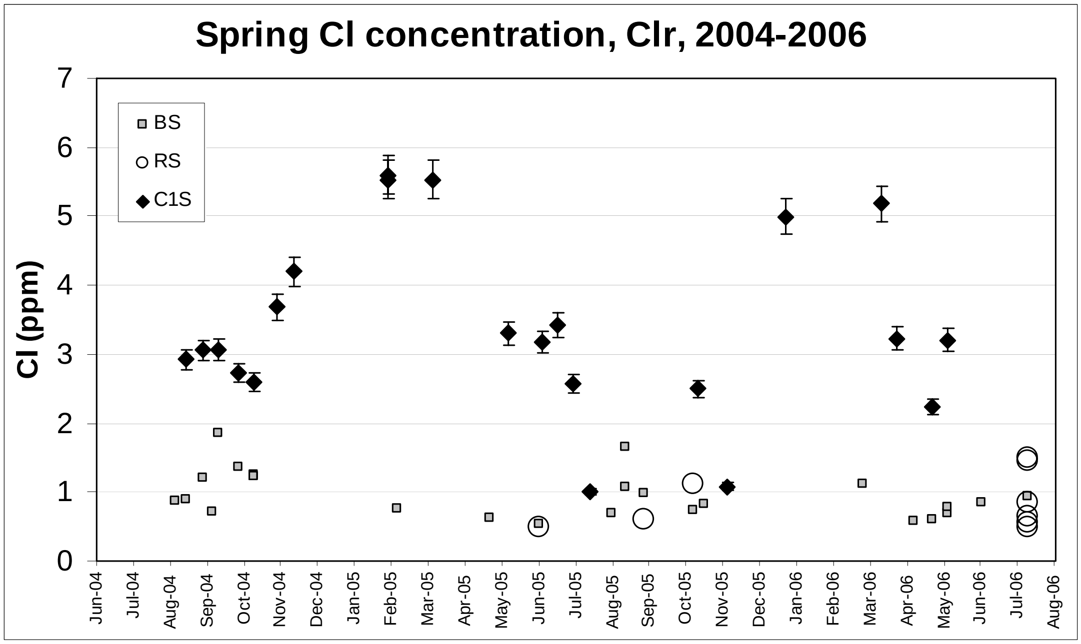


Figure 14. Precipitation chloride concentrations, 2004-2005, 2005-2006. Collector locations shown in Figure 2. Error bars represent maximum +/-5% in lab analysis.

Temporal trends in stream and spring chloride concentrations are strikingly apparent as measured at each outlet measurement point, with distinct differences in magnitude and timing of chloride peaks between catchments (Figure 15). The highest stream water chloride concentrations occurred at sample site C1W, with monthly discharge-weighted averages of 3.945 ppm and 3.402 ppm for study years 2004-2005 and 2005-2006. The lowest concentrations occurred at site BG with values at 0.533 ppm and 0.467 ppm. In general, stream and spring chloride concentrations are lowest in June/July and peak in December to March, with earliest peaks occurring in the headwater catchments.



a.



b.

Figure 15 a, b. a. Stream and b. Spring chloride concentrations 2004-2005, 2005-2006. Measurement locations in Figure 2.

The results for single-day sampling conducted in February, April and May, 2006, are shown in Figure 16.   Included sampling of roadside runoff reveals high chloride concentrations at minor runoff sites and at the head of tributaries draining into the west side of DCEW in February and April. The May synoptic sampling reveals high chloride concentrations in western tributaries at confluence with Dry Creek, particularly notable considering C1W stream chloride concentrations relative to adjacent study catchments (Figure 17).

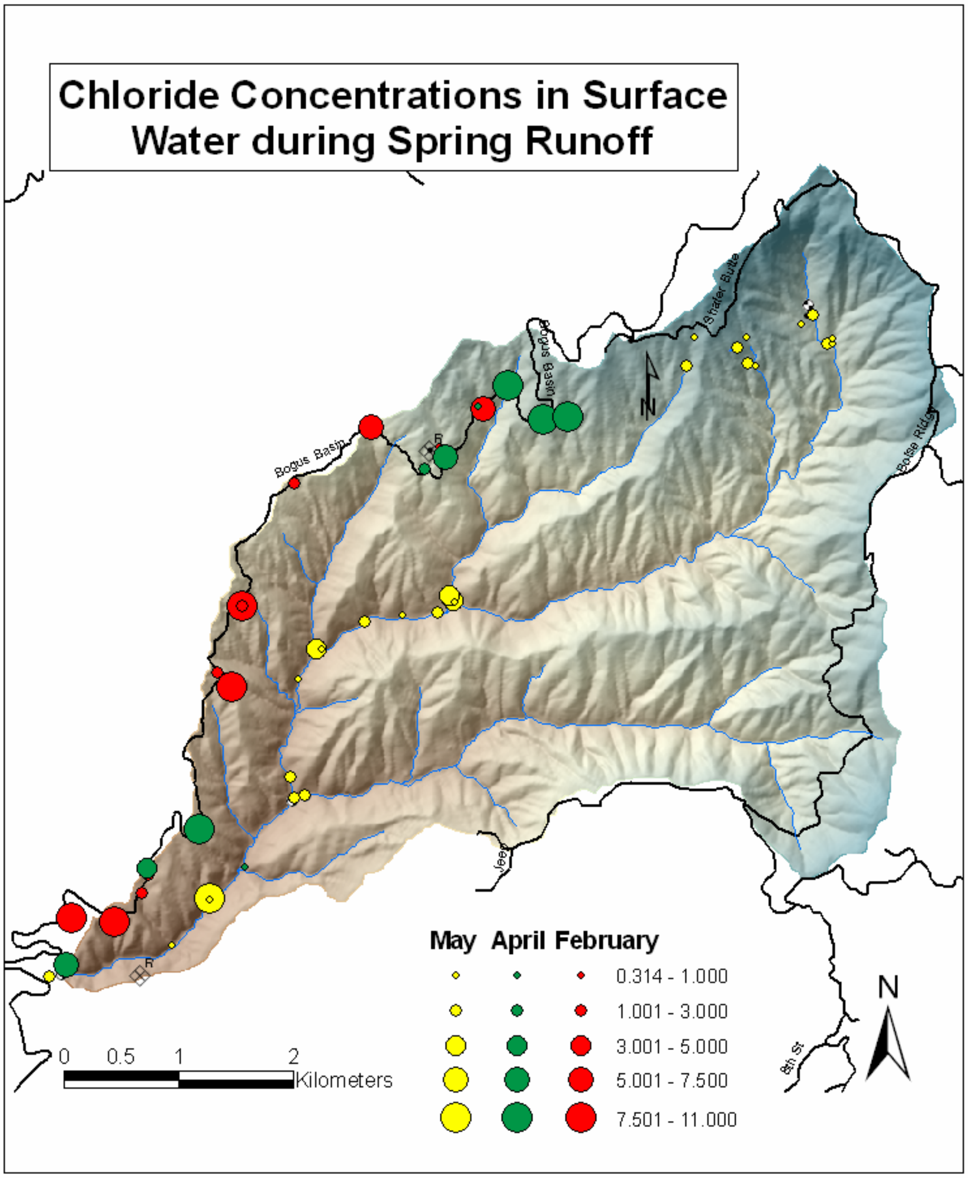


Figure 16. Single-day surface water chloride concentrations, DCEW.

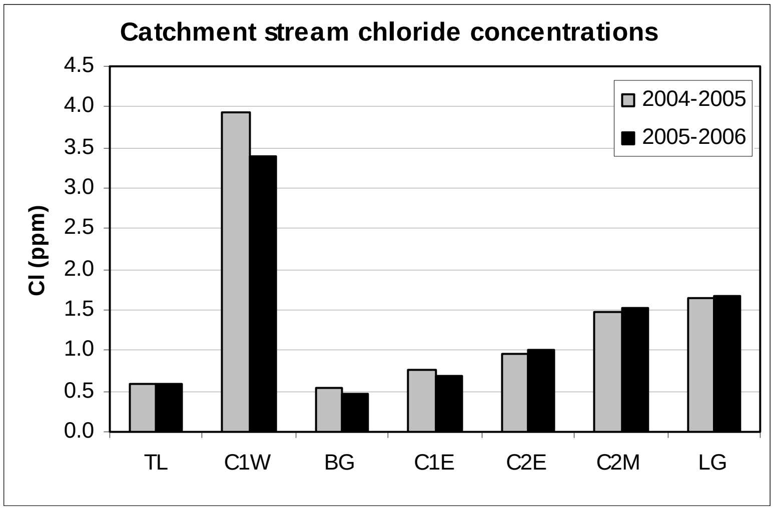


Figure 17. Monthly discharge-weighted stream chloride concentrations for each study site, 2004-2005, 2005-2006.

Time-series chloride data for springs sampled (Figure 15b), reveal parallel patterns and similar concentrations between spring samples and nearby sampled stream locations (Figure 15a). However, as described in methods section, spring chloride concentrations utilized in the CMB equation for this study are end of dry season sample averages. For the BS sample site (Figure 2), resultant values are 1.478 ppm and 1.139 ppm, for water years 2004-2005 and 2005-2006, respectively. For the Shingle Creek springs at the head of catchment C2E, corresponding resultant values are 1.110 ppm and 1.071 ppm.

Representation of groundwater chloride concentration at the lower elevations of DCEW is provided by a lower elevation wells sampled during a pump test in October 2006 with an average chloride concentration of 3.403 ppm. Groundwater chloride concentrations at the Treeline catchment as derived through the afore-described “stranded chloride method" employing the total volumes of fallen snow are outlined in Table 4 as 0.94 ppm and 0.59 ppm. These values are treated, however, with a high degree of uncertainty as assessed by applying the same "stranded chloride method" to the BG catchment. Stranded chloride calculation of Cl_r for the BG catchment produced values of 0.83 ppm and 0.53 ppm versus the corresponding measured Cl_r values of 1.478 for 2004 and 1.139 for 2005, respectively. Thus, the Cl_r calculated for the Treeline catchment may be half the actual groundwater chloride concentration, based on which the actual Treeline Cl_r values would be 1.880 ppm and 0.982 ppm. This adjustment is considered reasonable due to observed wind, mid-winter warming and limited vegetation dormancy at the Treeline Site which would contribute to sublimation and evapotranspiration of snow and snowmelt during the winter and spring months.

Table 4. Stranded chloride method input values and results for Cl_r at Treeline Site.

	P (m3)	Clp (m3)	snowmelt (m3)	Clr
2004-2005	8297	0.477	4225	**0.937**
2005-2006	14696	0.352	10528	**0.491**

In addition to suggested adjustment to Cl_r for the Treeline site, adjustment of Cl_r values determined for the remaining catchments is also considered due to under-representation of groundwater by single spring or well samples. Adjusted values for catchment C1E, C2E, C2M and LG are derived as an average of extreme values. For C1E, 2 ppm provides a conservative average between 1.478 ppm measured at BS, near the head of C1E and 3.403 ppm, measured at the Test well 1 km northeast of LG (Figure 2). The same result applies to C2E using 1.110 ppm measured at the Shingle Creek springs and the Test well concentration. For C2M and LG, an average of 2.5 ppm is applied for a conservative catchment average chloride concentration between 3.403 ppm and 1.478 ppm. Laboratory analysis of water samples for chloride concentration has been assessed at an average of +0.67% error, with all but one in-lab quality check analyses falling within the range of +/- 5.2% error.

Chloride Mass Balance Estimates of Net Groundwater Recharge (R)

Chloride mass balance calculations were conducted for catchments defined by outlet points TL, C1W, BG, C1E, C2E, C2M and LG (Figure 2). Input values and results for these calculations are given in Table 5 below and depicted in Figure 18. For water year July 2004 through June 2005, all catchment analyses produced positive initial estimates of net groundwater recharge as percentage of precipitation received, ranging from 2% to 44%, with the exception of C1W. Applying measurement error propagation and correction for uncertainty in Cl_r values, the range in values is 0% to 56% for water year 2004-2005. Due to the negative recharge value calculated for C1W, recharge results for this catchment are not included in Figure 18, nor related figures. However, C1W precipitation and stream discharge volumes are considered valid.

For water year 2005-2006, only the headwater catchments produced positive recharge estimates. A two-year CMB calculation was also conducted for each catchment, with positive net recharge values resulting only for TL, BG, C1E and C2E catchments.

Rules of error propagation applicable to Equation 6 include: 1) Product rule for systematic and random errors. When two quantities are multiplied, their *relative* errors add. 2) Quotient rule for random errors. When two quantities are divided, their *relative* errors add. 3) Addition and subtraction rule for random errors. The absolute errors add. Application of these rules follows standard order of operations. The result, using measurement errors listed in the section above for P, Q and Cl$_p$, Cl$_q$, Cl$_{r,}$differs for each net recharge estimate with resultant ranges in net recharge estimates given in Table 5.

Table 5. Chloride mass balance net recharge estimates for each study catchment, 2004 – 2005 and 2005 – 2006. Values in parentheses are adjusted groundwater chloride values and corresponding recharge and error propagation results.

DCEW	**TL**	**C1W**	**BG**	**C1E**	**C2E**	**C2M**	**LG**
gage elev (m)	1,607	1,347	1,698	1,335	1,158	1,143	1,036
Area (km^2)	0.02	3.8	0.52	8.58	7.50	23.90	26.93
2004-2005							
P (m^3)	11,214	2,243,363	345,111	5,194,109	4,416,549	13,581,508	15,052,622
Clp (ppm)	0.477	0.477	0.269	0.373	0.365	0.353	0.367
Q (m^3)	1,221	298,774	127,250	1,619,395	757,877	2,767,145	2,257,560
Clq (ppm)	0.600	3.945	0.533	0.767	0.971	1.464	1.646
Clr (ppm)	0.937 (1.880)	1.003	0.786	1.478 (2.0)	1.110 (2.0)	3.403 (2.5)	3.403 (2.5)
R (m^3)	4,928	-107,735	32,004	471,042	790,058	217,738	529,472
100*R/P	**44 (22)**	**-5**	**9**	**9 (7)**	**18 (10)**	**2 (2)**	**4 (5)**
Propagation error range	32to56 (16to28)		-5 to 24	-1 to 19 (-1 to 14)	7 to 29 (4 to 16)	-3 to 6 (-4 to 9)	-1 to 8 (-1 to 11)
2005-2006							
P (m^3)	14,696	2,954,540	492,877	6,869,123	5,867,692	17,740,402	19,594,077
Clp (ppm)	0.352	0.352	0.320	0.336	0.376	0.371	0.400
Q (m^3)	2,133	762,591	314,695	3,370,375	2,086,061	5,970,540	8,116,631
Clq (ppm)	0.582	3.402	0.467	0.684	1.019	1.520	1.566
Clr (ppm)	0.491 (0.982)	1.003	0.775	1.139 (2.0)	1.071 (2.0)	3.403 (2.5)	3.403 (2.5)
R (m^3)	8,002	-1550259	14,153	3,627	76,270	-732,701	-1,429,472
100*R/P	**54 (27)**	**-52**	**3**	**0(0)**	**1(1)**	**-4(-6)**	**-7(-10)**
Propagation error range	35-74 (17-37)		-17 to 23	-9 to 9	-9 to 10		

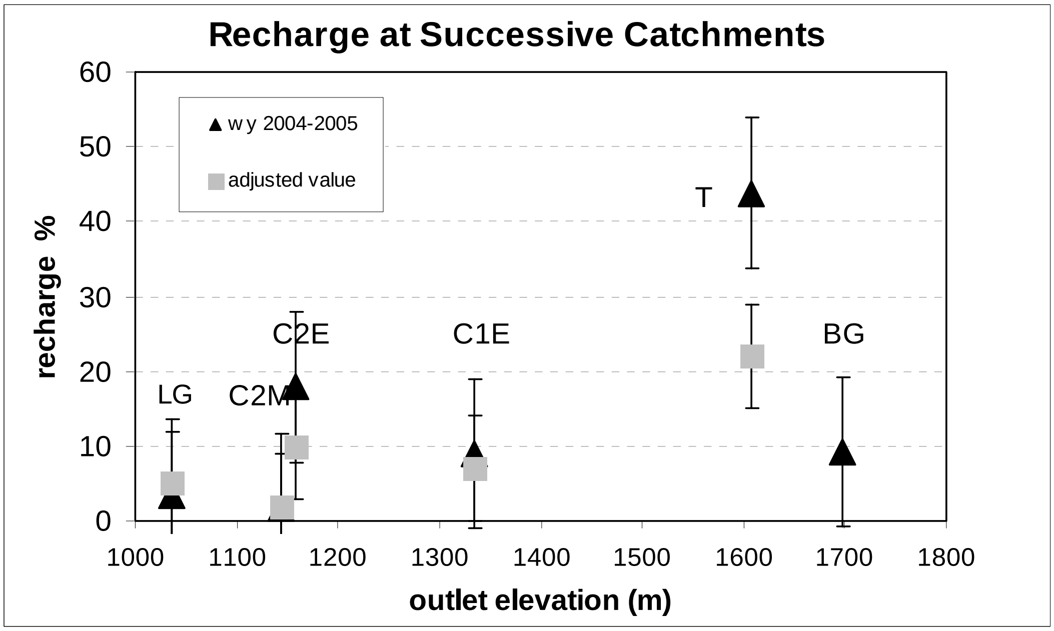


Figure 18. Initial and Cl_r-adjusted recharge estimates. Absolute error +/-10% and +/-7% recharge/precipitation, respectively.

Water Budget

Through application of Equation 6, evapotranspiration is calculated for water year 2004-2006, by which a water budget is constructed for each study catchment (Figure 19). A general trend is apparent in which net groundwater recharge as a percentage of precipitation received is greater in the higher elevation catchments, less in the larger, lower elevation catchments. An anomaly in this trend occurs at the Treeline catchment which displays the greatest rate of net recharge, paired with anomalous low stream discharge rate as percentage of precipitation received. With the exception of the Treeline site, the ratio of discharge to precipitation is notably high at BG, the primary headwater catchment for Dry Creek and secondly at C1E, while TL and C1W catchments are notably low and C2E, C2M and LG show a contrast in trend between the water years (Figure 19, 20). Evapotranspiration, consequently, comprises a lesser portion of catchment water budgets with increasing elevation.

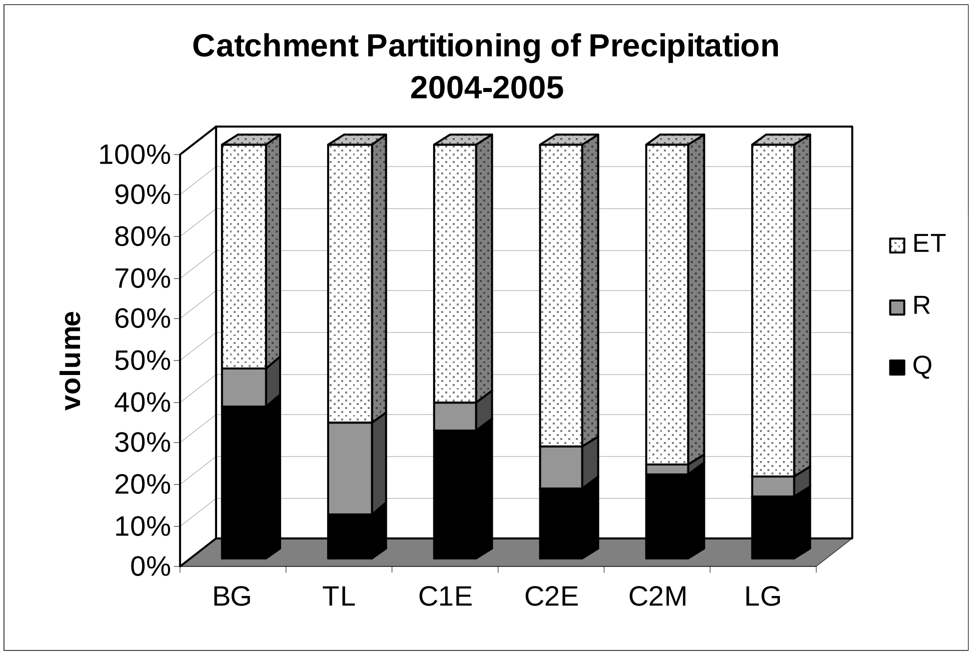


Figure 19. Water budget for study year 2004-2005, catchments arranged left to right in order of decreasing outlet elevation. Adjusted Cl_r values utilized.

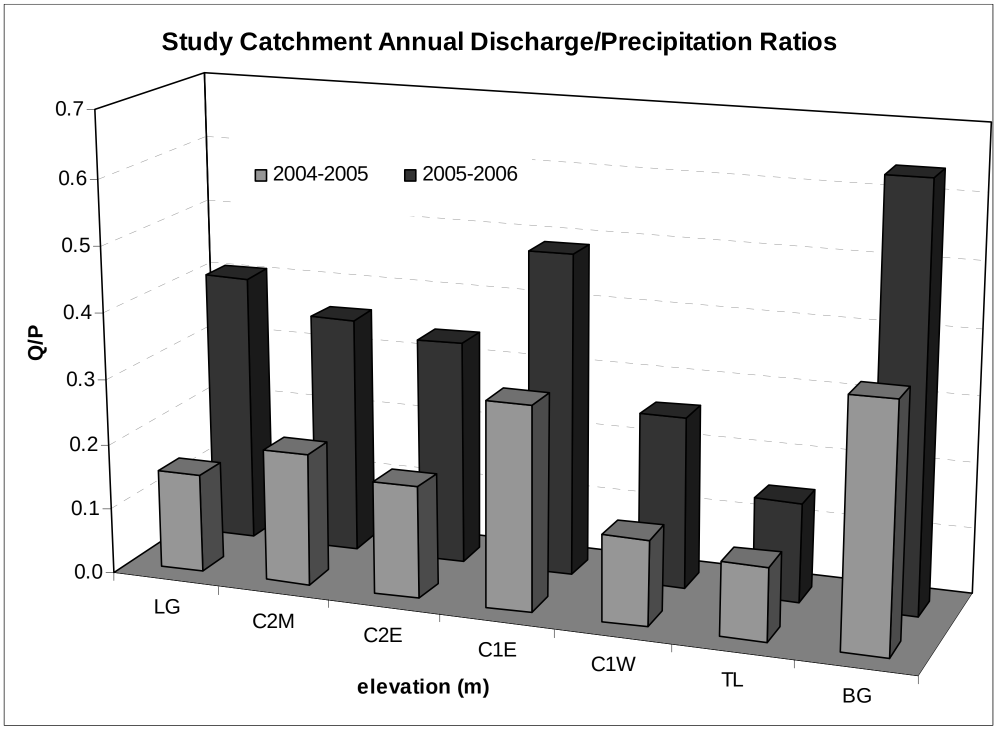


Figure 20. Annual discharge/precipitation ratios for each study catchment, 2004-2005 and 2005-2006.

Evapotranspiration determined by residual using Equation 6 and shown in Figure 19 for study catchments, water year 2004-2005, is compared with point value evapotranspiration calculated by chloride concentration factor using Equation 7 (Table 6). The results show fair agreement with reasonable variance. The concentration factor value calculated for the lower well site is, as expected, higher than the water budget value of evapotranspiration for the catchment overall which utilized a groundwater chloride concentration estimated as representative of the catchment overall. Similarly, the concentration factor value calculated for the high elevation Shingle Creek springs is lower than the water budget value of evapotranspiration for C2E catchment overall. For both BG and TL headwater catchments, evapotranspiration determined from the net recharge estimates is low compared to the point-value concentration factor values.

Table 6. Evapotranspiration calculated by water budget and concentration factor. Annual discharge/precipitation ratios are shown as Q/P, R/P is annual recharge as fraction of precipitation received and ET/P is annual evapotranspiration as fraction of precipitation received.

2004-2005	Q/P	R/P	Clr (ppm)	**ET/P by residual**	2yr avg Clp (ppm)	2yr avg Clr (ppm)	Clr sample location	**ET/P by concentration**
BG	0.37	0.09	0.786	**0.54**	0.295	0.783	BG	**0.62**
TL	0.11	0.22	1.880	**0.67**	0.414	1.428	TL	**0.71**
C1E	0.31	0.07	2.000	**0.62**	0.355	1.309	BS	**0.77**
C2E	0.17	0.10	2.000	**0.73**	0.371	1.091	R1S	**0.66**
C2M	0.20	0.02	2.500	**0.77**	0.362			
LG	0.15	0.05	2.500	**0.80**	0.383	3.403	Test well	**0.89**

Water Flux: Stream Flow Sources and Stream Reach Gain/Loss

Treeline Catchment

Stream flow source component analysis/hydrograph separation was conducted for Treeline catchment for the last two months of stream flow occurring at this site during water year 2005-2006, noting that minimal flow occurred prior to March and would have likely included chloride entrained from stream channel storage as evapotranspiration effects at the cessation of flow in spring 2005. Input values and results for the analysis are given in Table 7, from which summation between the two months results in 69% of stream flow attributed to low-chloride precipitation/snowmelt and 31% attributed to high-chloride lateral flux from the unsaturated zone. Lateral flux through the soil profile and bedrock interface flow are considered to be the only sources of high chloride contribution to stream flow (Yenko, 2003). Using the "stranded chloride" method previously outlined and the discussed value adjustment, a chloride concentration of 0.982 ppm was applied to water in the unsaturated zone. Use of the adjusted value is supported by the March stream flow chloride concentration of 0.780 ppm, which would be less likely if annual average soil water chloride concentration were only 0.491 ppm.

Table 7. Treeline stream flow source component analysis.

2005-2006 Treeline	**March**	**April**
Clq (ppm)	0.780	0.413
Clp (ppm)	0.392	0.360
Q total (m3/s)	561.000	846.000
%Q from rain/snowmelt	**0.342**	**0.915**
%Q from high-Cl flux	**0.658**	**0.085**
Clr (ppm), stranded Cl	0.491	0.491
Clr (ppm), adjusted value	0.982	0.982

A distinct difference is apparent between March and April stream flow source component proportions. The distinctly greater amount of stream flow attributed to unsaturated zone high-chloride flux to the stream channel in March indicates annual flushing of unsaturated zone stored chloride. The minimal amount of stream flow attributed to this source in April indicates near complete flushing of unsaturated zone stored chloride from the area of slope contributing to stream flow during this water year, particularly considering observation that overland surface flow does not predominate in this catchment characterized by highly permeable sandy soil. Thus, minimal inter-annual storage of chloride in the unsaturated zone is indicated for the Treeline site.

BG Catchment

Stream flow for the 2005-2006 water year in this primary Dry Creek headwater catchment is assessed as 48% of annual stream flow being attributable to low-chloride precipitation, with 52% attributed to groundwater and/or equally high-chloride unsaturated zone water. If water reaching the stream channel via lateral flux through the unsaturated zone is of average annual chloride concentration greater than groundwater chloride concentration, the amount attributed to a high-chloride source may be less than 52%. The monthly values for total stream flow volume and component volumes are shown in Figure 21, with table of values provided in Appendix C, from which it is apparent that high-chloride flux to the stream channel increases following fall rain and spring snowmelt. As with the Treeline catchment, chloride concentration of soil water available for lateral flux will be greatest at the onset of full soil profile wetting, with the concentration decreasing as stored unsaturated chloride is mobilized and transported to the stream channel. It should also be considered, as observed in this catchment, that under conditions of full soil profile saturation or snowmelt flux in excess of infiltration rates, overland flow to the stream channel does occur, as well as observed macropore flow.

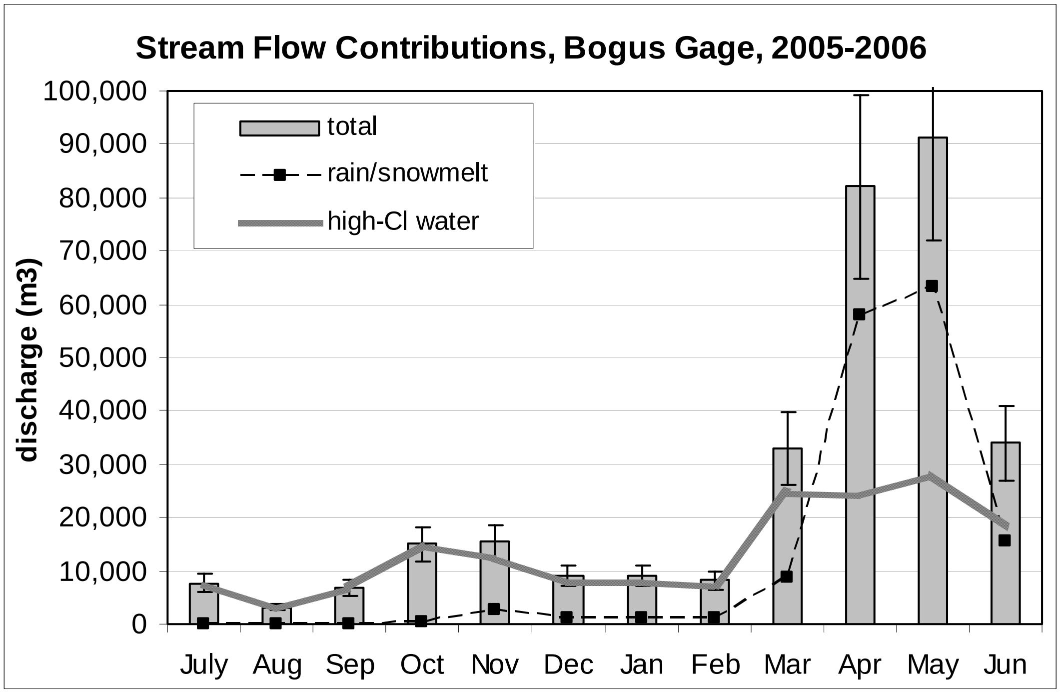
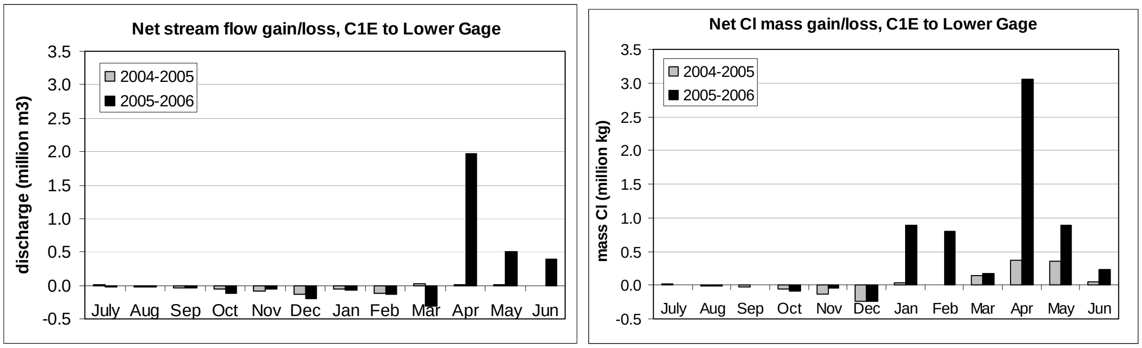


Figure 21. Monthly stream discharge and source contributions for Bogus catchment as rain/snowmelt and groundwater/equally high-chloride unsaturated zone flux to stream channel. Error bars indicate 21% maximum error in stream discharge.

<u>C1E to LG</u>

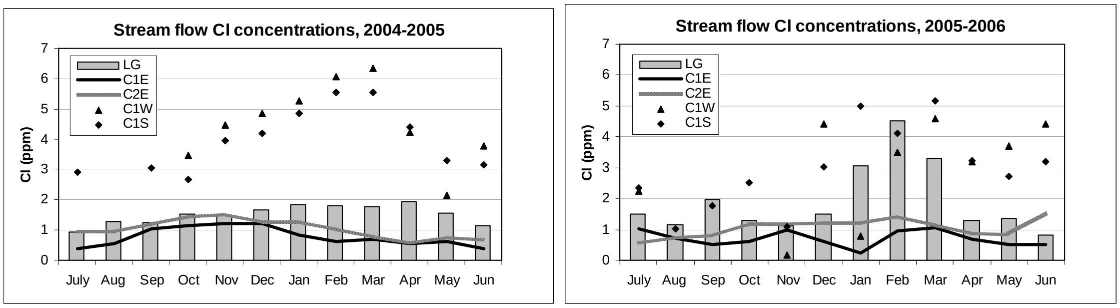
Stream flow source component analysis was conducted for this reach of Dry Creek for both study water years using Equations 9 through 17. Annual accounting of discharge and chloride mass indicates 17% loss of the stream flow contributed by C1S, C1W, C1E and C2E to groundwater recharge and/or evapotranspiration along Dry Creek from C1E to LG for 2004-2005, with concurrent additional chloride mass contribution from groundwater and/or surface runoff or shallow subsurface flow to Dry Creek as13% of the chloride mass measured at LG (Appendix C). In contrast, for water year 2005-2006, net stream flow gain occurred along Dry Creek from C1E to LG at 23% of the discharge measured at LG. Net chloride mass gained along the C1E to LG reach represents 52% of the total mass discharged at LG. Thus, for 2004-2005, Dry Creek between C1E and LG was a net-loosing stream and net-gaining for 2005-2006. Monthly distribution of discharge gain/loss and mass gain/loss is shown in Figures 22 a and b, illustrating predominantly loosing conditions during the dry months July/August to December.



a. b.

Figure 22. a. Net discharge gain/loss in Dry Creek C1E to LG. **b.** Net chloride mass gain/loss in Dry Creek C1E to LG.

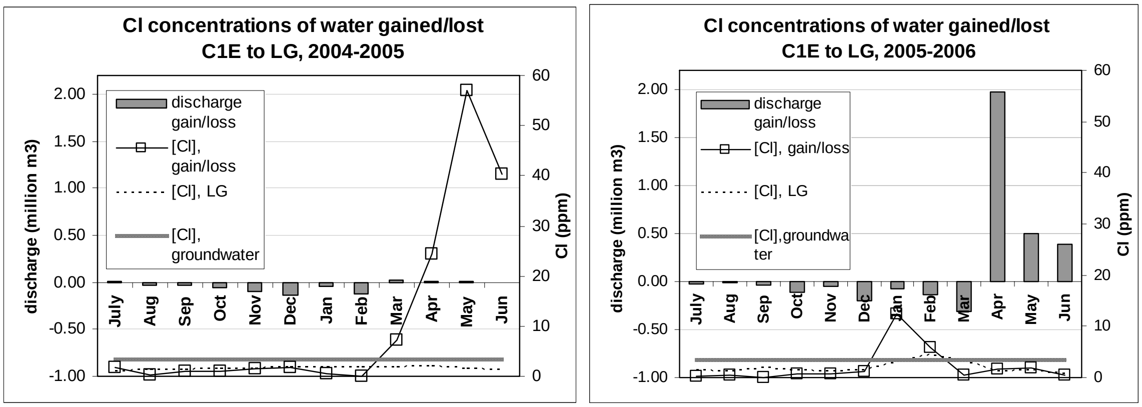
Chloride concentration of measured tributary and spring contributions to Dry Creek between C1E and LG is presented as monthly averaged values in Figures 23 a and b (Table of values in Appendix C). Perennial contribution is made by C1E and C2E, while C1W and C1S tend to cease flow during August and September. These monthly chloride concentration values were applied to Equation 14, along with monthly discharge volumes for each outlet and spring, C1E, C1W, C2E and C1S, to calculate the above stated values of net gain/loss values for chloride mass (Appendix C).



a. b.

Figure 23. Chloride concentrations at gage locations, C1E to LG for **a.** water year 2004-2005 and **b**. water year 2005-2006.

Monthly discharge volumes were applied to Equation 12 to calculate net gain/loss in discharge along Dry Creek between C1E and LG. The monthly values calculated for net gain/loss of water, Q_{net}, and mass, M_{net}, were applied to Equation 16 for calculation of chloride concentration, Cl_{net}, representative of net water supplied to Dry Creek between C1E and LG as groundwater input and/or surface/shallow subsurface flux to the stream channel. As discussed relative to Equation 17, the chloride concentration of this water, Cl_{net}, approximates stream flow contributions from groundwater and/or surface/shallow subsurface sources. The results of these calculations for both water years are shown in Figures 24 a and b, revealing peak high-chloride concentration in flux to stream flow during spring runoff during water year 2004-2005 versus and earlier, January peak in 2005-2006. Groundwater concentration, Cl_r, 3.403 ppm, as measured in well approximately 1 km northeast of LG, considered representative of groundwater beneath slopes down gradient of catchment C1E, is included in Figure 24 for interpretation of Cl_{net} as discussed previously.



a. b.

Figure 24. a. Monthly net gain/loss in stream discharge at LG. **b.** Calculated monthly average chloride concentration of water gained/lost.

Potentiometric Surface

In conjunction with these stream measurements, static water levels were measured in wells located along the southwest portion of DCEW (Figure 2) during the study period. From these water levels, a potentiometric surface is constructed (Figure 25) which indicates head gradient available to induce groundwater flow to Dry Creek. However, this potential for groundwater contribution to stream flow in the lower elevations may be contrasted against the gain/loss analysis results presented above for stream reach C1E to LG which indicate predominant loss to groundwater rather than gain from groundwater. This disparity suggests caution in interpreting the gain/loss analyses which are conducted using monthly values to determine monthly net gain/loss. Specifically, net loss to groundwater at the stream channel for a given month does not preclude intermittent baseflow to the stream during the same month.

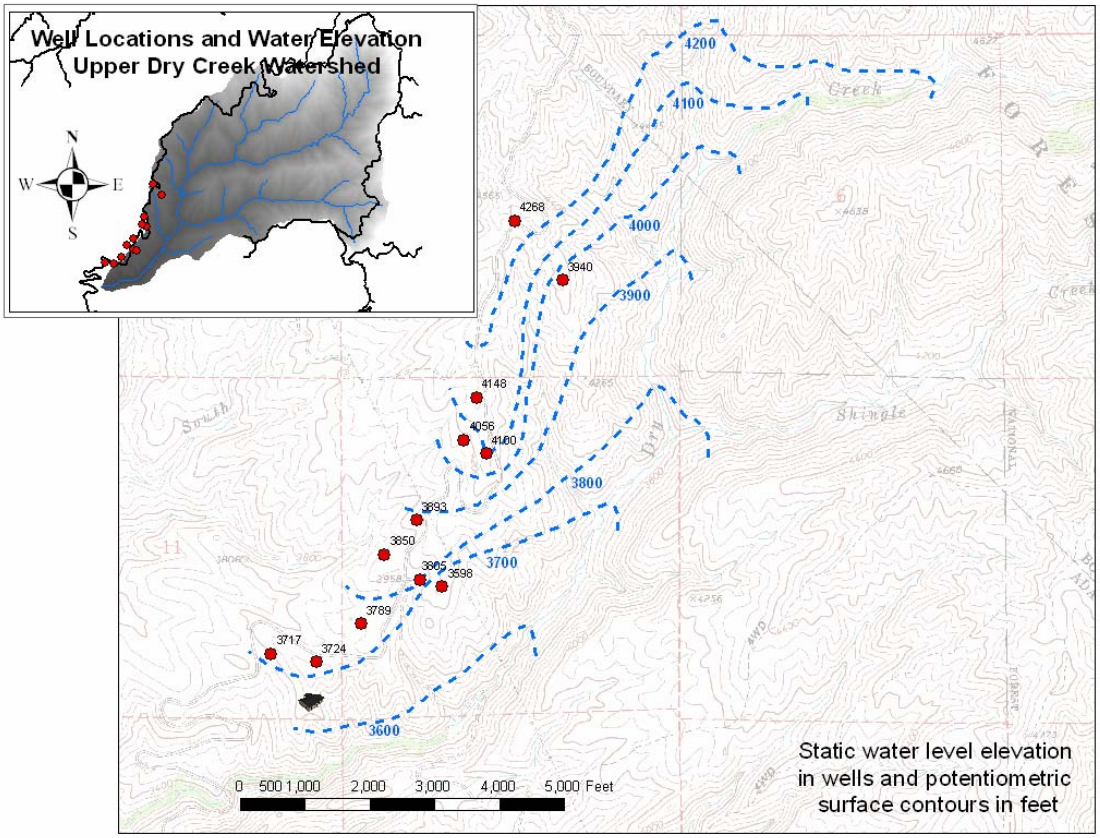


Figure 25. Potentiometric surface for lower DCEW, constructed from static water level measurements in wells, assuming equilibrium with the stream channel.

SENSITIVITY AND ERROR ANALYSIS

Prior to analyzing the results of chloride mass balance calculations, both measurement and model error must be addressed. Measurement error involved in this study includes both systematic and random error, addressed above with the results for each CMB parameter. Propagation of measurement errors in net recharge estimates was also explained and given for each recharge estimate (Table 5). The measurement errors will be further addressed below regarding effect on calculated net recharge through sensitivity analysis for each parameter. Model error will exist where model assumptions are not met within the physical environment. Where model violations exist, the net recharge estimate is considered invalid or skewed and will be discussed accordingly. Each of the six model assumptions will be discussed in detail relevant to the two study water years in DCEW.

Sensitivity Analysis

Sensitivity analysis conducted for each chloride mass balance calculation reveals that discharge values, Q, are slightly more sensitive than the precipitation parameters, P and Cl_p. Net recharge calculation was found to be least sensitive to groundwater chloride concentrations, Cl_r. The following detailed sensitivity analysis was conducted for C1E, with similar sensitivity test results for all catchments for year 2004-2005. A 10% increase in precipitation volume for water year 2004-2005 results in a 1.1% absolute increase in percent recharge above the stated 6.7% recharge, bringing the recharge estimate to 7.8%. The result is similar for a 5% change in precipitation chloride concentration from which calculated recharge changes by an absolute value of 0.9%. In contrast effect, and lesser magnitude, a 5% increase in stream water chloride concentration affects recharge by an absolute value of 0.6%, while a 10% change in stream discharge affects calculated recharge by an absolute +/- 1.2% and a 21% change in stream discharge affects calculated recharge by an absolute +/- 2.5%. Representing the least sensitive parameter, a 5% change in groundwater chloride concentrations results in less than +/- 1% absolute change in recharge estimate. A calculated net recharge value, stated as percentage of precipitation received, is thus conservatively considered to be accurate within +/- 6% of precipitation received, i.e. a stated net groundwater recharge value of 7% represents a range of 1% to 13% of precipitation received being partitioned to net groundwater recharge.

Model Error

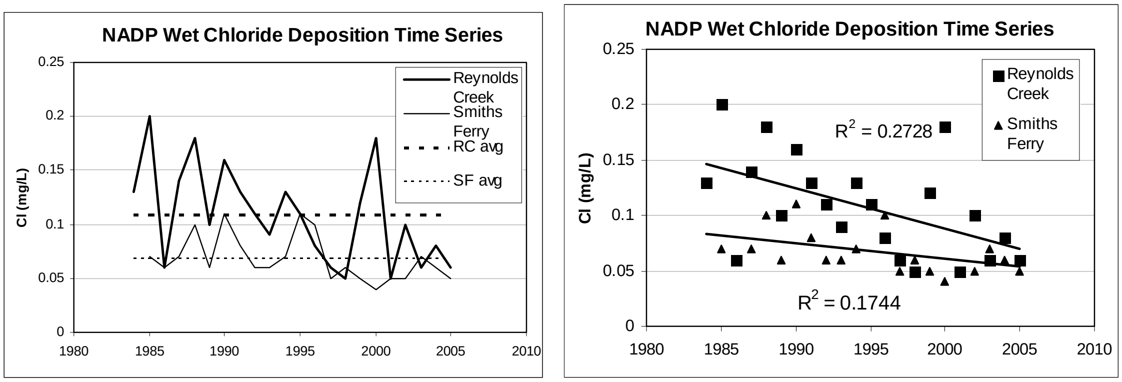
As mentioned in previous applications of CMB to recharge estimation (Wood, 1999; Dettinger, 1989), valid implementation of CMB requires that the system meet six assumptions, including 1) chloride mass flux into the system has not changed over time, i.e. average annual mass atmospheric input of chloride has remained constant during the time period represented by the recharged water, 2) bulk wet and dry fall are the only inputs of chloride to the system, no unmeasured chloride inputs exist, 3) chloride is conservative in the system, recycling or concentration of chloride within the aquifer does not occur, 4) no external surface water or groundwater input occurs, 5) the system is at steady state and 6) no unmeasured runoff from the system occurs. An additional avenue of model error for application of CMB to recharge estimation lies in the conceptual hydrologic model upon which the CMB equation is based for a given application. It may remain to future hydrologic research for a given study area to determine accuracy of the conceptual model. For this study, no observations or data acquired to date indicate contradiction to the presented conceptual mode.

Addressing Model Assumptions

1. Chloride mass flux into the system has not changed over time, i.e. average annual mass aerosol input of chloride has remained constant during the time period represented by the recharged water. To address this assumption, the time period represented by the recharged water and the variability of chloride input during that time span must be delineated.

a. Groundwater sampled for this study has not been dated, however, tritium analyses conducted for well and spring water samples from adjacent Bogus Basin ski resort denote groundwater age to be 9 to 23 years, while the Bogus Basin pump test results indicate a probable maximum hydraulic conductivity value of 5.18 cm/day (see discussion in above Conceptual Model section). In contrast, an aquifer test conducted on October 6, 2006 near the lower end of DCEW (Figure 25, well labeled as 3598) provides a maximum hydraulic conductivity value of 0.24 cm/day, which may suggest a greater groundwater age at this lower elevation than determined at the Bogus Basin ski resort.

b. Regional time series chloride aerosol data available for southwestern Idaho includes National Atmospheric Deposition Program (NADP) data for wet chloride deposition measured since 1984. Depicted in Figure 26 are time series data of average annual precipitation-weighted chloride wet deposition concentrations for Reynolds Creek located southwestward across the Snake River Plain from DCEW (Figure 27), average value 0.11 mg/L with standard deviation 0.04 mg/L, and Smiths Ferry located in the mountainous terrain north of DCEW, average value 0.07 mg/L with standard deviation 0.02 mg/L. These twenty-one and twenty-two year data sets reveal fluctuation of chloride wet deposition about a mean value with slight indication of a decreasing trend in chloride wet deposition during the past 22 years.



a. **b.**

Figure 26. National Atmospheric Deposition Program time series of annual average precipitation-weighted chloride wet deposition at two sites in southwestern Idaho. **a** depicts annual values compared to 22 year average for each side, Reynolds Creek and Smiths Ferry. **b** depicts annual values with linear regression to assess 22 year trend.

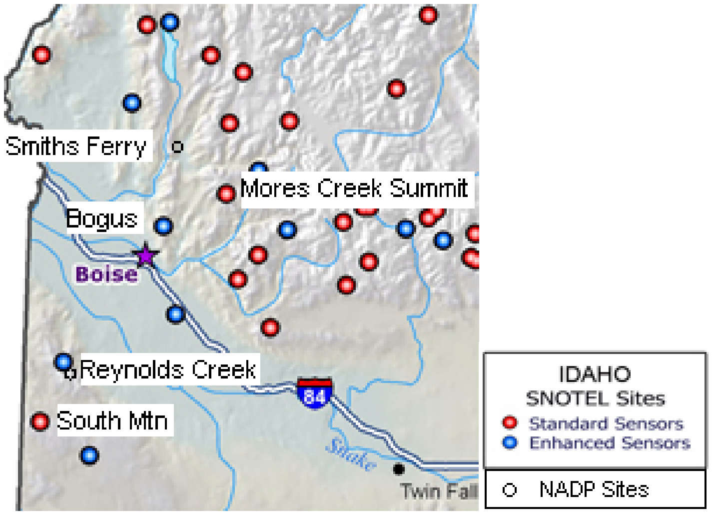


Figure 27. Precipitation and NADP collection site locations, southwest Idaho. Snotel Sites: Mores Creek Summit, Reynolds Creek, Bogus and South Mountain. NADP Sites: Reynolds Creek and Smiths Ferry. (Adapted from SNOTEL website http://www.wcc.nrcs.usda.gov/snotel/Idaho/idaho.html)

Based on the available information given above, the bulk chloride deposition for DCEW in study year 2004-2005 with annual average value 0.39 mg/L, standard deviation 0.4 mg/L for values ranging from 0.00 to 1.69 mg/L and study year 2005-2006 with annual average value 0.7 mg/L, standard deviation 0.86 mg/L for values ranging from 0.03 to 3.89mg/L may possibly be considered as representative low values for the time span represented by the sampled groundwater in DCEW. However, knowledge of chloride dry fall patterns over the past twenty-two years is needed to affirm this possibility. If it is true that chloride deposition during the study period represents low chloride deposition concentrations relative to that deposited across DCEW during the time span represented by the groundwater sampled, then the resultant, CMB estimate of groundwater recharge will be an underestimate.

c. Annual precipitation occurring in southwestern Idaho during the study period represents near-average long-term values, based on data shown in Figure 28.

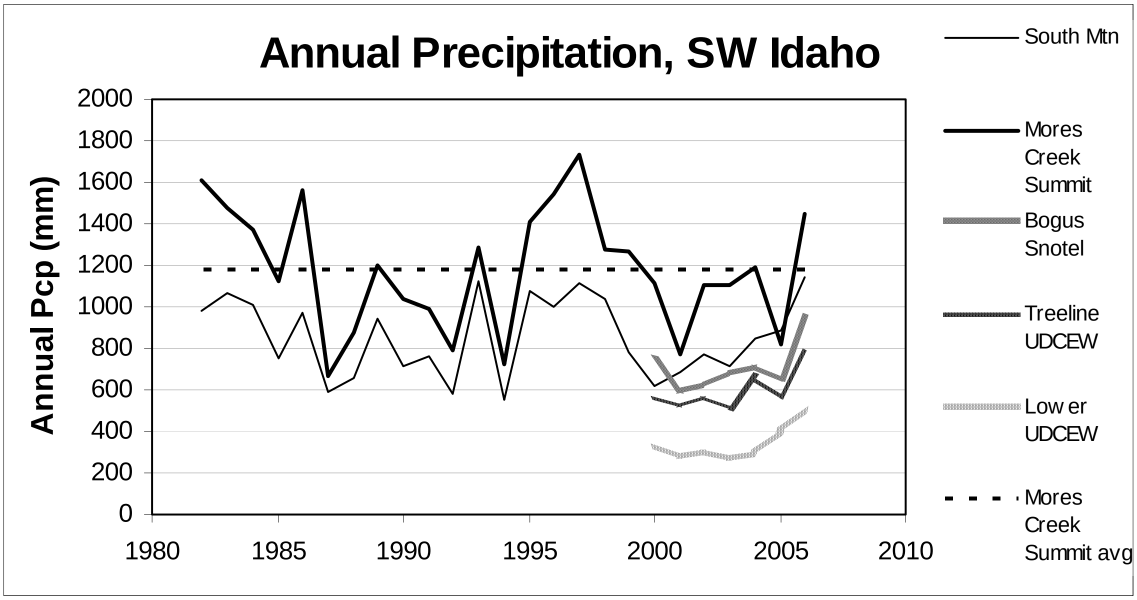


Figure 28. Precipitation trends in southwest Idaho. Station locations in Figure 27.

2. Bulk wet and dry fall chloride deposition are the only inputs of chloride to the system, no unmeasured chloride inputs exist.

a. The lithology of DCEW consists of granodiorite with minor occurrence of volcanic rock along the eastern ridge line. Neither of these lithologies pose a significant source of chloride addition (Claassen, 1986; Kuroda and Sandell, 1953).

b. Road salt input of chloride to DCEW occurs during the winter months along a portion of Bogus Basin road which traces the western ridge of DCEW subcatchment Con1West (Figure 2). Roadside snowmelt runoff sampling was conducted along the entire western edge of DCEW in February and April of 2006 to delineate possible inclusion of road salt chloride in surface runoff into DCEW. The results of these surveys and an additional surface water survey conducted in May 2006 are shown in Figure 16. Based on these findings, and lack of road salt application quantification, subcatchment Con1West and downstream portions of DCEW are not suitable to application of CMB for recharge estimation. Chloride mass balance calculations conducted for these catchment areas using only atmospheric chloride input will underestimate recharge to groundwater.

c. The completeness of employed methods for sampling atmospheric chloride input must be addressed also. Undercatch of dry fall by collectors is considered probable (Eriksson, 1960; Cerney et al.,1994), which would result in underestimation of recharge, assuming no annual storage of dry fall in soil and vegetation. Unmeasured aerosol catch by vegetation through impingement may also occur as suggested by study conducted at Israeli coast which estimated chloride catch by impingement to be 30% above that measured from precipitation collectors (Eriksson and Khunakasem, 1969). Though difficult to measure it is conceivable that impingement may be indicated in high chloride concentrations measured in throughfall. For example, the annual throughfall Cl^- flux for individual species in hardwood forest was 2 to 5 times that of precipitation (Peters, 1991). Similarly, Kauffman et al. (2003) determined a 3-year average measured chloride concentration in throughfall as 42.5% higher than that in precipitation.

With regard to projected degree of undercatch of dry fall and unmeasured vegetation impingement of chloride in DCEW, the likelihood of vegetation impingement of chloride would be greatest in the higher, forested elevations. However, the difference between annual average chloride concentration in precipitation and annual average chloride concentration in high elevation stream water (TL, BG, C1E, C2E, 2004-2005) at a range of 0.184 to 0 .659 ppm does not indicate significant unmeasured chloride input. To illustrate further, chloride concentration increase in stream water compared to precipitation input for a given catchment is a 26% increase at Treeline Site, 53% at BG, 79% at C1E, and 211% at C2E. This may be compared to the consistent 300% increase, excepting lesser concentrations in unforested areas, observed by Eriksson (1960) in a wide-scale assessment across Sweden. It was from this observation that Eriksson inferred impingement of chloride and undercatch of dry fall as 300% higher than chloride concentrations measured in precipitation. Were chloride impingement to occur to a significant degree in DCEW, greater discrepancy between precipitation and stream chloride concentrations would be expected at BG and C1E which contain the greatest percent tree coverage. Instead, discrepancy between stream and precipitation chloride concentrations seem to positively correlate with catchment potential for evapotranspiration and potential for vadose zone storage of chloride. This is not to say, however, that undercatch of dry fall and vegetation impingement have not occurred to some degree which would lend to underestimation of recharge.

3) Chloride is conservative in the system, recycling or concentration of chloride within the aquifer does not occur.

a. Chloride is considered conservative in most hydrogeologic systems, the exceptions including systems with highly saline water, sedimentary units and clay layers (Hem, 1985). The conservative behavior of chloride (Cl^-) arises from its stable outer electron configuration which results in low susceptibility to: oxidation or reduction reactions, formation of solute complexes, formation of less soluble salts and adsorbtion onto mineral surfaces. Thus, the circulation of chloride in the hydrologic cycle is largely through physical processes (Feth, 1981). This would be particularly true in DCEW watershed wherein water contains minimal chloride, lithology is igneous and significant clay layers are absent.

b. Evaporative loss of ground water within the study catchment would constitute recycling of chloride in the system (Bazuhair and Wood, 1996). Within DCEW, groundwater and surface water flow are dictated by head gradients and gravity towards perpetual movement down gradient, which, in general may preclude recycling of groundwater within the study catchment. An exception to this would be recycling of groundwater via upward flow along fractures wherefrom further evaporation or transpiration may occur. As long as this further chloride-concentrated water is not returned to ground water within the catchment under consideration, recycling has not occurred. If such evaporative loss of groundwater after recharge is represented in the groundwater samples utilized in CMB calculation for a given catchment, the result would be underestimation of groundwater recharge (Bazuhair and Wood, 1996). This exception may conceivably apply to spring discharge samples utilized in the study, although considered unlikely in springs with perennial flow at moderately high flow rates.

4) No external surface water or groundwater input occurs.

a. Observations in DCEW support the assumption of no external surface water inflow.

b. Lack of groundwater input remains a reasonable assumption for DCEW, based upon the concept of groundwater divides occurring in parallel with topographic divides and the role of such divides in delineating movement of groundwater within basins. Static water levels measured in wells along the lower elevation, western edge of DCEW indicate a water table surface characterized by a divide at the ridge line 2519). Due to the regional northward increase in elevation of the central Idaho mountains, of which the Boise Front marks the southernmost extent, the possibility exists for groundwater inflow at significant depth below the elevation of Dry Creek exists. This flow, however, is conceptually beneath the bounds of the DCEW conceptual model for CMB calculations.

5) The system is at steady state.

a. For application of CMB at the catchment scale, "steady state" refers to no net annual storage of chloride in the unsaturated zone, including soil and vegetation. This is likely true for soil in the upper elevations of DCEW where thin, highly permeable soils persist with significant snowmelt and spring rainfall to flush chloride accumulated at ground surface and in the vadose zone during the dry months, through to the saturated zone. This probable leaching process has been noted at Hubbard Brook Experimental Watershed in New Hampshire (Kauffman et al., 2003) wherein late fall/early winter precipitation drainage carries high chloride concentrations which decrease to background levels within three weeks as the wet season progresses, indicating that chloride accumulated in soil during the dry season is flushed out on an annual basis. However, at the lower elevations of DCEW, snowfall is minimal, therefore, winter and spring rainfall are the likely means by which accumulated chloride would be flushed from the unsaturated zone. For the past several years in DCEW, as indicated by lack of stream flow generation in low elevation tributaries, adequate wet-up and spring rainfall may not have occurred as necessary to flush out annually accumulated unsaturated zone chloride. High chloride concentrations measured in the rarely flowing low elevations tributaries during spring 2006, concurrent with record high spring runoff in DCEW, indicates prior net annual unsaturated zone chloride storage in slopes and stream channels wherein chloride remained in storage until spring 2006 during which time adequate precipitation conditions to flush such storage were completed. It is not known without extensive soil sampling whether the spring 2006 precipitation completely flushed stored unsaturated zone chloride from the system.

b. For the condition of steady state to be met within catchment vegetation, annual uptake of chloride by the vegetation must equal annual return of chloride from the vegetation to soil. Due to its role as a micronutrient, specifically its role in photosynthesis, chloride is not entirely excluded by vegetation in the uptake of water (White and Broadley, 2001). For DCEW, this involves consideration of annual chloride cycling and possible net annual gain or loss of chloride-inclusive biomass, in both evergreen and deciduous vegetation, both of which are present in the upper elevations of DCEW while sparse deciduous vegetation dominates the lower elevations. Investigation by Kauffmann et al. (2003) in the Hubbard Brook Experimental Forest in New Hampshire indicates storage of chloride in plant roots and litter (red pine and grass) which becomes available to leaching and transport at the onset of decomposition. In the Hubbard experiment, 1.5 years lapsed following clear-cutting of red pine and surface vegetation while chloride concentrations peaked and returned to background concentrations. Kauffann et al. (2003) attributed this chloride pulse to decomposition of plant roots and soil organic matter. During the past several years, disturbance by clear-cutting or fire which could result in offset of vegetation-controlled delivery of chloride has been minimal within DCEW.

Multiple investigations indicate that either net aggradation or net degradation of biomass may regularly occur in forested catchments on the annual scale (Velbel, 1995). From this, Velbel (1995, p202) states that on a time scale of months to decades in small forested catchments, ignoring botanical exchange can cause large errors in elemental mass balance calculations. However, in DCEW, under semi-arid conditions, net aggradation of perennial biomass may be considered minimal on an annual scale. Also, significant net annual degradation has not been observed. The effect of net annual storage in vegetation would be an overestimate of groundwater recharge. The result of chloride flush following disturbance would be an increase of chloride concentration in runoff with resultant underestimate of groundwater recharge.

6) No unmeasured runoff from the system occurs.

Stream flow is continuously monitored at the outflow of each subcatchment for which CMB calculation is performed. Where gaps exist in the data record, estimations of stream flow were conducted.

DISCUSSION

Net Recharge Estimates and Evapotranspiration

C1W, C2M and LG Catchments

Negative recharge values indicate invalid results arising from more chloride being removed from the system through surface water outflow than stated as input via wet and dry fall. Specifically, chloride mass balance calculations of net recharge conducted for catchment C1W are considered invalid due to unmeasured chloride input related to road salt application. Downstream study catchments, C2M and LG, are considered affected by road salt export from C1S and C1W, as well as occasional road salt application on the western edge of DCEW, which leads to qualification of recharge estimates for these catchments as invalid or underestimated. The presence of road salt chloride on and within the western edge of DCEW are identified in synoptic sampling results (Figure 16), while the effect on stream chloride is apparent in C1W compared with adjacent catchment stream chloride concentrations (Figure 17). Road salt is applied to Bogus Basin Road, especially the upper half of the road along DCEW, in unknown quantity as mixed with sand during the winter months associated with operation of Bogus Basin Ski resort. This resort has been in existence since 1942, thus, over a period of decades, an unknown amount of road salt chloride has entered the west edge of DCEW.

Further qualification of net recharge estimates conducted at C2M and LG involves the groundwater sampled and utilized in the CMB calculations. Within any catchment, variation from point to point in slope, aspect, soil, vegetation and elevation will affect evapotranspiration and, thus, affect the chloride concentration of infiltrating water at that point. Groundwater flow lines will likely dictate separate, down-gradient, paths for recharged water, with some flow occurring towards the nearest stream channel, and some flow, from higher slope points, possibly towards deep groundwater recharge. Thus, in a given catchment, chloride concentration in groundwater will likely vary at depth, as well as laterally. A groundwater sample which represents water recharged at the lower elevation, such as likely true of the lower well water, will provide an underestimate of overall recharge in DCEW. Thus, selection of the estimated catchment average value, 2.5 ppm, between a value of 1.478 ppm at Bogus spring and 3.403 ppm at the lower well, for an alternate calculation of recharge was presented in Table 5. Fortunately, as presented in the sensitivity analysis, the CMB calculation is least sensitive to the groundwater chloride concentration parameter, thus, the estimated average value for Cl_r provides a reasonable input. An alternate approach may include sampling groundwater outflow from the catchment in wells immediately down-gradient of the catchment as a method of sampling the bulk result of recharge in a catchment.

Chloride mass output, QCl_q, via stream flow at C2M or LG is considered to represent a mixture of surface, shallow subsurface and groundwater outflow to surface flow, including tributary and spring additions. The calculated chloride mass output is considered a valid parameter toward net recharge estimation when there is zero net annual storage of chloride in the unsaturated zone. Accomplishment of zero net unsaturated zone chloride may occur on an annual basis when chloride that accumulates in the unsaturated zone during the dry months is flushed through within the same water year by subsequent fall, winter and spring precipitation. The thin, permeable soils of DCEW lend positive conditions for mobilization and flushing of dry season stored chloride when adequate precipitation accumulation occurs. The removal of stored unsaturated zone chloride is considered to have been partly accomplished in spring 2005 (Figure 24a). The question remains, however, as to the period of time in which the chloride removed was stored. If the removed chloride includes same year storage as well as prior year storage, then net recharge is underestimated. An overestimate is possible if the chloride mobilized is less than that stored during the same year. Further question exists as to the upslope extent of full profile chloride mobilization and transport.

High Elevation Catchments: Treeline, BG, C1E and C2E

These catchments are characterized by the absence of road salt influence and winter snow accumulation. As presented in Table 5, net recharge estimated for Treeline, BG, C1E and C2E catchments are 22, 9, 7 and 10 percent of annual precipitation received for 2004-2005, respectively, using the adjusted or estimated catchment average values for groundwater chloride concentration. For the Treeline catchment, adjustment to the "stranded-chloride" method-derived calculation of groundwater chloride concentration suggested by application of the method to the Bogus catchment, correlates with inference that approximately 50% loss of snow water volume by sublimation and evapotranspiration. This is considered reasonable for the Treeline site, based on observed mid-winter temperature increases, wind and limited vegetation dormancy. If the entire snowpack is considered available for infiltration, the Treeline catchment recharge estimate is 44% for 2004-2005. Recharge estimates for 2005-2006 are discussed in a following section with regard to chloride mass balance model assumption discrepancies and consequent invalidity of results. This section focuses on the 2004-2005 results and validity assessment.

Model discrepancy via possible precipitation undercatch and/or dry fall chloride undercatch would result in underestimation of recharge for 2004-2005, and net annual storage of unsaturated zone stored chloride would result in overestimation. For example, the effect of 10% undercatch in precipitation or 5% low value for chloride concentration in precipitation is approximately 1% absolute change in net recharge stated as percentage of annual precipitation received, while a 5% low value in stream chloride concentration would overestimate net recharge by an absolute value of 0.6%. Due to the inter-annual variability in precipitation quantity and timing, possible variability in net annual storage of unsaturated zone chloride is unknown. In this study, attempt is made to assess positive net annual storage and/or mobilization and transport of chloride stored during prior years via time-series stream chloride data. Resultant inferences are described below.

For the Treeline catchment, annual flushing of unsaturated zone stored chloride during snowmelt and spring rainfall is indicated by the high stream chloride concentrations in March, which become minimal in April (Table 7). These processes are considered to be facilitated at Treeline by rainfall and frequent mid-winter, early spring snowmelt which promotes gradual flux of water through the soil profile across the catchment. Thus, recharge estimates for the Treeline catchment are considered valid relative to the steady state assumption. For the BG catchment, hydrograph separation

(Figure 20) reveals a pattern of increasing stream flow contributions from high-chloride source(s) which peak just prior to peaks in stream flow contribution from rain and snowmelt which is inferred as indicating the timing and progress of chloride mobilization and transport via lateral flux to the stream channel. The rise and fall of the high chloride contribution is similar to a tracer breakthrough curve, while the rise of the low-chloride contribution indicates lateral shallow subsurface flux through soil from which stored chloride has been virtually removed and/or the occurrence of overland flow. If the low-chloride peak is largely a result of overland flow, removal of unsaturated zone stored chloride may be less complete than if all flow to the stream channel occurred as lateral flux through the unsaturated zone.

The anomalously high net recharge estimates for Treeline is considered plausible on two accounts. One, because the Treeline catchment does not include groundwater discharge as either spring flow or baseflow common to the other study catchments, net groundwater calculations are likely to be higher for this catchment compared to otherwise comparable headwater catchments. The lack of ground water discharge indicates a lower water table at Treeline compared to BG, which would establish a greater head difference drive toward groundwater recharge. Secondly, the Treeline catchment is in a unique position of elevation and aspect whereby it experiences significant snowfall subject to repeated melt during the winter versus higher elevations, as well as receiving a mix of rain and snow versus snow domination at higher elevations. Thus, a more continual low flux of water is available to wet the profile and infiltrate to bedrock at the Treeline catchment. This is in contrast to the rapid springtime snowmelt rates at higher elevations which rates may exceed the infiltration capacity of the soil and bedrock. Overland flow is observed at the BG catchment due to saturation of the full soil profile during snowmelt in contrast to Treeline which experiences wetting of the full soil profile for slow unsaturated movement of water. The net result in contrasting processes, is more water available for bedrock infiltration over the course of the winter and spring at Treeline site with less partitioned to stream flow compared to the BG catchment. Fracture intensity at Treeline comparative to other locations in DCEW remains unassessed, but may be considered as a possible further explanation of anomalously high groundwater recharge if bedrock is comparatively more fractured at the Treeline site.

Comparison of evapotranspiration calculated by concentration factor and as a residual in the water budget for BG and C1E (Table 6) for Treeline, BG and C1E catchments may indicate overestimation of recharge by CMB, however, process assumptions of each method must be considered. The concentration factor method assumes no surface runoff and consequent loss to stream discharge. Runoff is observed, however, in these catchments to occur during the snowmelt period when runoff will be at the lowest annual chloride concentration. Thus, the unaccounted for occurrence of low-chloride runoff will provide a higher value for evapotranspiration by concentration factor than that derived by residual from CMB net recharge estimates where similar or even lesser values for groundwater chloride concentration are utilized. One may note that the disparity increases with increasing catchment area, emphasizing the difference between a point value calculation of evapotranspiration and a calculation which arises from a model incorporating lateral flux.

Suggested improvement on net recharge estimation for the BG catchment is to sample the numerous springs which are present within the BG catchment and to search for springs down-gradient of the BG catchment and inclusive of the catchment, with sampling conducted over the last months of the dry season. Also, for both methods of deriving evapotranspiration, more complete sampling of chloride in precipitation may affect the results. For this study, sampling for chloride in precipitation was conducted only for a portion of the precipitation events. Undercatch of dry fall chloride in the sampling or undercatch due to net vegetative uptake, both of which are likely to occur in the higher elevation, more intensely vegetated catchments, will result in underestimation of groundwater recharge and high evapotranspiration calculations.

The calculated chloride mass output value determined from stream flow data is considered a valid parameter toward net recharge estimation for these high elevation catchments**,** assuming zero net annual storage of chloride in the unsaturated zone as described above. Deep ground water outflow that may occur from these headwater catchments would not affect CMB estimation of net recharge for these catchments, due to non-inclusion in the CMB equation.

Water year 2005-2006

Negative recharge estimates for C2M and LG, water year 2005-2006, reflect more chloride mass discharged at catchment outlets than received via precipitation during the same year. The anomalously low net recharge estimates for the inclusive BG, C1E and C2E catchments may also reflect annual-excess chloride output. This excess chloride is suspected to be the result of net annual storage of unsaturated zone chloride accumulated over the prior six or more years of below average annual precipitation (Figure 28) which was mobilized and transported to stream channels via shallow subsurface water flux, i.e.

"chloride flushing" during water year 2005-2006. This interpretation is supported by unusually high and chaotic chloride concentrations during winter and spring of 2005-2006 (Figure 15), in conjunction with observation of more extensive slope soil wetting and ephemeral tributary stream flow occurring during spring 2006 than occurred during the previous study year.

Further, comparison of precipitation and stream discharge at all catchments (Figure 29) demonstrates the effective increase in stream discharge/precipitation resulting from the 30% inter-annual increase in precipitation, including the change from net annual loosing conditions along Dry Creek between C1E and LG during 2004-2005 to net gaining in 2005-2006.

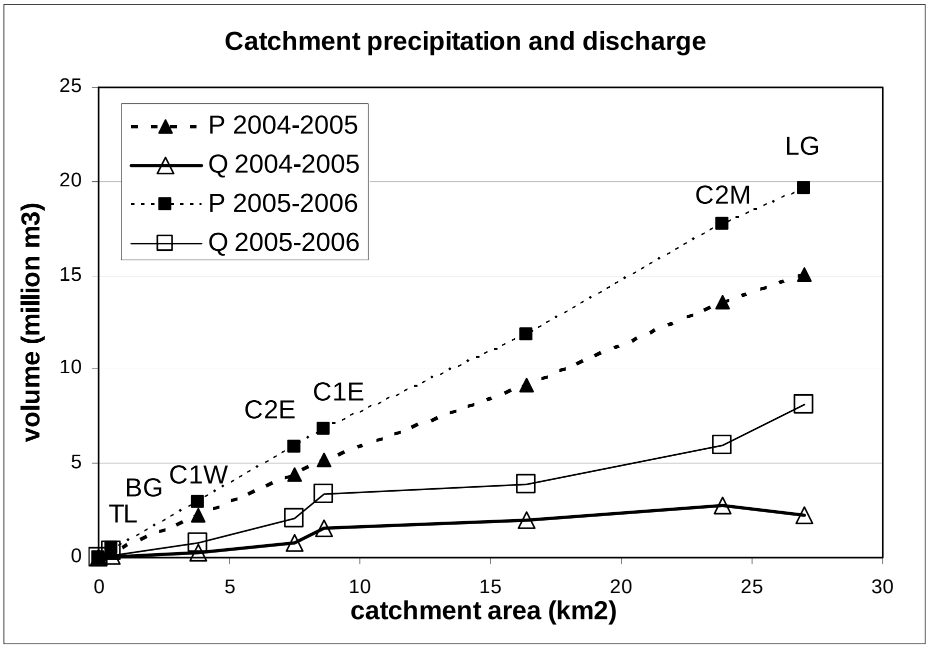


Figure 29. Precipitation and discharge comparison between study catchments, 2004-2005 vs. 2005-2006. Subtraction of C2E data from C2M data is represented as catchment at 16.4 km^2.

With regard to assessment of long-term net annual storage of unsaturated zone chloride, it may be noted that although a greater range in chloride concentrations over small time intervals is apparent for most of the catchment streams in water year 2005-2006 (Figure 16), most of the scatter in chloride concentrations occurs at the lower elevation sites. Specifically, concentrations at LG and C2M peak at over two times the concentrations occurring in water year 2004-2005, while concentrations at C2E trend only slightly higher than in the previous water year. January and February 2006 show the highest concentrations of chloride at the LG stream sampling site (Figures 23, 24, 25), possibly indicating these mid-winter months as the time of maximum chloride flushing for water year 2005-2006. The headwater stream and spring sample sites, TL, BS, BG and C1E, do not exhibit peak concentrations greater than the previous water year, nor do they exhibit a significant increase in scatter. However, the greater volume of snowmelt in 2006 would, conceptually, have resulted in lower annual stream chloride concentrations in 2005-2006 than during the previous year for all catchments, but only occurred for TL, BG and C1E. From these observations in may be concluded that while net annual storage of unsaturated zone chloride clearly occurred at all investigated catchments other that Treeline, the tendency for such net annual chloride storage increases with decreasing elevation in DCEW. Specifically, greater than 200% winter time increase in stream chloride concentrations were measured at LG and C2M in 2005-2006 compared to the winter of 2004-2005.

Stream Flow Source Component and Gain/Loss Analyses

For both study water-years, temporal trends in spring and stream chloride concentrations begin with annual low values in July which gradually increase to peak concentrations during the winter, between December and March (Figure 16). Timing of the peak in concentration varies by catchment, occurring latest at C1W and C1S and earliest at BS, BG, C1E and C2E. Following peak concentration, chloride concentration in spring and stream flow decreases as spring runoff progresses, returning to lowest concentrations in June/July. From this general annual trend in spring and stream chloride concentrations, field observation, hydrometric measurement, stream flow source component analyses/hydrograph separation and gain/loss analyses, various contributing processes are hypothesized and described in the sections below.

Spring Flow

Temporal trends in spring flow chloride concentrations tend to closely parallel adjacent stream flow chloride concentrations in the higher elevation catchments. The parallel in trend is observed for spring C1S adjacent to C1W and for spring BS, adjacent to BG (Figure 16). From the chloride concentration trends in spring flow, it is hypothesized that the observed spring flow occurs as a combination of groundwater rising upward through fractures at depth and water concurrently infiltrating downward through the vadose zone. The temporal parallel of this trend with stream chloride concentrations leads to conclusion that the mixing of water which contributes to spring flow occurs with the same time step as the in-stream mixing of observed spring addition to stream flow and water reaching stream channels via lateral throughflow and/or bedrock interface flow. It may be noted that the parallel but lower concentrations measured at BG compared to BS indicates generally lower groundwater chloride concentrations. Indication of surface water contribution to stream flow in addition to groundwater contribution may be construed from the parallel in C1W and C1S, even though the C1S chloride concentrations parallel lower than the adjacent stream chloride concentrations. The explanation for this would lay in greater chloride enrichment of surface water moving laterally toward the stream channel in catchment C1W, or resulting from entrainment of chloride stored in the stream channel, versus less chloride enrichment occurring in surface water interacting with the C1S spring system, which may be a phenomenon of the added road salt in catchment C1W.

From above described conceptualization of groundwater and surface water mixing in the high elevation springs at locations of inferred increased fracture-induced bedrock permeability, we may infer that bedrock infiltration does occur, especially where facilitated by fracture orientation and permeability, and has the potential to provide groundwater recharge on an annual basis within the high elevation catchments.

Contributions to Stream Flow at Higher Elevations: Treeline and BG Catchments

Field observations during snowmelt have identified macropore flow of snowmelt to stream channels, as well as matrix flow, at both Treeline and BG catchments, supporting conceptualized lateral flux through the unsaturated zone toward stream channels. Bedrock interface flow is considered a likely additional mechanism of lateral flux at both Treeline and the BG catchment with wetting of the full soil profile as discussed by McNamara et al. (2004) for the Treeline Site. However, increases in stream chloride concentrations which indicate unsaturated zone delivery of water to stream channels by lateral flux, do not provide distinction between mechanisms of the lateral flux, bedrock interface flow, matrix flow and macropore flow. The end-member analyses of stream flow source components, based upon low-chloride precipitation and high chloride groundwater/vadose zone concentration end-members, conducted for Treeline and Bogus catchments for water year 2005-2006, are utilized in this section to delineate time periods in which groundwater input dominates stream flow and to ascertain the timing of lateral unsaturated zone flux to the stream channel, irrespective of exact mechanism. Inference of mobilization and transport of dry season stored unsaturated zone chloride was discussed for these catchments relative to recharge estimate validity.

With regard to the question of when infiltration occurs, conditions which result in lateral flux to stream channels, wetting of the full soil profile and addition of rainfall/snowmelt at rates within soil infiltration capacity, are conditions also conducive to vertical flux toward bedrock infiltration and groundwater recharge. Thus, in these headwater catchments, groundwater recharge is most likely to occur in late fall and during spring snowmelt.

Contributions to Stream Flow at Lower Elevations: C1E to LG

The higher chloride concentrations measured at LG and C2M and later peak in concentrations compared to TL, BG, C1E and C2E indicate a contrast between higher elevation and lower elevation hydrologic processes. Lower water tables and contrasting precipitation regimes also suggest a difference in dominant surface and near surface hydrologic operating processes at lower elevations compared to that presented for the high elevation catchments. Static water levels are measured at 37 m to 136 m in the lower elevation wells, in contrast to 4m to 10 m at the higher elevation wells of Bogus Basin ski resort. The difference in precipitation regime for lower vs. higher elevations involves minimal snowfall at the lower elevations while snow pack dominates in the higher elevations. Similarity in field observations, however, occurs with regard to observed macropore and matrix flow to stream channels during late fall and spring within steep ephemeral tributary valleys in the lower elevations of DCEW, particularly at the base of steep slopes, with minimal soil cover, directly adjacent to stream channels. Below C1S, no spring flow addition to Dry Creek is observed. Additional stream flow to Dry Creek below C1S is thus attributed to tributary inflow, surface/shallow subsurface lateral flux to the stream channel and baseflow.

Further cause for making the distinction between routing of infiltrating water at higher elevations versus lower elevations is the disproportionately higher increase in discharge measured at LG for 2005-2006 resulting from peak springtime runoff. During the peak discharge period, multiple tributaries which had not produced flow during any years on record, did, during spring 2006, produce abundant flow. Along with this observation, is observation of soil profile wetting in the tributary drainages across the lower elevations, as developed during the winter low-flux period of 2005-2006. Additionally, the 2005-2006 winter climb in chloride concentrations to more than twice the concentrations of 2004-2005, as observed for LG and C2M, warrants explanation as indicative of water flux processes occurring in the lower elevations. The explanation may begin with the abundant precipitation received as rainfall in the lower elevations during the months of November 2005 to January 2006. From this received moisture, further inference may be made that the flux of water described in the preceding paragraph as throughflow and bedrock interface flow is responsible for the greater than 200% winter time increase in stream chloride concentrations at LG and C2M compared to same locations during the winter of 2004-2005. If this surface water flux is considered the contributing factor, then it is to be further surmised that the source of chloride is chloride mobilized from the unsaturated zone in the lower elevation hill slopes and/or tributary valleys. The scatter involved in the winter-time trends may reflect pulse surface water contribution to stream flow in the lower elevations.

An additional factor to consider in interpreting stream chloride concentrations is evapotranspiration. During the growing season, evapotranspiration occurring in the riparian zones may conceivably enhance chloride concentration in baseflow toward the streams as well as enhance chloride concentration in stream water during episodes of hyporheic flow. Substantial water consumption through riparian transpiration was noted in August 2005 when stream flow ceased in Dry Creek just below the lower weather station, but resumed in September when ambient air temperatures had decreased combined with shorter daylight hours. No precipitation event preceded the resumption of stream flow, thus the resumption of stream flow is inferred to have occurred as the result of decreased transpiration. High values of chloride seen as outliers from the general trend in July to September 2005 may reflect the effects of evapotranspiration-induced chloride concentration. However, because the general trend of increasing chloride predominates after the cessation of significant growing season evapotranspiration, the effects of riparian zone evapotranspiration on stream chloride concentration are considered minimal. What may be considered is the return of chloride to the stream channel by riparian vegetation as the growing season declines.

Further indication of contrasting hydrologic regimes between higher and lower elevations are chloride concentrations measured on January 6, 2006, following a week-long mid-winter increase in stream discharge from December 27, 2005 to January 6, 2006. The January 6 samples occur as outliers with headwater samples, TL, BG, C1E, C2E and C1W, being unusually low stream chloride concentrations and C2M being unusually high. The contrasting low chloride input at the higher elevation catchments may indicate surface flow resulting from rain on snow or frozen soil surfaces versus rain on wetted low elevation slopes. This contrast may be further attributed to the effects of mid-winter flux of water as throughflow and/or bedrock interface flow in contrasting environments of vadose zone chloride storage, with such storage being apparently greater in the lower elevation hill slopes contributing stream flow to C2M.

As indicated for both water years, Dry Creek, between C1E and LG is a net loosing stream during July/Aug through December (Figure 23). Net loss of discharge, combined with net loss of chloride mass indicates that water loss is, at least in part, the result of stream channel loss of flow to groundwater recharge. Stream channel loss to groundwater precludes concurrent groundwater contribution to stream flow. Thus, calculation of high-chloride contributions occurring during these conditions of mass loss would be the result of shallow subsurface contributions to stream flow or would indicate concentration due to evapotranspiration effects in the stream channel. January, February and March are transitional months along this reach of Dry Creek. The gain in chloride mass, paired with continued net loss or minimal gain of stream flow (Figures 22, 24), indicates input via shallow subsurface flow or surface runoff to the stream channel, and would indicate these months as times during which groundwater recharge may occur in the lower elevations at both slope and stream channel locations. For water year 2004-2005, the low chloride concentration calculated for the stream flow addition in January and February (Figure 24) indicates stream flow contribution by surface runoff observed in this catchment during January and February when rainfall may occur on snow or frozen surface soil, exacerbated by steep slopes. For water year 2005-2006, high chloride concentration calculated for the stream flow addition in January and February specifically indicates contribution by shallow subsurface flow by which chloride stored in the vadose zone during the dry months is transported to the stream channel. It is to be noted that wetting of the full soil profile occurs prior to initiation of lateral flux to the stream channel (McNamara et al., 2004), and, evidently it takes longer to accomplish this wetting in the lower elevations than in the higher elevations within DCEW.

For the months March through June/July, a net gain of stream flow, concurrent with a net gain in chloride mass (Figure 22) indicates a flow source possibly inclusive of groundwater contribution, surface runoff, and/or shallow subsurface flow to the stream channel. The calculated chloride concentration of the gained water provides a basis for distinguishing which source is dominant and/or which hydrologic processes are contributing to the chloride concentration of the gained water. For water year 2004-2005, chloride concentration of this gained water increases from March through May, then decreases in June. The indication is that the water source is shallow subsurface flow initiated in March and increasing in extent of contributing area during April and May as spring rainfall progressed, particularly with high rainfall in May. The lower concentration in June indicate that lower amounts of chloride persisted in the contributing area following the “chloride flushing” which occurred in May, particularly as the lower June chloride concentrations are paired with less rainfall.   For water year 2005-2006, the March through June chloride concentration of the contributing water, though much lower than concentrations calculated for March through June 2005, indicates the source as surface and/or shallow subsurface flow. In the case of shallow subsurface flow, observed as a dominant process in this catchment over surface runoff as overland flow, the chloride concentration of the gained water indicates that “chloride flushing” continued, because, while not as high as concentrations observed in spring 2005, the chloride concentrations did remain above the average precipitation chloride concentration, combined with a high volume of water input via this process. For either water year, it cannot be definitively inferred whether groundwater flow contributed part of the spring time stream flow gain between C1E and LG. The weight of observation lies with observed surface and shallow subsurface flow for spring 2006.   However, during July 2004, a net gain in stream flow, combined with gain in chloride mass and dry slope conditions indicate the source of water addition was most likely groundwater.

CONCLUSIONS

Chloride as a natural environmental tracer may be utilized as an effective tool in estimating catchment scale net groundwater recharge within semi-arid mountain front environments when applied at temporal and spatial scales necessary to meet model assumptions. In order to capture the effects of climatic variations on net groundwater recharge, particularly the effects of precipitation form and timing of water delivery, CMB must be applied to a number of years representative of local climatic variation. Net recharge estimates accomplished through the CMB method on an annual or multi-annual basis provide a basis for closure of the water budget. Values of net groundwater recharge in DCEW accomplished for the 2004-2005 water year, in which annual net storage of chloride is considered zero to minimal, range from 5 to 22% of precipitation received. With consideration of error, the resultant range in net recharge estimates is 0 to 28% of precipitation received being partitioned to net groundwater recharge in DCEW. A greater percentage of precipitation partitioned to recharge was found to occur at the Treeline catchment, uniquely located at the rain/snow elevation boundary. Thus this catchment experiences frequent mid-winter snowmelt, with slow snowmelt facilitated by its east-facing aspect. The timing of recharge within slopes is projected to occur concurrent with lateral flux to stream channels during two episodes annual, a lesser late fall/early winter flux period and the spring runoff period. The timing of these events is earlier in the higher elevations. Stream channel loss to groundwater recharge is determined as occurring during the dry months July/August through December along Dry Creek in the lower elevations and continually at the Treeline stream when water is present in the stream channel.

Routing of precipitation vertically through the unsaturated zone to groundwater is determined to occur across DCEW at rates affected by point variation in evapotranspiration and lateral flux to stream channels. Evapotranspiration is assessed to occur across DCEW at rates approximate to 80-89% in the lower elevations and 53-76% in higher elevations. Annual stream discharge to precipitation ratios vary between catchments, being as low as 0.11 to 0.15 at the Treeline catchment and 0.37 to 0.64 at the Bogus catchment, as measured during the two year study period. Vertical routing of water at the stream channel to groundwater recharge has been determined as outlined above. Lateral flux to stream channels by surface, shallow subsurface matrix, macropore and bedrock interface flow has been determined to occur within DCEW with differences in timing distinguished between upper and lower elevations, with flux occurring earlier in the higher elevations. The later timing of lateral flux during spring runoff in the lower elevations does place the unsaturated zone water subject to greater evapotranspiration, with a resultant decrease in percentage of soil water available for groundwater recharge and transport to stream channels.

Suggestions for improvement on the methods utilized in this study include use of groundwater samples taken from wells perforated exclusively within the mountain block aquifer. If springs are the only available source of groundwater, then samples should be taken at the end of the dry season, prior to fall precipitation input. The “stranded chloride method” for calculating groundwater chloride concentrations should be studied further, particularly for determination of percentage of snow pack contributing to unsaturated zone mobilization. To assess net chloride storage in the vadose zone, soil chloride sampling and analysis should be conducted at the beginning and end of a study period. Wet versus dry fallout samplers for measurement of chloride input is suggested, including placement of samplers under tree canopy to assess vegetative influence on chloride input. Due to high variability in stream chloride concentrations, sampling on a weekly schedule is suggested, especially during peak runoff periods. Further, continuous stream discharge measurements should be well maintained to minimize error in recharge estimates. For DCEW, considering the contrast in precipitation received during the two-year study period and apparent net annual storage of chloride in the unsaturated zone, compilation of several years of data is suggested for a reasonable estimate of average annual recharge.

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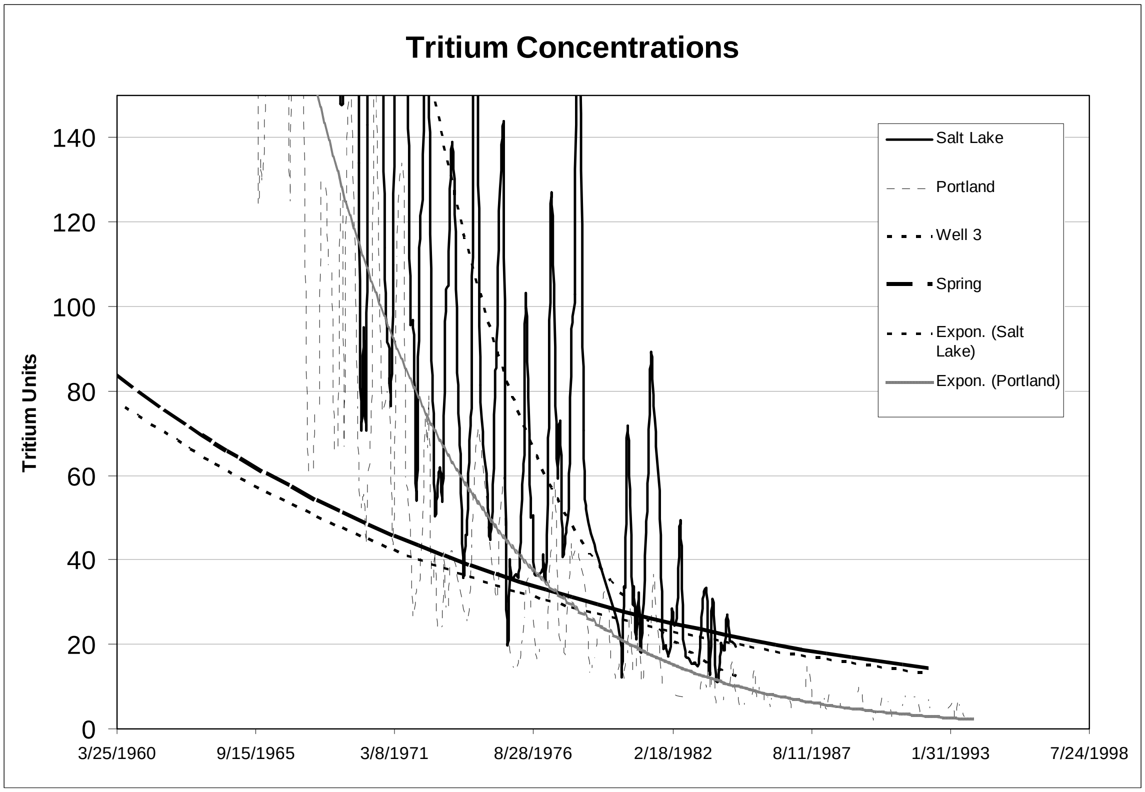
APPENDIX A

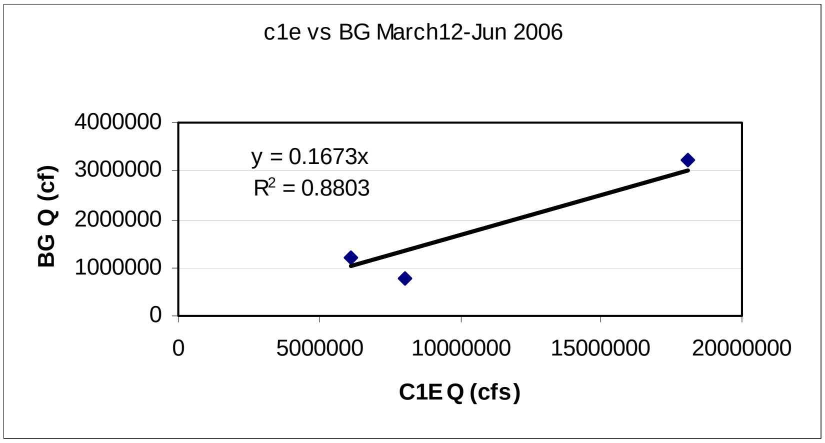
Tritium Concentrations



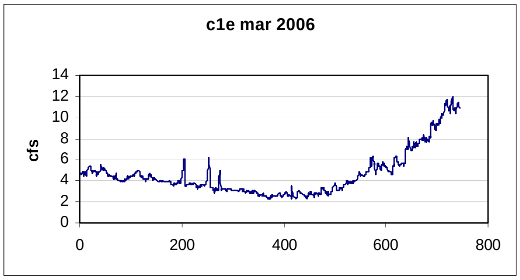
The above graph shows tritium concentrations in precipitation as measured for Salt Lake and Portland since the 1960's. The exponential curves for well 3 and spring are backward projections based on tritium decay rates, starting with tritium units measured at Bogus Basin ski resort well #3 and an adjacent spring. With tritium concentrations in precipitation for Bogus Basin assumed to be within the Salt Lake/Portland value range, age of the sampled Bogus Basin groundwater is projected as from the intersection of the Bogus Basin tritium decay curves with tritium concentrations of received precipitation. The curve intersections occur at 9 to 23 years prior to the groundwater sample date of 1993.

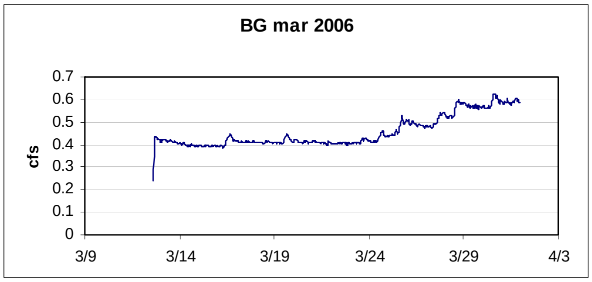
APPENDIX B

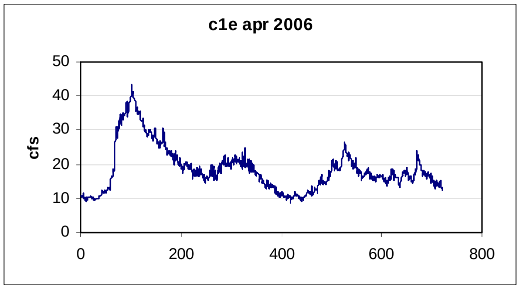
Calculation of Discharge, Bogus Catchment (BG)



The above displayed regression relationship is derived from monthly discharge data for C1E and BG for the months of March, May and April wherein a reasonably linear relationship in discharge volume is interpreted based on the hydrographs shown below. This regression relationship was utilized to interpolate discharge data for BG prior to March 2006, using monthly discharge data from C1E as the independent variable. Periodic dilution gaging at BG prior to March 2006 was further utilized to bound the interpolated discharge estimates. These steps were necessary due to equipment loss for several months prior to March 2006.


c1e mar 2006
cfs
14
12
10
8
6
4
2
0
0
200
400
600
800


BG mar 2006
cfs
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3/9
3/14
3/19
3/24
3/29
4/3


c1e apr 2006
cfs
50
40
30
20
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0
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200
400
600
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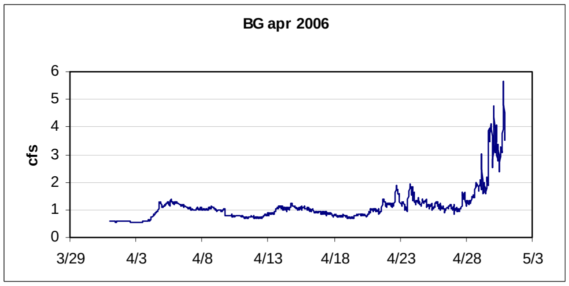
BG apr 2006
cfs
6
5
4
3
2
1
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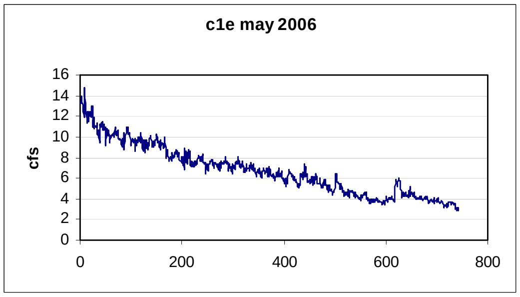
3/29
4/3
4/8
4/13
4/18
4/23
4/28
5/3


c1e may 2006
cfs
16
14
12
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4
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0
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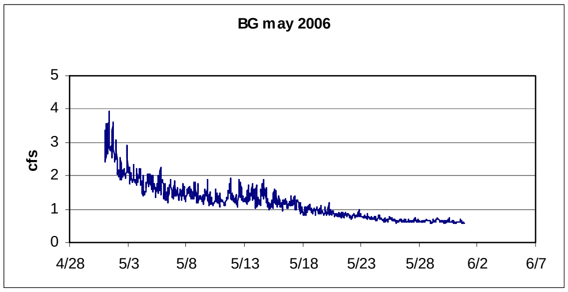
BG may 2006
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3
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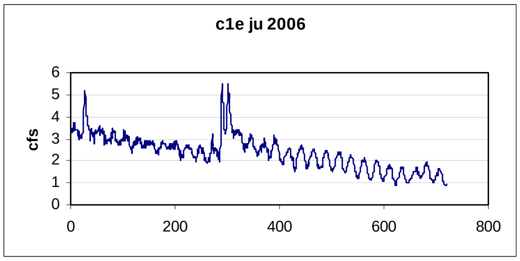
4/28
5/3
5/8
5/13
5/18
5/23
5/28
6/2
6/7


c1e ju 2006
cfs
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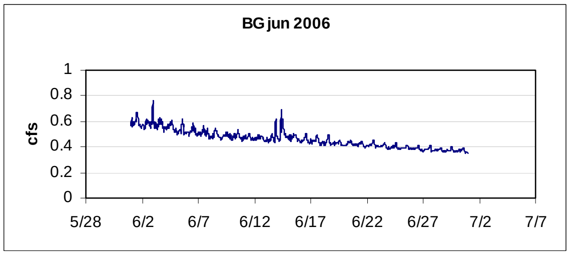
BG jun 2006
cfs
1
0.8
0.6
0.4
0.2
0
5/28
6/2
6/7
6/12
6/17
6/22
6/27
7/2
7/7

APPENDIX C

Cited Data and Results for Stream Flow Component Analyses

Two component analysis and data employed for Bogus Gage 2005-2006 stream discharge is shown in the table below. Note that data prior to March is interpolated data, from C1E and physical gaging conducted. Stream chemistry is interpolated as well for July through February.

month	**Cl p (ppm)**	**Clq (ppm)**	**fraction Q from pcp/runoff, x**	**fraction Q from groundwater, 1-x**	**Q (m3)**	**volume from pcp (m3)**	**volume from groundwater (m3)**
July	0.485	0.779	0.000	1.000	7755	0	7755
Aug	0.485	0.779	0.000	1.000	3179	0	3179
Sep	0.485	0.779	0.000	1.000	6742	0	6742
Oct	0.476	0.770	0.030	0.970	15071	448	14623
Nov	0.476	0.725	0.180	0.820	15413	2772	12641
Dec	0.276	0.725	0.108	0.892	9101	986	8115
Jan	0.076	0.679	0.142	0.858	9101	1295	7807
Feb	0.076	0.676	0.147	0.853	8220	1209	7011
Mar	0.076	0.597	0.259	0.741	32976	8537	24439
Apr	0.076	0.283	0.706	0.294	82017	57925	24092
May	0.200	0.378	0.692	0.308	91216	63119	28097
Jun	0.323	0.568	0.463	0.537	33904	15688	18216
						151979	162715
					314695	total	314695
Clq = x*Clp + (1-x)*Clr						0.48	0.52

Data and results for five-component analysis conducted for stream discharge at Lower Gage for both study water years.

2004-2005	**Lower Gage**			**C1E**			**C1W**		
Month	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**
jy	0.046	0.933	0.043	0.023	0.380	0.009	0.000		0.000
aug	0.015	1.292	0.020	0.030	0.563	0.017	0.000		0.000
sep	0.030	1.264	0.038	0.041	1.049	0.043	0.000		0.000
oct	0.077	1.529	0.118	0.083	1.130	0.094	0.003	3.481	0.009
nov	0.102	1.502	0.154	0.122	1.220	0.149	0.012	4.466	0.053
dec	0.193	1.670	0.322	0.213	1.220	0.259	0.042	4.865	0.205
jan	0.167	1.838	0.307	0.123	0.821	0.101	0.015	5.264	0.077
feb	0.144	1.793	0.258	0.195	0.621	0.121	0.013	6.062	0.078
mar	0.265	1.762	0.468	0.130	0.679	0.088	0.025	6.341	0.156
apr	0.452	1.941	0.878	0.240	0.554	0.133	0.071	4.239	0.300
may	0.542	1.574	0.854	0.289	0.617	0.179	0.091	2.137	0.195
jun	0.224	1.160	0.260	0.128	0.379	0.049	0.028	3.764	0.106
sums/avgs	**2.258**	**1.646**	**3.717**	**1.618**	**0.767**	**1.242**	**0.299**	**3.402**	**1.179**
	C1S			**C2E**			**Shallow sbsfc and/or gw gain/loss**		
Month	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl]* (ppm)**	**Cl mass (million kg)**
july	0.001	2.926	0.004	0.010	0.957	0.010	0.011	1.803	0.020
aug	0.000		0.000	0.010	0.957	0.010	-0.025	0.276	-0.007
sep	0.000	3.057	0.001	0.021	1.228	0.025	-0.032	0.982	-0.032
oct	0.001	2.662	0.002	0.047	1.444	0.067	-0.055	0.966	-0.054
nov	0.001	3.939	0.003	0.059	1.521	0.090	-0.092	1.537	-0.141
dec	0.001	4.196	0.002	0.076	1.273	0.097	-0.138	1.746	-0.242
jan	0.000	4.862	0.002	0.076	1.273	0.097	-0.048	0.613	0.029
feb	0.000	5.561	0.002	0.057	1.025	0.059	-0.121	0.014	-0.002
mar	0.001	5.534	0.007	0.090	0.813	0.073	0.020	7.324	0.143
apr	0.001	4.417	0.006	0.125	0.601	0.075	0.015	24.395	0.364
may	0.003	3.300	0.009	0.153	0.770	0.118	0.006	57.052	0.354
jun	0.001	3.167	0.004	0.066	0.707	0.046	0.001	40.306	0.056
sums/avgs	**0.011**	**3.818**	**0.041**	**0.788**	**0.971**	**0.765**	**-0.459**	**3.145**	**0.490**

2005-2006	**Lower Gage**			**C1E**			**C1W**		
Month	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**
jy	0.043	1.498	0.065	0.046	1.017	0.047	0.001	2.258	0.003
aug	0.006	1.151	0.007	0.019	0.720	0.014	0.000		0.000
sep	0.013	1.974	0.027	0.040	0.496	0.020	0.000		0.000
oct	0.048	1.291	0.061	0.090	0.622	0.056	0.000		0.000
nov	0.097	1.132	0.110	0.092	0.987	0.091	0.007	0.155	0.001
dec	0.150	1.490	0.224	0.202	0.616	0.125	0.049	4.428	0.219
jan	0.396	2.685	1.064	0.244	0.244	0.060	0.049	0.796	0.039
feb	0.317	4.527	1.435	0.243	0.937	0.228	0.053	3.508	0.187
mar	1.034	3.307	3.419	0.349	1.069	0.373	0.082	4.590	0.377
apr	4.890	1.281	6.266	1.359	0.696	0.945	0.359	3.195	1.148
may	1.312	1.349	1.771	0.511	0.507	0.259	0.127	3.697	0.468
jun	0.620	0.814	0.505	0.174	0.507	0.088	0.034	4.434	0.152
sums/avgs	**8.928**	**1.677**	**14.967**	**3.370**	**0.684**	**2.305**	**0.763**	**3.402**	**2.594**

	C1S			**C2E**			**Shallow sbsfc and/or gw gain/loss**		
Month	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl] (ppm)**	**Cl mass (million kg)**	**Q (million m3)**	**[Cl]* (ppm)**	**Cl mass (million kg)**
jy	0.001	2.332	0.002	0.015	0.592	0.009	-0.020	0.185	0.004
aug	0.000	1.003	0.000	0.002	0.757	0.001	-0.014	0.532	-0.008
sep	0.000	1.753	0.001	0.010	0.806	0.008	-0.037	0.043	-0.002
oct	0.001	2.502	0.002	0.073	1.174	0.086	-0.117	0.707	-0.082
nov	0.001	1.081	0.001	0.049	1.195	0.058	-0.052	0.800	-0.042
dec	0.001	3.038	0.002	0.102	1.216	0.124	-0.204	1.201	-0.246
jan	0.000	4.995	0.002	0.175	1.216	0.212	-0.072	10.446	0.751
feb	0.001	4.113	0.004	0.154	1.423	0.220	-0.135	5.926	0.797
mar	0.001	5.180	0.007	0.251	1.167	0.292	0.351	6.748	2.370
apr	0.001	3.231	0.002	1.055	0.881	0.930	2.116	1.532	3.241
may	0.001	2.723	0.001	0.178	0.837	0.149	0.496	1.800	0.893
jun	0.001	3.208	0.002	0.024	1.537	0.036	0.388	0.585	0.227
sums/avgs	**0.007**	**3.281**	**0.024**	**2.086**	**1.019**	**2.215**	**2.701**	**3.207**	**7.918**