STREAM-GROUNDWATER INTERACTIONS IN A MOUNTAIN TO VALLEY TRANSITION: IMPACTS ON WATERSHED HYDROLOGIC RESPONSE AND STREAM WATER CHEMISTRY

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ABSTRACT

As mountain headwater catchments increase in size to the meso-scale, they incorporate new landscape elements including mountain-valley transition zones. Mountain-valley transition zones form part of the mountain front, influence groundwater (GW)-stream interactions, and impact hydrologic response and stream water composition. Mountain front recharge (MFR) in mountain-valley transition zones and subsequent GW discharge to streams in the valley bottom are important hydrological processes. These GW-stream interactions are dynamic in both space and time, playing a key role in regulating the amount, timing, and chemistry of stream water reaching the valley bottom. I hypothesize that mountain-valley transitions function as hydrologic and biogeochemical buffers via GW recharge and subsequent GW discharge. More specifically, that streams often recharge GW near the mountain front and receive stored GW further downstream. To investigate these processes I applied physical hydrology techniques, and geochemical hydrograph separations in the Humphrey Creek watershed in southwestern Montana. This allowed me to assess the spatial and temporal variability of mountain front GW recharge and GW-stream interactions across a mountain-valley transition. Geochemical signatures were used to partition stream flow into alpine runoff and GW sources. These results indicate that much of the alpine stream water recharged GW at the mountain front and that stored GW of a different chemical composition sustained down-valley stream discharge. Down-valley stream discharge was dominated by GW inputs and responded to GW stage more closely than upstream reaches. A critical GW stage height was necessary for down-valley channel flow, as this was the only major input to channel flow during early and late season base flow. Conversely, GW contributed little to stream flow in the upper reaches of the study area. GW-stream water exchange served as a flow and geochemical buffer, resulting in significant changes in stream chemistry from the alpine, to the MFR zone, to the valley bottom and muting fluctuations in channel flow, both at high and low flow. Implications are that mountain front GW recharge magnitudes can control valley aquifer storage state which combined with alpine runoff magnitude and valley bottom GW discharge controls stream water quantity and geochemical composition downstream.

CHAPTER 1

INTRODUCTION

Scientific Background

The conceptual understanding that groundwater and surface water should be thought of as one hydrologic system has been emphasized by Winter (1995). Groundwater-surface water exchanges occur between streams and groundwater, wetlands and groundwater, and lakes/ponds and groundwater. However, the most common focus of groundwater-surface water interactions has been between streams and surrounding alluvial aquifers (Winter, 1995). These exchanges occur over a full range of small to large scales. Harvey et al. (1996) define smaller scale exchanges as those that occur along centimeter-long flow paths on timescales of minutes and, larger scale exchanges as those that occur over hundreds of meters on timescales of years. In mountainous terrain groundwater-surface water exchange research has focused primarily on stream flow generation in small headwater areas and the hyporheic zones surrounding small, high gradient streams (Winter, 1995).

Stream flow generation and hillslope hydrology in mountain watersheds has been extensively researched (Bonell, 1993; Bonell, 1998; McGlynn et al., 2002). Larger rivers are fed by smaller upstream tributaries that drain mountain headwater watersheds. The network of headwater streams that feed larger rivers, drain by far the largest area of the earth's surface (Freeze and Cherry, 1979). For this reason stream flow generation research has often focused on the movement of water into small

headwater streams. Studies have employed hydrometric methods, numerical simulations, and monitoring of dissolved constituents to determine the relative contribution of groundwater, rainfall, soil water, and other sources to stream flow (Freeze and Cherry, 1979).

Pinder and Jones (1969) demonstrated the usefulness of monitoring dissolved constituents (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-) to determine the contribution of groundwater to stream discharge, and reported that 32-42% of total storm discharge was from groundwater contributions. Newbury et al. (1969) found that specific conductance and SO_4^{2-} were useful for identifying the groundwater component of stream flow. Hydrochemical hydrograph separations have become widely used and accepted tools (Sklash and Farvolden, 1979; McDonnell et al., 1990; Bonnell, 1993; Mullholland, 1993; Harris et al., 1995; McGlynn et al., 1999). Many studies utilizing hydrochemical separation methods have found pre-event water to be the dominant component of stream flow (Sklash and Farvolden, 1979; McDonnell et al., 1991; Ladouche et al., 2001; and McGlynn and McDonnell, 2003).

Numerous mechanisms to account for the high proportion of pre-event water observed in stream flow have been postulated. Dunne and Black (1970) described the expansion and contraction of saturated 'variable source areas' outward from the stream. These areas contribute more water to stream flow as they expand with varying surface and subsurface inputs (Dunne and Black, 1970). Sklash and Farvolden (1979) proposed the groundwater ridging mechanism to explain this phenomenon. This is a situation where a tension saturated zone that exists above the water table becomes saturated with little input of water. This then leads to a rise in near stream water table levels, increased

hydraulic gradients toward the stream, and a subsequent increase in stream discharge. Beven (1991) suggested the displacement of pre-event water by event water to explain the rapid contributions of pre-event waters observed in stream responses to rain events. Other research has suggested the importance of subsurface preferential flow paths in delivering pre-event water to the stream in a rapid fashion. McDonnell (1990) proposed the large volumes of stored water relative to the small inputs of event water, coupled with zones of transient saturation and preferential subsurface flow paths to explain the dominance of pre-event water in streamflow generation. Although pre-event water contributions to stream flow have been widely documented, and the importance of subsurface flow paths has been accepted an understanding of broad scale stream-groundwater interactions is lacking.

Considerable stream-groundwater exchange research has focused on hyporheic exchange. The hyporheic zone (HZ) has been defined as the areas of interstitial saturation that exist beneath and beside the stream and contain some proportion of stream water (White, 1993). Some hydrologists have debated whether water in the HZ of high gradient streams in mountainous terrain qualifies as groundwater. It has been suggested that water in the hyporheic zone of high gradient streams is not groundwater but stream water flowing as subsurface flow for short distances before re-emerging in the stream channel (Harvey and Bencala, 1993). Regardless, HZ research has been crucial to developing the link between streams and groundwater.

HZ research has often utilized tracers, both conservative and non-conservative, to investigate the hydrological, biogeochemical, and ecological dynamics of the HZ. Wagner and Beisser (2005) injected stream water solutions enriched with glucose, and

inorganic nitrogen and phosphorous to determine benthic invertebrate and biofilm response to increased food resources. Hyporheic fauna responded to injected water solutions within two weeks with either increased abundance or mobility, indicating utilization of increased food resources; and dissolved organic carbon (DOC) was filtered from interstitial water and stored in biofilms (Wagner and Beisser, 2005). Wagner and Beisser (2005) suggested that the HZ functions as a DOC processing system, and refer to the HZ as a 'self-cleaning DOC filter'. Fernald et al. (2001) used dye tracers and transient storage modeling to determine the importance of hyporheic flow in transient storage. They found subsurface and surface flow paths, and noted the importance of hyporheic flow in transient storage (Fernald et al., 2001). This research demonstated that increased channel confinement, whether natural or anthropogenic, led to decreased hyporheic exchange (Fernald et al., 2001). Harvey and Bencala (1993) combined hydrometric methods with tracers to investigate the variability of stream-groundwater exchange in the HZ of mountain watersheds. This work suggested that streambed and water slope variations control the exchange of water between streams and surrounding aquifer in mountain watersheds (Harvey and Bencala, 1993). Specifically, stream water enters the subsurface at the upstream end of riffles and re-enters the stream at the downstream end of riffles (Harvey and Bencala, 1993). Other HZ research has shown that stream-groundwater exchange is an important mechanism involved in solute and contaminant transport (Ren and Packman, 2005); lotic ecosystem functioning (Wroblicky et al., 1998); and water resource management (Oxtobee and Novakowski, 2002). Although these studies have increased the understanding of small spatial and temporal scale stream-groundwater interactions, equivalent research focused

at larger scale interactions is lacking. Furthermore, a meso-scale conceptual model that incorporates the impact stream-groundwater exchange has on hydrologic response, source water contributions, and stream water chemistry is lacking.

Limited stream-groundwater exchange research at larger spatial and temporal scales has focused primarily on mountain front groundwater recharge. The term mountain front recharge (MFR) refers to the contributions from mountain regions to the groundwater recharge of adjacent basins (Wilson and Guan, 2004). The MFR zone is represented on Figure 1.1 as the piedmont zone located between points A and B, and the valley bottom is represented as the area downstream of the MFR zone between points B and C (Wilson and Guan, 2004). MFR has been noted as being a major component of groundwater recharge in semiarid regions (Manning and Solomon, 2003).

Efforts to understand and model MFR in arid to semi-arid regions have increased as growing populations demand adequate and sustainable water supplies, particularly in the southwestern United States (Hogan et al., 2004). Significant groundwater withdrawals in the southwestern United States over the past several decades led to groundwater depletion, land subsidence, and loss of riparian habitat (Hogan et al., 2004). MFR can either occur as percolation through the mountain block or as seepage losses from streams that exit the mountains. Maurer and Berger (1997) compared the surface and subsurface flow out of eight catchments in western Nevada and estimated that 30-90% of the total annual flow across the mountain front was stream flow. Niswonger et al. (2005) noted that numerous intermittent and ephemeral streams that discharge from mountainous catchments of the western United States lose most of their total discharge as seepage as they flow across alluvial fans and piedmont

alluvial plains; highlighting the importance of stream seepage in MFR. Although MFR has been noted as being an important source of groundwater recharge to valley aquifers in arid to semi-arid regions it remains poorly understood and quantified (Wilson and Guan, 2004).

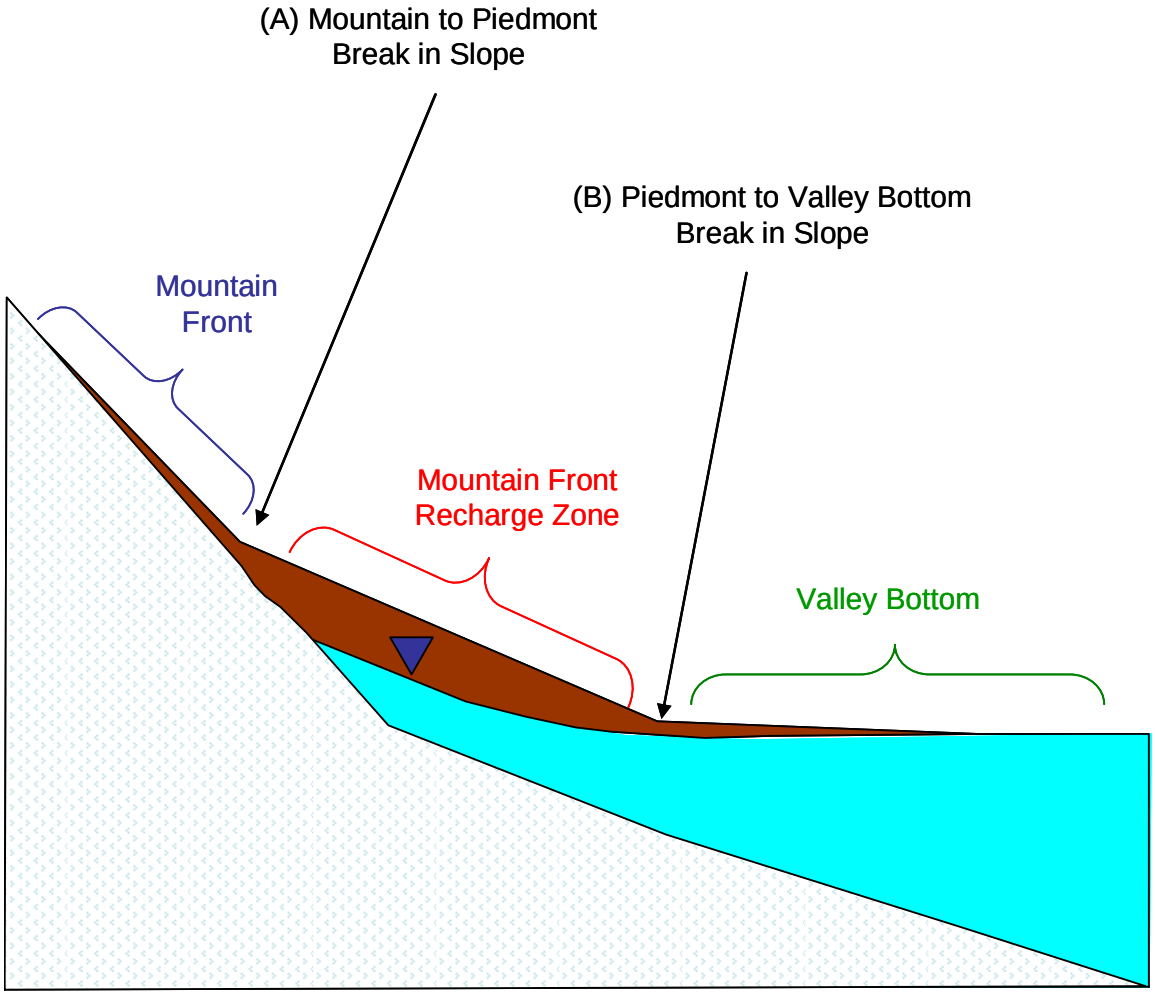

Figure 1.1. Conceptual diagram illustrating the mountain front recharge (MFR) zone, and the valley bottom. The MFR zone is the region between points A and B. (Adapted from Wilson and Guan (2004).

Current studies suggest that MFR is responsible for one third to nearly all of the groundwater recharge to inter-mountain basin fill aquifers (Anderson and Freethey,

1996; Prudic and Herman, 1996; and Mason, 1998). However, few studies have connected MFR to valley bottom hydrology. This research combines hydrometric and hydrochemical methods to investigate stream and groundwater exchange from the MFR zone to the valley bottom zone to determine how stream-groundwater exchanges change across landscape elements, and the impact these exchanges have on watershed hydrologic response, source water mixing, and stream chemistry.

Study Area Background

The Humphrey Creek watershed is located in the Centennial Mountains and Centennial Valley of southwestern Montana (MT), and lies partially within the Red Rock Lakes National Wildlife Refuge (Refuge) (Fig. 1.2). The Centennial Mountains

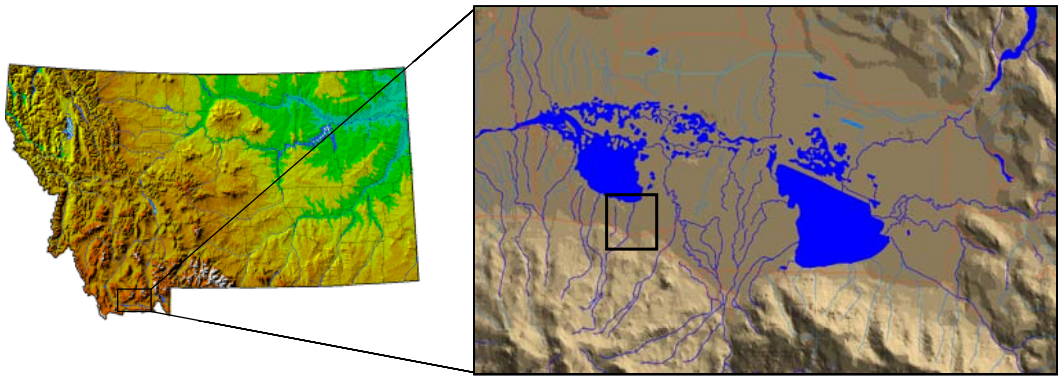

Figure 1.2. Location of the Humphrey Creek watershed in southwestern Montana.

are a block fault range, and are the only east to west trending range with significant relief in MT (Jean et al., 2002). The mountains lie at the southern extreme of Beaverhead County, MT and form the continental divide, and the MT-Idaho border in this region. The Centennial Mountains flank the southern edge of the Centennial

Valley, and reach elevations up to 3,112 meters (m). Considerable snow deposits in the Centennial Mountains feed the mountain streams and valley bottom lakes and marshes. The Centennial Mountains are headwaters for the Missouri River, and the Centennial valley is drained to the west by the Red Rock River.

The Centennial Valley is an undeveloped, high elevation, intermontane basin with an elevation of 2,073 m at its upper (eastern) end (Jean et al., 2002). The valley extent is 115,800 hectares (ha), of which 115,335 ha are managed by the Bureau of Land Management, Forest Service, Fish and Wildlife Service, and Montana Department of Natural Resource Conservation (http://montanapartners.fws.gov/mt3b.htm, accessed on 10/18/05). The Refuge comprises 18,210 of these managed hectares, and was established in 1935 to promote the long-term conservation of the Trumpeter Swan (*Cygnus buccinator*) (Banko, 1960).

The Centennial Mountains and Valley were formed during the Paleocene and Eocene, with further uplift in the late Pliocene (Jean et al., 2002). Subsequent erosion and deposition has filled the 10 kilometer (km) wide valley to variable depths with sediments from Miocene volcanics, and Paleozoic, Mesozoic, and early Tertiary sedimentary rock (Jean et al., 2002). Sonderegger (1982) estimated basement elevations in the valley to range from sea level to 1,524 m above sea level; this is equal to depths below ground surface that range from 549 m to 2,073 m. Pleistocene sediments have been deposited over the valley floor forming gently sloping alluvial fans or in lakes which have expanded and contracted with fluctuating climatic conditions over the Pleistocene and Holocene (Jean et al., 2002). The geology of the Humphrey Creek watershed consists of tertiary volcanics, underlain by upper Cretaceous,

Mesozoic, Paleozoic, and pre-cambrian rocks in the alpine zone and landslide debris, lake sediments, and alluvial deposits in the valley bottom. The headwaters of Humphrey Creek are characterized by irregular shaped masses that have slid downslope and formed thin ridges separated by deep narrow gullies (Ql) (O'Neill and Christiansen, 2004). These landslides are "composed of angular to subangular clasts, ranging from granules to large boulders, in a matrix of clay, silt and sand" (O'Neill and Christiansen, 2004). Moving downstream the landscape trends into "lava flows and flow breccias of basalt, basaltic andesite, and andesite, with less mafic flows occurring lower in the sequence" (Tfl) (O'Neill and Christiansen, 2004). Humphrey Creek then flows through another region of Ql landslide material (O'Neill and Christiansen, 2004). The watershed then grades to a region of "light-brown to light-gray siltstone and fine- to medium-grained sandstone; locally salt and pepper appearance; few thin interbeds of light-gray very fine-grained limestone", containing some subbituminous coal, and has been tentatively assigned to the Beaverhead Formation (TKb) (O'Neill and Christiansen, 2004). Moving further downslope are earthflows of "elongate to lobate, hummocky deposits of unconsolidated to partly consolidated unsorted debris" (Qe) (O'Neill and Christiansen, 2004). These earthflows (Qe) contain substantial clay, silt, and sand; and most were formed from soft siltstone and sandstone tentatively assigned to the Beaverhead Formation (O'Neill and Christiansen, 2004). As Humphrey Creek exits the mountains the landscape is composed of young (Holocene) alluvial fan deposits (Qfy) (O'Neill and Christiansen, 2004). These are "low, lobate deposits of unconsolidated and moderately well sorted silt, sand, gravel, and cobbles" (O'Neill and Christiansen, 2004). Fans contain sand and silt from the sandstone and siltstone facies

of the Beaverhead Formation, and fragments of rhyolite and basalt (O'Neill and Christiansen, 2004). Downstream of the young alluvial fans are old (Quaternery) alluvial fan deposits (Qfo) (O'Neill and Christiansen, 2004). These are broad, conical, deposits with gentle slopes and are composed of unconsolidated moderately well-sorted fluvial silt, sand, gravel, cobbles, and sparse boulders (O'Neill and Christiansen, 2004). It has been proposed that the older alluvial fans were developed during or before the period of the Centennial Valley glacial lake, while the younger alluvial fans were formed after the draining lake left only the Upper and Lower Red Rock Lakes as remnants (O'Neill and Christiansen, 2004). The lowest elevations of the Humphrey Creek watershed are comprised of "unconsolidated, moderately well-sorted, fluvial deposits of silt, sand, and gravel" (Qal) (O'Neill and Christiansen, 2004).

The climate in the Centennial valley is semi-arid, and has strong winter-summer temperature contrasts. The precipitation in the region is fairly consistent over the year, with the exception of May and June, during which one third of the annual precipitation can be deposited (Jean et al., 2002). The town of Lakeview, the Refuge headquarters, rests at an elevation of 2,042 m and records an annual average precipitation of 538 millimeters (mm) (Jean et al., 2002). The thirty year average annual precipitation recorded at the SNOTEL site, located 1.5 kilometers (km) southeast of the Humphrey Creek watershed at an elevation of 2,256 m, is 782 mm. The average July maximum temperature is 24°C; the average January minimum is -18°C; and the yearly mean temperature is 1.7°C, which is the lowest among recording sites in MT (Jean et al., 2002). The average frost free season is 51 days, from mid-June to mid-August (Jean et al., 2002).

Humphrey Creek drains a 351 hectare (ha) watershed. Humphrey Creek flows to the north out of the Centennial Mountains, which form the continental divide and the southern boundary of the watershed, and enters the Lower Red Rock Lake (LRRL) in the Centennial Valley. The Humphrey Creek watershed elevation ranges from 2,012 to 2,969 meters (m). The headwaters of the creek begin above tree line in the alpine region of the watershed. Humphrey Creek then flows through sub-alpine mixed coniferous forest, exits the forest and flows through upland grasses, willows, and shrubs and enters the valley bottom where the vegetation consists of sedges, rushes, grasses and willows.

Purpose

The purpose of this study was to investigate the exchange of water between Humphrey Creek and the surrounding groundwater at a broader scale than has generally been applied to stream-groundwater exchange research. This approach was adopted to highlight the role that different landscape elements have in controlling stream-groundwater exchange, and the subsequent implications of those exchanges. I pose three main research questions:

(1) How do alpine to valley bottom transitions impact stream discharge magnitude and timing?

(2) How does stream-groundwater exchange change over alpine to valley bottom transition zones?

(3) What are the relative proportions of alpine and groundwater inputs to stream discharge in Humphrey Creek from the MFR zone to the valley bottom?

These questions were addressed with physical hydrology techniques, and geochemical hydrograph separations. Multiple techniques were necessary to elucidate dynamic stream-groundwater exchange processes across the landscape. This approach allowed me to develop a conceptual model of stream-groundwater exchange across distinct landscape elements and the impact these exchanges have on stream hydrograph response and stream water chemistry.

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CHAPTER 2

STREAM-GROUNDWATER INTERACTIONS IN A MOUNTAIN TO VALLEY TRANSITION: IMPACTS ON WATERSHED HYDROLOGIC RESPONSE AND STREAM WATER CHEMISTRY

Introduction

The realization that streams and surrounding groundwater exist as a connected resource has helped to advance the fields of hydrology, biogeochemistry, and aquatic ecology. Stream-groundwater exchange plays an important role in the processes that affect watershed hydrologic response, water quality, and subsequent impacts on aquatic biota. The exchange of water between streams and groundwater has been noted as an important mechanism involved in solute and contaminant transport (Ren and Packman, 2005); dissolved organic carbon (DOC) cycling (Wagner and Beisser, 2005); lotic ecosystem functioning (Wroblicky et al., 1998); and water resource management (Oxtobee and Novakowski, 2002). Although these studies have increased understanding of these processes, many have focused on small spatial and temporal scale interactions. Furthermore, a watershed scale conceptual model that incorporates the impact of larger scale stream-groundwater exchange has on hydrologic response, source water contributions, and stream water chemistry is lacking.

Hydrologists, biogeochemists, and ecologists have become interested in the stream-groundwater exchanges that occur in the hyporheic zone (HZ), and considerable improvements in understanding have been made in this area. The HZ has been defined as the interstitial areas of saturation located beneath and beside the channel that contain a

proportion of stream water (White, 1993). Advances in the study of the HZ have been crucial to developing the link between streams and groundwater and the HZ is now viewed as an integral part of the stream itself (Malard et al., 2002). HZ interactions occur at small scales, which exist embedded within a larger framework of stream-groundwater exchanges. Harvey et al. (1996) define smaller scale exchanges as those that occur at centimeter-long flow paths, and timescales of minutes; and, larger scale exchanges as those that occur over hundreds of meters and timescales of years. At the larger scale, stream reaches can be defined as losing water to groundwater, or gaining water from groundwater. Whether a stream reach is losing (groundwater recharge) or gaining (groundwater discharge) will be spatially and temporally dynamic, and will have substantial impacts on the hydrologic and chemical characteristics of stream flow.

Limited stream-groundwater exchange research at larger spatial and temporal scales has focused on mountain front groundwater recharge. The term mountain front recharge (MFR) refers to the contributions from mountain regions to the groundwater recharge of adjacent basins (Wilson and Guan, 2004). Efforts to understand and model MFR in arid to semi-arid regions have increased as growing populations demand adequate and sustainable water supplies, particularly in the southwestern United States (Hogan et al., 2004). Significant groundwater withdrawals in the southwestern United States over the past several decades have led to groundwater depletion, land subsidence, decreased in-stream flows, and loss of riparian habitat (Hogan et al., 2004). MFR has been noted as being a major component of groundwater recharge in semiarid regions (Manning and Solomon, 2003). MFR can either occur as percolation through the mountain block or as seepage losses from streams that exit the mountains. Maurer and

Berger (1997) compared the surface and subsurface flow from eight catchments in western Nevada and estimated that 30-90% of the total annual flow across the mountain front was stream flow. Niswonger et al. (2005) noted that numerous intermittent and ephemeral streams that discharge from mountainous catchments of the western United States lose most of their total discharge as seepage to groundwater as they flow across alluvial fans and piedmont alluvial plains; highlighting the importance of stream seepage in MFR. Although MFR has been noted as being an important source of groundwater recharge to valley aquifers in arid to semi-arid regions, it remains poorly understood and quantified (Wilson and Guan, 2004).

Exchanges of water between the stream and groundwater vary across different landscape elements within a watershed. These hydrologic systems will affect streams and the degree that streams will either gain or lose water to/from the local groundwater table. If we break a watershed into three distinct landscape elements such as a mountain collection zone, a mountain front recharge (MFR) zone, and a valley bottom zone we could begin to determine the dominant hydrological features of each landscape element. We can define the mountain collection zone as the headwaters of the watershed where channels originate; the MFR zone as the piedmont zone between points A and B on Figure 2.1 (Wilson and Guan, 2004), and the valley bottom zone as the basin floor downstream of the MFR zone (Fig. 2.1). Mountain collection zones typically have higher precipitation, lower evapotranspiration (ET), and less soil development than downslope landscape elements (Wilson and Guan, 2004). Recent studies suggest that MFR is

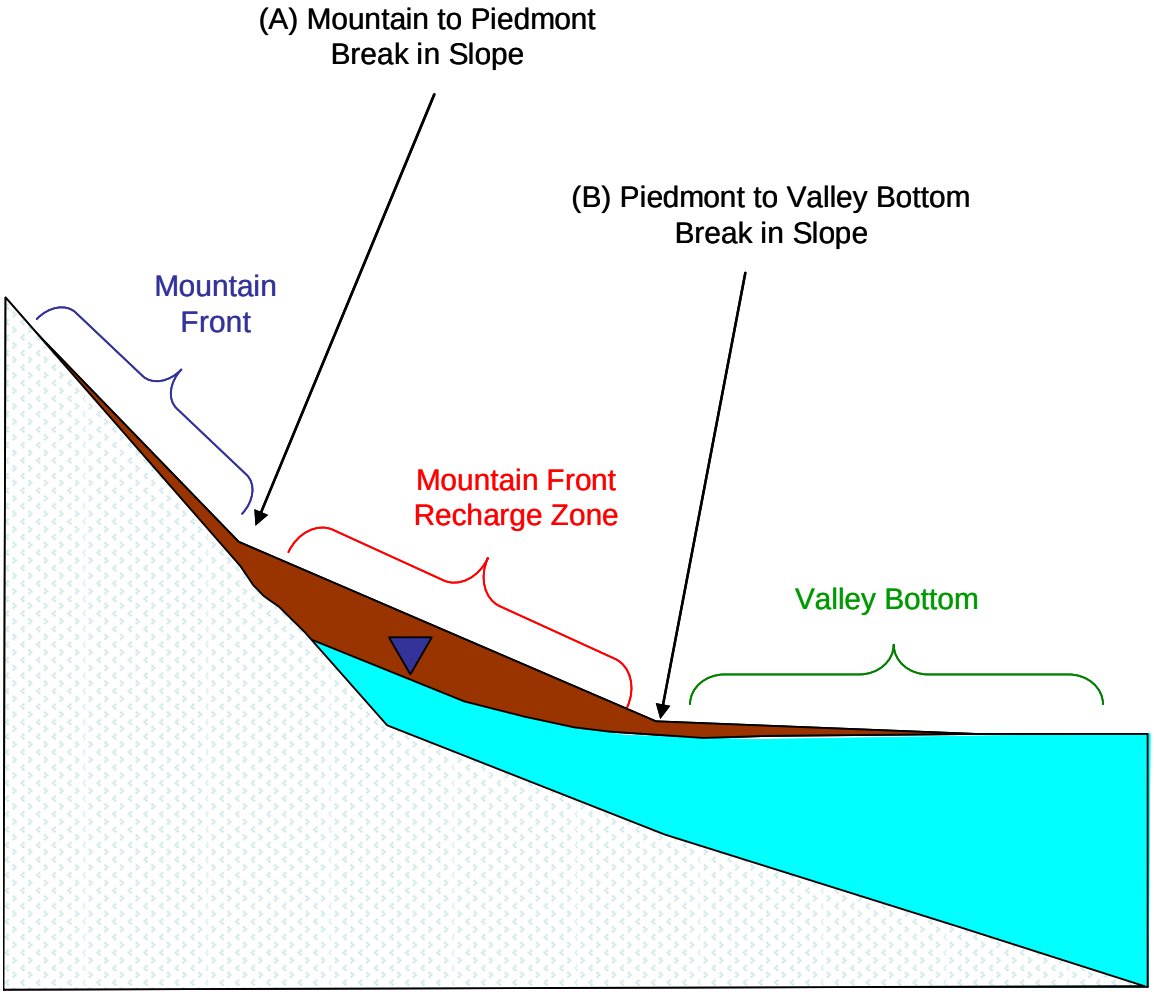

Figure 2.1. Conceptual diagram illustrating the mountain front recharge (MFR) zone, and the valley bottom. The MFR zone is the region between points A and B. (Adapted from Wilson and Guan (2004).

responsible for one third to nearly all of the groundwater recharge to inter-mountain basin fill aquifers (Anderson and Freethey, 1996; Prudic and Herman, 1996; and Mason, 1998). However, few studies have connected MFR to valley bottom hydrology. Investigating the hydrology and geochemistry of the stream and groundwater in both the MFR zone and the valley bottom zone allows determination of how stream-groundwater exchanges can change from one landscape element to the next, and the impact these exchanges can have on watershed hydrologic response, source water mixing, and stream chemistry.

Large scale stream-groundwater exchanges and the impact they have on MFR and valley bottom hydrology are poorly understood. I used groundwater monitoring wells, in stream piezometers, stream gauging stations, and geochemical hydrograph separations in the Humphrey Creek watershed in southwestern Montana to investigate the following questions:

(1) How do alpine to valley bottom transitions impact stream discharge magnitude and timing?

(2) How does stream-groundwater exchange change over alpine to valley bottom transition zones?

(3) What are the relative proportions of alpine and groundwater inputs to stream discharge in Humphrey Creek from the MFR zone to the valley bottom?

I hypothesize that mountain-valley transitions function as hydrologic and biogeochemical buffers via groundwater recharge and subsequent groundwater discharge. More specifically, I hypothesize that streams recharge groundwater near the mountain front, and that stored groundwater discharges to the stream in the valley bottom. The spatial and temporal dynamics of these interactions impact stream hydrograph response and chemistry. Implications are that MFR magnitudes can control valley aquifer storage state which combined with alpine runoff magnitude and valley bottom groundwater discharge controls stream water quantity and geochemical composition downstream.

Study Area

The Humphrey Creek watershed is located in the Centennial Mountains and Red Rock Lakes National Wildlife Refuge in southwestern Montana at 111.82778 degrees

west longitude, and 44.61778 degrees north latitude (Fig. 2.2). The continental

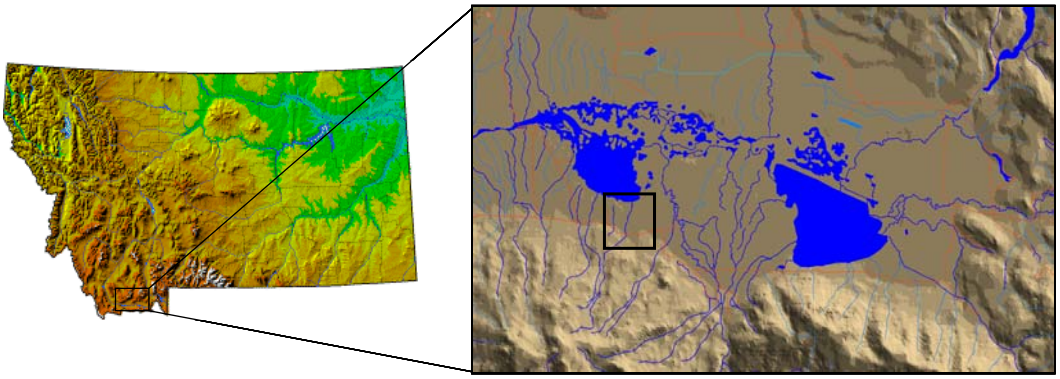

Figure 2.2. Location of the Humphrey Creek watershed in southwestern Montana.

divide forms the southern boundary of the watershed and Humphrey Creek flows from south to north. Humphrey Creek flows into Lower Red Rock Lake (LRRL), and drains a 351 hectare (ha) watershed. The Humphrey Creek watershed elevation ranges from 2,012 to 2,969 meters (m). The headwaters of the creek begin above tree line in the alpine region of the watershed. Humphrey Creek then flows through sub-alpine mixed coniferous forest, exits the forest and flows through upland grasses, willows, and shrubs and enters the valley bottom where the vegetation consists of sedges, rushes, grasses and willows.

The area of instrumentation begins where Humphrey Creek exits the coniferous forest and continues to the lake edge (Fig. 2.3A). Instrumentation covers the mountain

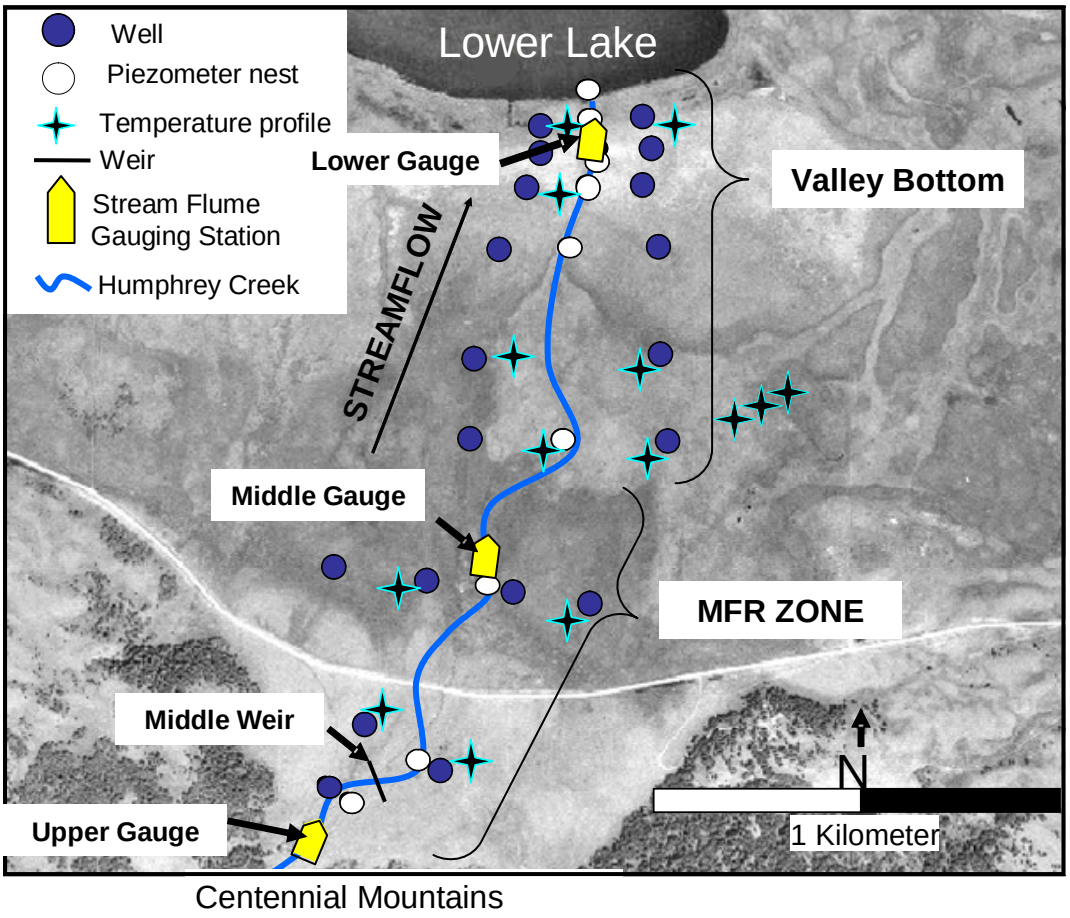

Figure 2.3A. Instrument layout in the Humphrey Creek watershed. Ten transects perpendicular to the stream channel, alternatively viewed as three to four transects parallel to the stream channel. Instrumentation includes: nine piezometer nests (two piezometers per nest), nineteen wells, fourteen temperature profile nests (ten depths in each nest), and four stream gauging stations. Plan view of mountain front recharge (MFR) zone and valley bottom shown on map.

front recharge (MFR) zone (where Humphrey Creek exits the coniferous forest) to the valley bottom zone (where Humphrey Creek enters the lake). I define the MFR zone as the piedmont zone between points A and B on Figure 2.1 (Wilson and Guan, 2004). The headwaters of the watershed are characterized by landslides of angular to subangular clasts that range from granules to large boulders; lava flows and flow breccias of basalt, basaltic andesite and andesite; to light-brown to light-grey siltstone and fine to medium-

grained sandstone with few thin interbeds of very fine-grained limestone (O'Neill and Christiansen, 2004). As Humphrey Creek exits the mountains the landscape is composed of young (Holocene) alluvial fan deposits (O'Neill and Christiansen, 2004). These are low, lobate deposits of unconsolidated and moderately well sorted silt, sand, gravel and cobbles (O'Neill and Christiansen, 2004). The valley bottom floor of the Humphrey Creek watershed is characterized by unconsolidated, moderately well-sorted, fluvial deposits of silt, sand, and gravel (O'Neill and Christiansen, 2004).

Average annual precipitation data was obtained from the Lakeview Ridge SNOTEL site, which is located 1.5 kilometers (km) southeast of the Humphrey Creek watershed at an elevation of 2,256 m. The thirty year average annual precipitation is 782 millimeters (mm).

Methods

Groundwater Measurements

I installed nine transects of wells perpendicular to Humphrey Creek from the upstream edge of the MFR zone to the lake edge to measure the shape and dynamics of the local groundwater table surrounding the stream (Fig. 2.3B). Wells were 2 inch diameter, schedule 40, 0.010 inch slot, poly vinyl chloride (PVC). Well screening

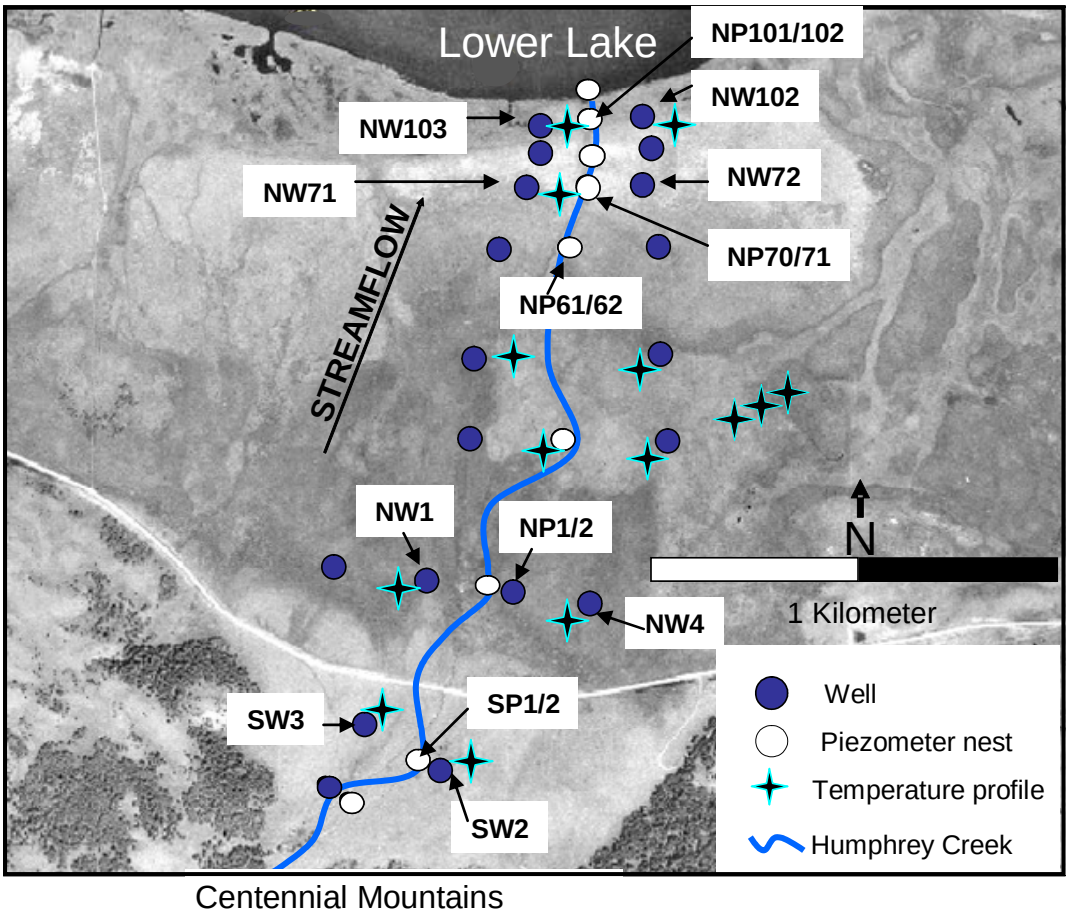

Figure 2.3B. Instrument layout in the Humphrey Creek watershed showing location and names of wells and piezomerters. Nested piezometers are in-stream piezometers.

extended from well completion depths to approximately 10 centimeters (cm) below the ground surface. Wells were installed by hand augering to refusal, inserting the well, backfilling around the well, and sealing at the ground surface with mounded excavated soil. Most wells were instrumented with TruTrack, Inc. recording capacitance rods that recorded groundwater height and temperature at ten minute intervals. Tru Track, Inc. recording capacitance rods have a +/- 1 millimeter (mm) water height resolution, and have a +/- 0.3°C linear accuracy over a 0°C to 70°C range . I manually measured groundwater wells for depth to groundwater, groundwater specific conductance (SC), and

groundwater temperature at variable intervals depending on season (daily to weekly intervals). Groundwater temperature and SC were measured with a YSI model 63 hand held pH, conductivity and temperature probe. The YSI model 63 probe has a 0.1 µS/cm resolution over a 0 to 499.9µS/cm range, a 1 µS/cm resolution over a 0 to 4999 µS/cm range, and a 0.1°C resolution over a -5 to 75°C range.

At the middle of each perpendicular to the stream well transect I installed two nested piezometers in the streambed to determine the vertical groundwater gradients (Fig. 2.3B). Piezometers were 1.5 inch diameter PVC pipe, and were open only at completion depths (no screening). Piezometers were installed by driving them into the ground with a removable solid piezometer driver that occupied the volume of the PVC in order to keep them from filling with sediment. TruTrack, Inc. recording capacitance rods were installed in most piezometers and recorded groundwater height (total potential) and temperature at ten minute intervals. I manually measured groundwater total potential, SC, and temperature at variable intervals depending on season (daily to weekly intervals). Well and piezometer measurements began in March, 2004 and continued through September, 2004.

Stream, Soil, and Meteorological Measurements

I installed three Parshall flumes (three-inch constriction) in Humphrey Creek during the spring of 2004: one in the upper reach of the study area, referred to as the upper gauge, a second in the middle reach of the study area, referred to as the middle gauge, and a third in the downstream reach of the study area, referred to as the lower gauge (Fig. 2.3A). The upper gauge was located at the upstream edge of the MFR zone,

the middle gauge was located at the downstream edge of the MFR zone, and the lower gauge was located in the valley bottom zone near the lake edge. I instrumented each flume with stage recording data loggers (either Druck pressure transducers connected to Campbell CR10X data loggers, or TruTrack, Inc. recording capacitance rods) installed in stilling wells recording at ten minute intervals. Discharge was then calculated from developed stage-discharge rating curves. Gauge measurements began at the end of April, 2004 and continued until the end of September, 2004.

A rectangular weir existed in Humphrey Creek prior to the project, and was utilized for stream gauging. This weir was located between the upper gauge and the middle gauge in the middle of the MFR zone and is referred to as the middle weir (Fig. 2.3A). I widened and deepened a section of stream behind the middle weir to create a stilling pool, and constructed a stilling well on the upstream side of the weir which was instrumented with a TruTrack, Inc. recording capacitance rod. Stage measurements were recorded at ten minute intervals, and were taken from the end of April, 2004 to the end of September, 2004. Again, I developed a stage-discharge rating curve to calculate discharge.

I utilized velocity-area gauging at each flume and the weir to develop the rating curves. A Marsh-McBirney Flo-Mate 2000 portable flow meter was used for velocity-area gauging of the stream, and the six-tenths depth method was applied (according to U.S. Geological Survey practice to use six-tenths depth method when $Y_i < 0.75$ m) (Dingman, 2002). Velocity-area gauging occurred on a regular basis (nearly daily) from the beginning of May to the end of August, 2004. To further calibrate rating curves I also performed dilution gauging with sodium chloride (NaCl). I obtained breakthrough curves

with Campbell CS547A conductivity and temperature probes connected to Campbell CR10X data loggers. Campbell CS547A conductivity probes are accurate to +/- 5% over a 0.44 to 7 mS cm^{-1} range and +/- 10% over a 0.005 to 0.44 mS cm^{-1} range. Measurements were taken every 5 seconds during dilution gauging experiments. Integration of the area under the breakthrough curves yielded discharge (Dingman, 2002).

I recorded stream SC, stream temperature, and local soil moisture status at the upper gauge, the middle gauge, and the lower gauge. Stream SC and temperature were measured with Campbell CS547A conductivity and temperature probes at ten minute intervals. Local soil moisture status was measured with Campbell CS616 water content reflectometers at ten minute intervals. I installed a Campbell TE525 tipping bucket rain gauge at the middle gauge to collect rain data, and a Thermocron I-Button to record air temperature. The rain gauge recorded each 0.1 millimeter (mm) of rain and air temperature was recorded at ten minute intervals. Snow water equivalent (SWE) data was obtained from the Lakeview Ridge SNOTEL site. The SNOTEL site was located 1.5 kilometers (km) southeast of the Humphrey Creek watershed at an elevation of 2,256 m.

To measure soil temperature profiles I inserted soil temperature nests, co-located with groundwater wells in the study area (Fig. 2.3B). Soil temperature nests extended to depths up to 2.5 m. I fastened Thermocron I-Buttons to wooden dowels at 5 cm intervals near the ground surface, and at spacing of up to 50 cm deeper in the soil profile. I sought higher resolution near the ground surface, where soil temperatures fluctuate more than soil temperatures deeper in the profile. The dowels with I-Buttons attached were wrapped with spiraled foam insulation to prevent vertical translation of heat, and a small notch was cut for each I-Button so that they would not be insulated from soil temperature

fluctuations. The temperature probes were placed in 0.048 inch wall PVC tubes that were sealed at the top and bottom to protect the data loggers from groundwater, and freezing soil water. Notches in foam insulation allowed I-Buttons to press against the PVC sleeve. Soil temperature nests were installed by hand augering to refusal, inserting the temperature nest, backfilling around the nest, and sealing at the ground surface with mounded excavated soil. Soil temperature nests recorded measurements at 10 to 30 minute intervals (depending on season) and measurements were recorded from October, 2003 through April, 2005.

Water Sampling

Groundwater samples were collected from wells, piezometers, and springs for chemical analysis. I used a hand held peristaltic pump and pumped and purged lines before sample was collected in 250 milliliter (mL) HDPE bottles and refrigerated at 4°C until filtering. Stream samples were collected from gauging locations either as grab samples or with ISCO auto samplers. Stream grab samples were collected in 250 mL HDPE bottles and refrigerated at 4°C until filtering. I filtered all water samples through 0.45 µm polypropylene filters and stored them in the dark at 4°C until analysis.

Chemical Analysis

I analyzed water samples for major ions with a Metrohm-Peak compact ion chromatograph on Montana State University campus. Sodium (Na), ammonium (NH_4), potassium (K), calcium (Ca), and magnesium (Mg) were measured on a Metrosep C-2-250 cation column. Nitrate (NO_3), chloride (Cl), phosphate (PO_4), and sulphate (SO_4) were measured on a Metrosep C-2-250 anion column. And silica (Si) was measured as

silicate (SiO_2) on a Hamilton PRP-X100 anion column. IC analysis protocol was developed following manufacturer instructions. Standards and blanks were analyzed at the beginning of each sample run, were inserted between every ten field water samples, and were analyzed at the back end of each sample run for quality assurance/quality control (QA/QC).

Hydrograph Separation and Uncertainty

Hydrograph separations are powerful tools for determining contributions to stream flow from various sources (e.g. alpine zone surface water and valley bottom groundwater) (McGlynn and McDonnell, 2003). If two sources contributing to stream flow are unique, and their signatures are known, a two component separation can be performed. I developed real-time separations for the middle gauge and the lower gauge using specific conductance (SC), under the assumption that SC was conservative over the time and space of the study. Substitution of SC for ion concentrations has been previously established by Gooseff and McGlynn (2005). Groundwater SC was measured in wells and piezometers at daily to weekly intervals (dependent on season). Alpine stream SC, the middle gauge stream SC, and the lower gaguge stream SC were measured at ten minute intervals. I defined alpine SC as the SC of water exiting the mountains and entering the MFR zone as channel flow. Chemical analysis of samples and regression of ion concentration versus SC was used to corroborate this separation. Further validation was obtained by plotting snap-shot separations using geochemistry of groundwater and surface water grab samples and comparing them to SC separations.

A two-component separation can be solved by simultaneously solving equations one (1), two (2), and three (3) (Pinder and Jones, 1969).

$$Q_{AL} = \left[\frac{C_{ST} - C_{GW}}{C_{AL} - C_{GW}}\right] Q_{ST} \quad \textbf{(1);}$$

$$Q_{GW} = \left[\frac{C_{ST} - C_{AL}}{C_{GW} - C_{AL}}\right] Q_{ST} \quad \textbf{(2);}$$

$$Q_{ST} = Q_{GW} + Q_{AL} \quad \textbf{(3)}$$

Where Q_{AL} is the contribution to discharge from the alpine zone, Q_{GW} is the contribution to discharge from valley bottom groundwater, Q_{ST} is stream discharge, and C_{AL}, C_{GW}, and C_{ST} are the concentration of tracer (either SC or a solute) from alpine sources, groundwater sources, and resultant stream concentration, respectively. I applied uncertainty analyses to the hydrograph separations following the methods of Genereux (1998) using equations four (4) and five (5).

$$W_{f_{AL}} = \left\{\left[\frac{C_{GW} - C_{ST}}{(C_{GW} - C_{AL})^2} W_{C_{AL}}\right]^2 + \left[\frac{C_{ST} - C_{AL}}{(C_{GW} - C_{AL})^2} W_{C_{GW}}\right]^2 + \left[\frac{-1}{C_{GW} - C_{AL}} W_{C_{ST}}\right]^2\right\}^{1/2} \quad \textbf{(4)}$$

$$W_{f_{GW}} = \left\{\left[\frac{C_{AL} - C_{ST}}{(C_{AL} - C_{GW})^2} W_{C_{GW}}\right]^2 + \left[\frac{C_{ST} - C_{AL}}{(C_{AL} - C_{GW})^2} W_{C_{AL}}\right]^2 + \left[\frac{-1}{C_{AL} - C_{GW}} W_{C_{ST}}\right]^2\right\}^{1/2} \quad \textbf{(5)}$$

Where $W_{f_{AL}}$ is the uncertainty in the alpine component, $W_{f_{GW}}$ is the uncertainty in the groundwater component, $W_{C_{AL}}$, $W_{C_{GW}}$, and $W_{C_{ST}}$ are the analytical errors in alpine, groundwater, and stream concentration measurements, and C_{AL}, C_{GW}, and C_{ST} are alpine, groundwater, and stream concentrations (SC or a solute). Stream SC measurements were accurate to +/- 5% over a 0.44 to 7 mS cm^{-1} range, and +/- 10% over

a 0.005 to 0.44 mS cm^{-1} range; and groundwater SC measurements were accurate to +/- 0.5% of full scale of the measurement.

Results

Stream Discharge

Stream discharge was greatest at the upper gauge where water exited the mountains and entered the mountain front recharge (MFR) zone (Fig. 2.4). The annual hydrograph at the upper gauge was driven primarily by mountain snow-melt, and responded to rain events with pulsed increases in discharge. Discharge was consistently greater at the upper gauge than the middle gauge, however, the magnitude of the differences in discharge varied over the duration of study. Five day total discharges at the upper gauge were 66 m^3 to 7,504 m^3 greater than five day total discharges at the middle gauge over the course of study (Appendix A, Table 1). The middle gauge five day total discharges ranged from 43-97% of the upper gauge five day total discharges. The upper gauge and the middle gauge bracketed the MFR zone, with the upper gauge at the upstream end of the MFR zone and the middle gauge at the downstream end of the MFR zone. The discharge differences between the upper gauge and the middle gauge show that a significant amount of water exiting the mountains as channel flow was lost from Humphrey Creek. These losses were likely due to stream seepage losses to groundwater recharge as Humphrey Creek flowed through the MFR zone.

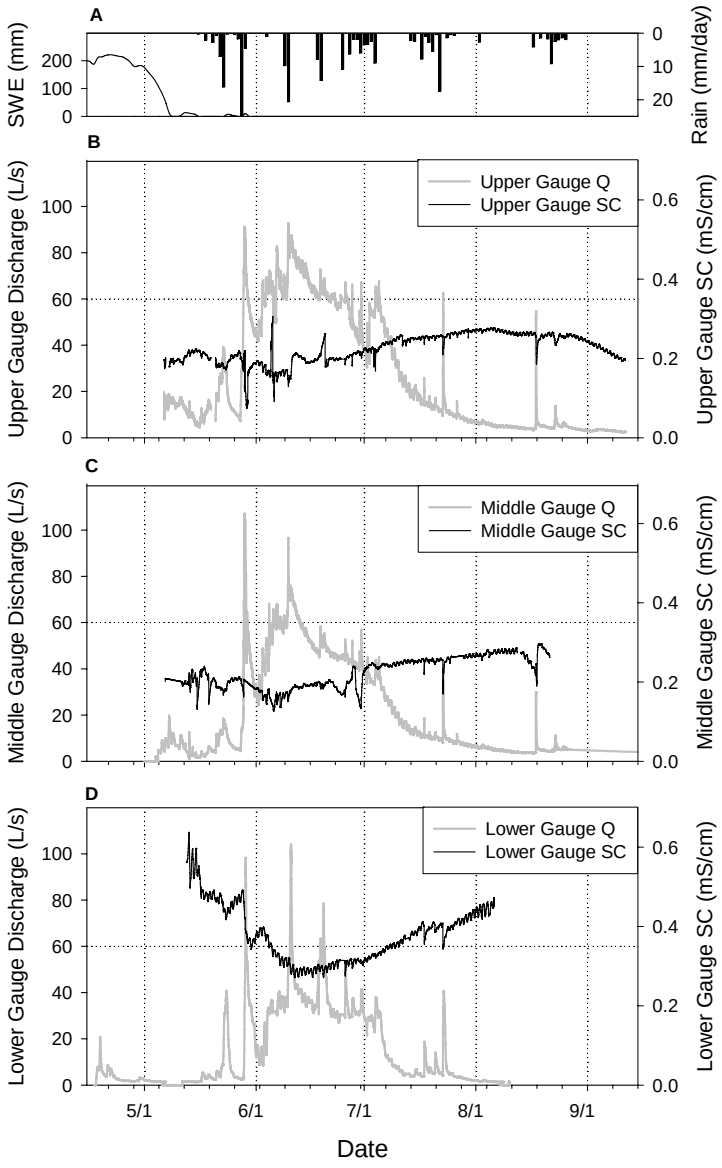

Figure 2.4. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 15 April, 2004 through 15 September, 2004. Time series stream hydrographs and stream specific conductance (SC) for: (B) the upper gauge located at the upstream edge of the mountain front recharge zone; (C) the middle gauge located at the downstream edge of the mountain front recharge zone; and (D) the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

The shapes of the upper gauge and middle gauge hydrographs were similar, as was the onset and cessation of channel flow (Fig. 2.4 B & C). Both the upper gauge and

the middle gauge showed peaks in stream discharge driven by a rain event on 28 May, 2004. Annual peak discharge occurred on 9 June at both of these gauges. Rain events on 22 July and 22 August caused similar peaks in the hydrographs for both the upper gauge and the middle gauge.

The hydrograph for the lower gauge, located in the valley bottom ~ 80 m upstream of Lower Red Rock Lake (LRRL), had a different hydrograph shape and duration than those for the upper gauge and the middle gauge (Fig. 2.4 D). Channel flow at the lower gauge began two weeks before flow commenced at the upper gauge or the middle gauge. Discharge magnitude was consistently less at the lower gauge compared to discharge in the MFR zone. Differences in discharge magnitude between the upper gauge and the lower gauge varied over the duration of study. The five day total discharge deficits for the lower gauge compared to the upper gauge ranged from 1,624 m^3 to 15,099 m^3 (Appendix A, Table 1). Five day total discharges at the lower gauge were between 0-73% of five day total discharges at the upper gauge (0% indicating no flow at the lower gauge) (Appendix A, Table 1). Discharge at the lower gauge was typically lower than discharge at the middle gauge, except for the fourth five day period on record, when total discharge was greater at the lower gauge than the middle gauge (Appendix A, Table 1). During the fourth five day discharge period a 1,778 m^3 greater discharge total at the lower gauge than the middle gauge was recorded (Appendix A, Table 1). The middle gauge total discharge was 68% of total discharge at the lower gauge during this period. For all other five day discharge totals on record, the middle gauge had greater discharge than the lower gauge, and these differences varied between 293 m^3 and 10,873 m^3 (Appendix A, Table 1). The lower gauge five day total discharges ranged between 0-

94% of middle gauge five day total discharges during these time periods (0% indicating no flow at the lower gauge).

The hydrograph for the lower gauge was flashier than the hydrographs for the upper gauge or the middle gauge (Fig. 2.4D). Rain events caused large departures from baseflow in the valley bottom; much more so than in the MFR zone. In particular, rain events that occurred on 19 June, and 25 June caused sizeable peaks in the hydrograph for the lower gauge, whereas rain induced peaks in discharge at the upper gauge and the middle gauge during this time period did not diverge substantially from baseflow (Fig. 2.4). Peak discharge at the lower gauge occurred one day later than it did in the MFR zone (June 10 for the lower gauge, June 9 for the upper gauge and the middle gauge). Discharge at the lower gauge ceased roughly three weeks prior to cessation of channel flow at the upper gauge and the middle gauge, and did not respond to a 22 August rain event, although the upper gauge and the middle gauge did.

Three time periods were chosen for closer evaluation of discharge dynamics. These were 20 May to 30 May which included two rain induced peaks (Fig. 2.5), 8 June to 15 June which included peak discharge (Fig. 2.6), and 15 July to 31 July where ten days of rain caused two peaks at the upper gauge and the middle gauge and three peaks in discharge at the lower gauge (Fig. 2.7).

A rain event on 21 May caused a hydrograph response at all three gauges. The largest hydrograph response was measured at the lower gauge, followed by the upper gauge, then the middle gauge (Fig. 2.5). The lower gauge discharge rose from 5 to 40 L s^{-1}, the upper gauge discharge rose from 15 to 40 L s^{-1}, and the middle gauge discharge rose from 5 to 18 L s^{-1} (Fig. 2.5). The peak at the lower gauge was a greater departure

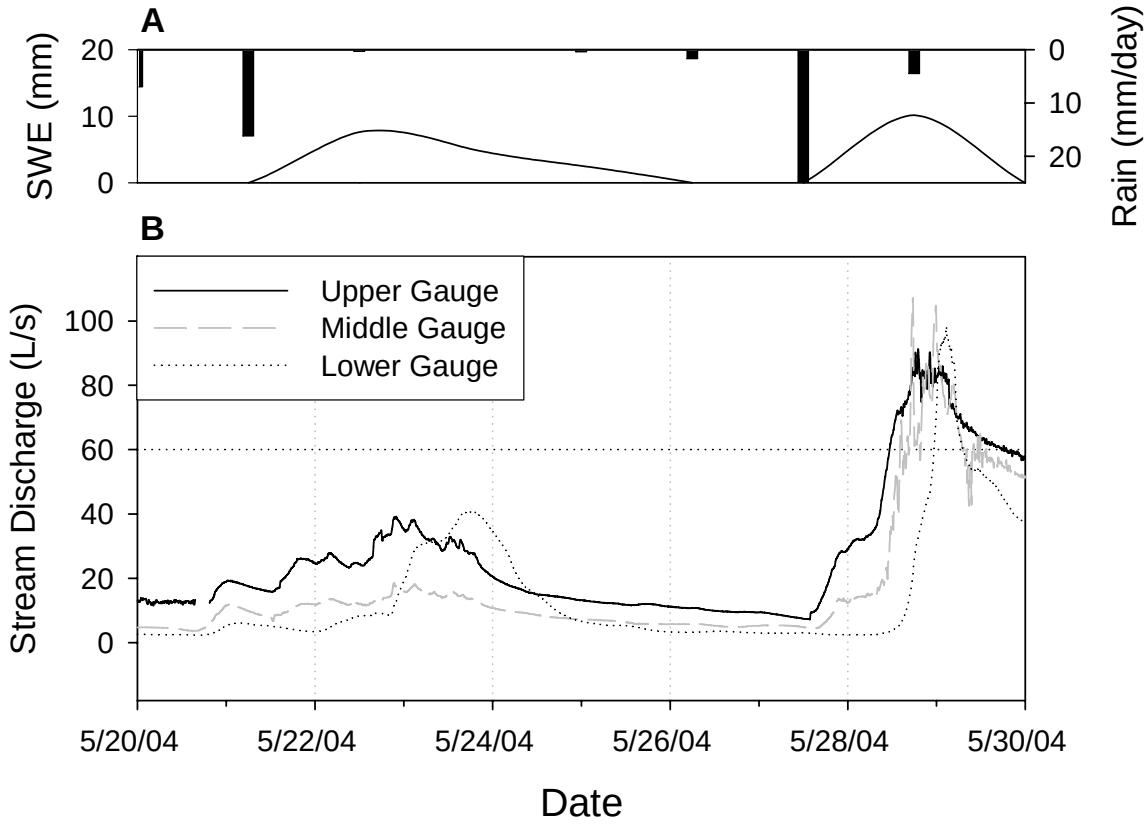

Figure 2.5. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 20 May, 2004 through 30 May, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

from baseflow than those for the upper gauge or the middle gauge, and was delayed by one day compared to the upper gauge and the middle gauge (Fig. 2.5). The timing of the rain induced peak on 29 May was similar for all three gauges (Fig. 2.5). However, the hydrographs at the upper gauge and the middle gauge began to rise before any response at the lower gauge. The middle gauge had the highest peak at 104 L s^{-1}, followed by the lower gauge at 98 L s^{-1}, and the upper gauge at 90 L s^{-1} (Fig. 2.5). Although the middle gauge had the highest peak, the upper gauge had the greatest total discharge over the

course of the event, followed by the middle gauge, then the lower gauge. The 29 May hydrograph response for the middle gauge had numerous peaks, whereas the hydrograph responses for the upper gauge and the lower gauge were single peaks (Fig. 2.5). Peak seasonal discharge occurred on 9 June at the upper and middle gauges and on 10 June at the lower gauge. The upper gauge and the middle gauge hydrographs

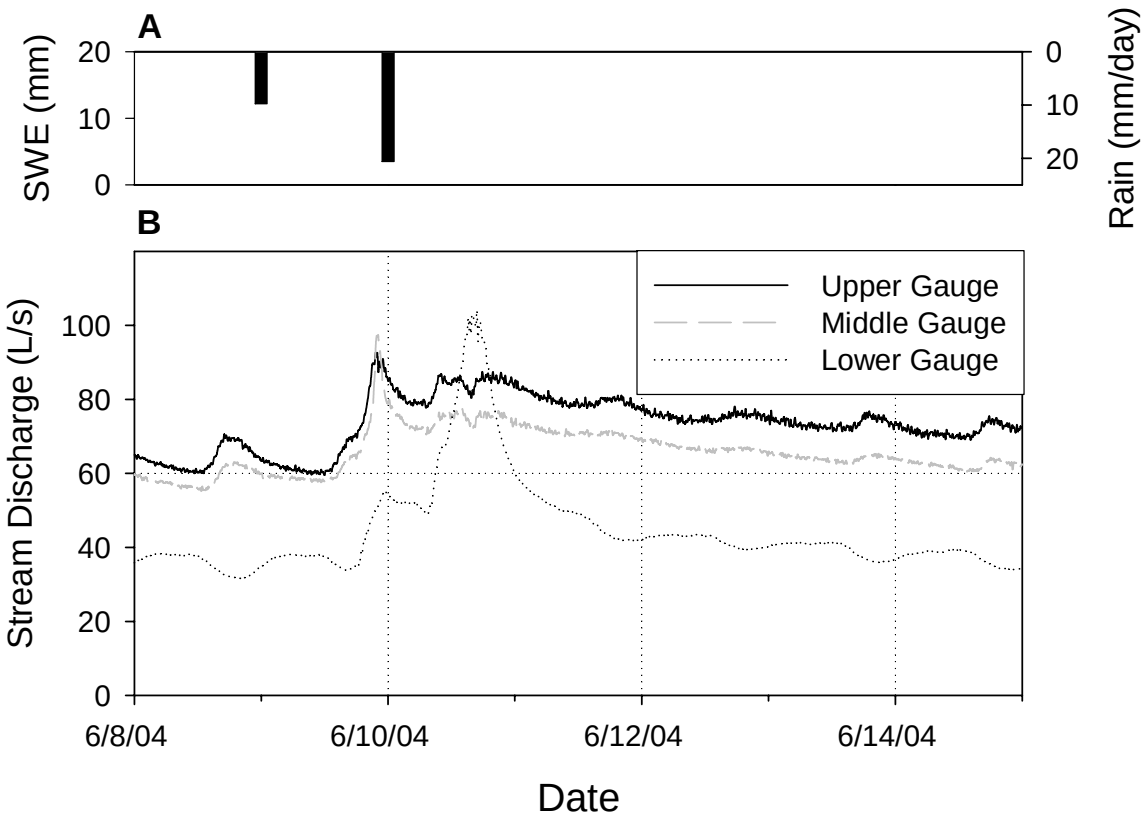

Figure 2.6. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 8 June, 2004 through 15 June, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

began rising from ~ 60 L s^{-1} near mid-day 9 June to peaks of ~ 95 L s^{-1} near midnight on 9 June (Fig. 2.6). The rise to peak for the middle gauge was more abrupt than that for the

upper gauge. The upper gauge discharge decreased to ~ 70 L s^{-1} by 15 June, while the middle gauge discharge decreased to ~ 60 L s^{-1}. The lower gauge hydrograph rose from ~ 40 L s^{-1} with similar timing to the upper gauge and the middle gauge hydrographs, however the rising limb for the lower gauge stalled ~ 55 L s^{-1} for 8 hours on 10, June (Fig. 2.6). The lower gauge hydrograph began rising again and reached a peak discharge ~ 100 L s^{-1} on 10 June (Fig. 2.6). The lower gauge discharge then decreased to ~ 40 L s^{-1} by 12 June and leveled off. Again, the peak for the lower gauge was a large departure from baseflow, yet total discharge was low due to the low baseflow discharge (~ 40 L s^{-1}), compared to higher baseflow discharge at the upper gauge and the middle gauge.

A rain induced peak occurred on 17 July at all three gauges (Fig. 2.7). Fine time scale resolution shows that the timing of these three peaks was staggered. The upper gauge peak occurred first, followed by the middle gauge, then the lower gauge. The lower gauge peak induced by this rain event was substantially larger than those for the upper gauge or the middle gauge despite little additional watershed area added between the MFR zone and the lower gauge (Fig. 2.7). The upper gauge and the middle gauge peaks were narrower, and the lower gauge peak was broader. Higher baseflow discharge at the upper gauge and the middle gauge accounted for higher total discharge compared to the lower gauge. Three days later on 20 July a rain induced peak was measured at the lower gauge, however no peaks were observed at the upper gauge or the middle gauge (Fig. 2.7).

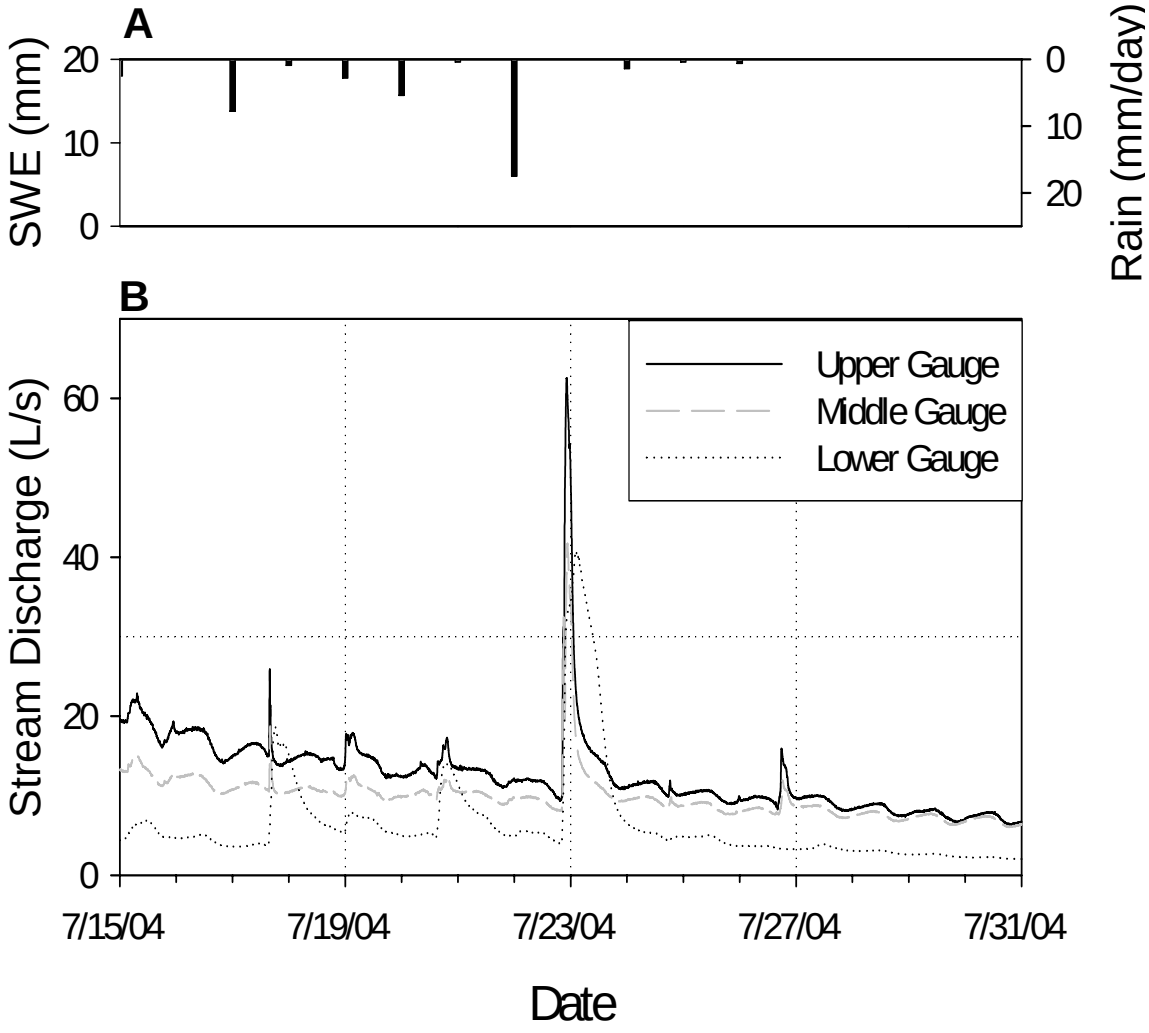

Figure 2.7. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 15 July, 2004 through 31 July, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

A third rain driven peak over this time period occurred on 23 July, and was observed at all three gauges (Fig. 2.7). The upper gauge had the highest peak ~ 62 L s^{-1}, and the middle gauge and the lower gauge had peaks ~ 40 L s^{-1} (Fig. 2.7). The lower gauge peak

was broader compared to the upper gauge and the middle gauge peaks, and all three peaks were substantial departures from baseflow (Fig. 2.7).

In summary: discharge decreased moving downstream, hydrograph responses at the upper gauge and middle gauge were tightly coupled but hydrograph responses at the lower gauge were more disconnected from hydrograph responses at the upper gauge and the middle gauge, and rain events cause larger departures from baseflow at the lower gauge than at the upper gauge or the middle gauge

Groundwater Well Hydrometric Data

Depths to groundwater were typically greater than instrument completion depths in the mountain front recharge (MFR) zone. Figure 2.8B shows groundwater time series for south wells 2 (SW2) and 3 (SW3) along with local stream hydrograph time series. These wells were located in the middle of the MFR zone on a transect north (downstream) of the middle weir (Fig. 2.3B). SW2 was completed to 1.64 meters (m), and SW3 was completed to 0.98 m. Rocky soils limited completion depths. Due to shallow completion depths and significant depth to groundwater, there was rarely groundwater in these wells. The saturated zone began at some depth greater than 1.64 m on this transect. Groundwater levels in SW2 and SW3 were generally greater than the depth of the channel bed, resulting in a disconnected groundwater-stream system, ie. no saturated connection between the stream and the groundwater table. There was a small rise in groundwater levels in SW2 and SW3 during the last week of March/first week of April, 2004 which was likely driven by local snowmelt in the MFR zone.

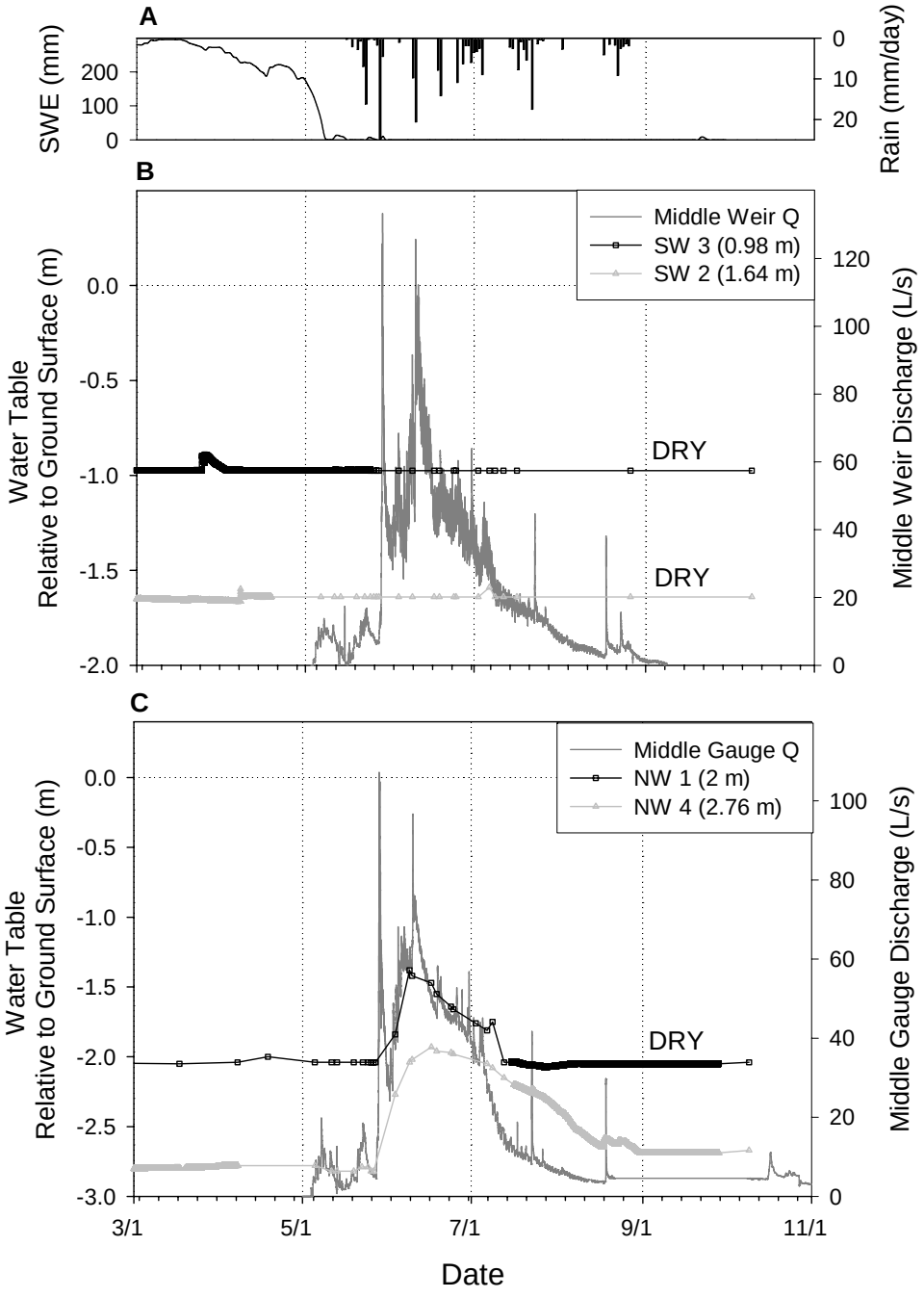

Figure 2.8. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 1 November, 2004; (B) time series water table dynamics for south well 2 (SW2) and SW3 (located in the middle of the mountain front recharge zone) along

with the local stream hydrograph; and (C) water table dynamics for north well 1 (NW1) and NW4 (located at the down stream edge of the mountain front recharge zone) along with the local stream hydrograph.

It is possible that infiltration was impeded by ice lenses or frozen soils which led to a perched water table. Soil temperature data shows that soils were frozen to depths approaching 1.2 meters during the winter and these soils rapidly thawed in early April (Fig. 2.9).

Figure 2.8C displays north well 1 (NW1) and north well 4 (NW4) groundwater time series along with local stream hydrograph time series. NW1 and NW4 were installed at the down stream end of the MFR zone (Fig. 2.3B) and completed to depths of 2 m and 2.76 m, respectively. Groundwater levels in these wells began to rise on 28 May. This rise in groundwater levels was coincident with a peak in local stream discharge, and appears to have been initiated by a rain event on 28 May. Subsequently, groundwater levels in NW1 and NW4 rose and fell with the stream hydrograph, which suggests stream seepage losses over this reach. Groundwater levels in NW4 receded more slowly than in NW1, however due to the shallow completion of NW1 a complete analysis of the falling limb of groundwater levels in this well was not possible.

Depths to groundwater in the valley bottom were shallow, and groundwater was typically at or near the ground surface in this zone. Figure 2.10 shows groundwater time series and local hydrograph time series for north wells 71 (NW71), NW72, NW102, and

NW103. The completion depths for NW71, NW72, NW102, and NW103 were 2.4 m,

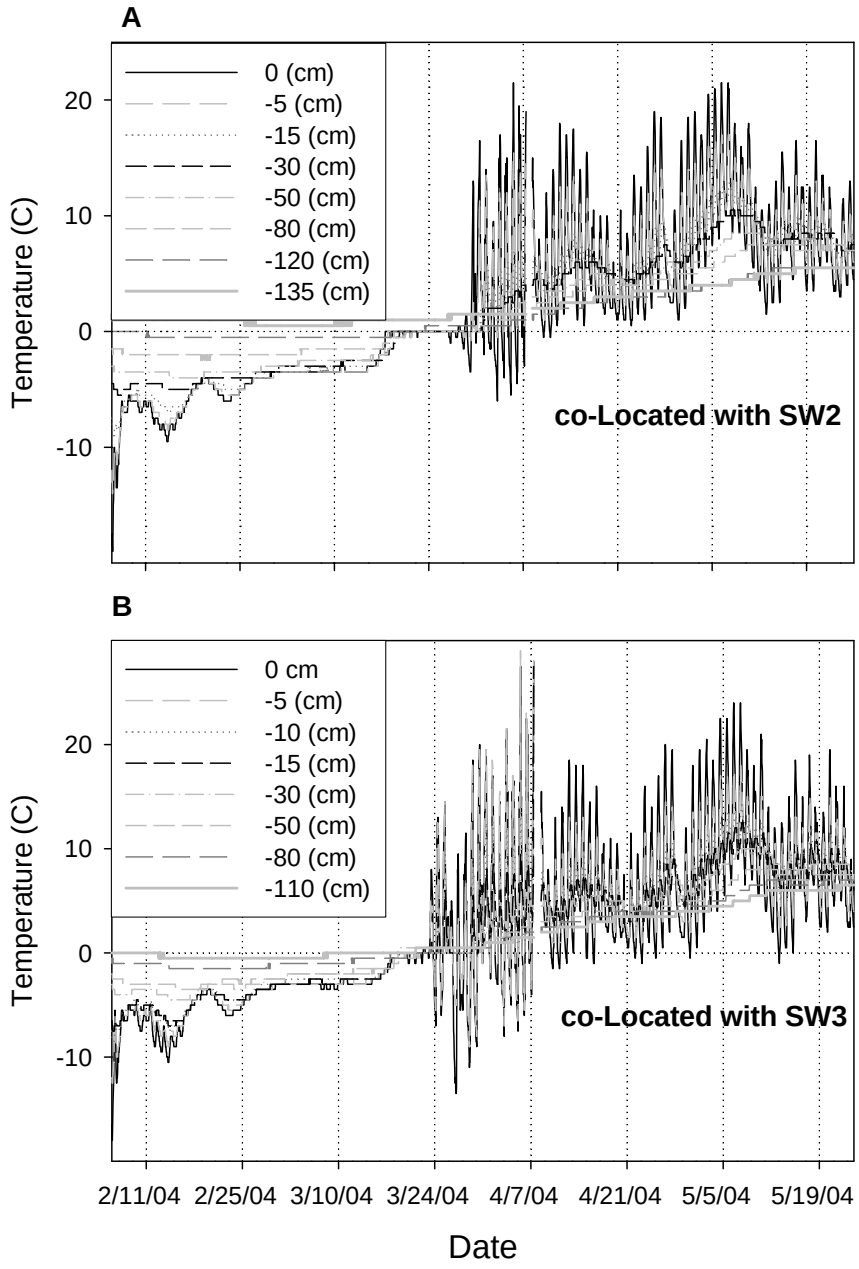

Figure 2.9. Soil temperature time series dynamics in the mountain front recharge zone during spring snowmelt. (A) Soil temperature nest co-located with south well 2 (SW2) in the middle of the mountain front recharge zone (MFR); and, (B) soil temperature nest co-located with south well 3 (SW3) in the middle of the MFR zone. Legends indicate the depth below ground surface of the temperature recording.

2.09 m, 2.5 m, and 2.12 m, respectively. A sharp rise in groundwater levels was measured in these wells on 20 March (Fig. 2.10). This increase in groundwater levels was likely driven by local snowmelt. This event contributed significantly to local groundwater recharge, and also initiated Humphrey Creek channel flow in the valley bottom at the lower gauge. Once channel flow was initiated, groundwater levels in this zone remained fairly constant throughout the season. A small rise in groundwater levels in NW72 was measured between 28 May and 7 June, and peaked on 5 June (Fig. 2.10B). A rain event on 28 May likely drove this increase in groundwater levels. Increased groundwater levels were not measured in NW71, NW102, or NW103. Groundwater levels in the valley bottom zone were relatively unresponsive to rain events and were particularly unresponsive to local stream discharge. Inputs to the groundwater table in this area appeared to be from local snowmelt, and deeper groundwater dynamics were not affected by surface processes or stream discharge. As groundwater levels in NW71 and NW72 began to decrease in early August, channel flow at the lower gauge in the valley bottom decreased abruptly.

Piezometeric Data

Completion depths of piezometers in the MFR zone were limited by rocky soils, and these piezometers were typically dry, despite being completed in the streambed.

Piezometers in the MFR zone included south piezometer 1 (SP1), south piezometer 2

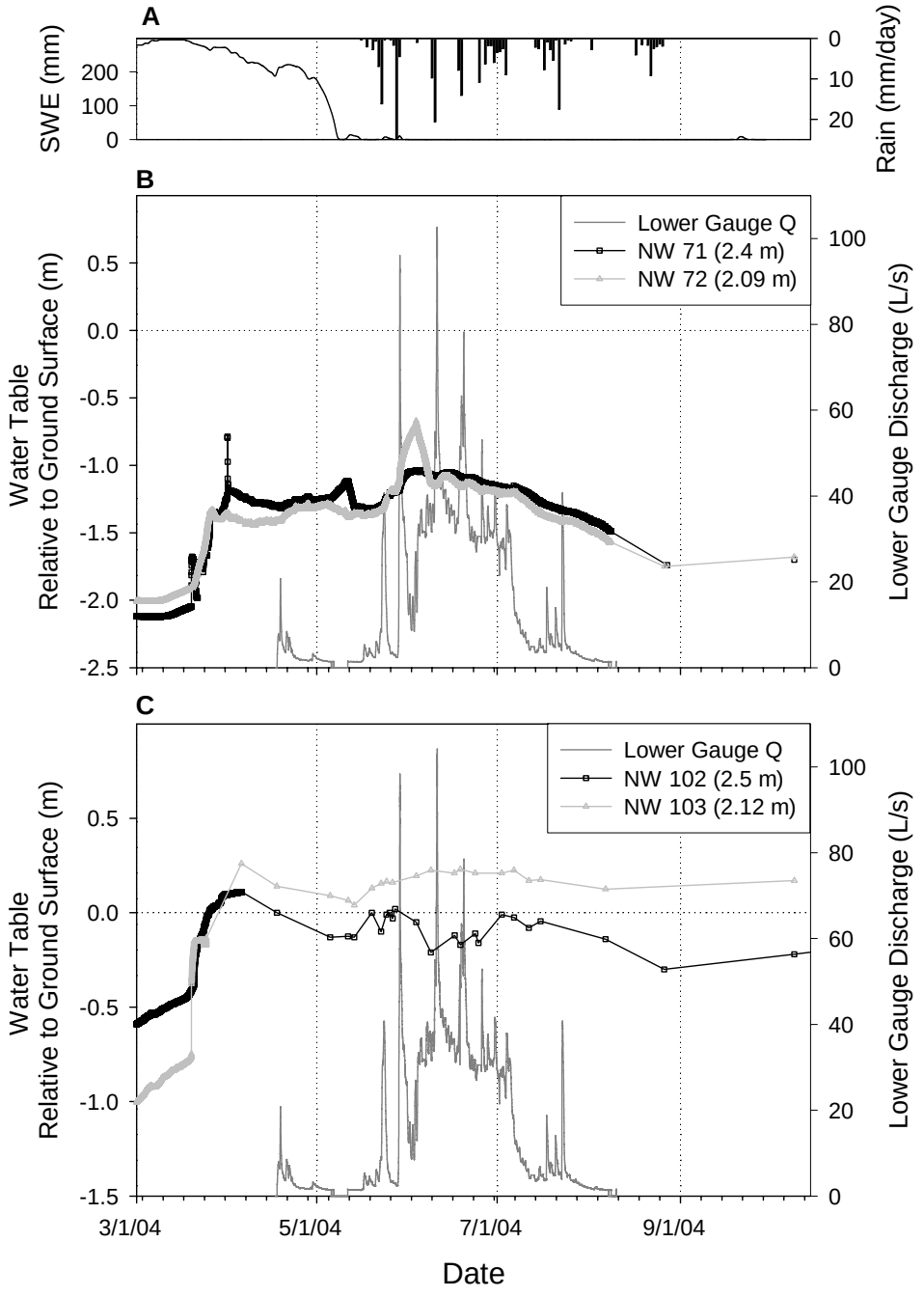

Figure 2.10. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 November, 2004; (B) time series water table dynamics for north well 71 (NW71) and NW72 (located in the valley bottom) along with the local

stream hydrograph; and, (C) water table dynamics for north well 102 (NW102) and NW103 (located at the Lower Red Rock Lake Edge) along with the local stream hydrograph.

(SP2), north piezometer 1 (NP1), and north piezometer 2 (NP2) which were completed to 0.87 m, 1.76 m, 0.8 m, and 1.75 m, respectively. SP1 and SP2 were located in the middle of the MFR zone, and NP1 and NP2 were located at the downstream end of the MFR zone (Fig. 2.3B). Groundwater was not observed in SP1 or NP1 over the duration of the study (Fig. 2.11). A small increase in groundwater total potential in SP2 was measured during the first week of May, but SP2 was dry at all other times during the study (Fig. 2.11). The rise in groundwater total potential in SP2 was coincident with declining snow water equivalent (SWE) in the mountain snow pack. Total potential in NP2 began to rise on 28 May and subsequently rose and fell with the local stream hydrograph suggesting groundwater recharge from stream seepage in this reach, along with inputs from snowmelt. Groundwater levels in the MFR zone were typically deeper than the channel bed, indicating hydraulic gradients out of the stream (stream water losses to groundwater).

Upward vertical groundwater gradients were observed in the valley bottom zone. North piezometer 61 (NP 61) and north piezometer 62 (NP 62) were installed as a nest in the valley bottom zone and were completed to 1.29 m, and 0.66 m, respectively. These piezometers were located half way between the downstream edge of the MFR zone and Lower Red Rock Lake (LRRL) (Fig. 2.3B). Time series of groundwater total potential

for NP61 and NP62 along with local stream hydrograph are shown in Figure 2.12B.

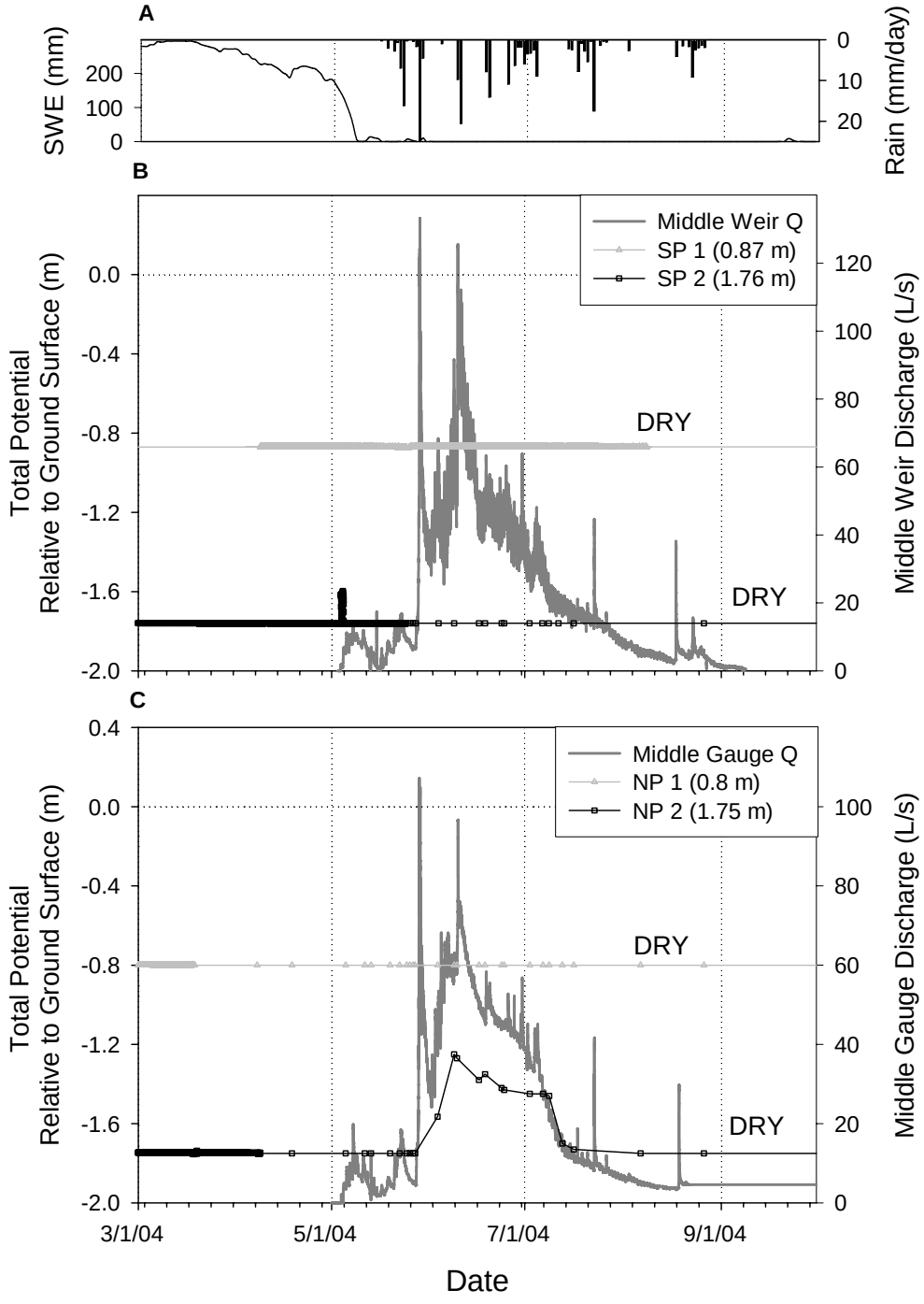

Figure 2.11. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 1 October, 2004; (B) time series groundwater total potential

dynamics for south piezometer 1 (SP1) and SP2 (located in the middle of the mountain front recharge (MFR) zone), along with the local stream hydrograph; and, (C) time series groundwater total potential dynamics for north piezometer 1 (NP1) and NP2 (located at the downstream edge of the MFR zone), along with the local stream hydrograph.

Total potentials in NP61 and NP62 were above ground surface during periods of channel flow in the valley bottom, and upward vertical gradients were measured during this period (Fig. 2.12). Groundwater total potentials in these piezometers peaked before local stream discharge, suggesting groundwater controls on stream discharge. Further, upward groundwater gradients were strongest during peak discharge in the valley bottom zone.

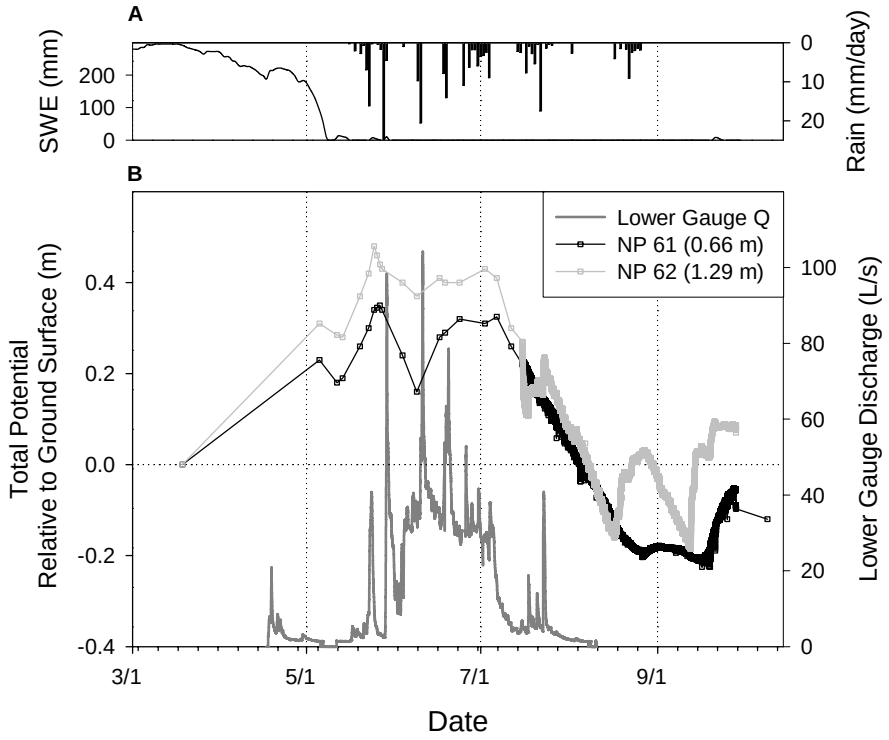

Figure 2.12. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 October, 2004; and, (B) time series groundwater total potential dynamics for north piezometer 61 (NP61) and NP62 (located in the valley bottom), along with the local stream hydrograph.

Upward gradients resulted in significant groundwater contributions to channel flow in the valley bottom reach of Humphrey Creek. As groundwater total potentials in NP61 and NP62 fell below the ground surface during the middle of August, channel flow ceased in the valley bottom. An increase in groundwater total potential was measured in NP62 between 18 August and 11 September, and peaked on 28 August (Fig. 2.12B). Rain events during this time frame may have initiated the increase in total potential measured in NP62 (rain data was not available after 1 September) (Fig. 2.12A). A much smaller increase in groundwater total potential was measured in NP61, which was not only a considerably smaller response than the response measured in NP62 but also was delayed by 10 days (Fig. 2.12B). A sharp increase in total potential began at NP62 on 12 September and at NP61 on 20 September (Fig. 2.12B). None of the increases in groundwater total potentials measured in NP61 and NP62 during this time frame led to re-initiation of valley bottom channel flow.

Farther downstream toward LRRL, groundwater gradients were predominantly lateral during the period of study (Fig. 2.13B & C). North piezometer 70 (NP70) and north piezometer 71 (NP71) were located three-quarters of the way from the MFR zone to the LRRL edge (Fig. 2.3B), and were completed to 1.18 m, and 1.91 m, respectively. A sharp rise in groundwater total potentials was measured in NP70 and NP71 on March, 20 (Fig. 2.13B). Lateral groundwater gradients persisted at this location from March through August of 2004 (Fig. 2.13B). Groundwater total potentials in NP70 and NP71

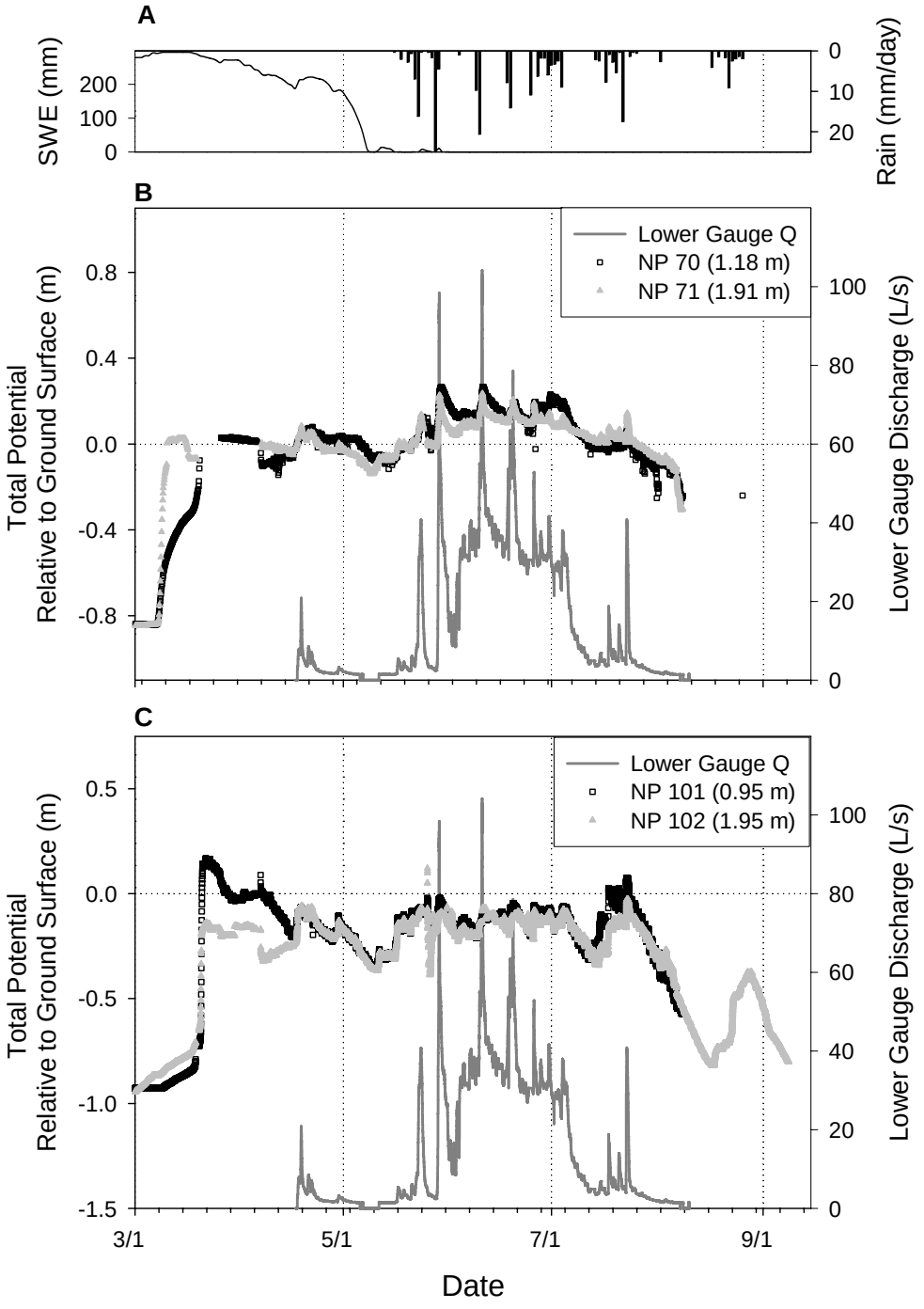

Figure 2.13. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 September, 2004; (B) time series groundwater total potential dynamics for north piezometer 70 (NP70) and NP71 (located in the valley bottom), along with the local stream hydrograph; and, (C) time series groundwater total potential

dynamics for north piezometer 101 (NP101) and NP102 (located at the Lower Red Rock Lake edge), along with the local stream hydrograph.

were consistently at or above ground surface during times of channel flow in the valley bottom. Total potentials in these piezometers rose before local stream discharge, suggesting groundwater controls on local stream discharge. As groundwater total potentials in NP70 and 71 dropped below the ground surface in mid-August, channel flow in the valley bottom ceased. North piezometer 101 (NP101) and north piezometer 102 (NP102) were located about 50 m from the LRRL edge in the valley bottom zone, and were completed to 0.95 m and 1.95 m, respectively (Fig. 2.3B). The dynamics of total potentials measured in these piezometers was very similar to the dynamics measured in NP70 and NP71. An abrupt rise in total potentials was measured on 23 March in NP101 and NP102 (Fig. 2.13C). Subsequently, total potentials remained fairly constant and lateral gradients persisted during the duration of local channel flow. Groundwater total potentials began to fall in NP101 and NP102 on 24 July, and local channel flow ceased on 10 August (Fig. 2.13C). Groundwater dynamics seemed to have a substantial impact local channel flow in the valley bottom. A rise in groundwater total potential was measured in NP102 between 22 August and 17 September, and peaked on 29 August (Fig. 2.13C). This rise in groundwater total potential coincided with a 22 August rain event but did not re-initiate local channel flow (Fig. 2.13A).

In summary: groundwater levels were deep in the MFR zone, shallow in the valley bottom; gradients were out from the stream in the MFR zone, and into the stream

or lateral in the valley bottom; and groundwater had a substantial impact on stream discharge in the valley bottom, but not in the MFR zone.

Stream Discharge and Local Groundwater
Affect on Lake Stage

LRRL stage did not control local stream discharge or near shore groundwater levels in the study area. Near shore groundwater levels rose before local stream discharge or LRRL stage (Fig. 2.14). The lower gauge discharge and LRRL stage began

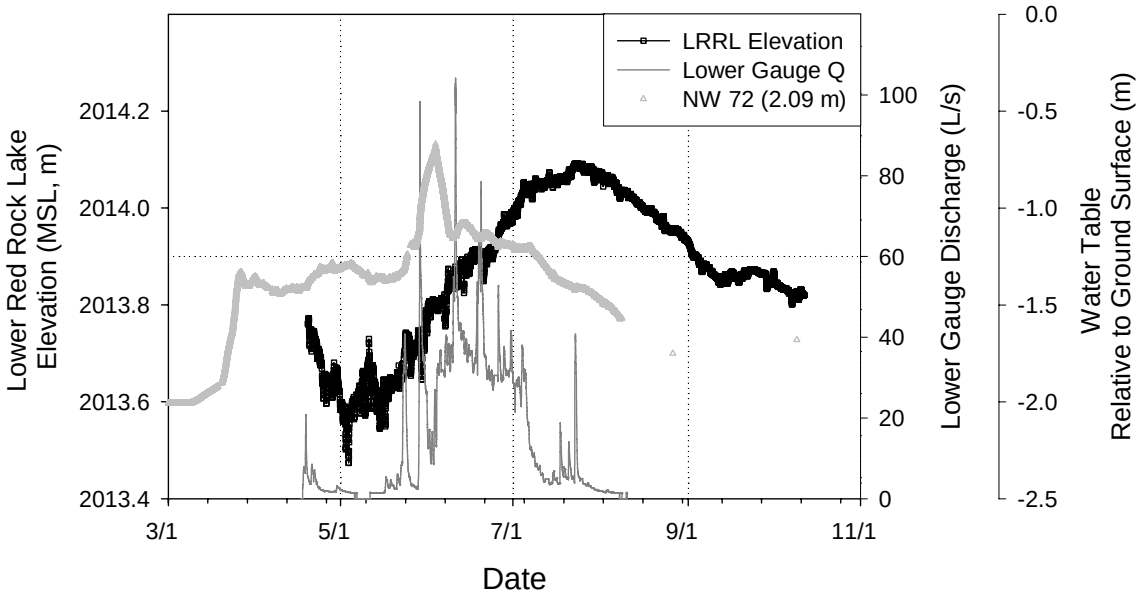

Figure 2.14. Time series of Lower Red Rock Lake (LRRL) elevation, lower gauge stream discharge (located ~80 meters upstream of the LRRL edge), and groundwater table dynamics for north well 72 (located ~200 meters upstream of the LRRL edge).

to increase near the same time, however stream discharge peaked 6 weeks prior to LRRL peak stage (Fig. 2.14). Local groundwater levels rose abruptly ~ 20 March, remained relatively constant through June, and began to decline in July. The timing of the near shore hydrology measured was groundwater levels peaked first, followed by stream

discharge, then LRRL stage (Fig. 2.14). Local groundwater was at peak levels from March through June, local stream discharge peaked on 10 June, and LRRL stage peaked on 25 July (Fig. 2.14). Local groundwater levels and local stream discharge had declined significantly, and continued to decline, by the time LRRL stage peaked (Fig. 2.14).

Stream Water Conductivity

Stream water specific conductance (SC) was measured at the upper gauge, the middle gauge, and the lower gauge. SC at the upper gauge and the middle gauge was similar (Fig. 2.4). The SC was ~ 0.2 mS cm^{-1} during the rising limb and peak of the hydrographs for both of these gauges (Fig. 2.4). The SC at the upper gauge and the middle gauge rose slightly during late season base flow (Fig. 2.4). Rain events caused sharp decreases in SC, due to increased contributions of low SC water to stream flow. The lower gauge early season SC was much higher compared to the upper gauge and the middle gauge (Fig. 2.4). SC was near 0.6 mS cm^{-1} when channel flow began in May at the lower gauge (Fig. 2.4). SC at the lower gauge was similar to groundwater SC. Valley bottom groundwater conductivity was ~ 0.6 mS cm^{-1} +/- 0.05 mS cm^{-1}. Stream SC at the lower gauge was ~ 0.6 mS cm^{-1} during early season (May) channel flow, decreased to ~ 0.3 mS cm^{-1} during peak discharge (June), and rose to ~ 0.5 mS cm^{-1} during late season baseflow (July) (Fig. 2.4).

Chemistry Data

Geochemical analysis of water samples was used to corroborate hydrograph separations based on SC (next section). Regression of milli-equivalents versus SC for

calcium (Ca), and magnesium (Mg) showed strong linear relationships; the R^2 for Ca was 0.949, and 0.932 for Mg (Fig. 2.15). Comparable results would have been obtained had

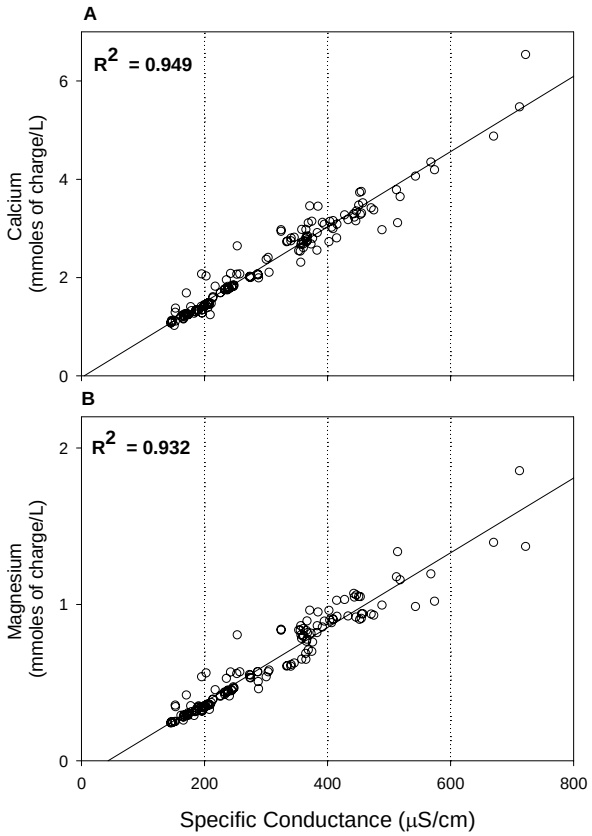

Figure 2.15. (A) Regression analysis of calcium milli-equivalents (mmole of charge/L) vs. specific conductance (µS/cm); and, (B) regression analysis of magnesium milli-equivalents (mmole of charge/L) vs. specific conductance (µS/cm).

hydrograph separations been based on any of these ion concentrations, however this would not have allowed real-time separations (10 minute intervals). Snap-shot-in-time separations were made using geochemical concentrations of groundwater and stream water samples, and were plotted with corresponding SC separations (Fig. 2.16). The geochemical snap-shot separations further validated hydrograph separations based on SC.

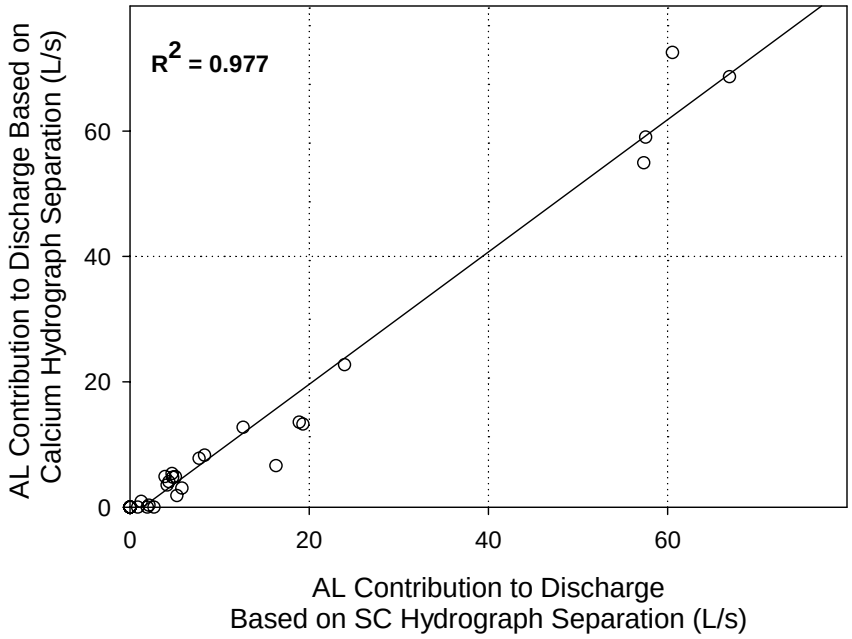

Figure 2.16. (A) Regression analysis of the calculated alpine runoff contribution to stream discharge using calcium milli-equivalents from stream and groundwater grab samples vs. the calculated alpine runoff contribution to stream discharge using specific conductance of the grab samples.

Hydrograph Separations and Uncertainty Analysis

Hydrograph separations allowed determination of the relative contributions of alpine and groundwater sources to stream discharge at the middle gauge and the lower gauge. I defined alpine water as water exiting the mountains as channel flow at the upper gauge. Real-time (10 minute interval) measurements of stream SC at the upper gauge were used to determine the signature of alpine water. The signature of groundwater was determined by averaging SC from ~ 100 groundwater samples, and was determined to be relatively constant at 0.6 mS cm^{-1} +/- 0.05 mS cm^{-1}. This value was chosen as the groundwater end-member because it represented an average signature of shallow valley

bottom groundwater, particularly where vertical groundwater gradients were upward. Resultant SC of stream discharge at the middle gauge and the lower gauge was measured real-time (10 minute intervals). This approach was developed following the methods of Gooseff and McGlynn (2005), and enabled real-time hydrograph separations from May, 2004 through August.

Uncertainty is displayed as error bars on the hydrograph separation time series (Fig. 2.17). Uncertainty was determined for each ten minute time step, but was plotted once daily at noon on the hydrograph separation time series. Error bars show that uncertainty in the separations is not confounding and does not affect interpretation.

Marked shifts in stream water composition (source water) were apparent between the middle gauge and the lower gauge (Fig. 2.17). Four month stream discharge totals at the middle gauge were composed predominantly of alpine water, whereas, water at the lower gauge stream flow was ~ 50% groundwater (Fig. 2.17).

Greatest groundwater contributions were measured at the middle gauge during the rain induced hydrograph peak on 28 May (Fig. 2.17B). From this time onward, including peak stream discharge, flow at the middle gauge was composed primarily of alpine water. In contrast, stream discharge at the lower gauge had substantial contributions from groundwater sources throughout the study period (Fig. 2.17C). During early season flow, groundwater sources dominated stream discharge contributions at the lower gauge. Rain induced peaks in discharge for the lower gauge occurring on 23 May, and 29 May were composed nearly entirely of groundwater. From 1 June, to 5 July, groundwater contributions were responsible for ~ 50% of stream discharge at the lower gauge (Fig. 2.17C).

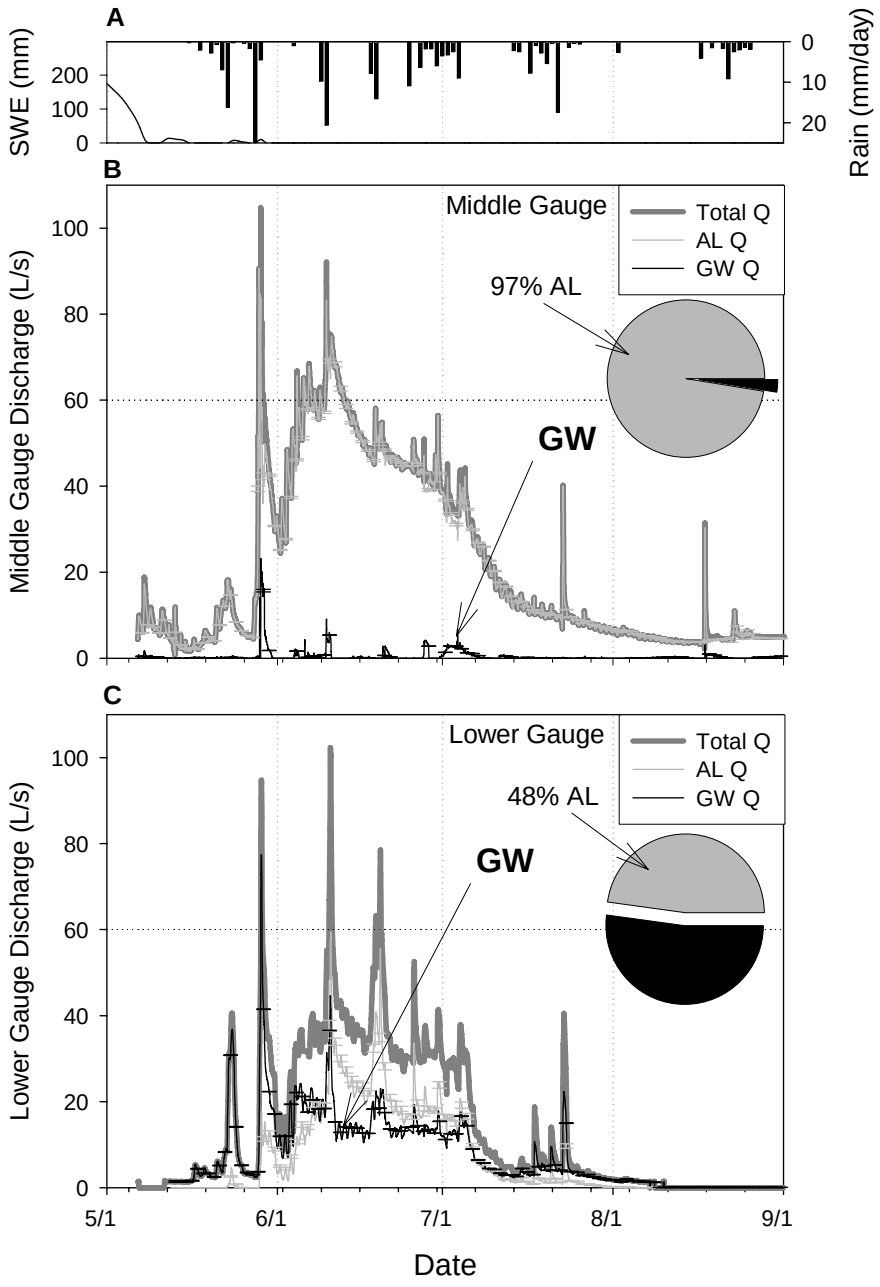

Figure 2.17. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 May, 2004 through 1 September, 2004. (B) Ten minute interval time series hydrograph separation for the middle gauge (located at the downstream edge of the mountain front recharge zone) into alpine runoff (AL) and groundwater (GW) contributions to stream discharge. Pie-chart represents the alpine runoff and groundwater contributions to total discharge over the four months. (C) Ten minute interval time series hydrograph separation for the lower gauge (located in the valley bottom at the upstream edge of Lower Red Rock Lake) into alpine runoff and groundwater contributions to stream

discharge. Pie-chart represents the alpine runoff and groundwater contributions to total discharge over the four months.

During early season flow, groundwater sources dominated stream discharge contributions at the lower gauge. Rain induced peaks in discharge for the lower gauge occurring on 23 May, and 29 May were composed nearly entirely of groundwater. From 1 June, to 5 July, groundwater contributions were responsible for ~ 50% of stream discharge at the lower gauge (Fig. 2.17C). Late season baseflow was strongly dominated by groundwater sources at the lower gauge (Fig. 2.17C). From 5 July, to 8 August, groundwater comprised nearly all of the water flowing in the channel at the lower gauge. This was in strong contrast to the hydrograph separation for the middle gauge where alpine contributions dominated throughout the season.

Over the period of stream flow at the middle gauge, groundwater contributions accounted for ~ 3% of total discharge, while alpine water contributions comprised ~ 97% of total discharge (Fig. 2.17B pie-chart). Conversely, groundwater contributions over the period of stream flow at the lower gauge were responsible for ~ 52% of the total discharge, while alpine water contributions comprised ~ 48% of the total stream discharge (Fig. 2.17C pie-chart). The shift in source water contributions to channel flow between the middle gauge and the lower gauge substantially altered the geochemistry of stream water, increased total discharge and lengthened the duration of valley bottom channel flow. Conversely, stream seepage losses in the MFR zone decreased total discharge at the middle gauge while contributing to groundwater recharge.

Two week discharge totals for the three gauges were determined and separated into groundwater and alpine water components for each two week period from the

beginning of May to the end of August. The upper gauge had the highest total discharge for all two week periods except the last two weeks of August, (Fig. 2.18). The upper gauge discharge was composed completely of alpine water as the gauge was located at the mouth of the mountain watershed, and I defined stream water exiting the mountains as alpine water. The middle gauge discharge totals were typically less than the upper gauge discharge totals, and greater than the lower gauge discharge totals. Groundwater contributions to channel flow at the middle gauge were minor. Weeks 3-4 had the greatest relative groundwater contributions to stream discharge at the middle gauge (Fig. 2.18). Early and late season base flow at the middle gauge was comprised almost entirely of alpine water, and minor groundwater contributions were measured during rain events.

The lower gauge stream discharge was comprised almost entirely of groundwater during weeks 1-2 (Fig. 2.18). A slightly higher alpine water contribution was evident during weeks 3-4 at the lower gauge, yet discharge was still primarily driven by groundwater contributions (Fig. 2.18). Groundwater and alpine water contributions to the lower gauge stream discharge during weeks 5-6 were nearly equal (Fig. 2.18). Alpine water contributions were greater than 50% at during weeks 7-8. Weeks 9-10 showed nearly equal contributions from alpine water and groundwater. Late season flow was comprised primarily of groundwater; the lower gauge stream discharge during weeks 11-12 was ~ 80% groundwater and 100 % groundwater during weeks 13-14 (Fig. 2.18). There was no channel flow at the lower gauge during weeks 15-16.

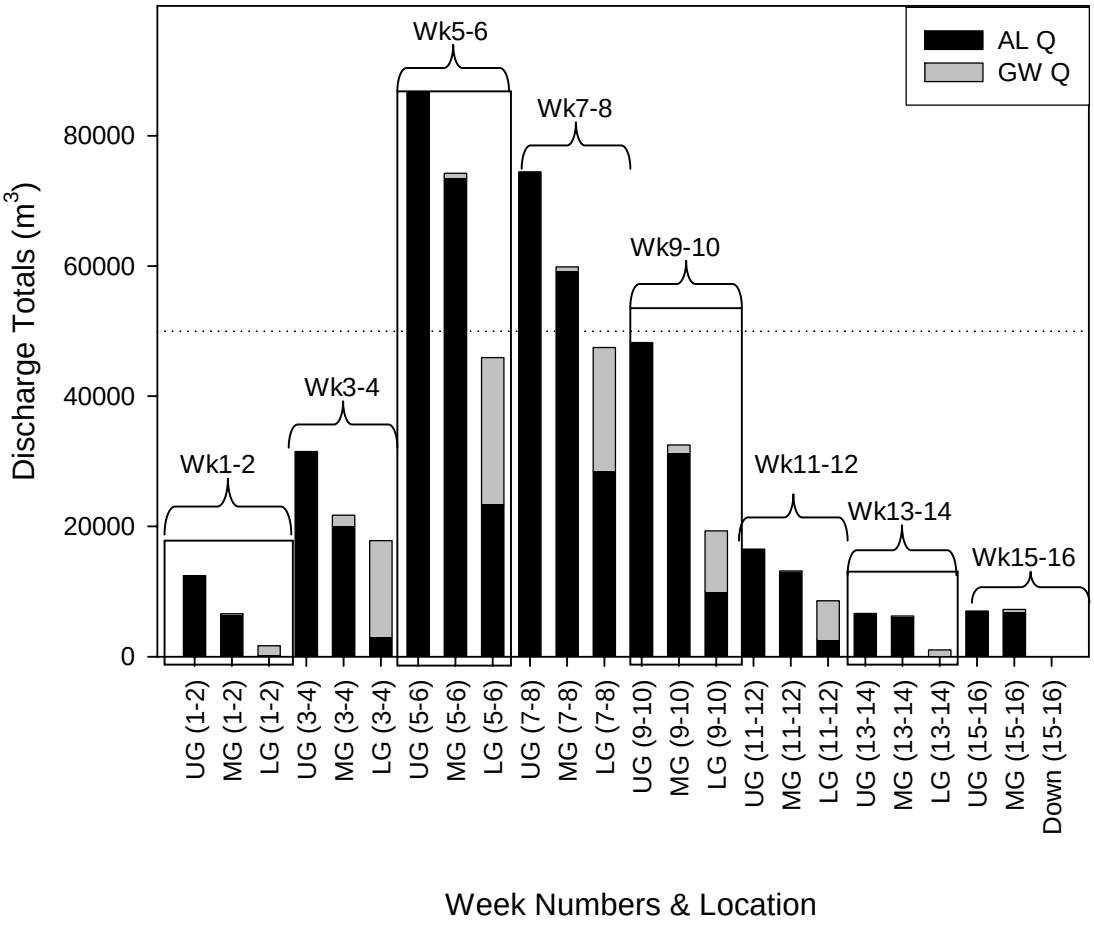

Figure 2.18. Two week discharge totals separated into alpine runoff (AL) and groundwater (GW) contributions to stream discharge for the upper gauge, middle gauge, and lower gauge. The upper gauge was located at the upstream edge of the mountain front recharge (MFR) zone and upper gauge stream discharge was defined as alpine runoff. The middle gauge was located at the downstream edge of the MFR zone, and the lower gauge was located in the valley bottom near the Lower Red Rock Lake edge. All measurements were made at ten minute intervals from 12 May, 2004 through 23 August, 2004.

Groundwater was a major component of valley bottom stream discharge but not MFR zone discharge. Groundwater contributed to MFR zone discharge during rain events, and baseflow was dominated by alpine water contributions. Alpine water

contributions to valley bottom discharge were increased during peak annual discharge, and baseflow was dominated by groundwater contributions.

Discussion

How do Alpine to Valley Bottom Transitions Impact Stream Discharge Magnitude and Timing?

As Humphrey Creek flowed through the mountain front recharge (MFR) zone and across the valley bottom, stream discharge decreased. Stream discharge was greatest at the mountain watershed outlet and least in the valley bottom. Discharge at the upper gauge was 10% of the annual average precipitation. Between 7 May, 2004 and 23 August, stream discharge was 63,005 m^3 greater at the upper gauge than the middle gauge, and 129,551 m^3 greater at the upper gauge than the lower gauge. Total discharge at the middle gauge was 77% of total discharge at the upper gauge, and total discharge at the lower gauge was 50% of total discharge at the upper gauge. Stream seepage losses contributed to evapotranspiration (ET), and soil moisture and groundwater recharge across the transition from alpine to valley bottom.

Stream losses in the MFR zone were partly driven by the physical disconnection between the stream and groundwater system (ie. no continuous zone of saturation between the stream and groundwater). When a discontinuity between the stream and groundwater exists, stream seepage will occur and the rate of loss will be a function of stream stage, wetted perimeter, hydraulic conductivity, and bed armoring (Niswonger et al., 2005). Stream seepage losses have been noted as an important source of groundwater recharge in the Basin and Range Province of the Western United States, where streams

exiting the mountains can lose the majority of their water as seepage (Niswonger et al., 2005). In the Humphrey Creek watershed, stream discharge at the downstream edge of the MFR zone was 77% of the stream discharge at the upstream edge of the MFR zone. Since there were minimal groundwater inputs to channel flow in this zone, I conclude that ~ 23% of stream water was lost as seepage across the MFR zone. The stream gauges in the MFR zone were separated by ~ 0.5 km, therefore, ~ 23% of the stream water exiting the mountain watershed was lost from the stream in the first 0.5 km. If we assume constant seepage losses across the MFR zone, ~ 126 m^3 of water per m of stream length (m^3/m) would have been lost from the stream between 7 May and 23 August. This is equal to 1.2 m^3/m/day of stream seepage losses contributing to groundwater recharge.

A significant amount of water was lost from the stream at the break in slope where the MFR zone met valley bottom. This break in slope, where two distinct landscape elements met, was an important location for stream seepage losses and groundwater recharge. Channel slope decreased and fine sediment deposition was evident. In this area Humphrey Creek becomes a multiple thread channel that flows through sedges, rushes, grasses and willows. Occasionally surface flow was not observed in the area where the MFR zone and the valley bottom zone met. In this area surface water had four possible fates: 1) it continued to flow across the surface to where Humphrey Creek was again a single channel; 2) it infiltrated and contributed to soil moisture and groundwater recharge; 3) it was transpired by marsh plants; and, 4) it evaporated from the surface. The wetland-marsh area decreased the velocity of Humphrey Creek stream water, which increased the time available for interaction between stream water and the surrounding soil environment. This was a function of

decreased slope and increased surface roughness. Such a situation provides increased opportunity for surface water infiltration to the subsurface, even with low hydraulic conductivities that may be expected in fine sediment depositional areas. The MFR zone stream gauging, groundwater levels, and hydrograph separation support the possibility that MFR zone stream seepage losses are an important source of groundwater recharge to basin aquifers adjacent to mountain watersheds.

Short time-scale hydrograph response to rain events was similar for both the valley bottom and the MFR zone. Although initial hydrograph responses were nearly synchronous, the rain induced hydrograph peaks in the valley bottom were broader than those in the MFR zone. This is likely due to the large groundwater reservoir connected to the stream in the valley bottom and greater upstream contributions. During rain induced discharge peaks, rain, groundwater, and upstream channel flow could contribute to increased stream discharge in the valley bottom. However, in the MFR zone groundwater could not contribute to increased stream discharge due to the disconnected stream-groundwater system. Valley bottom groundwater contributions to stream discharge combined with in-channel travel time of upstream storm runoff, would cause broader hydrograph peaks in the valley bottom than in the MFR zone.

Peak annual discharge was snowmelt driven in the MFR zone and the valley bottom of the Humphrey Creek watershed. However, peak annual discharge occurred one day later in the valley bottom than in the MFR zone. This was likely due to in-channel travel time from the MFR zone to the valley bottom. The valley bottom annual discharge peak was broader than the MFR zone peaks. This was likely due to the connected stream-groundwater system in the valley as opposed to the disconnected

stream-groundwater system in the MFR zone. I suggest a similar mechanism broadens the snowmelt driven peak and the rain driven hydrograph peaks.

These data suggest that in-channel travel times delay snowmelt driven hydrograph responses from the MFR zone to the valley bottom, and stream-groundwater exchanges and in-channel travel times broaden hydrograph responses to snow and rain driven hydrograph peaks in systems where the stream and groundwater are connected.

How does Stream-Groundwater Exchange Change Over Alpine to Valley Bottom Transition Zones?

Exchange between stream water and local groundwater are dynamic both spatially and temporally. Stream-groundwater exchanges occur at both small and large scales. Small scale exchanges occur along centimeter-long flowpaths, and timescales of seconds to minutes; while, larger scale exchanges occur over hundreds of meters and timescales of days to years (Harvey et al., 1996). At meso-scales, stream-groundwater exchange is impacted by a range of factors including channel sinuosity, width, slope, and aquifer penetration (Sharp, 1977; Larkin and Sharp, 1992); stream water flow through point bars; (Vervier et al., 1993; Wroblicky et al., 1998); temporal variations in groundwater height and stream stage (Pinder and Sauer, 1971); the geometry of the surrounding aquifer, water balance, and hydraulic properties (Freeze and Witherspoon, 1967, 1968; Winter, 1995); and channel changes from constrained to unconstrained (Stanford and Ward, 1993; Fernald et al., 2001). Constrained reaches of the stream channel are often groundwater discharge zones, whereas unconstrained reaches are often groundwater recharge zones (Gregory et al., 1991; Stanford and Ward, 1993).

This research investigated larger scale stream-groundwater exchange and identified groundwater recharge and groundwater discharge zones. Groundwater recharge and discharge zones were associated with specific landscape elements. Groundwater recharge was most pronounced in the upper reaches of the study area (the MFR zone), while groundwater discharge was associated with the valley bottom zone. Although recharge consistently occurred in the MFR zone, and groundwater discharge occurred consistently in the valley bottom, the rates of recharge/discharge were temporally variable.

The area from the outlet of the mountain watershed to the beginning of the valley bottom was a groundwater recharge zone and was defined as the MFR zone. Recharge rates in the MFR zone were highest during early season flow through peak discharge. I suggest that this was due to higher stream stage, lower soil moisture, and deeper groundwater levels during early season flow. Since the stream in the MFR zone was losing water between the upper gauge and the middle gauge, the stream water chemistry remained relatively constant between these two gauges. Consistent stream water chemistry across the MFR zone corroborates the stream hydrograph, groundwater level, and piezometric data that indicated stream seepage. Losing streams which do not have input of groundwater do not have mixing of multiple source waters that would lead to changing chemistry across a reach. The stream water flowing across the MFR zone was from the same source, the alpine zone of the watershed.

The valley bottom zone, the area between the MFR zone and the Lower Red Rock Lake (LRRL) edge, was a groundwater discharge zone. Upward and lateral groundwater gradients were observed, and groundwater levels in the valley bottom zone constrained

the stream channel. The hydrology in the valley bottom was distinct from the hydrology in the MFR zone. Specifically, instead of the stream supplying water to the groundwater system, as in the MFR zone, the opposite occurred in the valley bottom. Groundwater inputs to the stream channel drove stream discharge and a critical groundwater level was necessary to sustain channel flow. While alpine runoff was the major input to channel flow in the MFR zone, groundwater was the major input to channel flow in the valley bottom. Since substantial amounts of water were lost from Humphrey Creek before the stream reached the valley bottom, another source of water was necessary for channel flow. When groundwater levels decreased below a threshold value, stream discharge in the valley bottom ended abruptly. This suggests that water exiting the mountains was not adequate to sustain valley bottom channel flow.

Groundwater inputs to the stream channel led to mixing of alpine water inputs and groundwater inputs to valley bottom stream discharge. This altered the chemistry of stream water flowing downstream across the valley bottom zone. Stream water in the valley bottom had a chemical signature closer to that of groundwater than alpine water, particularly during baseflow. Harvey et al. (1996) noted timescales of years for stream-groundwater exchange on larger spatial scales. This coupled with the small mixing volume of alpine water compared to the large mixing volume of valley bottom groundwater suggests that the bulk of alpine water that exits the stream will have obtained a groundwater signature by the time it re-enters the stream channel. This caused stream water chemistry to be substantially different over a relatively a short distance of 1.5 km from MFR zone to the valley bottom. Distinct hydrologic systems from the MFR

zone to the valley bottom impacted stream hydrograph response, stream-groundwater exchange, and stream water chemistry.

What are the Relative Proportions of Alpine and Groundwater Inputs to Stream Discharge in Humphrey Creek from the MFR Zone to the Valley Bottom?

Geochemical tracers are powerful tools for determining the proportions of various source water contributions to stream flow and have been applied worldwide across a full range of environmental conditions (Pinder and Jones, 1969; Sklash and Farvolden, 1979; McDonnell et al., 1990; Bonnell, 1993; Mullholland, 1993; Harris et al., 1995; McGlynn et al., 1999).

Gooseff and McGlynn (2005) demonstrated that specific conductance (SC) can be substituted for geochemical tracers in hydrograph separations. I used SC to develop real-time hydrograph separations and was able to determine the relative proportions of alpine water and groundwater contributions to stream discharge at the middle gauge and the lower gauge at 10 minute intervals.

Stream discharge in the MFR zone was dominated by alpine water in 2004. Alpine water was responsible for ~ 97% of the total discharge at the middle gauge. This corroborates hydrometric data which suggested that Humphrey Creek was losing over this reach. Groundwater inputs to stream discharge occurred during rain events at the middle gauge. This suggests that rain events displaced groundwater into the stream channel. More specifically that rain increased groundwater levels and groundwater gradients toward the stream. After rain ended, groundwater contributions to channel flow decreased to ~ 0% of total discharge. Due to the lack of groundwater inputs to stream

flow in the MFR zone, the difference in discharge between the upper gauge and the middle gauge was ~ equal to the stream losses that occurred over this reach. Furthermore, the chemistry of stream water across the MFR zone was relatively constant due to the lack of groundwater source water contributions to stream discharge.

In contrast to the hydrology in the MFR zone, groundwater contributed ~ 52% of the total discharge at the lower gauge in 2004. This corroborated hydrometric data (wells, and piezometers) which suggested that Humphrey Creek was gaining over this reach. Hydrograph separations allowed me to determine how much of the alpine water that exited the mountains reached the valley bottom as channel flow. For instance, the upper gauge total discharge was 129,551 m^3 more than the lower gauge total discharge in 2004. However, by separating the lower gauge total discharge into alpine water and groundwater components, we find that alpine discharge at the upper gauge was 202,214 m^3 greater than the alpine discharge at the lower gauge. Although the lower gauge total discharge equaled ~ 50% of the total discharge at the upper gauge, in terms of the alpine water component the lower gauge discharge equaled only ~ 24% of the upper gauge discharge. Groundwter contributions to valley bottom stream discharge not only increased the amount of discharge but also substantially altered the chemistry of the stream water in the valley bottom compared to MFR zone stream water. Valley bottom stream water was similar in geochemical signature to valley bottom groundwater, while MFR zone stream water was similar to alpine water. This suggests that stream-groundwater exchange and groundwater inputs to stream discharge are an important mechanism in valley bottom stream flow generation and that local groundwater chemistry largely dictates the chemistry of stream water in gaining valley bottom streams.

Conclusions

Stream and groundwater hydrometric data coupled with geochemical hydrograph separations in the Humphrey Creek watershed of southwestern Montana suggest that:

(1) Humphrey Creek recharged groundwater in the mountain front recharge (MFR) zone, and stream seepage losses were an important mechanism for valley bottom groundwater recharge,

(2) Valley bottom groundwater was the predominant source of valley bottom stream discharge, and sustained channel flow,

(3) Stream-groundwater exchange in the valley bottom attenuated stream hydrograph response and altered stream water chemical composition,

(4) Spatially and temporally dynamic stream-groundwater exchange is important for valley bottom aquifer status, hydrograph response to snow and rain inputs, and can determine stream water chemistry.

A better understanding of large scale stream-groundwater exchange is important to hydrologists, biogeochemists, and ecologists. This research provides insight into the impacts that large scale stream-groundwater exchanges can have on watershed hydrologic responses and their potential impact on the timing, quantity, and chemistry of water moving through a watershed; which has implications for biogeochemical cycling and

ecosystem functioning. To continue to improve the understanding of stream-groundwater exchange and their impact on watershed hydrology, biogeochemistry and ecosystem processes it is imperative that further studies of large scale stream-groundwater exchange be undertaken. The results presented in this paper highlight the necessity of a combined approach to the study of dynamic stream-groundwater exchange.

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CHAPTER 3

SUMMARY

The impacts that large scale stream-groundwater exchanges have on watershed hydrologic response and stream water chemistry are poorly understood. A better understanding of large scale stream-groundwater exchange is important to hydrologists, biogeochemists, and ecologists. This research provides insight into the impacts that large scale stream-groundwater exchanges have on watershed hydrologic responses and their impact on the timing, quantity, and chemistry of water moving through the watershed; which has implications for biogeochemical cycling and ecosystem functioning.

In this study I combined stream and groundwater hydrometric data and geochemical hydrograph separations in the Humphrey Creek watershed in southwestern Montana to investigate the following questions:

(1) How do alpine to valley bottom transitions impact stream discharge magnitude and timing?

(2) How does stream-groundwater exchange change over alpine to valley bottom transition zones?

(3) What are the relative proportions of alpine and groundwater inputs to stream discharge in Humphrey Creek from the MFR zone to the valley bottom?

Combined methods allowed me to investigate dynamic, large scale stream-groundwater exchange, and these results suggest that:

(1) Humphrey Creek recharged groundwater in the mountain front recharge (MFR) zone, and stream seepage losses were an important mechanism for valley bottom groundwater recharge,

(2) Valley bottom groundwater was the predominant source of valley bottom stream discharge, and sustained channel flow,

(3) Stream-groundwater exchange in the valley bottom attenuated stream hydrograph response and altered stream water chemical composition,

(4) Spatially and temporally dynamic stream-groundwater exchange is important for valley bottom aquifer status, hydrograph response to snow and rain inputs, and can determine stream water chemistry.

MFR has been noted as being a major to dominant mechanism of groundwater recharge to inter-mountain basins in semi-arid regions (Manning and Solomon, 2003). Furthermore, it has been suggested that stream seepage losses in the MFR zone are a major contributor to MFR (Niswonger et al., 2005). These data suggest that seepage losses to groundwater across the MFR zone are an important source of groundwater recharge. Over the course of study ~23% of the MFR zone discharge was lost as seepage losses, which equaled a recharge rate of 2.3 m^3/m/day. MFR zone seepage losses may be integral in maintaining valley bottom aquifer storage state.

Valley bottom channel flow was dominated by groundwater inputs. Groundwater inputs to stream discharge in the valley bottom were responsible for ~52% of stream flow over the period of study. MFR of valley bottom groundwater sustained valley aquifer storage state, which in turn contributed to valley bottom stream flow. It has been noted

that increased groundwater withdrawals and groundwater depletion has led to land subsidence, decreased in-stream flows, and loss of riparian habitat (Hogan et al., 2004). A critical groundwater height was necessary to sustain valley steam flow in Humphrey Creek, which supports the idea that adequate aquifer storage is necessary for maintenance of in-stream flow and riparian habitat.

The exchange of water between streams and groundwater has been noted as an important mechanism involved in solute and contaminant transport (Ren and Packman, 2005); dissolved organic carbon (DOC) cycling (Wagner and Beisser, 2005); lotic ecosystem functioning (Wroblicky et al., 1998); and, water resource management (Oxtobee and Novakowski, 2002). However, many stream-groundwater exchange studies have focused on small spatial and temporal scale interactions. This larger scale research demonstrated that changing source waters can substantially impact stream chemistry over relatively short distances. Specifically, increased groundwater contributions to stream flow moving across the valley floor changed the stream water chemical signature from an alpine to a valley bottom groundwater signature. This has implications for solute transport, and suggests that substantial time may elapse between the time that a parcel of water exits the stream to when it re-enters.

As populations in arid to semi-arid regions continue to grow and demands on stream and groundwater resources increase it becomes of greater importance to understand MFR and watershed scale stream-groundwater exchanges. Currently, this understanding is incomplete and future research needs to continue to improve the understanding of MFR, large scale stream-groundwater exchange, and the impacts these have on valley bottom hydrology and stream chemistry.

This research provides insight into the impacts that large scale stream-groundwater exchanges have on watershed hydrologic responses and their impact on the timing, quantity, and chemistry of water moving through the watershed; which has implications for biogeochemical cycling and ecosystem functioning. To continue to improve the understanding of stream-groundwater exchange and their impact on watershed hydrology, biogeochemistry, and ecosystem processes it is imperative that further studies of large scale stream-groundwater exchange be undertaken. Further, the results presented in this paper highlight the necessity of a combined approach to the study of dynamic stream-groundwater exchange.

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APPENDICES

APPENDIX A

FIVE DAY DISCHARGE TOTAL

Appendix A, Table 1. Five day discharge totals for the upper gauge (UG), middle gauge (MG), and lower gauge (LG). Discharge (Q) is broken into total five day discharge, and contributions from alpine (AL) and groundwater (GW).

5 Day Time Series	UG Total Q (m3)	MG Total Q (m3)	LG Total Q (m3)	UG - MG (Total Q, m3)	UG - LG (Total Q, m3)	MG - LG (Total Q, m3)	UG - MG (Alpine Q, m3)	UG - LG (Alpine Q, m3)	MG Alpine Q (m3)	MG GW Q (m3)	LG Alpine Q (m3)	LG GW Q (m3)
1	6594	3870		2724			2877		3716	154		
2	2636	1405	574	1231	2062	831	1241	2636	1395	10	0	574
3	5491	2357	1597	3133	3894	760	3186	5491	2305	52	0	1597
4	7484	3715	5493	3769	1991	-1778	3810	7235	3674	42	249	5244
5	17328	13870	9726	3459	7602	4144	4961	15128	12367	1502	2201	7526
6	23573	16807	8474	6766	15099	8334	6872	21179	16701	106	2394	6080
7	28661	26442	15569	2220	13092	10873	2450	21810	26212	230	6851	8718
8	33144	27642	20484	5501	12659	7158	5818	20358	27325	317	12785	7699
9	27960	21817	18695	6143	9265	3122	6185	16052	21775	42	11908	6787
10	23446	18273	13341	5173	10105	4932	5372	15684	18073	200	7762	5579
11	19258	16416	12602	2843	6656	3814	3126	11941	16132	284	7317	5285
12	20861	16510	13147	4351	7714	3363	5177	13441	15684	826	7420	5727
13	19345	11841	6581	7504	12764	5260	7728	16017	11616	224	3328	3253
14	10064	6598	2162	3466	7902	4436	3569	9167	6495	103	897	1264
15	6976	4936	2800	2040	4176	2136	2083	6104	4893	43	872	1928
16	6073	4742	4449	1331	1624	293	1336	4542	4737	6	1532	2917
17	3925	3441	1464	484	2461	1977	500	3612	3424	16	313	1151
18	2907	2752	828	155	2078	1923	157	2844	2750	2	63	765
19	2282	2216	561	66	1721	1655	108	2270	2174	43	12	549
20	1927	1727	22	200	1906	1706	288	1925	1640	87	3	19
21	2476	2097	0	378	2476	2097	487	2476	1989	108	0	0
22	2304	2235	0	69	2304	2235	164	2304	2140	94	0	0
Sum =	274714	211709	138569	63005	129551	69270	67496	202214	207218	4491	65906	72663

APPENDIX B

SALT TRACER EXPERIMENT

Injected salt tracers are a useful tool for tracking particle movement through a watershed and have been used in numerous watershed studies (Bencala and Walters, 1983; Bencala et al., 1983; D'Angelo et al., 1993; Harvey and Bencala, 1993; Laenen and Bencala, 2001; Gooseff and McGlynn, 2005). Chloride is a suitable choice as a tracer because it is quite soluble, has very low natural concentration in the stream, is not biological or physical active over experimental time-scales, is easy to detect, and not harmful to the environment (Dingman, 2002). Furthermore, the concentration of Cl in the stream can be determined by developing a calibration curve for the relationship between conductivity and Cl concentration.

I applied salt tracer experiments over numerous stream reaches in Humphrey Creek (HC) during May, June, July, and August, 2004. To investigate GW-SW exchange in the valley bottom I injected NaCl as a slug above the lower gauge (LG) and collected breakthrough curve (BTC) data at the LG with a Campbell CR10X on 5 second intervals. To investigate GW-SW exchange in the MFR zone I injected sodium chloride (NaCl) as a slug above the upper gauge at the upstream edge of the mountain recharge (MFR) zone. BTC's were gathered at five downstream locations during MFR zone injections. Breakthrough data was collected at the upper gauge, the middle weir, a transect between the road and middle weir (referred to as south transect 1), a transect between the road and the middle gauge (referred to as north transect 0), and at the middle gauge. Data was collected at the three most upstream locations (the upper gauge, the middle weir, and south transect 1) with Campbell data loggers and Campbell CS547A conductivity and temperature probes at five second intervals. At the two most downstream locations

(north transect 0, and the middle gauge) data was collected with a YSI model 63 hand held pH, conductivity and temperature probe at ten second intervals.

I sought to use these data to determine the amount of water lost from or supplied to the stream over each reach. Breakthrough data can be used in conjunction with discharge data from stream gauges to quantify gains and losses over stream reaches by applying a mass balance technique. By knowing the amount of mass recovered at each location, the amount of gain or loss to or from the stream over a stream reach can be determined. If there is 100% recovery (no loss) gains can determined by difference between discharges.

Due to the complex nature of stream-GW exchange in Humphrey Creek this technique was inadequate for determining gains and/or losses. Losses of water from the stream coupled with error in discharge measurements made salt injection experiments difficult. This would have been another line of evidence to investigate the gains and losses to and from the stream and used in conjunction with stream hydrographs and hydrograph separations. An improved technique would be to use multiple injections. The method would combine short-reach and longer-reach injections. Short-reach injections would allow one to accurately determine stream discharge at multiple locations. Data from longer-reach injections could then be used in conjunction with salt discharge data to more accurately assess gains and/or losses over a particular reach.

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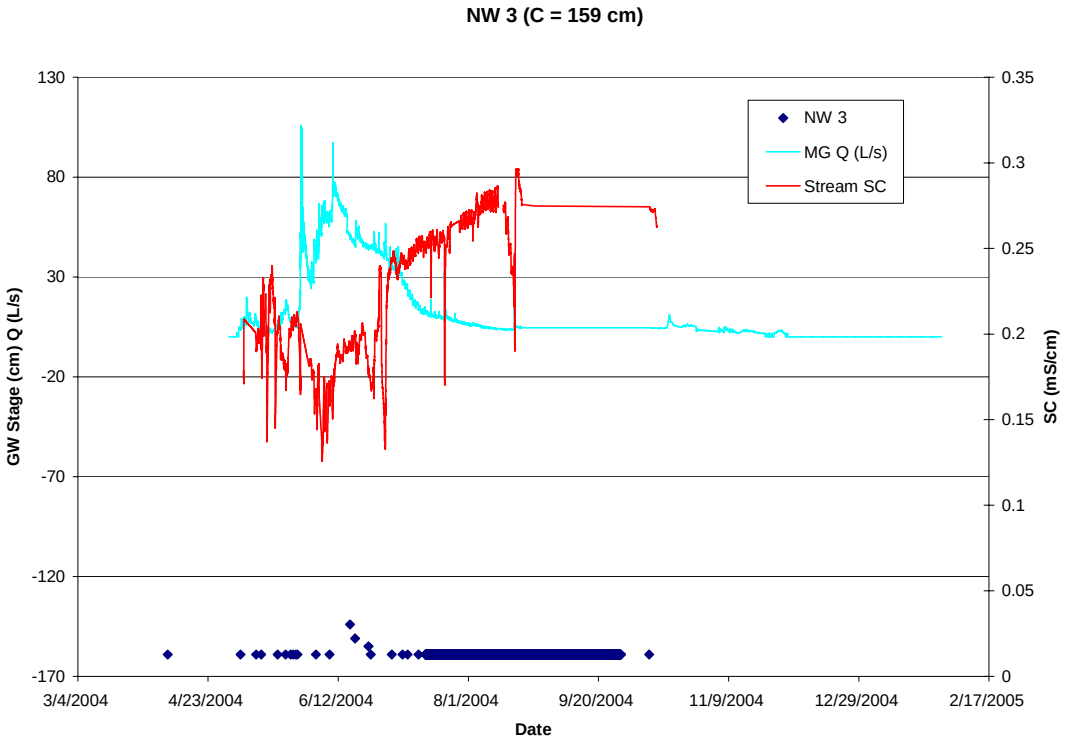
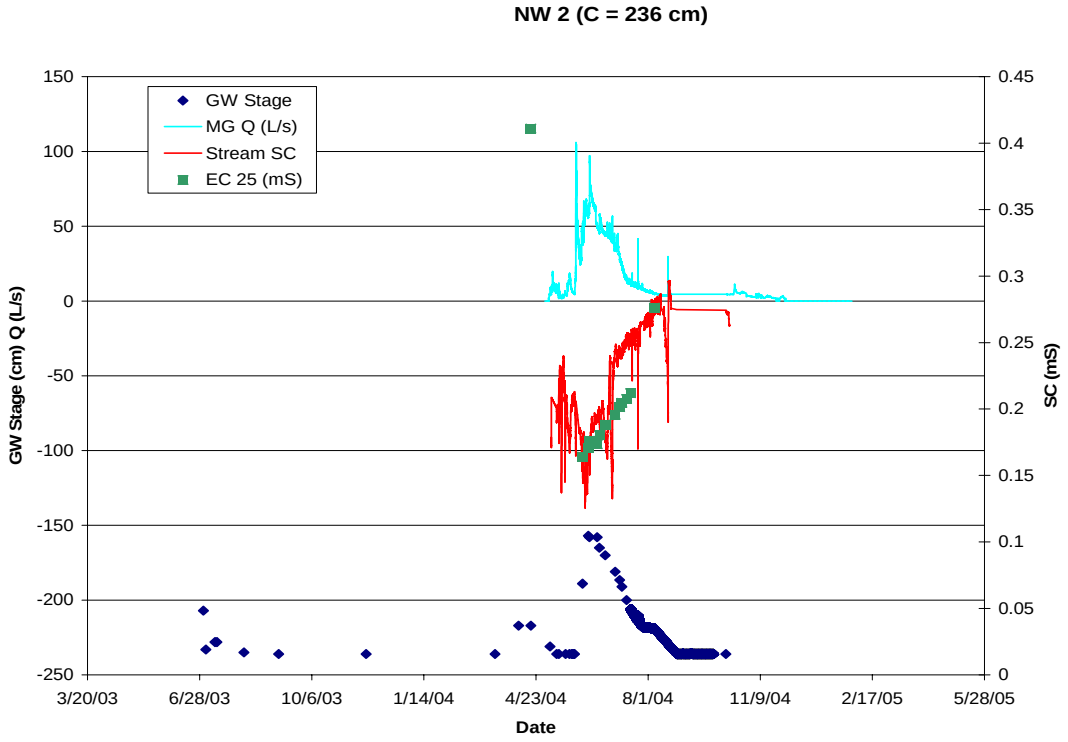
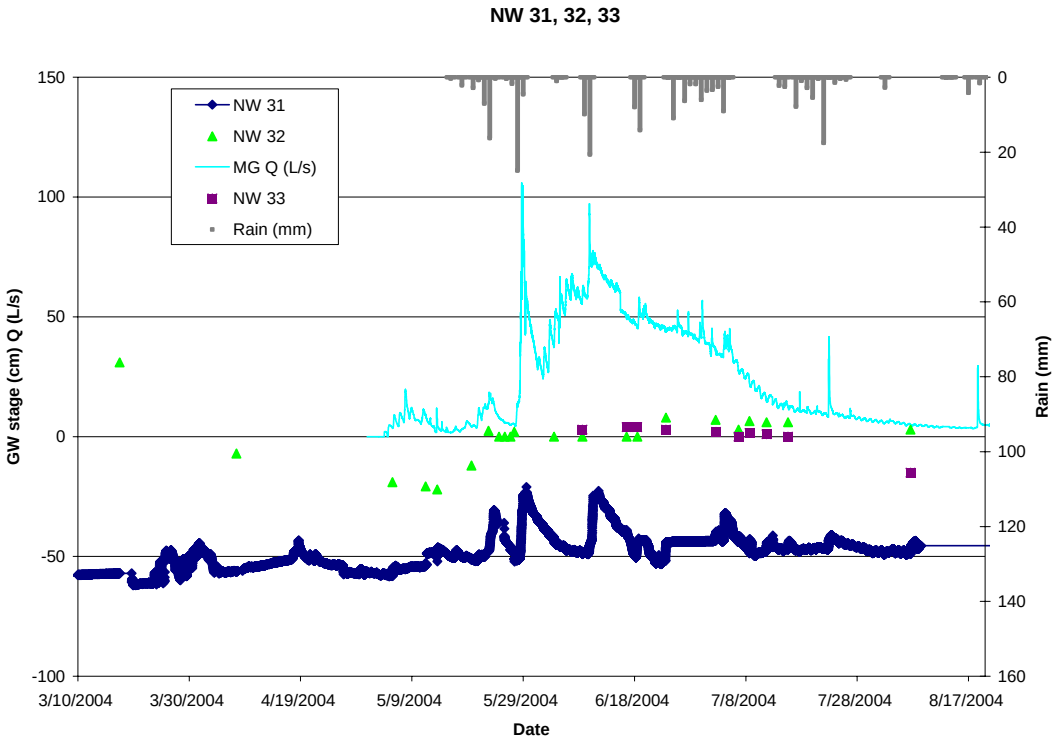
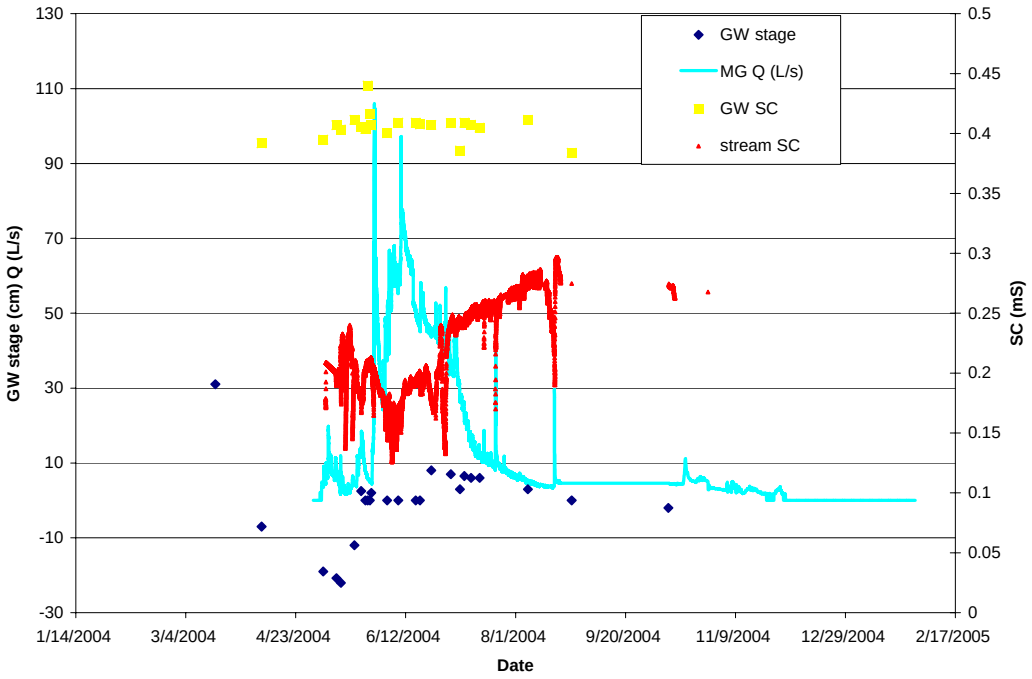
APPENDIX C

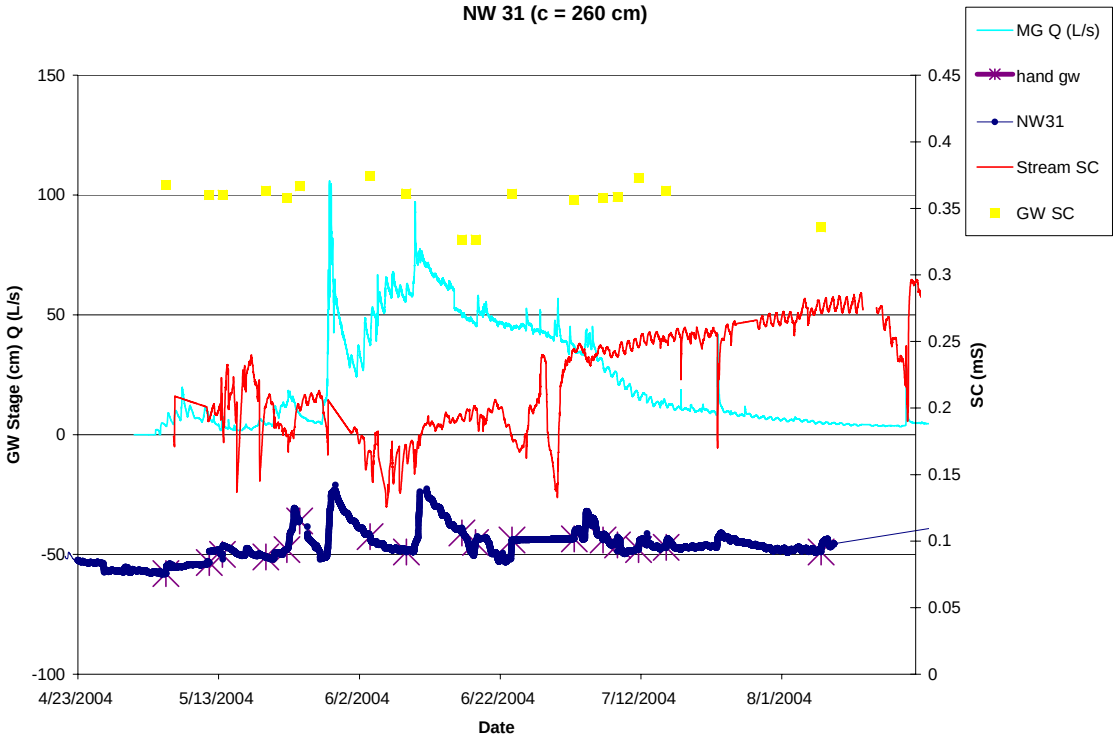
GROUNDWATER WELL DATA

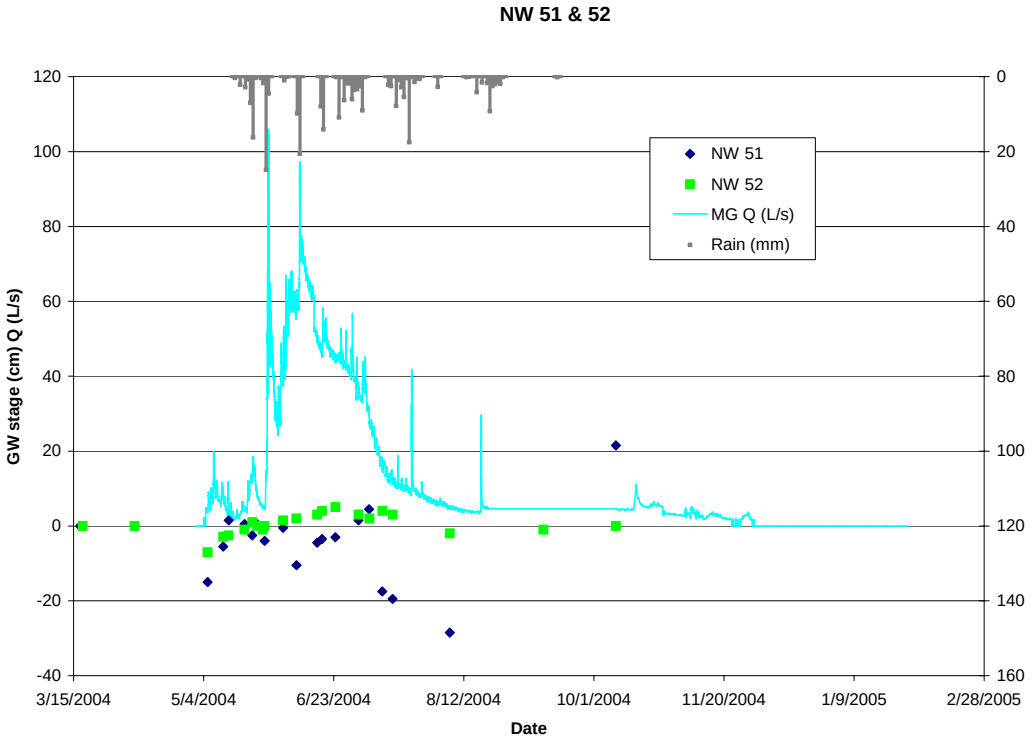

NW 3 (C = 159 cm)
NW 3
MG Q (L/s)
Stream SC
GW Stage (cm) Q (L/s)
SC (mS/cm)
Date
130
80
30
-20
-70
-120
-170
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3/4/2004
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004
12/29/2004
2/17/2005

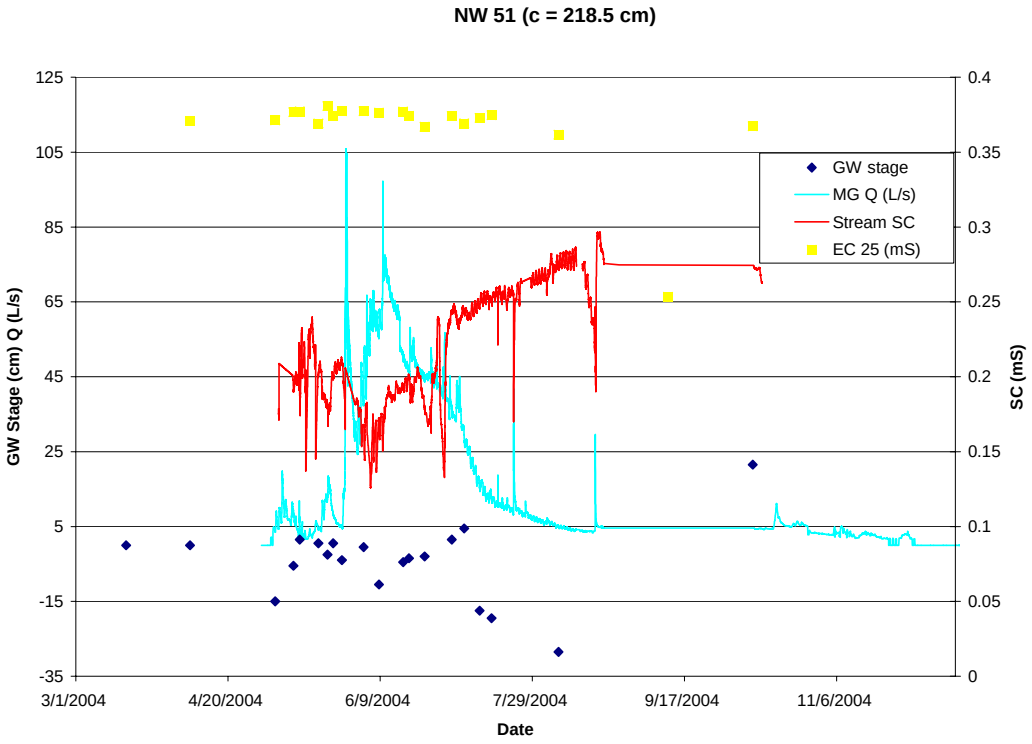

NW 2 (C = 236 cm)
GW Stage
MG Q (L/s)
Stream SC
EC 25 (mS)
GW Stage (cm) Q (L/s)
SC (mS)
Date
150
100
50
0
-50
-100
-150
-200
-250
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3/20/03
6/28/03
10/6/03
1/14/04
4/23/04
8/1/04
11/9/04
2/17/05
5/28/05

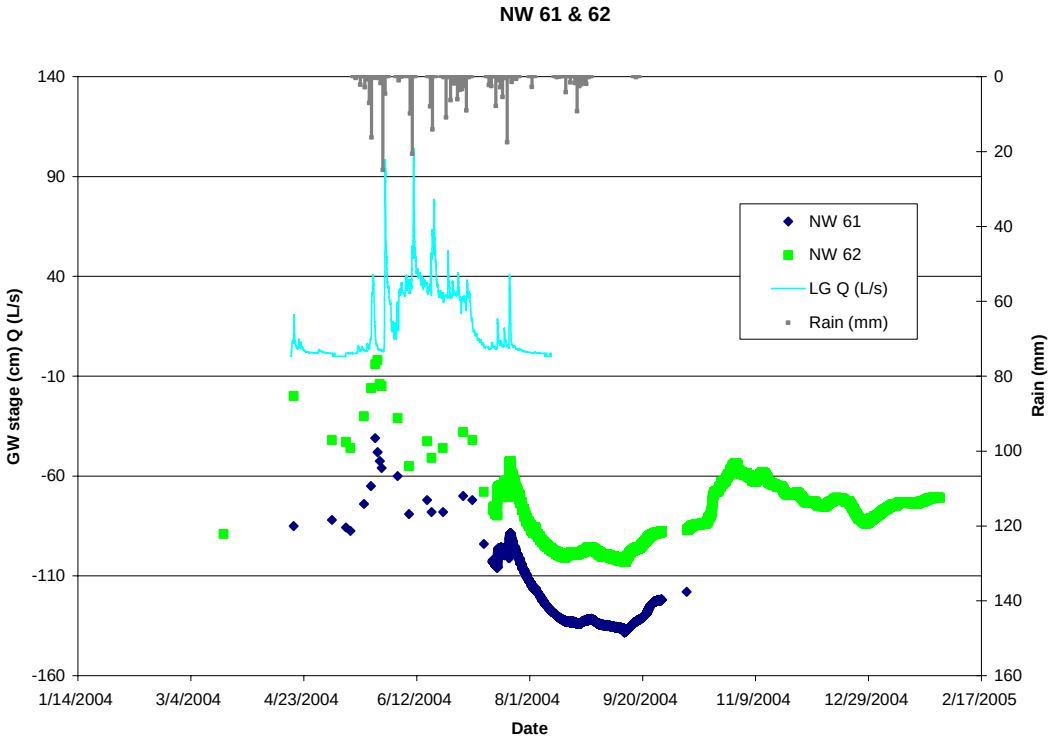

NW 31, 32, 33
NW 31
NW 32
MG Q (L/s)
NW 33
Rain (mm)
GW stage (cm) Q (L/s)
Rain (mm)
Date
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
160
3/10/2004
3/30/2004
4/19/2004
5/9/2004
5/29/2004
6/18/2004
7/8/2004
7/28/2004
8/17/2004

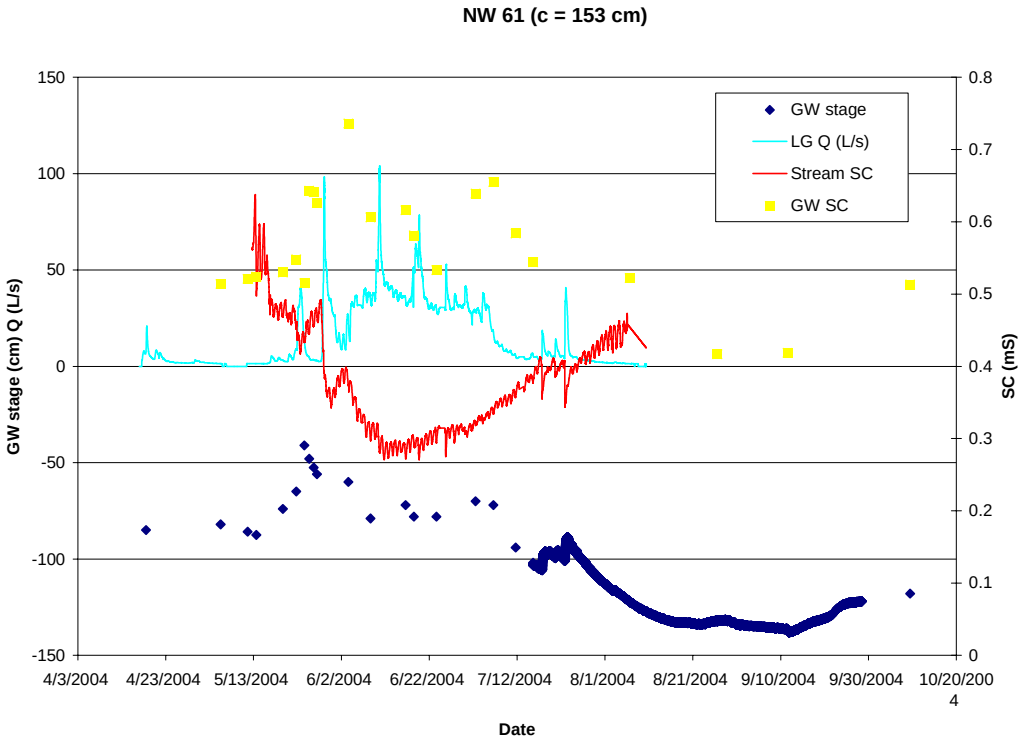

NW 32
GW stage
MG Q (L/s)
GW SC
stream SC
GW stage (cm) Q (L/s)
SC (mS)
Date
130
110
90
70
50
30
10
-10
-30
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1/14/2004
3/4/2004
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004
12/29/2004
2/17/2005

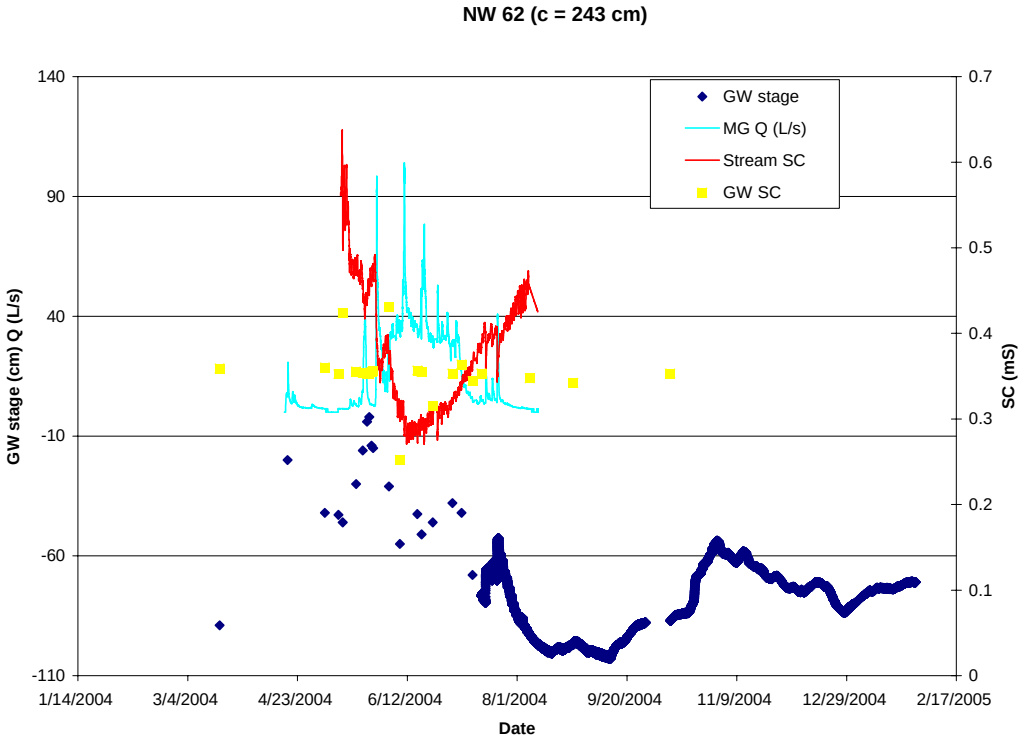

NW 31 (c = 260 cm)
MG Q (L/s)
hand gw
NW31
Stream SC
GW SC
GW Stage (cm) Q (L/s)
SC (mS)
150
100
50
0
-50
-100
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4/23/2004
5/13/2004
6/2/2004
6/22/2004
7/12/2004
8/1/2004
Date

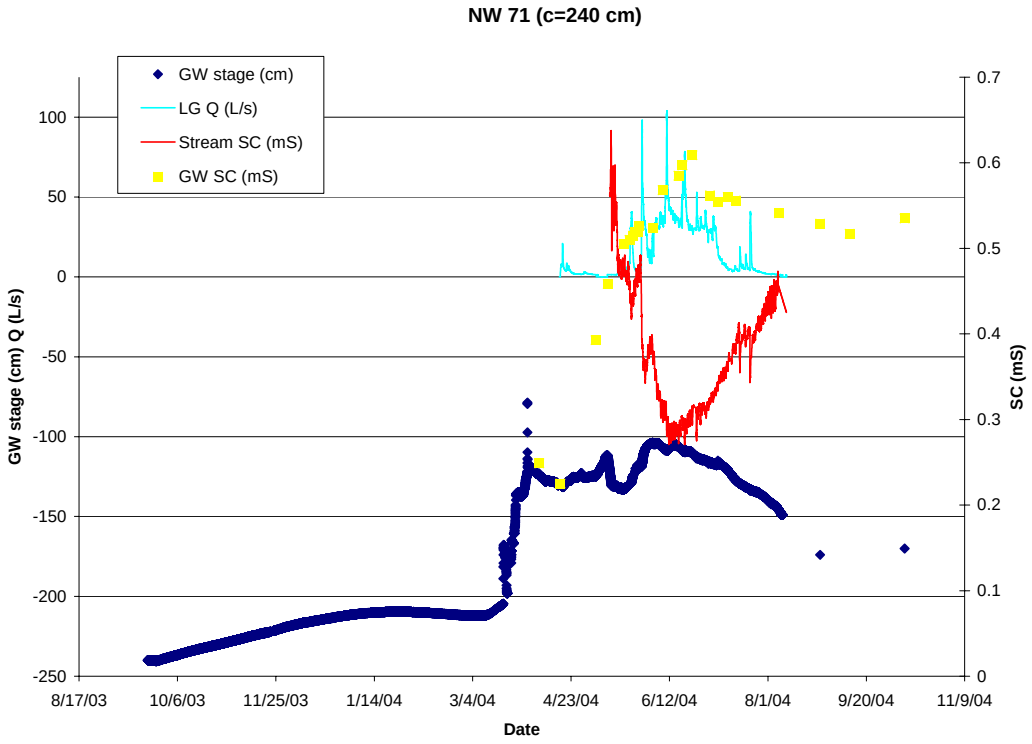

NW 51 & 52
NW 51
NW 52
MG Q (L/s)
Rain (mm)
GW stage (cm) Q (L/s)
120
100
80
60
40
20
0
-20
-40
0
20
40
60
80
100
120
140
160
3/15/2004
5/4/2004
6/23/2004
8/12/2004
10/1/2004
11/20/2004
1/9/2005
2/28/2005
Date

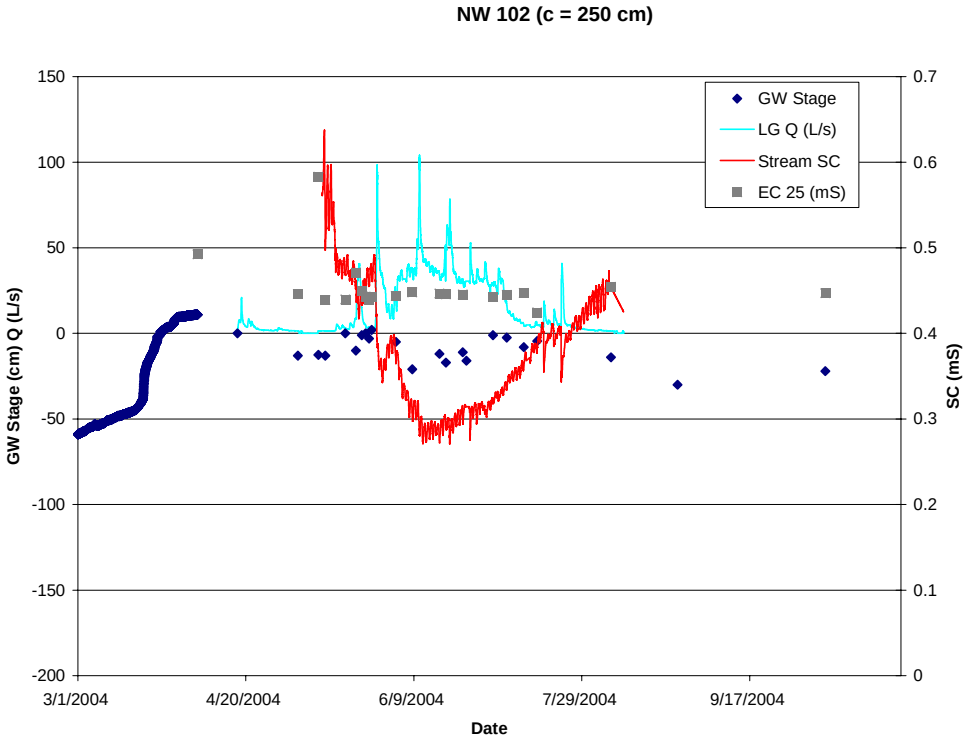

NW 51 (c = 218.5 cm)
GW Stage (cm) Q (L/s)
SC (mS)
Date
GW stage
MG Q (L/s)
Stream SC
EC 25 (mS)
125
105
85
65
45
25
5
-15
-35
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3/1/2004
4/20/2004
6/9/2004
7/29/2004
9/17/2004
11/6/2004

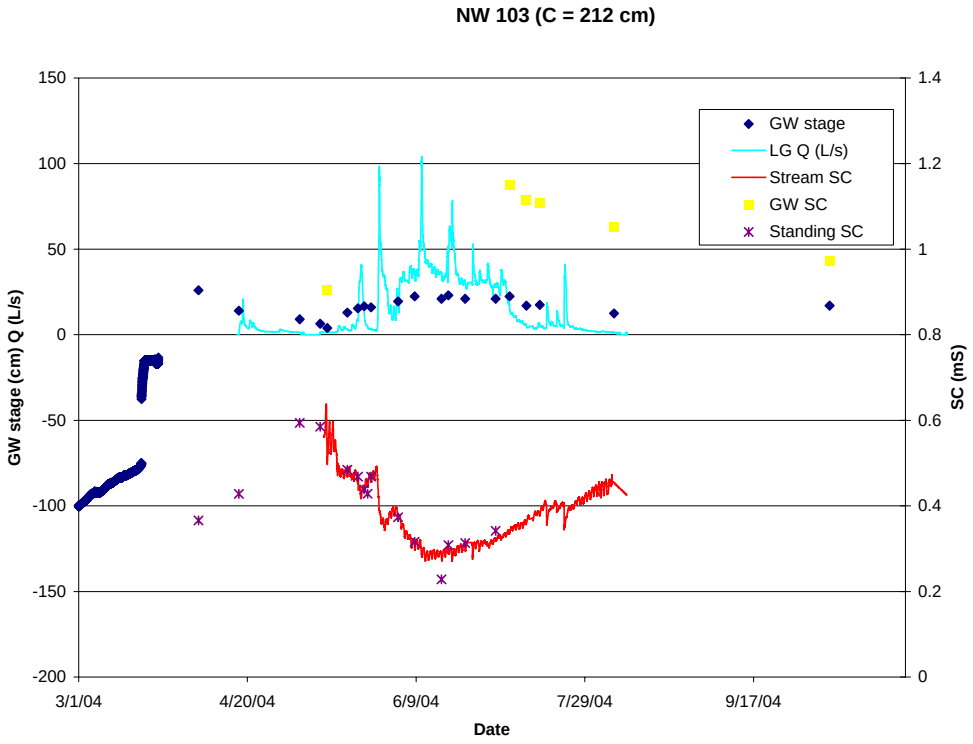

NW 61 & 62
GW stage (cm) Q (L/s)
Rain (mm)
Date
NW 61
NW 62
LG Q (L/s)
Rain (mm)
140
90
40
-10
-60
-110
-160
0
20
40
60
80
100
120
140
160
1/14/2004
3/4/2004
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004
12/29/2004
2/17/2005


NW 61 (c = 153 cm)
GW stage
LG Q (L/s)
Stream SC
GW SC
GW stage (cm) Q (L/s)
SC (mS)
150
100
50
0
-50
-100
-150
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4/3/2004
4/23/2004
5/13/2004
6/2/2004
6/22/2004
7/12/2004
8/1/2004
8/21/2004
9/10/2004
9/30/2004
10/20/2004
Date


NW 62 (c = 243 cm)
GW stage
MG Q (L/s)
Stream SC
GW SC
GW stage (cm) Q (L/s)
SC (mS)
140
90
40
-10
-60
-110
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/14/2004
3/4/2004
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004
12/29/2004
2/17/2005
Date

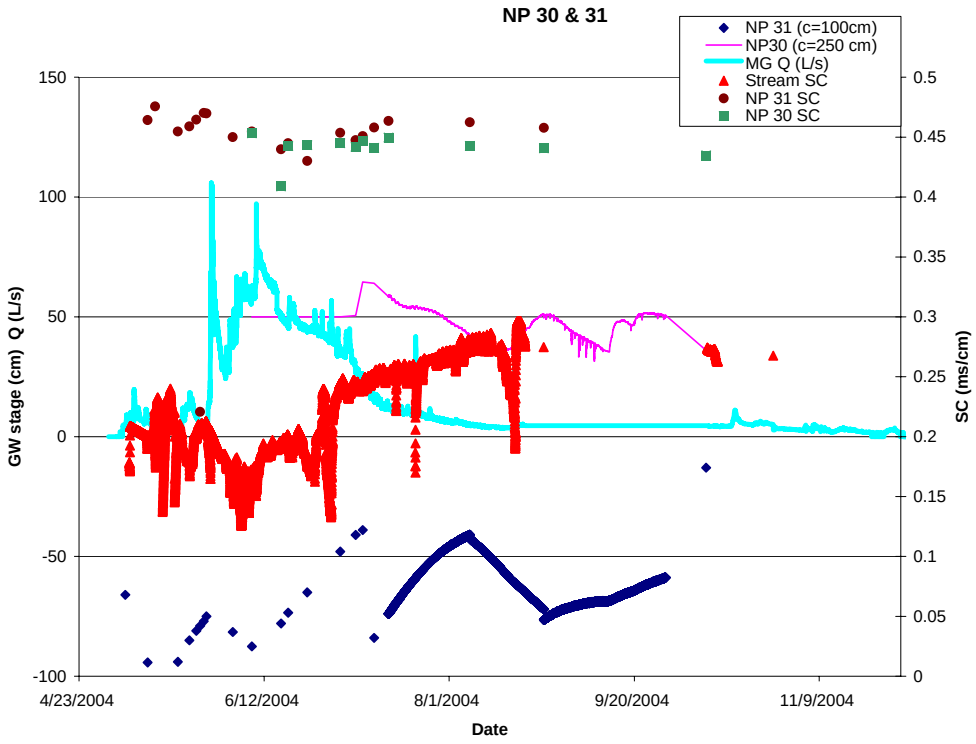

NW 71 (c=240 cm)
GW stage (cm)
LG Q (L/s)
Stream SC (mS)
GW SC (mS)
GW stage (cm) Q (L/s)
SC (mS)
100
50
0
-50
-100
-150
-200
-250
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
8/17/03
10/6/03
11/25/03
1/14/04
3/4/04
4/23/04
6/12/04
8/1/04
9/20/04
11/9/04
Date

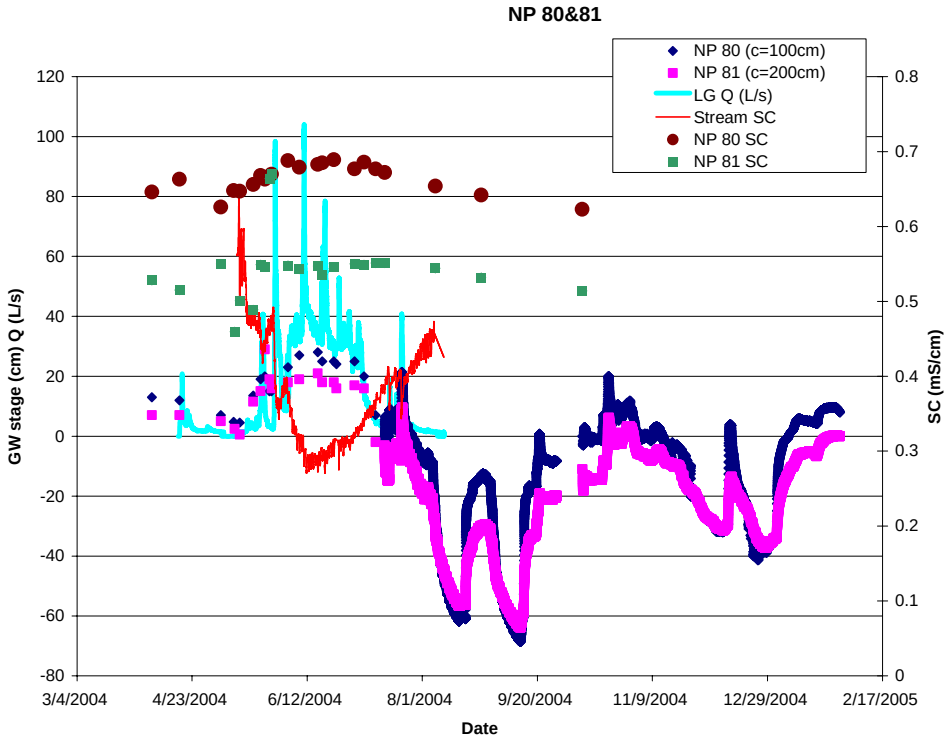

NW 102 (c = 250 cm)
GW Stage
LG Q (L/s)
Stream SC
EC 25 (mS)
GW Stage (cm) Q (L/s)
SC (mS)
150
100
50
0
-50
-100
-150
-200
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3/1/2004
4/20/2004
6/9/2004
7/29/2004
9/17/2004
Date


NW 103 (C = 212 cm)
GW stage
LG Q (L/s)
Stream SC
GW SC
Standing SC
GW stage (cm) Q (L/s)
SC (mS)
Date
150
100
50
0
-50
-100
-150
-200
1.4
1.2
1
0.8
0.6
0.4
0.2
0
3/1/04
4/20/04
6/9/04
7/29/04
9/17/04

APPENDIX D

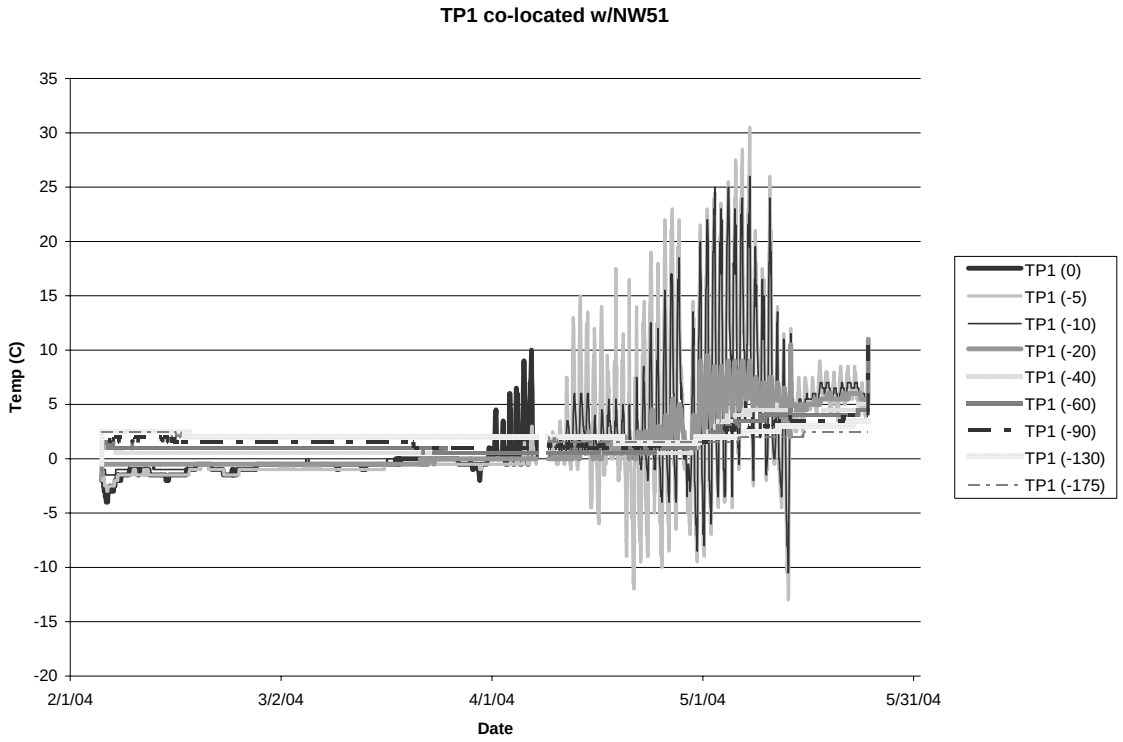
PIEZOMETRIC DATA

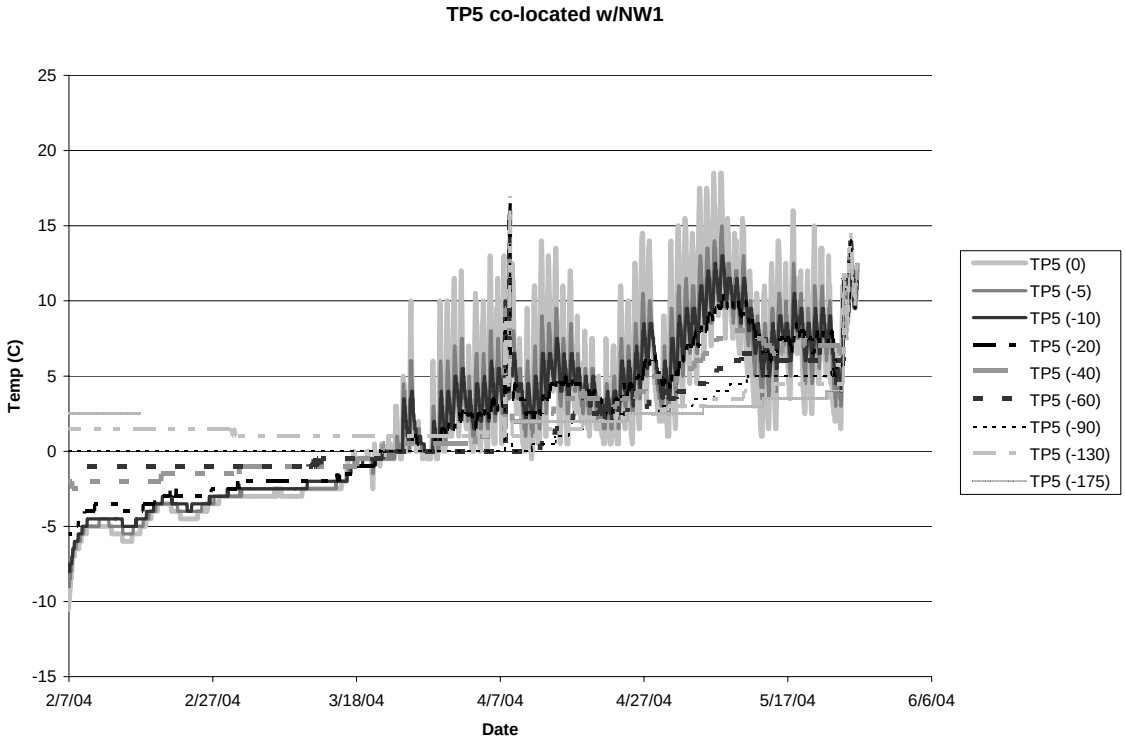

NP 30 & 31
NP 31 (c=100cm)
NP30 (c=250 cm)
MG Q (L/s)
Stream SC
NP 31 SC
NP 30 SC
GW stage (cm) Q (L/s)
SC (ms/cm)
Date
150
100
50
0
-50
-100
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004

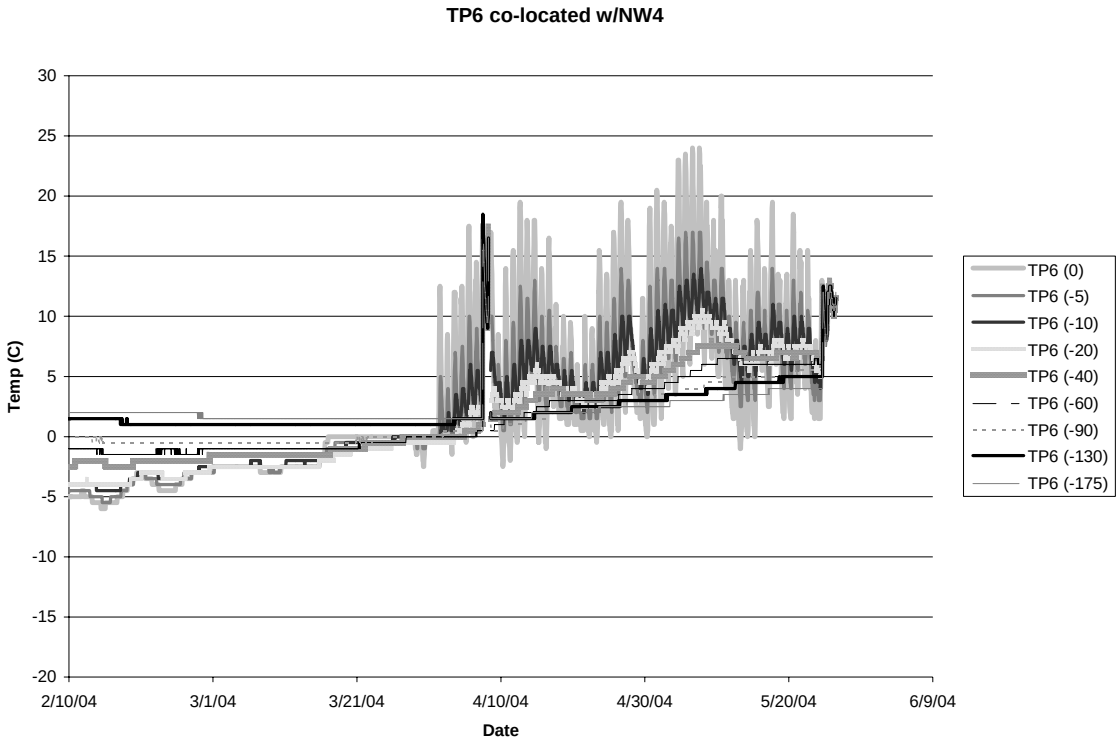

NP 80&81
NP 80 (c=100cm)
NP 81 (c=200cm)
LG Q (L/s)
Stream SC
NP 80 SC
NP 81 SC
GW stage (cm) Q (L/s)
SC (mS/cm)
Date
120
100
80
60
40
20
0
-20
-40
-60
-80
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3/4/2004
4/23/2004
6/12/2004
8/1/2004
9/20/2004
11/9/2004
12/29/2004
2/17/2005

APPENDIX E

SOIL TEMPERATURE DATA

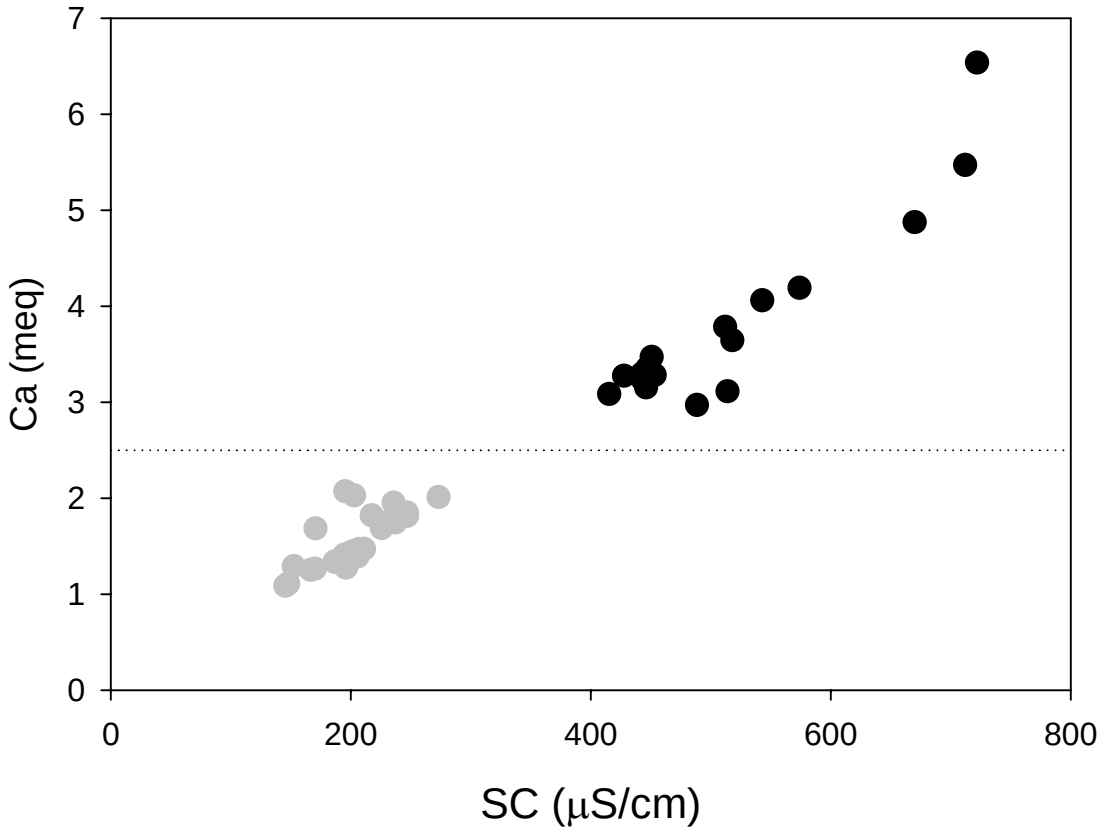

TP1 co-located w/NW51
35
30
25
20
15
10
5
0
-5
-10
-15
-20
Temp (C)
2/1/04
3/2/04
4/1/04
5/1/04
5/31/04
Date
TP1 (0)
TP1 (-5)
TP1 (-10)
TP1 (-20)
TP1 (-40)
TP1 (-60)
TP1 (-90)
TP1 (-130)
TP1 (-175)


TP5 co-located w/NW1
25
20
15
10
5
0
-5
-10
-15
Temp (C)
2/7/04
2/27/04
3/18/04
4/7/04
4/27/04
5/17/04
6/6/04
Date
TP5 (0)
TP5 (-5)
TP5 (-10)
TP5 (-20)
TP5 (-40)
TP5 (-60)
TP5 (-90)
TP5 (-130)
TP5 (-175)

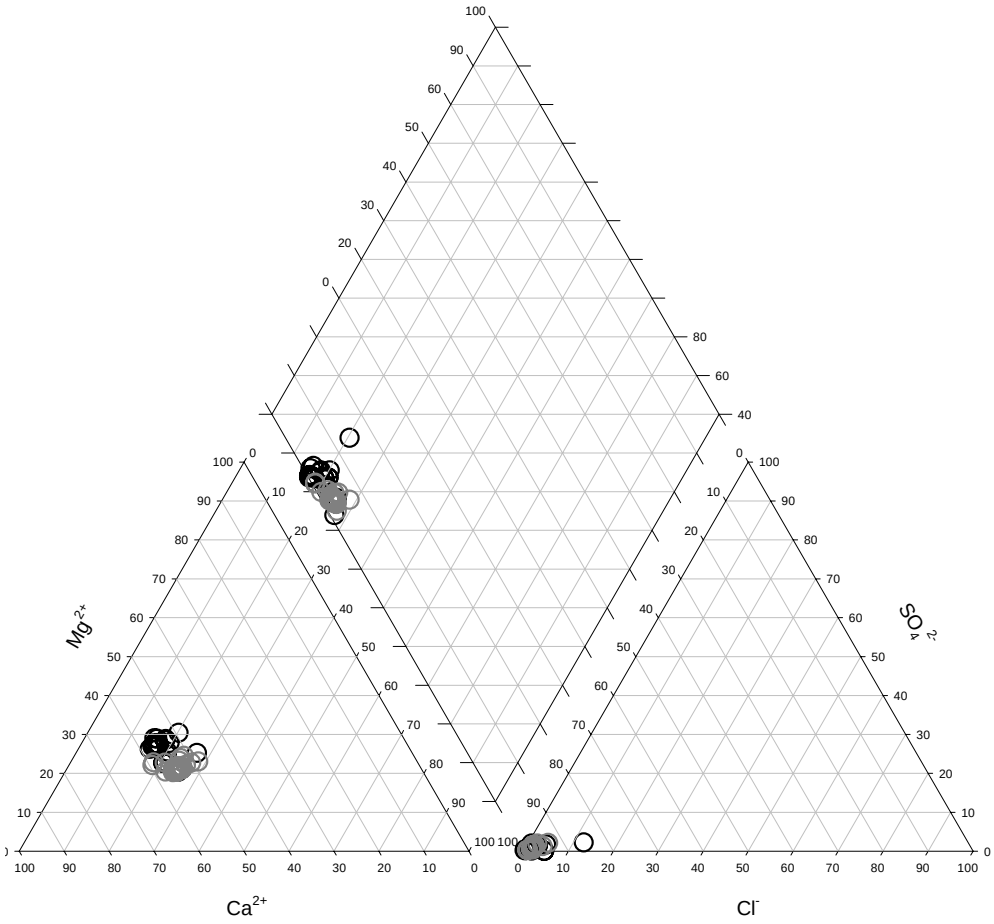

TP6 co-located w/NW4
30
25
20
15
10
5
0
-5
-10
-15
-20
Temp (C)
2/10/04
3/1/04
3/21/04
4/10/04
4/30/04
5/20/04
6/9/04
Date
TP6 (0)
TP6 (-5)
TP6 (-10)
TP6 (-20)
TP6 (-40)
TP6 (-60)
TP6 (-90)
TP6 (-130)
TP6 (-175)

APPENDIX F

CHEMICAL DATA



Alpine (AL) samples are shown in gray, and valley bottom groundwater (GW) samples are shown in black.



Piper plot of Humphrey Creek water samples. Grey circles are stream samples and black circles are groundwater samples.