University of Nevada, Reno

Eastern Truckee Meadows Groundwater Interactions with the Truckee River

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Hydrogeology

By

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Abstract

Understanding hydrogeology within the Truckee Meadows is important because its aquifers and the Truckee River supply water to the communities of Reno and Sparks in Washoe County, Nevada. Residents of this area rely solely on these aquifers when surface water from the Truckee River is unavailable for municipal use. Researching the complex groundwater interactions with the Truckee River will help water managers understand how increased pumping might reduce groundwater seepage to the river, while determining how recharge from injection wells may return flow to the river. The objective of this research is to compare the results of several different methods assessing groundwater-surface water interactions with previous studies along the Truckee River in the eastern Truckee Meadows. Several techniques were used; including analyzing temperature changes along the streambed to simulated groundwater flux from a mixing model, applying a stream discharge differencing method to compute a surface water balance and calculate groundwater accretion, comparing river stage with groundwater elevation to identify gradients, creating potentiometric maps to help visualize regional groundwater flow, along with studying groundwater fluctuations and hydrographs to interpret groundwater trends. According to thermal analysis results, the most influential parameters for simulating downstream temperature were upstream temperature and groundwater temperature.

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Chapter 1 Introduction

Hydrogeology and groundwater/surface water interactions in the Truckee Meadows are important to conceptualize because the Truckee River and aquifers are the water resource for the most populous area in the Truckee River Basin. Most industrial and municipal water for Reno and Sparks comes from the Truckee River, while groundwater wells can supply over 20% to the surrounding area (Chris Benedict, written communication). Yet groundwater can be the sole short-term source for the entire population of the Truckee Meadows if surface water becomes unavailable due to drought, problems with surface water infrastructure, and surface water quality issues.

In semi-arid regions like the Truckee Meadows, groundwater and surface water interactions are paramount because precipitation is scarce, leaving groundwater and the Truckee River as key components of the hydrologic system (Duque, 2010). Quantifying groundwater interaction with the Truckee River would be advantageous to understand what percentage of water in the river actually originates from aquifers, and how much water in the shallower aquifers comes from the river. Even though most diversions for irrigation and Truckee Meadows Water Authority (TMWA) in the Truckee Meadows occur upstream of the study's extent, this information is important because appropriated demands downstream still need to be met. River quantity and quality must to be sufficient for communities that divert river water for consumption and irrigation, along with fish and other organisms that live in the Truckee River. At times when river discharge is very low in the summer and fall, base-flow from groundwater may be the principal source of flow in the river. Municipal pumping may lower water levels in the deeper aquifer, which can cause the shallow water table to respond by lowering as well (where sections of the deep and shallow aquifer are hydraulically connected). This situation may prevent groundwater from discharging to the river (where the streambed and shallow aquifer are hydraulically connected) and deprive the river of a sustainable flow. Under the previously mentioned circumstances the Truckee River may become dry. Hence it is beneficial to identify groundwater interactions with this river in the eastern Truckee Meadows.

Existing groundwater models have not included efforts to more accurately address these aquifer interactions with the Truckee River (Worley Parsons Komex, 2007; INTERA, 2006). Generally there is limited field research focusing on reach-scale exchange and methods quantifying spatial and temporal changes in fluxes (Shope, 2009; Fleckenstein, 2006; Becker, 2004). The methodology used in this research has the potential to help establish which approaches are reliable for estimating groundwater flux to or from a river reach.

The Truckee Meadows encompasses downtown Reno and Sparks, whose population has grown steadily for the last 25 years (U.S Census Bureau, Population Division). Increased water demand associated with population growth has the potential to stress available water resources if average annual winter and spring river flows decrease, aquifer recharge (from precipitation, irrigation and artificial injection) remains the same or decreases, and/or efficient use and conservation of water is not practiced.

The Truckee Meadows Hydrographic Basin (527 square kilometers) is part of the Truckee River System and is located in the Basin and Range Physiographic Province (Figure 1.1) (Tarbuck, 2002; Harrill et. al., 1998; Horton, 1997). The Truckee River originates from Lake Tahoe, California, and flows 190 kilometers northeast towards the terminal Pyramid Lake in Nevada (Figure 1.2), at some point flowing west to east though the Truckee Meadows. Truckee Meadows lies in the Sierra Nevada rain shadow and receives a mean annual rainfall of 18.5 centimeters (Western Regional Climate Center, 2009). The climate is semi-arid with hot summers and cold winters.

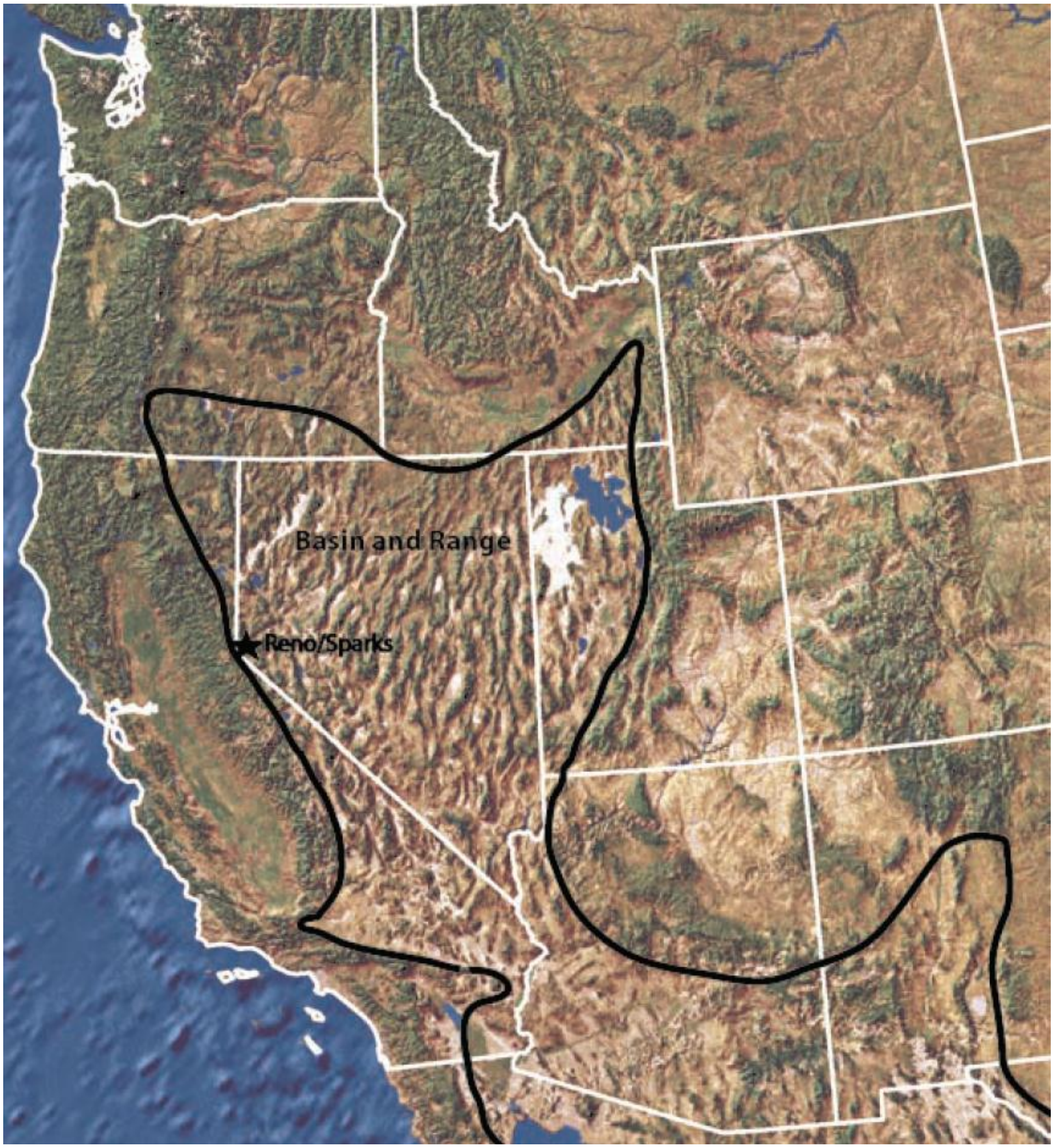

Figure 1.1 Basin and Range Physiographic Province. Tarbuck and Lutgens (2002).

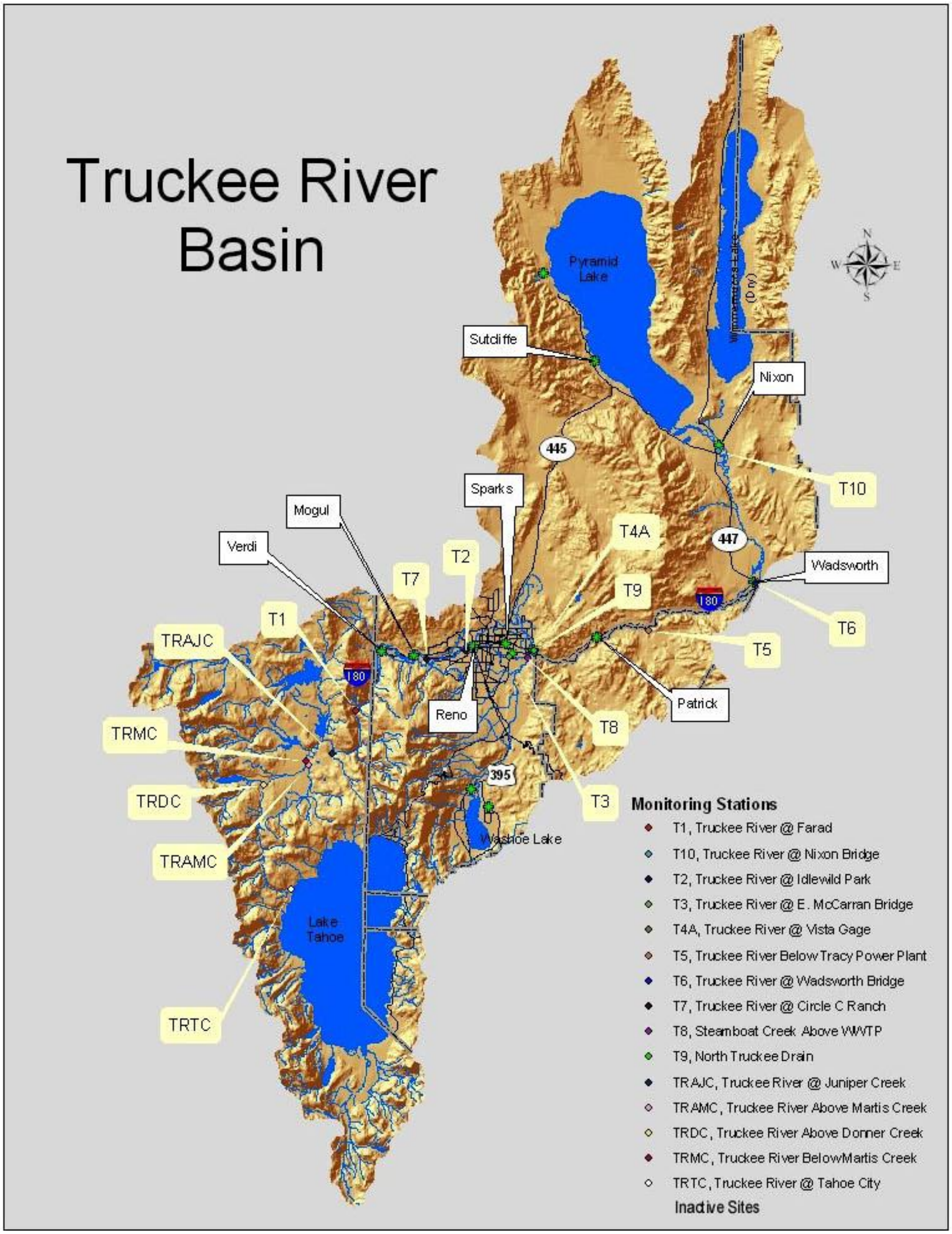

Figure 1.2 Truckee River Basin and associated surface water monitoring stations, NDEP.

1.1 Objective-Scope of Study

Research objectives were to locate and quantify groundwater flux into a portion of the Truckee River in the eastern Truckee Meadows. This required the collection and analysis of temperature data along the Truckee River streambed to simulate groundwater flux using a mixing model, applying a stream discharge differencing method to compute a surface water balance and calculate groundwater accretion, comparing river stage with groundwater elevation to identify gradients, creating potentiometric maps to help visualize regional groundwater flow, along with studying groundwater fluctuations and hydrographs to interpret groundwater trends.

It is hypothesized (Schumer et. al., 2009; McKenna, 1990; Cohen et. al., 1964) that the Truckee River switches to a gaining regime between the USGS Sparks and Vista Gages (Figure 2.1), and it's anticipated that results will show groundwater is more likely to discharge to the river during lower flows.

Results will help to answer to following questions:

1) Where does the Truckee River become a gaining stream?
2) Can groundwater flux into and out of the Truckee River be quantified?
3) What hydrogeologic regime alternatives exist in the Eastern Truckee Meadows, and why is it significant?

Results will be useful to the Washoe County Department of Water Resources (WCDWR), Truckee Meadows Water Authority, Truckee Meadows Water Reclamation Facility (TMWRF), Pyramid Lake Paiute Tribe (PLPT), and any other municipality downstream of the Truckee Meadows because these identities reclaim and deliver water to their respective communities.

1.2 Approach

The interaction between stream temperature, streamflow, along with flux volume and direction can differ for gaining and losing reaches (Constantz, 1998). Groundwater pumping commonly influences the gradient in both gaining and losing reaches. If pumping occurs near a river that is gaining, the effect on groundwater flux to the river may be significant, particularly during times of low flow. Pumping may divert groundwater from discharging into a river or create an unsaturated zone between the river and surrounding aquifer if a portion of the pumped aquifer is hydraulically connected to a portion of the aquifer that is contributing water the to river (Sophocleous, 2002; Cunningham, 1977). At losing reaches pumping may induce a stronger downward gradient away from the river. After accounting for all ditches and diversions, streamflow increases downstream in a gaining reach and decreases in a losing reach. In a gaining reach groundwater may change stream temperature if seepage is a high percentage of stream flow and/or difference in temperature is large enough (though meteorological heat flux can also change stream temperature).

1.2.1 Balancing Streamflow

A streamflow-differencing method is beneficial over many discrete measurements because a given point of groundwater flux to a stream may not represent total gain from an aquifer along the length of interest (Becker et. al., 2004).

Equation 1 is the sum of differences between streamflow measurements at two locations, which can be presumed to equal groundwater flux:

$$Q_{GW} = Q_{RiverDownstream} - Q_{RiverUpstream} \tag{1}$$

where Q_{GW} is the calculated groundwater flux, and Q_{RiverX} is measured river flow.

The standard deviation for calculated groundwater flux is equivalent to the square root of cumulative variances:

$$\sigma_{GW} = \sqrt{\sigma^2_{RiverUpstream} + \sigma^2_{RiverDownstream} + \sigma^2_{Diversions} + \sigma^2_{SwInfluents}} \qquad (2)$$

and the standard deviation of components are calculated via:

$$\sigma_X = (\alpha Q_X) \div 1.96 \qquad (3)$$

where α is the stream gage accuracy rating, provided by the USGS National Water Inventory System.

The range of calculated groundwater flux with 95% confidence is represented by: $Q_{GW} \pm (\sigma_{GW} \times 1.96)$

Errors are assumed to be random and follow a normal distribution with zero mean, and are not correlated.

1.2.2 Groundwater

Increased magnitude and duration of precipitation generally correlates positively with higher river flows, and correlation with higher groundwater elevations tends to have a time lag and irregular spatial distribution (Kalbus, 2006; Cowdery, 2005; Donato, 1998). Municipal pumping can decrease groundwater elevations and change the gradient between the river and groundwater in potentially gaining reaches, and increase the gradient between the river and groundwater in potentially losing reaches.

Elevation changes of groundwater level are influenced by the surrounding hydrogeology and occur when there is a change of groundwater volume in storage in an unconfined aquifer, which is directly caused by changes in proximal sources of recharge and discharge. Large net annual fluctuations (about 100 feet) can indicate an aquifer with proximity to the near surface conditions, response to a large pumping well, presence of a flow barrier, and aquifer recharge (Donato, 1998). Small net annual fluctuations may reveal a section of the aquifer with poor hydraulic connection between the location of measurement and its water source, or a good connection to a large water source that can buffer stress from pumping and evapotranspiration.

Long term (greater than a year and dismissing drought) declines in groundwater levels may reflect a changing climate, increased groundwater withdrawals, and/or land use changes like converting agricultural land to urban space (Van Denburgh, 1973). These longer term groundwater declines may cause sediments to consolidate and compact, preventing the aquifer from recharging to its original storage capacity. Long term groundwater levels are addressed under the Groundwater Trends Methodology.

1.2.3 Groundwater and River Exchange

Flow and exchange of groundwater with a river is controlled by the presence of flow paths, magnitude and distribution of hydraulic conductivities, head difference between groundwater and adjacent river stage, and streambed characteristics of the river channel in a fluvial valley (Woessner, 2000). Commonly the local hydrogeology is spatially variable within stream reaches that are gaining, losing, or even flow-through; where gradient is perpendicular to the river at meandering sections (Woessner, 2000). Hydraulic conductivities in fluvial environments can change vertically and horizontally, because of spatially dynamic depositional processes and spatially variable deposits associated with fluvial systems (Woessner, 2000; Harrill, 1998). Different hydrofacies cause spatially variable seepage rates, which can impact river-aquifer connectivity (Fleckenstein et. al., 2006) and can determine where and how much seepage occurs. The greatest hydraulic conductivities and transmissivities typically occur near an alluvial valley river (as opposed to a mountain stream) because of poorly sorted streambank deposits left by migrating streams (Woessner, 2000; Fetter, 2001), hence providing the capacity for productive aquifers.

Seepage rate is controlled by hydraulic gradient (function of head difference) between a river and aquifer. Water tables similar to river stage elevation are a common problem that leads to uncertainty regarding whether the river is gaining or losing (Duque, 2010). Yet a river clearly has the potential to lose water to an unconfined aquifer (Figure 1.4) if stage is higher than surrounding groundwater levels (Donato, 1998; Sophocleous, 2002; Woessner, 2000). Moreover, a river may gain from an aquifer through its banks and streambed if stage is lower than the adjacent potentiometric elevation (Rushton, 2003; Sophocleous, 2002) and a hydraulic connection is present (see Figures 1.3). During high river flows concentrated seepage can raise the water table to the same elevation as a river bed, thereby reducing or halting seepage to the aquifer (Fleckenstein et. al, 2006). These concepts can be quantified with Darcy's Law, which has the same form as Fourier's law for heat transport (Anderson, 2005).

$$\mathrm{Q} = \mathrm{kA}\nabla h \qquad (4)$$

where Q is seepage, k is hydraulic conductivity, A is cross-sectional area normal to direction of flow, and ∇h is gradient (expanded in the equation below).

$$\nabla h = \hat{x}\frac{\partial h}{\partial x} + \hat{y}\frac{\partial h}{\partial y} + \hat{z}\frac{\partial h}{\partial z}$$

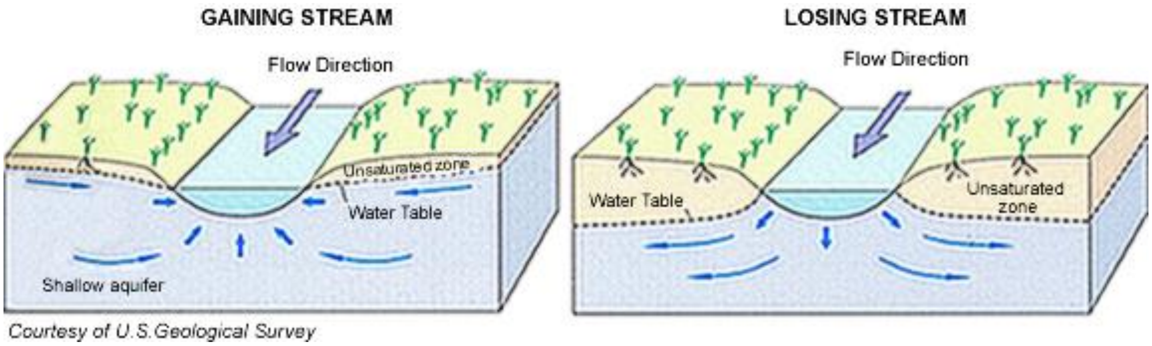

Figure 1.3 Schematics for gaining and losing streams (U.S. Geological Survey).

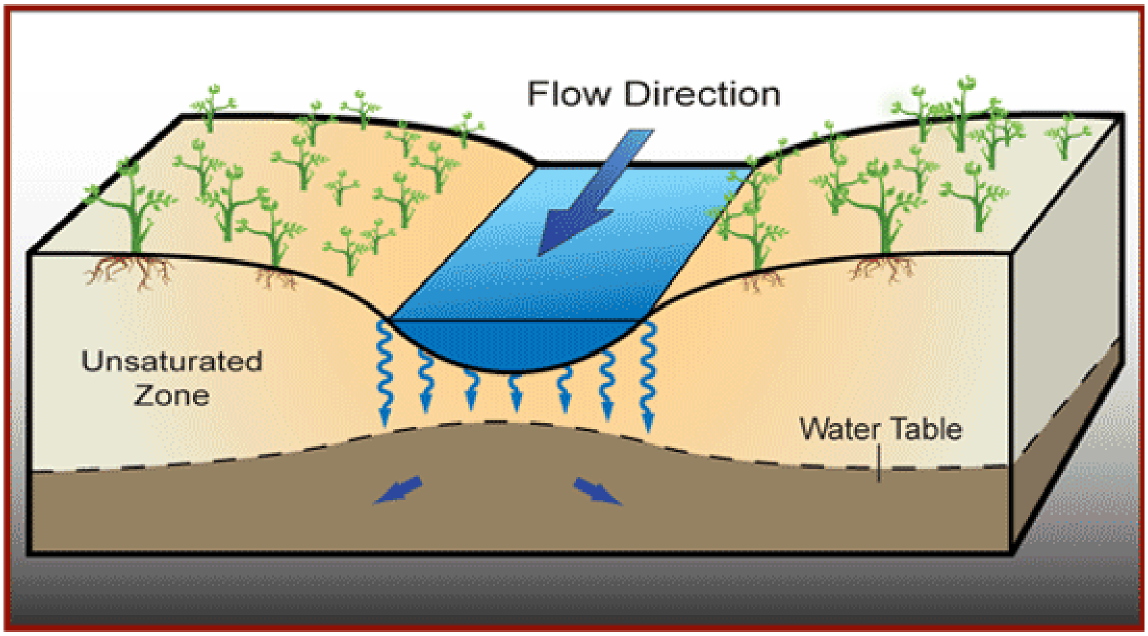

Figure 1.4 Stream disconnected from groundwater (www.connectedwater.gov.au).

Surface-water/groundwater interaction along a river is also dependent on hydrogeologic characteristics of the streambank and streambed, which are essentially determined by the sediment’s grain size and distribution (Fanelli, 2008; Constantz, 1998). If a channel is armored or cemented, there can be little to no connection between that river and surrounding aquifer. Streambed conductivity can also change in response to seasonally variable flow regimes (Fanelli, 2008; Cunningham, 1977; Sophocleous, 2002). Scouring occurs at high flows, which can increase the conductivity. However, finer particles settle into the streambed at lower flows, decreasing the streambed’s conductivity (Niswonger, 2005; Shump, 1985; Sophocleous, 2002).

Water seeping into the river through the streambed can be groundwater, re-emerging surface water (hyporheic exchange), or both. Hyporheic exchange is the interchange of water between a river and its streambed below, and is usually driven by pressure fluctuations associated with bedforms (Woessner, 2000). Spatial heterogeneities of hyporheic exchange are small enough to be dismissed for this study’s extent since fluxes simulated in the Stream Budget and Thermal Analysis methods are averaged over long reaches (Kalbus et. al., 2006).

Pumping from nearby municipal wells can change the natural groundwater and surface water interactions (Cowdery, 2005; O’Driscoll and DeWalle, 2004). Pumping may lower the potentiometric surface, creating an unsaturated zone between the river and shallower section of the surrounding aquifer, leading to groundwater and surface water interactions that change with pumping regime (Rushton, 2003). Short-term groundwater withdrawals can create large net fluctuations in groundwater elevation, whereas long-term pumping may decrease the amount of groundwater that discharges to the river (Cowdery, 2005).

Groundwater flux to or from a river can be identified by discrepancies in streamflow after accounting for diversions, tributaries, and associated uncertainties. An increase or decrease in flow downstream can imply a gaining or losing reach, respectively.

1.2.4 Heat as a Tracer

Groundwater discharge can be identified by comparing the temperature difference between groundwater and surface water, given the difference is large enough to be reliably measured and compared, and the ratio of groundwater flux to river flow is also high enough to change streambed temperature downstream. Using heat flux as a tracer is practical because it occurs naturally, is not associated with contamination issues like some tracer dyes, it's cost-effective, and temperature data is easy to collect (Constantz, 2008; Hatch, 2006). Heat as a tracer combines Darcy's Law and Fourier's Law, in that heat conduction is similar to hydraulic conductivity.

Multiple tools are used to measure temperature for hydrological studies. Generally thermal analyses using thermistors are convenient because they can be conducted quickly and cheaply when compared to seepage meters and peizometers. Also, thermistors are less likely to be tampered with. The main disadvantage is that thermal methods can not always quantify groundwater movement directly.

Along the streambed, measurements generally represent the average temperature within centimeters to meters around that measured point (Hatch et. al., 2006; Conant, 2004). The effective radius around a measured point can be influenced by temperatures upstream, groundwater discharge, meteorological variables, river stage, and friction. It is expected that groundwater influx will either shift or dampen signals recorded by temperature sensors because of a difference in temperature; therefore thermistors have the potential to detect where groundwater flows into the river (Selker et. al., 2006; Hatch et. al. 2006; Sakaguchi et. al., 2000). Multiple thermistors placed along a streambed may show changing temperatures downstream due to tributaries, meteorological conditions, or it could be an indication of groundwater flux into the river. During the spring, river temperatures are colder than the groundwater in the Truckee Meadows, so an addition of warmer groundwater to the river would either show an increase in temperature downstream or dampen the diurnal temperature fluctuations (Westhoff et. al., 2007; Conant 2004; Webb et. al., 1997). An addition of cooler groundwater or surface water influents in the late summer/early fall could show a decrease in temperature.

Shallow (less than 1.5 meters below land surface) groundwater temperatures remain relatively constant and increase with depth (Anderson, 2005), and groundwater temperature tends to show a moderate annual variation, but no diurnal variation which occurs with surface water temperature (Constantz, 1998). Deeper groundwater temperatures are more reflective of long term climatic conditions and in some regions influenced by geothermal systems. Given streambed temperature at two locations, groundwater temperature, upstream and downstream river flow, density and heat capacity (specific heat) of water, heat flux from meteorological conditions and friction, along with surface area of a given stream reach, potential groundwater flux may be estimated using the mixing equation from Becker et. al. (2004):

$$\rho c Q_2 T_2 = \rho c Q_1 T_1 + \rho c Q_{GW} T_{GW} + FA \tag{5}$$

Under conditions with no diversions or surface water influents:

$$Q_2 = Q_1 + Q_{GW} \tag{6}$$

To predict groundwater flux, the thermal mixing model must be coupled with the mass balance (Becker, 2004). Combining equations 5 and 6 yield:

$$Q_{GW} = \frac{Q_R(T_{R2} - T_{R1})}{T_{GW} - T_{R2}} - \frac{FA}{\rho c(T_{GW} - T_{R2})} \tag{7}$$

Q_{GW} **:** Groundwater flux into river **Variable of Interest**

Q_R : River discharge

T_{GW} : Groundwater temperature

T_{R1} : Upstream river temperature

T_{R2} : Downstream river temperature

F: Sum of all heat fluxes across stream

A: Area along stream surface

ρ : Density of water

c: Heat capacity of water

Equation 7 should provide useful results if there are no other significant sources of heat from tributaries or other return surface water flows. Groundwater temperature is assumed to be constant along the stream reach (Becker, 2004). Heat flux occurring in the river is illustrated in Figure 1.5. Variables for the heat flux (F) parameter and groundwater advection are defined in Section 1.2.5.

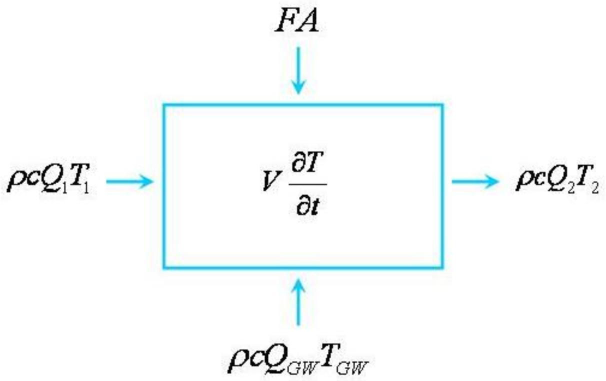

Figure 1.5 Variables of heat flux for a river reach. Adapted from Becker et. al., 2004.

1.2.5 Variables of Heat Flux in a River System

Thermal energy in a river system is influenced by solar radiation, longwave radiation, streambed conduction, latent heat, sensible heat, friction, and advection from groundwater. Theses parameters vary spatially and temporally, controlled by changes in channel morphology and annual solar cycles. Equation (8) includes parameters that contribute to the net heat exchange of a short river reach where there are no tributaries or diversions (Webb et. al., 1997).

$$Q_N = \pm Q_R \pm Q_E \pm Q_S \pm Q_B + Q_F \pm Q_A \qquad (8)$$

Where Q_N is the net heat exchange, Q_R is heat flux from net radiation, Q_E is heat flux from evaporation and condensation (latent heat), Q_S is sensible heat flux, Q_B is heat flux from streambed conduction, Q_F is heat flux from friction, and Q_A is heat flux from groundwater advection and precipitation (when and where these occur). The F variable in equation (6) is equivalent to $Q_F \pm Q_R \pm Q_E \pm Q_S \pm Q_B$. Meteorological and site specific conditions that affect these parameters are described below.

Solar radiation is influenced by shading, is composed of both direct and diffuse heat, and is a positive heat flux to the river system (Westhoff et. al., 2007). Strong diurnal variation in river temperature is supporting evidence that solar radiation plays a critical role in the energy balance, as its heat can penetrate through water.

Longwave radiation is comprised of atmospheric, landcover, and back radiation from the earth. Atmospheric radiation has a positive heat flux, back radiation has a negative heat flux and a very slight diurnal variation at the heat of the day when negative flux is greater (Westhoff et. al., 2007). Back radiation is influenced by the temperature and emissivity of water (Bartholow, 2002). Landcover is also known as vegetative radiation, and is a constant positive source of heat to the river system, though its magnitude is usually not as large as atmospheric or back radiation (Westhoff et. al., 2007).

Net radiation is the sum of total shortwave and longwave radiation, or solar minus infrared radiation (Barry et. al., 2001). Hence total heat flux is comprised of net radiation plus streambed conduction, groundwater advection, friction, along with latent and sensible heat (Webb et. al., 1997). Net radiation varies spatially due to shading from vegetation, steep banks, and topography. Temporal variations in the absolute flux and magnitude of net radiation arise from seasonal changes in shading from deciduous vegetation, cloud cover and the annual solar cycle. Positive radiative fluxes are more influential in the summer, while large losses are more common in the winter.

Sensible heat flux (enthalpy) is driven by a difference in temperature as Earth's surface turbulently transfers heat between the water's surface and overlying atmosphere (Webb et. al., 1997; Barry et. al., 2001). A positive heat flux is most commonly contributed to the river system, though occasionally a slight negative flux can be attributed to sensible heat (Westhoff et. al., 2007). Temporal variations occur as the temperature difference between the air and water change seasonally and daily.

Latent Heat is a negative flux because the process of evaporation consumes heat (Barry et. al, 2001). The Latent Heat parameter is influenced by both solar and longwave radiation and is significant during sunny days. Increased losses occur at shallow stages, and temporal variations arise from seasonal changes in humidity and wind speed (Webb et. al., 1997).

Streambed conduction is the propagation of heat by internal molecular motion through the streambed and is controlled by the material's thermal gradient and thermal conductivity. Conduction most commonly can be a source of heat during the night and a heat sink during the day (Webb et. al., 1997; Westhoff et. al., 2007). Hence streambed conduction has both positive and negative components to the thermal energy balance. Heat flux through streambed conduction has a greater relative importance during the summer in reaches that are shaded by riparian vegetation. Spatial variations occur where streambed stratum changes from bedrock to gravel, to sand and silt, etc.

Groundwater Advection is only pertinent to a river's thermal budget when groundwater is discharging into the river. When this occurs, groundwater advection can either cool or heat a stream, depending on temperature differences and discharge volume. The magnitude of discharge and temperature differences can vary over short reaches due to heterogeneous streambed properties, and seasonal changes in water table relative to river stage (Webb at. al., 1997).

Chapter 2 Background and Literature Review

The western extent of the study area is upstream of the USGS Reno stream gage, and the eastern extent aligns with the USGS Vista stream gage. Extent of the study area along with relevant stream gages and monitoring wells is displayed in Figure 2.1. The eastern extent coincides with the USGS Vista Gage (chosen to address the stream budget), and the western extent was delineated to coincide just upstream of the first thermistors deployed for the Thermal Analysis. Northern and southern extents were drawn roughly parallel to the Truckee River in order to minimize the number of monitoring wells analyzed for this project. Northern and southern extents are not implemented as no-flow or constant head boundaries.

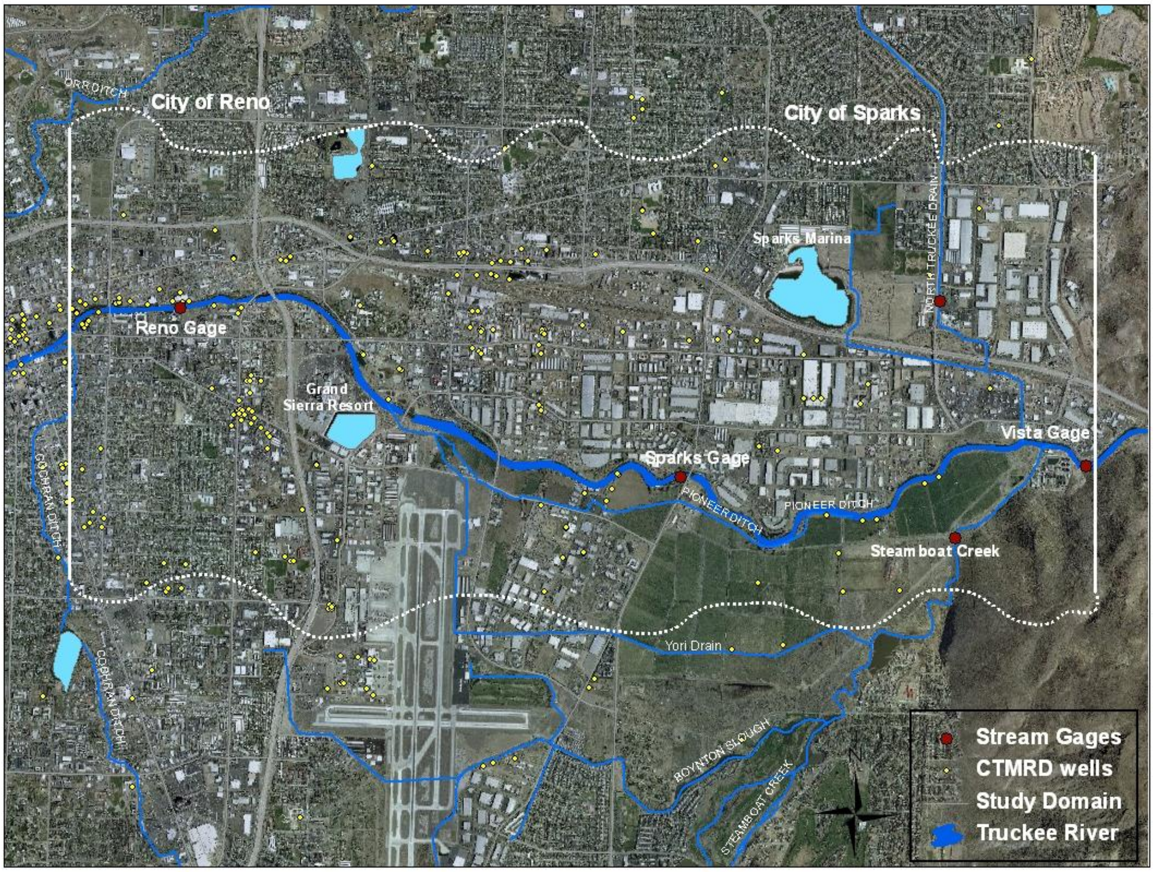

Figure 2.1 Recognized boundaries for the study's extent in eastern Truckee Meadows.

Previous studies suggest that the Truckee River generally gains in the eastern side of the valley (McKenna, 1990; Peterson, 2003; Cooley, 1971; Cohen and Loeltz, 1964), as potentiometric surfaces are higher than the elevation of the river (Figure 2.3 and Figures 4.20 to 4.23). Also see Figure 4.13 for a comparison of river stage and nearby water table.

2.1 Geology

The Truckee Meadows lies near the convergence of the Sierra Nevada and the Great Basin. This valley is bound to the west by the Carson Range, to the east by the

Virginia Range, to the south by the Steamboat Hills, and to the north by Peavine Mountain. Lithology and structural geology are important to understand because they influence hydrogeologic properties, which affect the general framework of the complex aquifer system in the Truckee Meadows. Fluvial deposits control porosity and permeability. These geologic characteristics, along with depth to bedrock, ultimately determine the regional groundwater flow.

The western half of the geologic map in Figure 2.2 was published by Nevada Bureau of Mines and Geology (Bonham and Bingler in 1973), and the eastern section was later mapped by Bell and Bonham in 1987. Surfacially mapped units within the study area are mostly floodplain deposits (Qfl) and Tahoe Outwash (Qto). Other units within the study area are mainstream river gravel (Qmg), Donner Outwash (Qdo), Tioga Outwash (Qti), alluvium (Qa), and the volcanic Alta Formation (Ta).

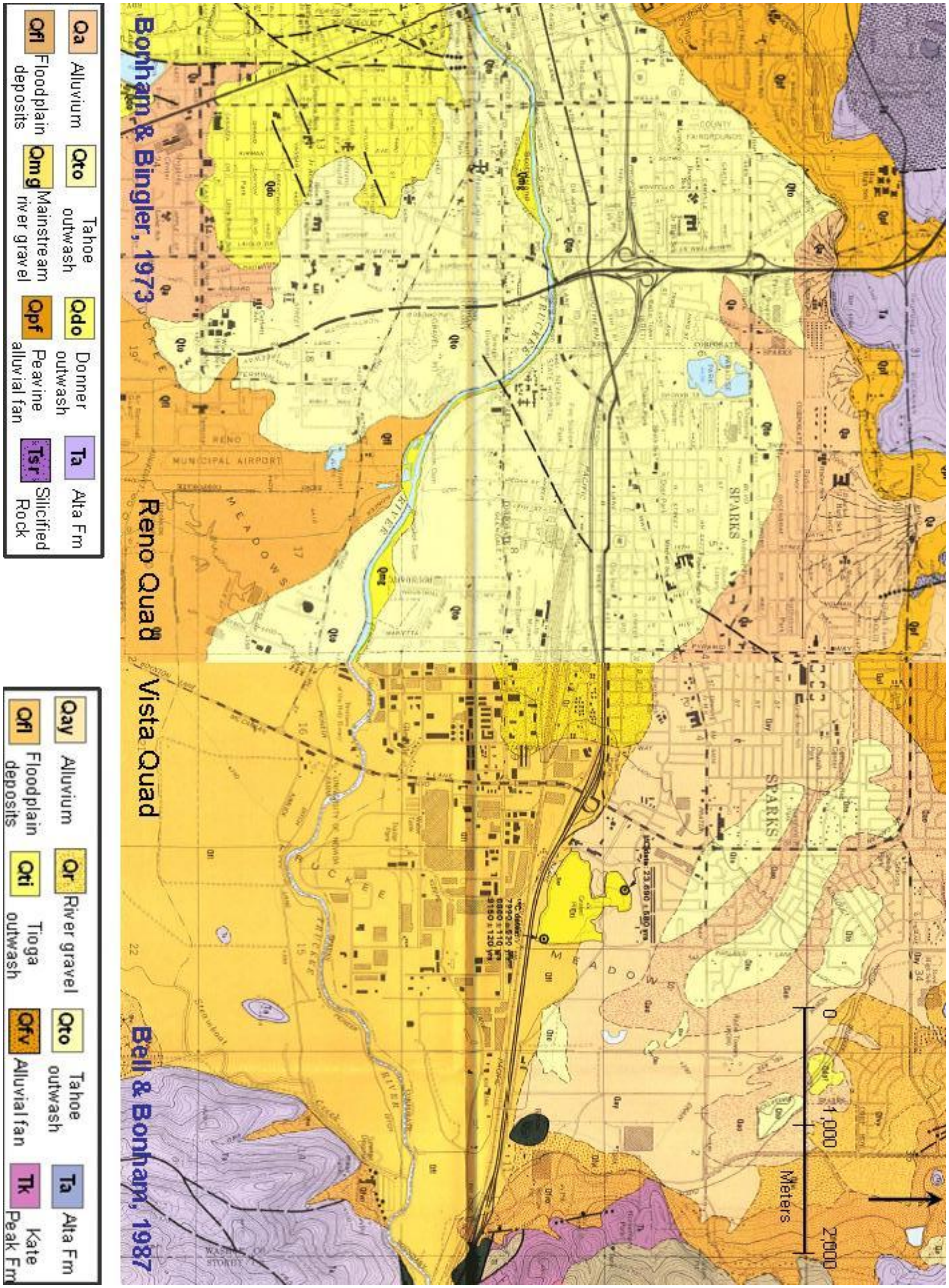

Figure 2.2 Geologic maps of the Reno and Vista quadrangles.

The following descriptions are evidence of different lacustrine and fluvial geologic stages of the Truckee Meadows. The source of most alluvium in the Truckee Meadows originates from glacial outwash deposits, flood deposits from the Truckee River, and alluvial fans adjacent to surrounding mountains. South of the Truckee River in the eastern Truckee Meadows, lacustrine deposits containing silt and clay are incised by fluvial gravel deposits (Cohen and Loeltz, 1964). An old aggregate pit at the current site of the Grand Sierra Resort exposed stream, floodplain, and shallow lake deposits. There is sand, gravel and large boulders indicative of catastrophic floods (Bell, 1974), likely caused when ice dams broke. There is also evidence of poorly sorted glacial outwash deposits (seen as terraces west of Reno) of the Donner, Tahoe and Tioga units (Bonham et. al., 1973; Bell et. al., 1987). While the Tioga Outwash deposit is only described in the subsurface (as discovered in Helms Pit), the Donner Lake and Tahoe Outwash deposits have been mapped throughout the Truckee Meadows and continuing down Vista Canyon to Mustang. These Quaternary glacial outwash deposits are significant aquifers in the Truckee Meadows (Widmer et. al., 2007) because they are, in part, poorly sorted and therefore ideal for storing and transmitting water. Tertiary deposits can also be good aquifers where volcanics are fractured and sediments are not completely consolidated (Cohen et. al., 1964).

2.1.1 Virginia Lake Fault Zone

The Virginia Lake Fault Zone (VLFZ), which may cross the Truckee River, is significant because it affects groundwater flow. The VLFZ is an extension of the Carson Range Fault System, and trends north-northeast through the Truckee Meadows (Clark, 2008). It is mapped between Holcomb and Wells Ave (Bonham & Bingler, 1973), and recent supporting geophysical evidence suggests that it extends further north-northeast towards the Truckee River (Clark, 2008). Location of VLFZ is shown in Figure 4.13.

Faults can be barriers to groundwater flow (Cooley, 1971) when particles are preferentially aligned or clays are smeared, and when an aquifer is juxtaposed against a lower permeability unit (Evans et. al., 1997). This fault zone is considered a barrier to groundwater flow since water levels on the east side of VLFZ are about 30-40 feet below water levels on the west side, boundary affects are present during pumping tests, and because faults in poorly lithified sediments (alluvium) rarely act as conduits to groundwater flow (Widmer 2007; Clark, 2008). There may be an aquifer-river connection immediately west of the fault because water level elevations coincide with river stage, and an unsaturated zone beneath the river east of the fault (Westfall, 2008), though the river reconnects with the aquifer again further downriver before leaving the Truckee Meadows. A Morrill PW aquifer test (see Appendix G) also gave more supporting evidence that the VLFZ is a barrier to flow because monitoring wells that showed no correlation to pumping lie on the opposite of this fault zone (data from WCDWR). Since the VLFZ is at least a partial barrier to groundwater flow, slope of the water table steepens in this area (Worley Parsons Komex, 2006).

2.2 Hydrogeology

Generally groundwater moves from west to east through the eastern Truckee Meadows, roughly moving parallel to the Truckee River. Hydraulic conductivity can change vertically and horizontally because of the differing fluvial properties associated with the Truckee River and glacial outwash deposits (Harrill, 1998; Bell, 1974), which can lead to spatially variable seepage rates.

The Carson and Virginia Ranges are consolidated mountain blocks and therefore only permeable at localized fracture zones (Harrill et. al., 1998; Cohen et. al., 1964). Less than 1 cubic foot per second (cfs) infiltrates from the valley west of Reno in the Mogul area (Cohen et. al., 1964). Cohen and Loeltz (1964) also estimated that only 0.2 cfs infiltrates from Spanish Springs to the north, while Van Denburgh (1973) stated that underflow from Spanish Springs could be as much as 12cfs. Although the water budget may have since changed, or simply vary from year to year, underflow from Mogul and Spanish Springs is not pertinent to the methods used in this research. Subsurface flow through Vista Canyon is less than 1 cfs (MMA, 1993; Van Denburgh et. al., 1973; Cooley, 1971; Cohen et. al., 1964), which is irrelevant because Vista Canyon is outside the study's boundary.

Groundwater had a strong upward vertical gradient in the eastern Central Truckee Meadows east and north east of the airport during the 1960s (Cooley, 1971). Currently the gradient can be downward near municipal wells during pumping (Figure 4.18). Interferometric Synthetic Aperture Radar (InSAR) provides evidence that slight land subsidence occurs around production wells during pumping, followed by a return to original land surface elevation with recovery of water level after pumping ceases (Westfall, 2008). Historically upward vertical gradients were present at regional zones of discharge (Cooley, 1971; Mifflin, 1968) which is still seen in the eastern Truckee Meadows near Vista Canyon at the USGS Tracy monitoring wells (CDM 2002; Figure 4.17). Shallow and deeper zones of the aquifer are connected hydraulically where conduits are present, and leakage occurs if a gradient exists, which is sometimes caused by pumping.

Figure 2.3 is a map showing the potentiometric surface and areas of groundwater discharge during the first half of December 1971 (Cooley, 1971). Water level contours curve towards the river on the eastern edge of the valley, indicating groundwater flow towards the river. Large areas of groundwater discharge expressed as springs and wetlands are also shown in the eastern Truckee Meadows, which are reduced in extent today (Worley Parsons Komex, 2007).

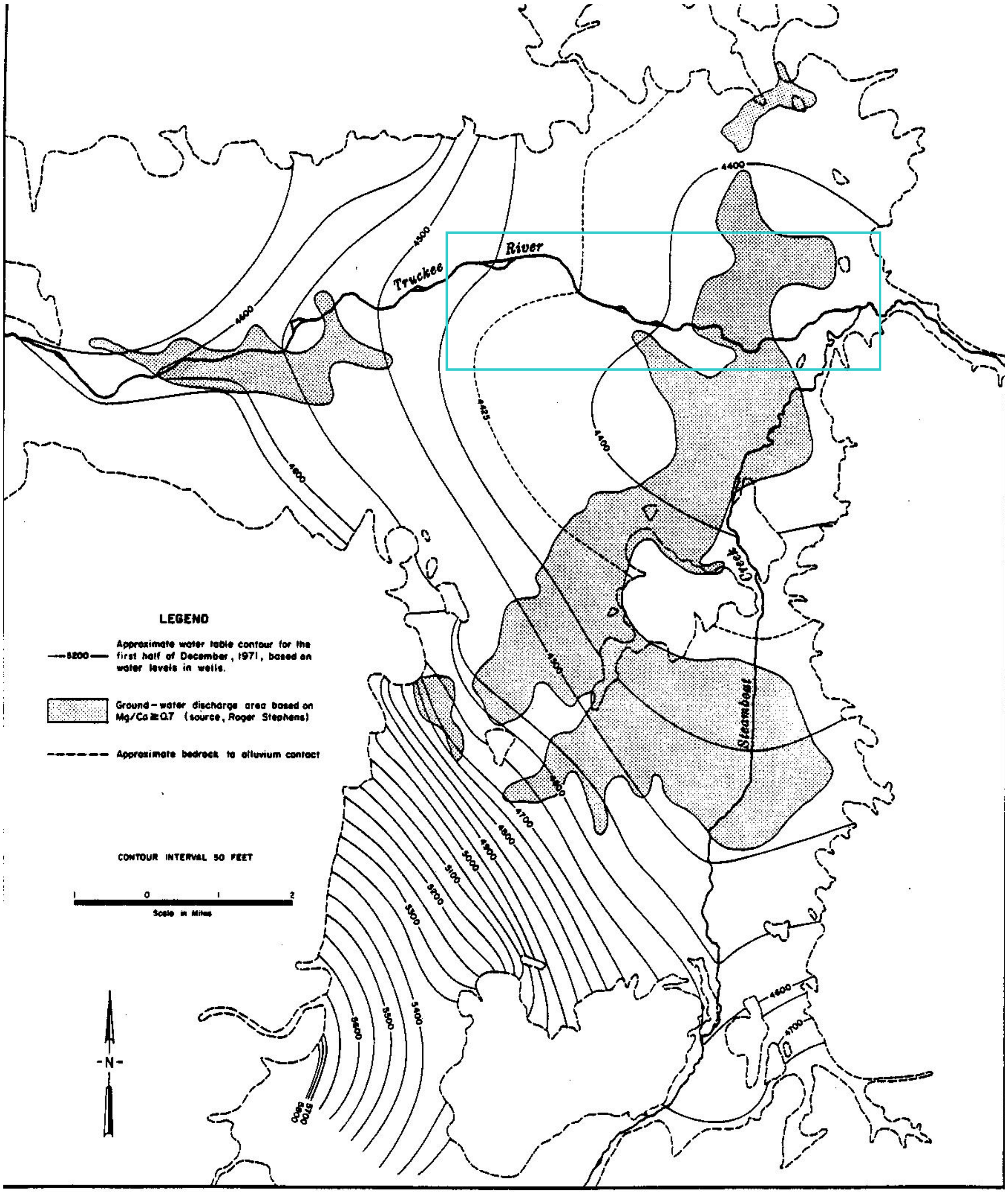

Figure 2.3 Truckee Meadows potentiometric surface map and areas of groundwater discharge (Cooley, 1971). Study area is outlined in the blue rectangle.

Aquifer recharge can originate from precipitation flowing through the intermediate alluvial fans between the Carson Range and the valley fill, and infiltration from the Truckee River (Harrill et. al., 1998; MMA, 1993; Van Denburgh et. al., 1973). The source of mountain front recharge (MFR) is also supported by the isotopic composition and sulfate found in groundwater at valley margins, which can be sourced to altered granitic and volcanic rocks (Cohen et. al, 1964). Recharge also occurs via infiltration from irrigation.

Shallow groundwater temperatures measured in the Truckee Meadows are higher than the mean annual air temperature (16.6°C), and fluctuate seasonally (data from WCDWR). Temperatures measured from monitoring wells in the Central Truckee Meadows average almost 15°C, with a maximum of 18°C and an anomalous minimum of 6°C (data from WCDWR). Surface water temperatures fluctuate above and below these values, depending on the season. Smaller daily temperature fluctuations occur in surface water during the winter, and larger daily fluctuations occur during the summer in the Truckee River (Taylor, 1998). Fluctuation of shallow groundwater temperatures may be caused by large surface temperature variations which is also characteristic of drier climates (Shump, 1985). Slightly higher regional groundwater temperatures probably arise from the arid/semi-arid environment, and locally higher temperatures are most likely linked to geothermal sources. Groundwater temperature in the Truckee Meadows reflects two sources: deep circulation from the VLFZ or warmer geothermal sources, and cooler shallow circulation from irrigation and infiltration (Mifflin, 1968). While flow through Truckee Meadows aquifers are the key groundwater element in the hydrogeological conceptual model, the Truckee River is also the key surface water element in this conceptual model.

2.3 Truckee River

The Truckee River is largest surface water body in the Truckee Meadows, and while flowing through this basin, the river meanders from an elevation of 1408 meters at

Chalk Bluff to 1332 meters at Vista Canyon; a total drop of 76 meters (CDM, 2002). Surface water in the Truckee Meadows is diverted mainly for domestic, agricultural, and industrial use. The Truckee River generally flows year round, with maximum sustained flows in the spring, low flows in the summer and fall, and occasional large peak flows when warm or spring winter storms rapidly melt the snowpack. Figure 2.4 shows a Truckee River hydrograph, with higher than usual flows in spring 2006. Much of the river’s discharge during low flow periods (late summer and early fall) is now sustained by releases from upstream dams and groundwater seepage as base-flow. Discharge measured at Vista is typically larger than discharge at Reno and Sparks because of Steamboat Creek and treated discharge of effluent from TMWRF (with the exception of late summer and early fall when flows at Steamboat Creek are minimal, less than 5 cfs). Measured flow statistics through the Truckee Meadows are provided in Table 2.1. Note the Steamboat Creek gage is not on the Truckee River.

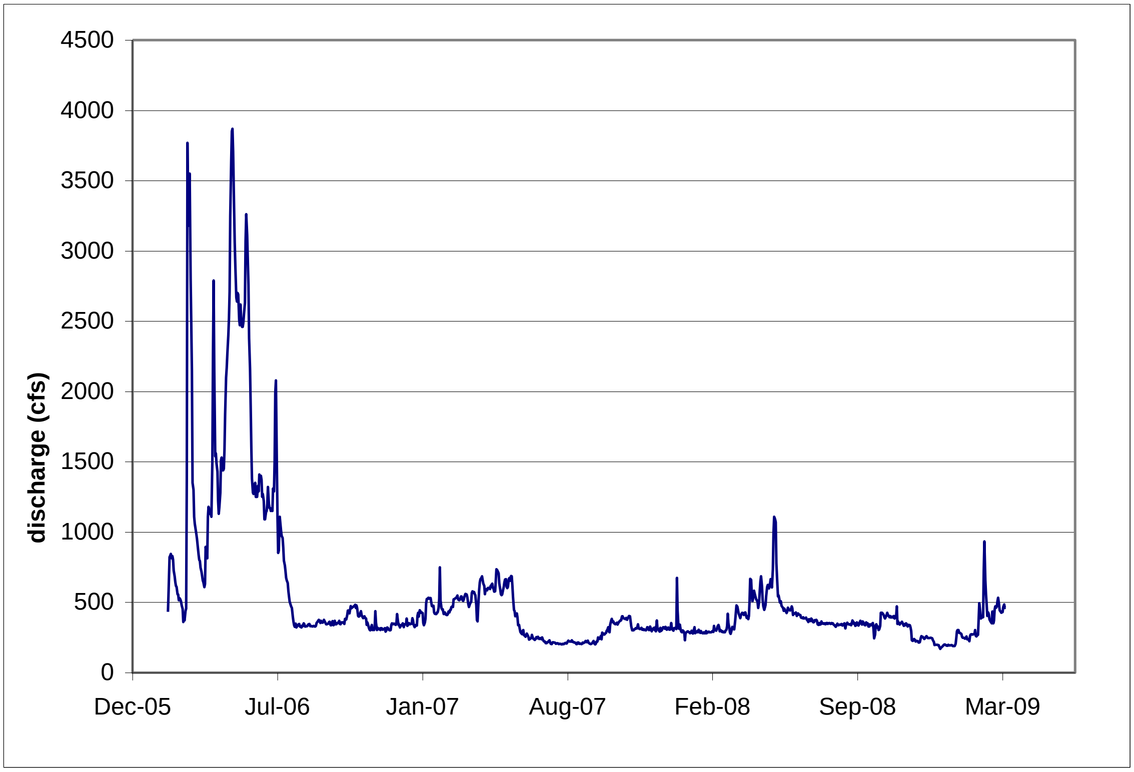

Figure 2.4 Truckee River discharge at the USGS Sparks gage from 2006 to early 2009**.**

Table 2.1 Mean, maximum and minimum flows through the Truckee Meadows.

Truckee Flow Statistics			
USGS Gage	**Mean (cfs)**	**Max (cfs)**	**Min (cfs)**
Reno	691	15,800	0.4
Sparks	671	15,000	0
Vista	815	16,100	28
Steamboat Creek	49	2,000	0

Water released from upstream reservoirs along the Truckee River can increase river flows and potentially decrease river temperature (Taylor, 1998). Solar radiation can be a major source of heat for the Truckee River along large reaches, while localized heating occurs at locations where influent groundwater or surface water temperature is higher than temperature in the river (Taylor, 1998). Localized cooling occurs at locations where influent groundwater and tributary temperatures are lower than the river's temperature (Taylor, 1998). These temperature differences can be used to help distinguish where higher temperature water sources, including groundwater, may be entering the river.

2.4 Surface and Groundwater Interactions

Previous research theorized that the Truckee River becomes a mostly gaining stream at some location between Highway 395 and East McCarran (Cooley, 1971; Cohen et. al., 1959). Just beyond the western boundary of this study extent, river and shallow groundwater elevations are similar near Wingfield Park (C. Benedict, personal communication). River stage and groundwater elevations are separated upstream of Wingfield Park due to topography, while river stage and shallow groundwater remain coincident downstream until their relative elevations are separated east of the VLFZ. This was further discussed in Section 2.2.1. Water level elevation in the Central Truckee Meadows east of the VLFZ is generally lower than the Truckee River, which supports the possibility that the river is potentially losing along much of downtown Reno (Westfall, 2008). A recent study concluded that infiltrating water from the Truckee River appears to be rapidly replacing groundwater in the shallow zone of the aquifer that moves downward in response to pumping in the deep zone of the aquifer (Worley Parsons Komex, 2007). Another recent publication that studied depletions in the Truckee Meadows (Schumer et. al., 2009) concluded the reach from the Reno gage to the Sparks gage is generally losing June though September, and is mostly gaining between the reach from the Sparks gage to the Vista gage. Moist soil along the southern streambank is evident above the Truckee Rivers' stage along the University of Nevada Reno (UNR) Agricultural Main Station (though this could also be influenced by irrigation at the farm).

As mentioned previously, it is hypothesized that the Truckee River is a gaining reach at the easternmost region of the Truckee Meadows; see Table 2.2 and associated Figure 2.5 for results from previous research (Reno gage to Sparks gage is Reach 1 and Sparks gage to Vista gage is Reach 2, which are discussed in more detail in section 3.1). It should be noted that there is some discrepancy between later and earlier conclusions due to increased groundwater pumping and decreased irrigation since the publication by Cohen and Loeltz in 1964. Data provided in Table 2.2 are described in more detail in the following paragraphs.

Table 2.2 Comparing groundwater flux to the river among previous studies. Negative numbers represent losing, and positive numbers represent gaining.

Relevant year & author	upstream of Reno	W. to E. McCarran	Reno to Sparks	Sparks to Vista
1959, Cohen & Loeltz	(--) 6 cfs			(+) 24 cfs
1960, MMA		(+) 9 cfs		
1988, McKenna			(-) 33 cfs	(+) 19.5 cfs
1991, MMA		(+) 2.3 cfs		
1985-1997, Schumer et. al.	(-) 35 to (+) 19		(-) 14 to (+) 35 cfs	(+) 5 to (+) 35 cfs
2002, Peterson				(+) 2 cfs

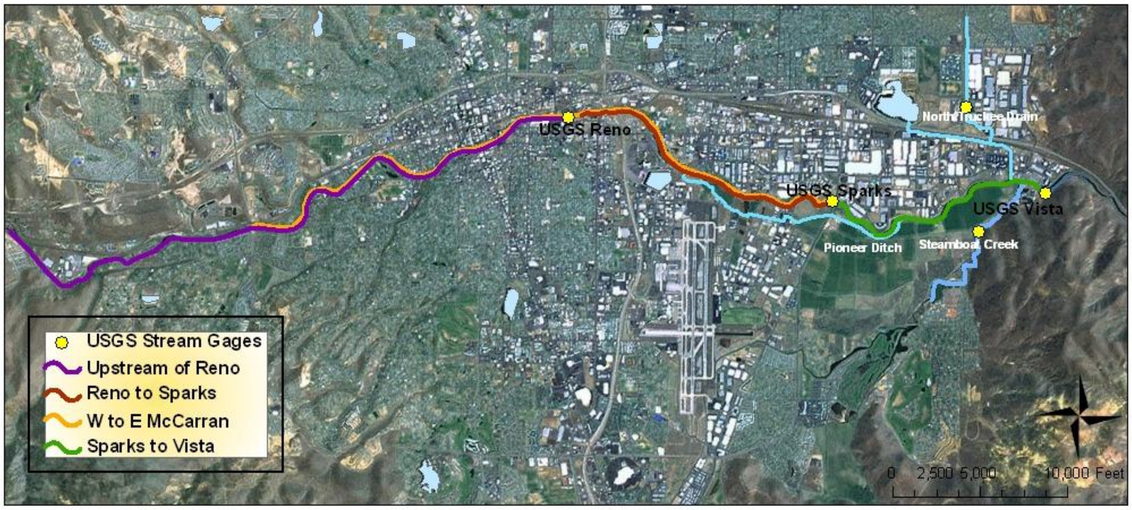

Figure 2.5 Map of respective reaches in Table 2.1

Peterson used water quality in a mixing model and reconciled her results with a stream mass balance (using USGS gage measurements) and nearby water levels in wells to model groundwater nutrients entering the Truckee River (Peterson, 2003). Results suggested that about 2 cfs of groundwater entered the river along 2.5 miles of the UNR Main Agriculture Station (Peterson, 2003).

McDonald Morrissey & Associates estimated that groundwater flux to the river between 1960 and 1991 decreased from approximately 9 to 2.3 cfs along the entire Truckee Meadows because increased pumping at production wells along the Truckee River, decreased irrigation, and dewatering of Helms gravel pit (MMA, 1993).

Schumer et. al. (2009) separated known from unknown depletions (calculated by subtracting downstream river flow from upstream river flow) along the Truckee River and averaged those by month. Unknown depletions (gains and losses) were attributed to groundwater surface water interactions, evapotranspiration (ET) from phreatophytes, evaporation from surface water, un-gaged diversions and return flows, and precipitation (Schumer et. al., 2009). Table 2.2 provides a range of these average monthly depletions from December to February. Only seepage rates from winter months were considered because it was assumed there was little to no ET, and diversions/un-gaged flows would be minimal with an absence of irrigation. Schumer et. al. considered average depletions of less (-) 15 cfs to be statistically indicative of a losing reach, and average depletions greater than (+) 15 cfs to be indicative of a gaining reach.

McKenna (1990) used Deuterium and Oxygen-18 to estimate base flow in the Truckee Meadows. On October 5, 1988, McKenna estimated that the Reno gage to Sparks gage reach lost 33 cfs, while the Sparks gage to Vista gage reach gained about

19.5 cfs. McKenna's results with respect to locations of groundwater gains are generally consistent with previous estimates, though the quantity of groundwater flux is lower than results from Cohen and Loeltz (1964), and larger than Peterson's results in 2002.

Bank storage from the hyporheic zone can be dismissed as the only source for changes in the stream budget because McKenna used channel parameters, along with bulk and pore volumes, to reveal that groundwater input to the Truckee River is greater than the river bank's storage capacity (McKenna, 1990). Along the Reno reach groundwater accretion was estimated at approximately 6440 acre-ft and along the Vista reach groundwater accretion was estimated at approximately 3480 acre-ft, while pore volume was only 2330 acre-ft at both reaches (McKenna, 1990). Spatial heterogeneities of hyporheic exchange are small enough to be dismissed for this study area since fluxes calculated for the stream budget are averaged over long reaches (Kalbus et. al., 2006), and sensors for the thermal analysis were placed along the river's thalweg (more details provided in the Methodology Chapter) which should not be affected by release of water from bank storage.

Cunningham installed peizometers along the eastern boundary of UNR's Agricultural Main Station. Results in Figure 2.6 demonstrate that peizometers closest to the Truckee River responded to the river's stage (Cunningham, 1977).

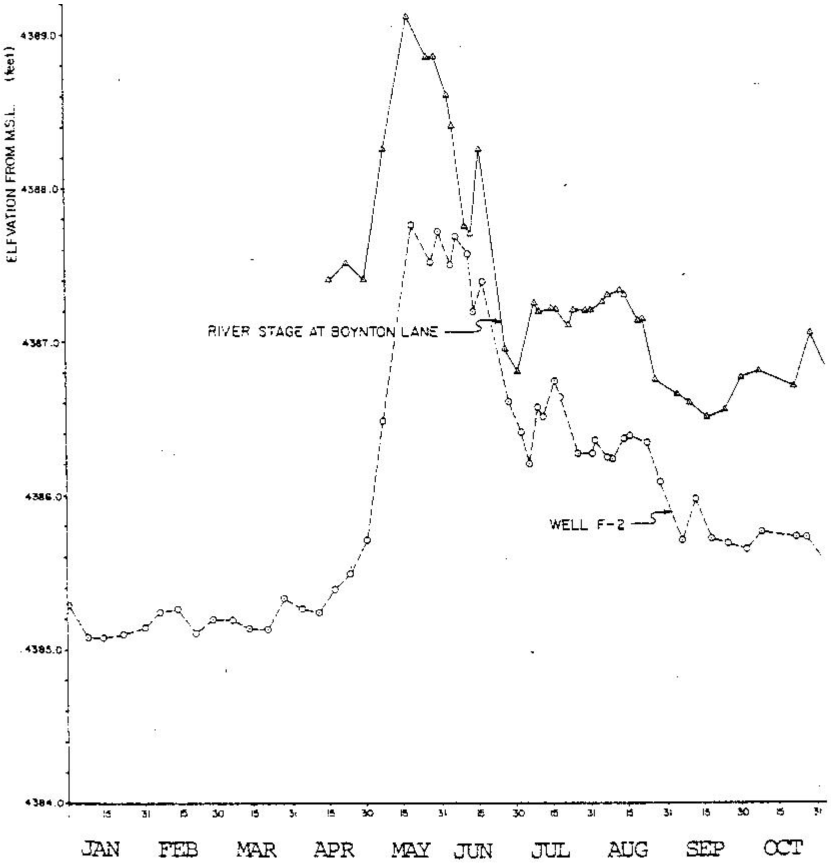

Figure 2.6 Truckee River hydrograph and nearby water level. Cunningham, 1977.

Pumping may divert groundwater from discharging into a river or create an unsaturated zone between the river and surrounding aquifer (Sophocleous, 2002; Cunningham, 1977). This has already occurred in some parts of the Truckee Meadows where sediments between the Truckee River and aquifer can change seasonally from a saturated to an unsaturated zone (Westfall, 2008), as can be interpreted in the Results section 4.3 where the water table is below river stage. An older study from the Desert Research Institute (DRI) estimated that 60-90% of water pumped from the Hilton aggregate pit (now the Grand Sierra Resort Aqua Range) would ultimately have come from the Truckee River (Bell, 1974). Yet a large portion of pumped groundwater returns to the shallow zone of the aquifer by infiltration from lawns (4.5 percent of municipal deliveries), leakage from old distribution pipes (3.5 percent of water deliveries), and eventually returns to the river via TMWRF (CDM, 2002).

2.5 Groundwater Budget

Surface and groundwater budgets are key to understanding water resources and how natural and anthropogenic changes may affect the local hydrologic cycle (Reilly et. al., 2008). A water budget is pertinent when considering safe yields for groundwater development. There are several previous estimates for the Truckee Meadows groundwater budget. Cohen and Loeltz estimated a recharge of 35,000 acre-feet per year (afy) in 1959 (Cohen & Loeltz, 1964), while MMA calculated a recharge (which included mountain front infiltration) of 43,500 acre-feet per year in 1960 (MMA, 1993). Therefore around 1960 the contributing volume of water to the Truckee Meadows was attributed to recharge (averaged at 40,000 afy) and river infiltration (averaged at 4,500 afy); a combined total of 44,500 acre-feet per year (Figure 2.7). The volume of water removed from the Truckee Meadows in 1960 was attributed to ET (20,000 afy), pumping (5,760 afy) and seepage to the river (averaged at 20,250 afy); a combined total of 46,010 acre-feet per year (Figure 2.7). This leads to an average discrepancy of 1,510 acre-feet per year in the control volume of the groundwater budget in 1960, which can be accommodated by estimated underflow through Vista Canyon (mentioned in section 2.2). The 1960 pumping rate incorporated both municipal and domestic wells, along with pumping from the Helms Gravel Pit and the Nevada Aggregate Pit. According to the Truckee Meadows Regional Planning Agency (TMRPA), population throughout the Truckee Meadows in 1960 was less than 100,000.

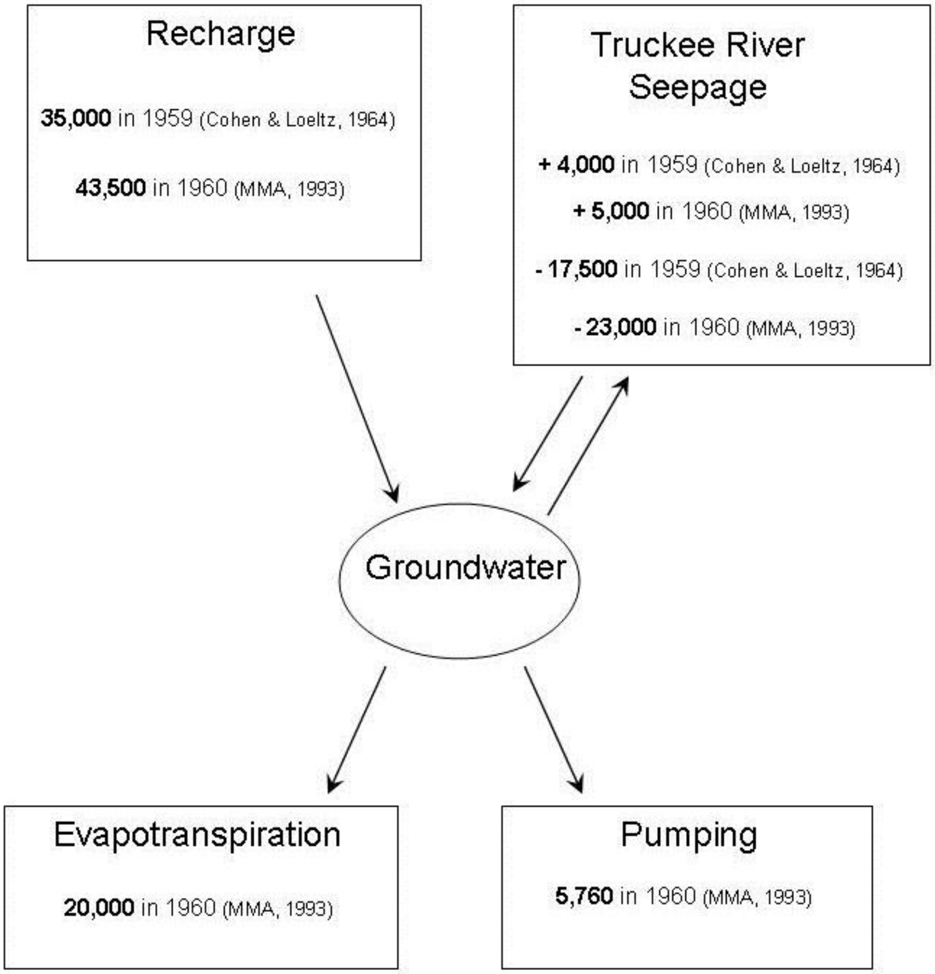

Figure 2.7 Approximate 1960 Truckee Meadows groundwater budget in acre-feet per year.

Artesian wells commonly flowed south of the river in the eastern Truckee Meadows, and land around the Reno-Tahoe International Airport (which expanded around 1960) used to be a region of groundwater discharge (Cooley, 1971; CDM, 2002; Cohen et. al., 1964). The hydrogeologic regime had since changed due to extra production wells and increased groundwater pumping (mostly along the Truckee River) (MMA, 1993), and the conversion of agricultural farms to urbanized land. These conditions lead to decreased recharge and evapotranspiration, and increased potential Truckee River recharge to the aquifer. During 1991 the contributing volume of water to aquifers in the Truckee Meadows was attributed to recharge (30,700 afy) and river infiltration (15,000 afy); a combined total of 45,700 acre-feet per year (Figure 2.8). The volume of water removed from aquifers in the Truckee Meadows during 1991 was attributed to ET (17,700 afy), pumping (24,000 afy) and seepage to the river (4,000 afy); a combined total of 45,700 acre-feet per year. The 1991 pumping rate incorporated both municipal and domestic wells, along with pumping from the Helms Gravel Pit and the Nevada Aggregate Pit. Population was approximately 250,000 at that time (data from TMRPA).

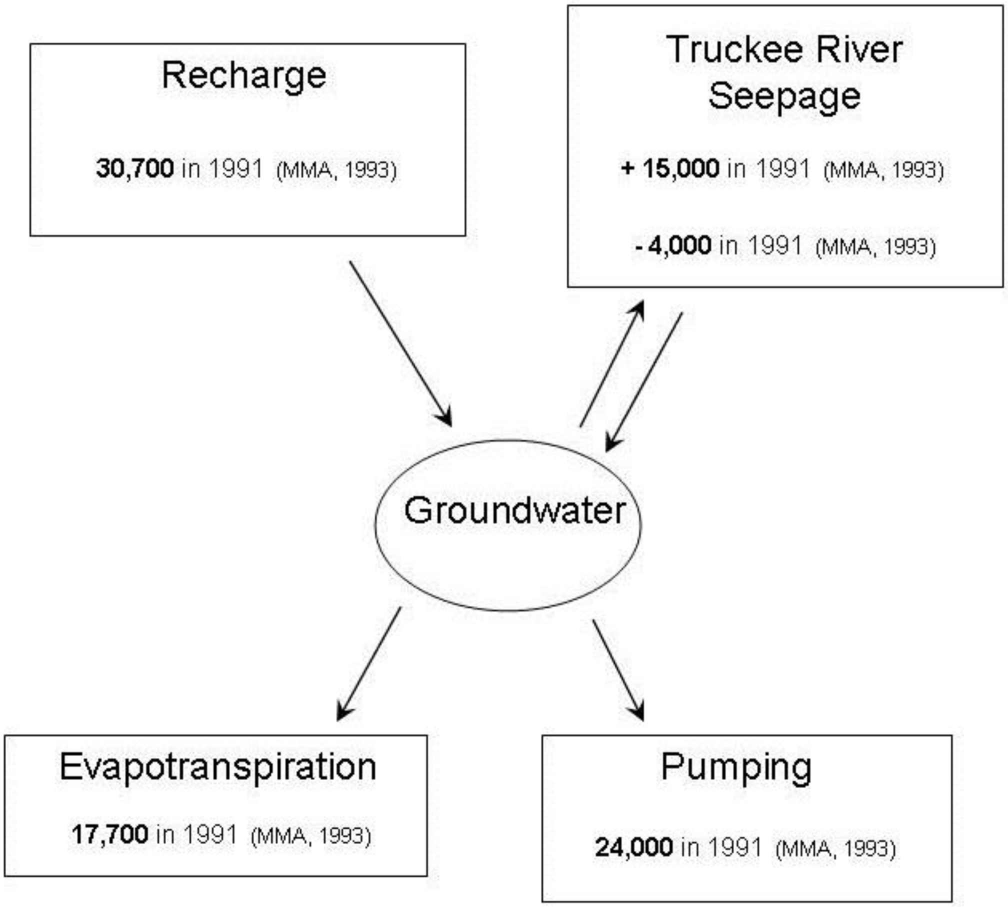

Figure 2.8 1991 Truckee Meadows groundwater budget in acre-feet per year.

No current estimates for recharge and ET have been published for the Truckee Meadows. It is expected that both recharge and ET have decreased since most water previously diverted for irrigation is now used for municipal consumption, hence more water eventually returns to the Truckee River via effluent from the Truckee Meadows Water Reclamation Facility (TMWRF). Evapotranspiration is localized to a riparian zone along the river corridor, which has not changed much since 1960. In the last 50 years upstream municipal diversions have increased while irrigation on agricultural land (mostly in Sparks east of the airport) has decreased, leading to less recharge and ET. As of 2008, population in the Truckee Meadows was over 400,000 (data from TMRPA), and municipal water pumped by TMWA and WCDWR was approximately 10,432 acre-feet per year. The given 2008 pumping rate is lower than the MMA 1991 pumping rate because 2008 data does not include groundwater discharge from domestic wells or gravel pits. The Helms Gravel Pit ceased pumping after the 1997 flood and the old Nevada Aggregate Pit at the Hilton near 2160 East 2nd Street (Bell, 1974) had since become a pond.

Chapter 3 Methodology

The objective of this research is to locate and quantify groundwater/surface water interactions along the Truckee River corridor in the eastern Truckee Meadows. The use of multiple methods will help to constrain estimated flux and help support the combined results. Methods used to accomplish this are:

- Stream Budget

A surface discharge differencing method used to analyze streamflow is calculated from discharge data gathered along the Truckee River within the study extent between USGS Reno gage and USGS Vista gage.

- Thermal Analysis

  Analysis of changes in streambed temperature used to determine hydrologic flux. Groundwater entering the river is detected using small temperature sensors (thermistors).

- River Stage versus Groundwater Levels

  Detailed river stage measured from LIDAR (Light Detection and Ranging) run along the Truckee River Corridor in July 2008 is compared to groundwater level elevations measured from monitoring wells during the same month.

- Groundwater Trends

  Fluctuations in the water table were studied and potentiometric maps were created with data from wells in the shallow zone of the complex aquifer system to help formulate a conceptual model.

3.1 Stream Budget

The stream budget methodology is a differential streamflow measurement is used to calculate seepage (groundwater flux) and is practical over long reaches (Becker, 2004). Parameters of the stream budget include measured upstream and downstream flow, diversions and surface water influents, and associated statistical uncertainties. Historical low flows were isolated and analyzed to provide a potentially higher ratio of groundwater flux to total river flow, therefore allowing easier identification of changes in river flow attributable to groundwater flux.

Groundwater and surface water exchange was calculated using differences in streamflow at successive stream gages. For most seasons (with the exception of late summer/early fall), there was an expected increase in Truckee River flow between Downtown Reno and Vista Canyon due to groundwater discharge, influx from Steamboat Creek, North Truckee Drain, and TMWRF discharge. Hence a stream budget was calculated by measuring flow between the USGS Reno and Vista gages, with the Sparks gage as an intermediary measuring point. Streamflow differences are practical because averages flux over reaches several miles in length, the effects of hyporheic exchange can be dismissed. Equation 1 states:

$$Q_{GW} = Q_{RiverDownstream} - Q_{RiverUpstream} \tag{1}$$

Separated into different reaches and expanded to incorporate diversions and surface water influents, equation 1 expands to:

$$Q_{GW}1 = Q_{Sparks} - Q_{\mathrm{Re}no} + Q_{Glendale} + Q_{PioneerDitch} \tag{9}$$

$$Q_{GW}2 = Q_{Vista} - Q_{Sparks} - Q_{PioneerSpill} - Q_{NTDrain} - Q_{Marina} - Q_{Steamboat} - Q_{TMWRF} \tag{10}$$

Where $Q_{GW}1$ is groundwater flux at Reach 1, $Q_{GW}2$ is groundwater flux at Reach 2, Q_{Sparks} is flow measured at the Sparks gage, $Q_{\mathrm{Re}no}$ is flow measured at the Reno gage, $Q_{Glendale}$ is the diversion measured at the Glendale Treatment Plant, $Q_{PioneerDitch}$ is the irrigation diversion measured at Pioneer Ditch, Q_{Vista} is flow measured at the Vista gage, $Q_{PioneerSpill}$ is discharge measured at Pioneer Spill, $Q_{Steamboat}$ is flow measured at Steamboat Creek, Q_{TMWRF} is discharge measured from TMWRF, $Q_{NorthTruckeeDrain}$ is flow measured at North Truckee Drain, and Q_{Marina} is overflow measured at the Sparks Marina Park.

Surface water flows and diversion data were obtained from the USGS National Water Inventory System (NWIS), the Federal Water Master's Office, and TMWA. Four factors affecting the accuracy of USGS gage measurements are: instrumental, personal, computational and sampling errors (McKenna, 1990). USGS streamflow measurement accuracy ratings are listed as Excellent, Good, Fair and Poor; with 95% of flows within 5%, 10%, 15% and >15%, respectively, of the true value (Steven Berris, USGS, written communication). The Poor accuracy rating (>15%) was applied as 20% for practical calculations. These accuracy ratings were used to determine the standard deviations of each component in the stream budget, as represented by equation 3 in section 1.2.1:

$$\sigma_X = (\alpha Q_X) \div 1.96 \qquad (3)$$

During low-flow periods of interest, accuracy ratings (α) for the Reno USGS stream gage ranged from Fair to Good, while accuracy ratings for the Sparks, Vista, North Truckee Drain (when available), and Steamboat Creek USGS stream gages ranged from Poor to Good. Diversions and other surface water influents monitored by TMWA and the Federal Water Master had the highest uncertainties because those measurements did not have accuracy ratings. Hence 95% of flows measured from TMWA and the Federal Water Master were assumed to be 15% of the true value, or equivalent to the USGS Fair accuracy rating. Standard deviation for groundwater flux (Q_{GW}) was then quantified using equation 2 from section 1.2.1:

$$\sigma_{GW} = \sqrt{\sigma^2{}_{RiverUpstream} + \sigma^2{}_{RiverDownstream} + \sigma^2{}_{Diversions} + \sigma^2{}_{SwInfluents}} \qquad (2)$$

Surface water inputs to the river within the study area included Pioneer Spill at UNR's Agricultural Farm, North Truckee Drain, Steamboat Creek, and TMWRF discharge, which flows into Steamboat Creek (see Figures 3.1 and 3.2). Sparks Marina Park overflow joins the North Truckee Drain below the USGS gage, and TMWRF discharges into Steamboat Creek beyond the USGS gage. Therefore, daily discharges for both TMWRF and Sparks Marina Park must be accounted for in the stream budget.

The only significant diversions from the Truckee River in the study area are the Glendale Intake (Phase 1 sensor location T2 in Figure 4.1) and Pioneer Ditch (see Figures 3.1 and 3.2). The Glendale Intake is managed by TMWA and can divert up to 40 cfs between May and September. Pioneer Ditch has an average withdrawal rate of 15 cfs during seasonal irrigation between April and October, and returns some of that water to the river at the UNR Agricultural Farm via the Pioneer Spill. The North Truckee Ditch, located just upstream of the Glendale diversion, historically diverted less than 1 cfs from the Truckee River, but no diversions have been recorded since 2002.

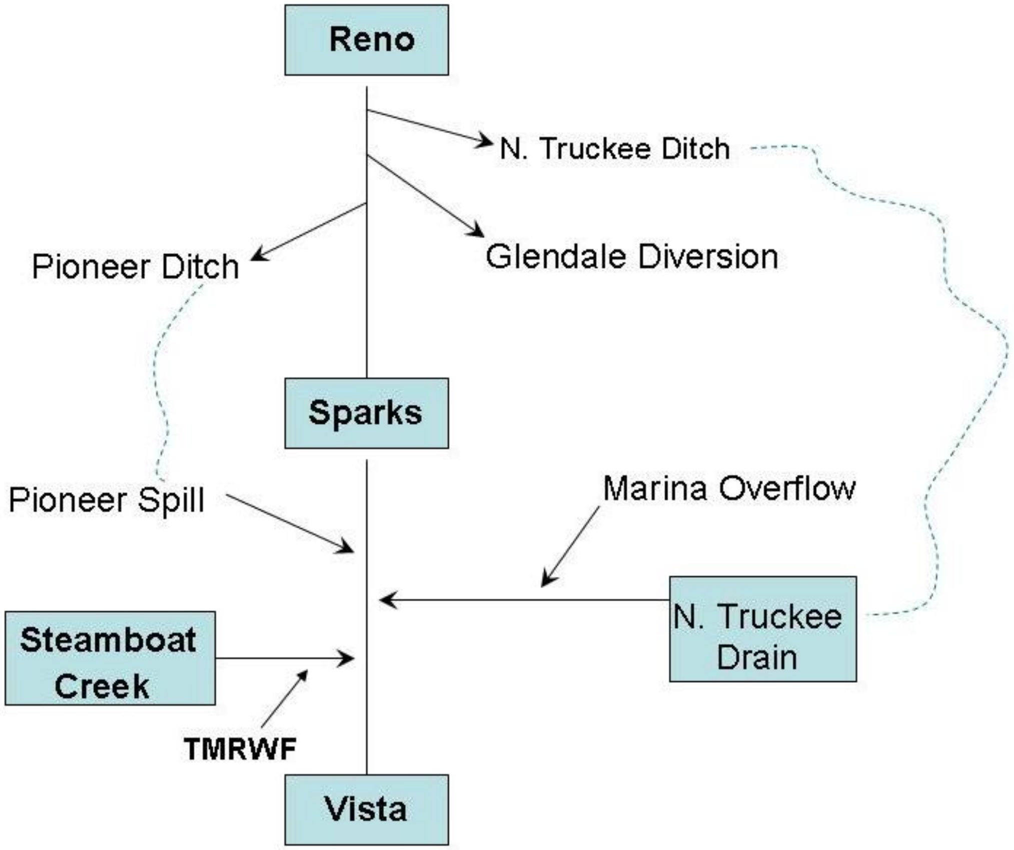

Figure 3.1 Diversions and surface water influents in study area. USGS stream gages present at blue boxes. Not to scale.

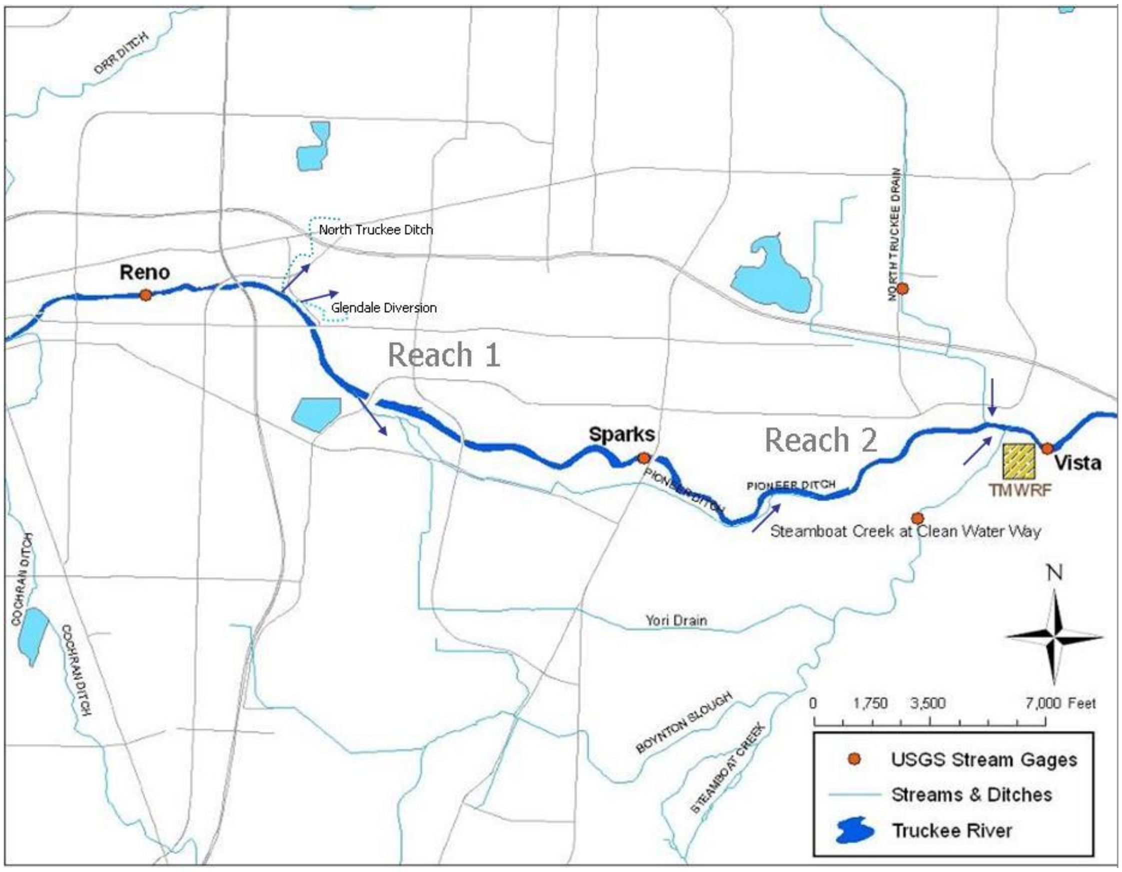

Figure 3.2 Truckee River, ditches, diversions and associated USGS stream gages.

Seepage rates must be greater than the standard error of measurement to reduce uncertainty. A seasonal low-flow period on the Truckee River is ideal because it provides better resolution for detection of groundwater seepage (Kalbus et. al., 2006). For this method, flows are considered low when a sustained discharge over a five day period (or longer) is below 50 cfs at Reno and Sparks, and discharge is below 100 cfs at Vista. If flows are significantly higher than the given baselines of 50 and 100 cfs, any potential groundwater flux may fall within the range of the data’s standard error.

If stream budget results are reliable, calculated flux can be used to simulate seepage using the thermal analysis. In order to compare these results with the thermal analysis described in section 3.2, a more robust stream budget with a greater frequency of measurements was calculated during the thermistor deployment from February 28 to March 21 (Phase 1), and again from August 14 to September 5, 2008 (Phase 2).

3.2 Thermal Analysis

The objective of the thermal analysis was to locate and reliably measure changes in streambed temperature of a sufficient magnitude (larger than changes attributable to atmospheric conditions) that coincide with areas of groundwater influx. During the early spring, river temperatures are colder than the groundwater (annual mean temperature is almost 15°C) in the Truckee Meadows, so an addition of warmer water would either show an increase in temperature downstream or dampen the diurnal temperature fluctuations (Westhoff et. al., 2007; Conant 2004; Webb et. al., 1997). An addition of cooler water from groundwater discharge in the late summer/early fall would show a decrease in temperature downstream. In the early spring Truckee River temperatures at the USGS Vista gage fluctuate between 0 and 16°C, and in the late summer/early fall temperatures fluctuate between 12 and 25°C (Taylor, 1998). Shallow groundwater temperatures measured at monitoring wells in the eastern Truckee Meadows range from 14 to 16.5°C during the early spring, and 16 to 18.5°C in August and September (data from WCDWR).

Below is the linear mixing equation used to solve a simplified version of the thermal energy balance (Becker et. al., 2004; Selker et. al., 2006), followed by an equation representing base-flow conditions:

$$Q_1 T_1 + Q_{GW} T_{GW} = Q_2 T_2 \tag{11}$$

Where Q_1 is upstream flow, T_1 is upstream temperature, Q_{GW} is groundwater flux, T_{GW} is groundwater temperature, Q_2 is downstream flow, and T_2 is downstream temperature. Streamflow data is necessary because thermal surveys can not independently predict groundwater flux without accounting for conservation of mass (Becker, 2004). Combining equations 11 with 6 from Section 1.2.4, then solving for groundwater flux yields:

$$Q_{GW} = \frac{Q_1(T_2 - T_1)}{T_{GW} - T_2} \tag{12}$$

It is assumed Equation 12 is invalid if the river loses to the aquifer because there is no mixing in the surface water system (where T_1 and T_2 are measured), and where no change in temperature is measured. If no change in temperature is measured, then equation 10 yields a groundwater flux of zero. The mixing equation requires a parameter for groundwater temperature (T_{GW}), therefore, if the river is losing to the aquifer, then T_{GW} is void and the equation is not appropriate for this method. T_{GW} is also assumed constant along the stream reach. If the river is neither gaining nor losing then there is no groundwater flux and therefore the up and downstream temperatures would be the same, and difference in temperature between the upstream and downstream should be larger than the thermistor's standard error to be reliably measured. Also, although viscosity and density are temperature dependent, the range of temperature change is not large enough to significantly alter these parameters.

In addition to groundwater advection, stream temperature is also influenced by the following variables: ambient air temperature, solar radiation, longwave radiation, sensible heat flux, latent heat flux, streambed conduction, friction, ground surface temperature, surface water inflows (including storm water), and precipitation (Webb et. al., 1997; Becker et. al., 2004; Westhoff et. al., 2007). Though these variables are not included in equation 10, the Stream Segment Temperature Model (SSTEMP) accounts for the heat flux from these variables (Bartholow, 2002) with the exception of surface water inflows, which are not expected to occur during deployment periods, and precipitation.

3.2.1 SSTEMP Application

The main objective for using SSTEMP was to discover which variables strongly affect streambed temperature. Another objective of accompanying the thermal analysis with SSTEMP was to see whether changes in temperature downstream could be accounted for by channel characteristics and atmospheric conditions, because these variables were not accounted for in equation 12. Another objective was to see how much groundwater advection would result in a change in downstream temperature and whether a significant difference in groundwater advection is needed when input variables are changed. This was accomplished by changing segment outflow until modeled downstream temperature equaled measured downstream temperature.

SSTEMP 2.0.8 is a scaled-down version of the Stream Network Temperature Model (SNTEMP) and simulates mean daily downstream temperature based on stream channel geometry, along with hydrological, meteorological, and shading conditions (Bartholow, 2002; Theurer, 1984). Four models work interactively with SSTEMP; heat transport model, solar model, shade model, and meteorological model (Bartholow, 2002). The heat transport model predicts mean daily downstream temperature as a function of reach distance and streamflow. The solar model predicts how much solar radiation penetrates the water as a function of latitude, date, and meteorological conditions. The shade model predicts interception of solar radiation due to topography, riparian vegetation, and average azimuth of the stream reach. The meteorological model predicts changes in air temperature, relative humidity, and pressure as a function of elevation. SSTEMP assumptions include; homogenous and constant boundary conditions, no lateral or vertical temperature dispersion, water is instantaneously mixed at all times, and simulated downstream temperature is unreliable below 4°C (Bartholow, 2002).

SSTEMP accommodates the FA term in equations 5 and 7, and the Q_N term from equation 8. Output heat fluxes calculated by SSTEMP include; sensible heat, streambed conduction, evaporation (latent heat), solar radiation penetrated through water, back radiation, atmospheric radiation, vegetative radiation, friction, and simulated downstream temperature. Net Radiation, Q_R, is accommodated by solar radiation recorded by the Western Regional Climate Center (WRCC) and longwave radiation calculated by SSTEMP in the forms of back, atmospheric, and vegetative (landcover) radiation. Latent heat, Q_E, is calculated as evaporation or condensation by SSTEMP using humidity, air and water temperature. Sensible heat, Q_S, is calculated by SSTEMP using wind speed, atmospheric pressure, air and water temperature. Streambed conduction, Q_B, is calculated by SSTEMP using a thermal conductivity instead of a hydraulic conductivity and the gradient between streambed equilibrium temperature at some depth below surface and water temperature (Theurer, 1984). Friction, Q_F, is calculated by SSTEMP using the streambed gradient, flow, channel width, and the Manning's *n* value. Groundwater advection, Q_A, is accommodated by the change of inflow versus outflow in SSTEMP.

Channel geometry input variables include: latitude, segment length, upstream elevation, downstream elevation, width, and Manning’s *n* (Bartholow, 2002). A Manning’s *n* value of 0.04 was chosen based on streambed characteristics (Chow, 1959). Each stream segment location was determined by thermistor placement (see Figure 4.1). Hence one segment lies between thermistors T1 and T2, and another segment lies between thermistors T2 and T3, etc.

Hydrological input variables included: upstream flow, upstream temperature, downstream flow (upstream flow plus groundwater advection), and accretion (groundwater) temperature (Bartholow, 2002). Upstream flow was provided by the nearest USGS gage, with diversions and influents in the stream segment accounted for. Upstream temperature data was obtained by thermistors, and groundwater temperature was interpolated by nearby shallow monitoring wells.

Meteorological input variables included: air temperature, relative humidity, wind speed, ground temperature, thermal gradient, possible sun % (technically % cloud cover), and solar radiation. Western Regional Climate Center provided daily mean measurements for air temperature, relative humidity, wind speed, and solar radiation (Bartholow, 2002). Truckee Meadows mean annual air temperature of 16.6°C was used for ground temperature. Defaults were used for thermal gradient and possible sun %.

Shading input variables included: segment azimuth, topographic altitude, vegetation height, vegetation crown, vegetation offset, and vegetation density (Bartholow, 2002). Values for shading variables were determined from field observations and Google Earth, whereas vegetation density was varied seasonally to account for changes in foliage.

Sensitivity analyses were performed on variables that were unknown, variables that were believed to have a strong influence on downstream temperature, and for reaches where groundwater accretion (advection) was expected to occur. The resultant sensitivity coefficient should express which variables contribute significant uncertainty to the thermal analysis:

$$X = \frac{\partial Q_{GW}}{\partial P} \tag{13}$$

where X is the sensitivity coefficient, ∂Q_{GW} is the change in groundwater advection from base conditions in order for simulated downstream temperature to equal measured downstream temperature, and ∂P is the change in variable of interest. Equation 13 implies a linear relationship between downstream temperature and its variable, and also assumes the variables are not correlated (Bartholow, 2002). The sensitivity coefficient for total shade is not linear and is addressed in Equation 14.

$$\frac{\partial Q_{GW}}{\partial P_{SHADING}} = \frac{Q_{GW(P+25\%)} + Q_{GW(P-25\%)}}{P_{+25\%} - P_{-25\%}} \tag{14}$$

Equation 14 expresses the non-linear relationship of changing variables that influence total shade, and hence how much groundwater advection is needed for simulated downstream temperature to equal measured temperature. Table 3.1 provides sources of measurement and standard deviation for nine variables used in SSTEMP. Sensors at the weather station are audited annually (personal communication, Greg McGurdy). The sensitivity analysis is presented in the results section.

Table 3.1 SSTEMP variables with unknown values or predicted to have strong influence on downstream temperature.

Variable	σ	Source of σ calculation	Source of variable measurement
Inflow Temp	varies	thermistor standard error	thermistors
Groundwater Temp	varies	covariance of multiple measurements	WCDWR, monthly
Air Temp	varies	Visalla 50 Y, HMP 50 Sensor	WRCC
Relative Humidity	0.3	Visalla 50 Y, HMP 50 Sensor	WRCC
Wind Speed	0.3	RM Young Wind Monitor	WRCC
Thermal Gradient	0.41	Assumed covariance of 25%	default
Possible Sun %	17.5, 19	Assumed covariance of 25%	default
Solar Radiation	P(0.03)	LICOR, LI-200S	WRCC
Total Shade	varies	Assumed covariance of 25%	field observations and Google Earth

3.2.2 Field Methods

Fieldwork consisted of deploying High-Resolution Thermochron i-Button thermistors (Model # DS1921Z) along the Truckee River streambed (Maxim, 2009 A). Epoxy was applied to seal the thermistors against water. Model # DS1921Z thermistors have an accuracy of +/- 1°C, a range of (-) 5°C to (+) 26°C, and a resolution of 0.125°C (Maxim, 2009 A).

Thermistors were calibrated prior to Phase 1 deployment using a Thermo Neslab RTE 17 refrigerated circulation bath (Thermo, 2008) at 2, 4, 6, 8, and 10°C, as this was the expected temperature range to be encountered in the Truckee River during the early spring. Uncalibrated temperature differences were 0.5°C below the observed temperatures in the circulation bath (Thermo, 2008). Phase 2 thermistors were calibrated at higher temperatures (13, 14 and 15°C) prior to deployment. Linear regressions for every thermistor prior to each deployment were calculated by comparing the measured versus actual temperature and were used to correct temperature measurements recorded in the river (see Appendix D). This application increased accuracy from 1°C to 0.05°C for Phase 1 and 0.07°C for Phase 2. Data were retrieved from the thermistors with a DS1402D-DR8+ Blue Dot Receptor (Maxim, 2009 B).

Deployment Phases were chosen to coincide with expected low flow periods. Late spring/early summer deployments did not occur due to expected larger flows arising from snowmelt, and late fall/early winter deployments did not occur because of possibly high and erratic flows from large precipitation events. Nineteen thermistors (Figure 3.3) were placed along the streambed's thalweg in the Truckee River. Data were recorded from February 28 to March 21 (Phase 1) for the first deployment and provided temperature every 20 minutes. Due to theft and equipment failure, data from only 8 of the deployed thermistors at a total of 6 sites was usable (Figure 4.1). To avoid confusion, thermistor locations in Phase 1 were organized downriver numerically, and Phase 2 locations were organized alphabetically. Temperature data for the second deployment (Phase 2) was collected from the same thermistors during August 14 to September 5. Temperature was recorded every 15 minutes to coincide with stream discharge measurements. Due to more theft, temperature data exist for only three locations during the summer (Figure 4.1). Locations where two thermistors were present, mean temperature was used to calculated groundwater flux using the thermal analysis, as opposed to averaging a flux from two different model results.

Figure 3.3 Weights tied on thermistors for stability before placing in river.

3.3 River Stage versus Groundwater Level

Truckee River stage and shallow groundwater levels were compared to reveal where the river may be gaining or losing. Detailed river stage measured from a LIDAR (Light Detection and Ranging) run along the Truckee River Corridor in July 2008 was compared to groundwater level elevations measured from monitoring wells during the same month. Water levels in shallow monitoring wells located near the river were plotted along the river stage's elevation profile. A potentiometric surface including both shallow monitoring wells and the rivers' stage was created using Golden Software Surfer 8 (Golden Software, 2005) for a July 2008 snapshot.

Depth to groundwater was measured at a resolution of 0.01ft (data from the WCDWR), and LIDAR data (provided as 1 meter grids) of river stage along the river provided elevations with a resolution of 0.01ft. Data was dismissed on and near overpasses and interpolated to avoid inaccurate elevations. LIDAR data is dubious in shallow water less than 0.3 meters (LaRoque, 1990), and stages recorded at all three USGS gages during July 2008 were higher than 1 meter (NWIS data). Yet it is possible that river stage may been shallower than 0.3 meters in between measured gages.

3.4 Groundwater Trends

Groundwater trends in the eastern Truckee Meadows provide insight to the hydrogeologic regime of this study area, which can help to determine where and how groundwater interacts with the river. Methods used to determine groundwater trends include: transient simulations (hydrographs), and potentiometric contours of the water table. If there are strong ground-surface water interactions, shallow monitoring wells near the Truckee River are most likely to show a reaction to changes in river stage.

A transient simulation incorporated monitoring well hydrographs along the river in eastern Truckee Meadows. These hydrographs of wells in both the deep and shallow zones were compared to the Truckee River’s hydrograph as well. All groundwater data came from WCDWR. Depth to water in monitoring wells was measured quarterly to catch each seasonal change in the water level.

Potentiometric maps in the central and eastern Truckee Meadows were created quarterly for one year. Depth to groundwater measurements were acquired from WCDWR to find the aquifers’ potentiometric surface. The Sparks Marina and a pond south of the Grand Sierra Resort are connected to the groundwater in their immediate area (Glancy et. al., 1984), so those respective elevations were used to further constrain potentiometric surfaces.

Evaluation of Results

4.1 Stream Budget

A stream budget during low flows was calculated using monthly averages to decrease noise in the data. Reach 1 (5,230 meters) is bounded by Reno and Sparks USGS gages and Reach 2 (4,400 meters) is bounded by Sparks and Vista USGS gages (Figure 4.1).

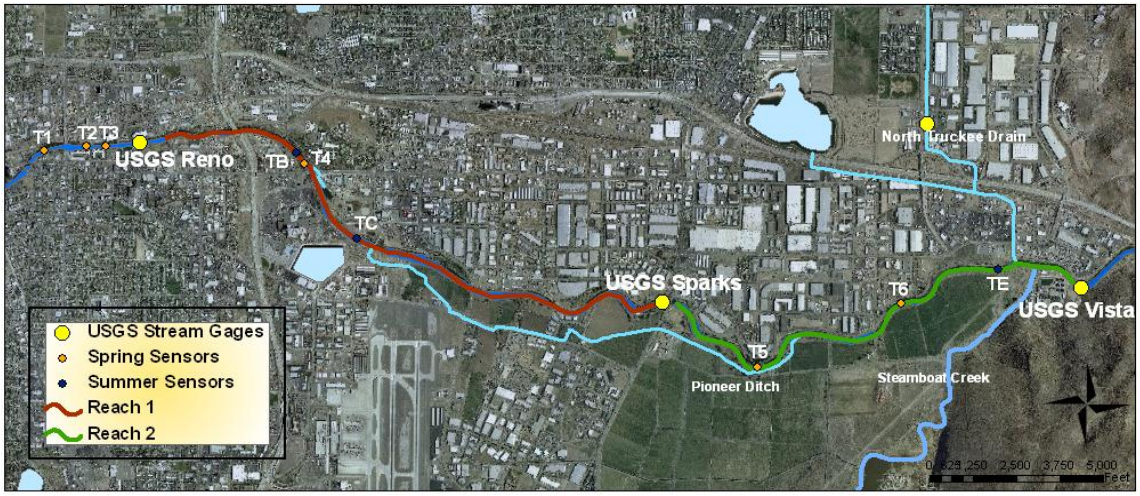

Figure 4.1 Reach and thermal sensor locations**.**

Low stream flows were analyzed to increase the ratio of groundwater discharge to total Truckee flow and to reduce uncertainty in the seepage estimates. A baseline for low flows was determined to be 50 cfs at the Reno and Sparks gages, and 100 cfs at the Vista gage over a five day period (or longer). Periods of these low flows occurred in 1976-

1977, 1988, 1990, 1991, 1992, 1994, and 2004 (Figure 4.2) (NWIS data; McKenna, 1990; Fordham, 1984).

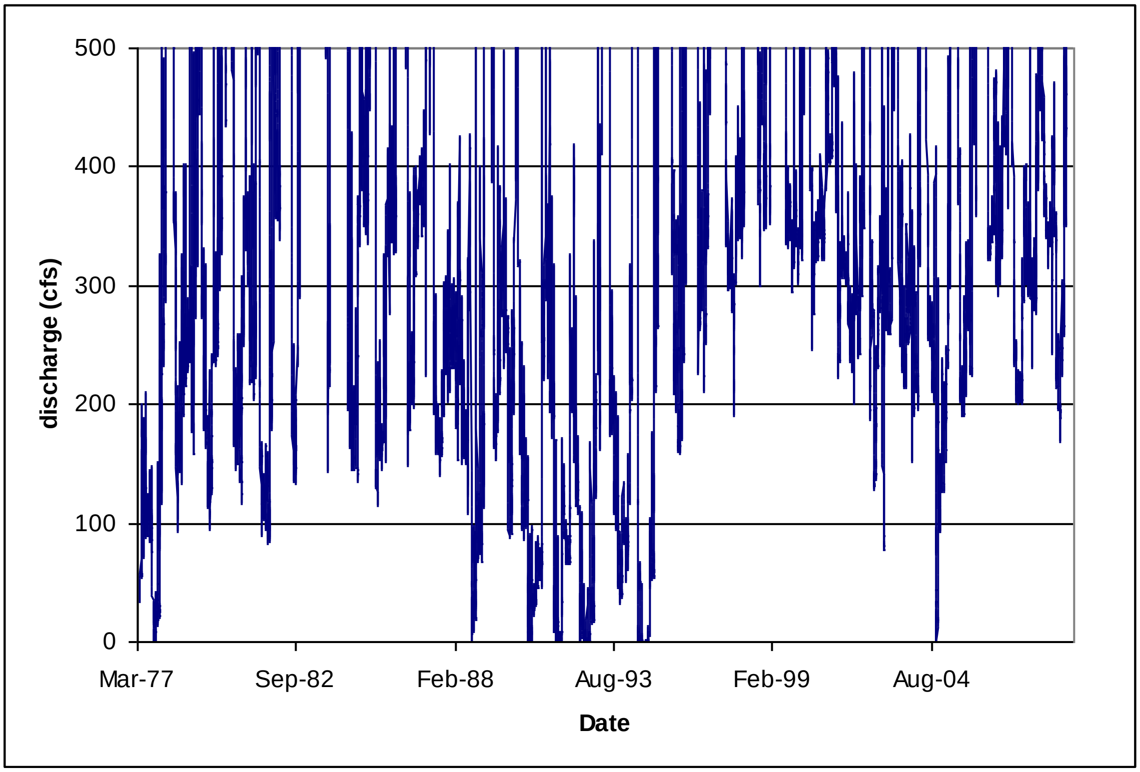

Figure 4.2 Discharge at the USGS Sparks gage, scaled down to highlight low flows.

Seepage was calculated using equations 9 and 10 from section 3.1:

$$Q_{GW}1 = Q_{Sparks} - Q_{Reno} + Q_{Glendale} + Q_{PioneerDitch} \tag{9}$$

$$Q_{GW}2 = Q_{Vista} - Q_{Sparks} - Q_{PioneerSpill} - Q_{NTDrain} - Q_{Marina} - Q_{Steamboat} - Q_{TMWRF} \tag{10}$$

Assuming all diversions and return flows are accounted for, Reach 1 consistently looses (or there are possible unknown diversions) while Reach 2 gains (or there are possible unknown return flows) (Figure 4.3). October 1990 is the only low flow period where Reach 2 looses, which may be explained by precipitation patterns. Precipitation that month was recorded at only 0.06 inches, whereas mean historical precipitation for the month of October is 0.41 inches (data from WRCC). Precipitation for both August and September in 1990 were equivalent to mean historical data. Daily calculated flux for each reach is listed in Appendices B and C. No low flows occurred during thermistor deployment periods or the LIDAR run.

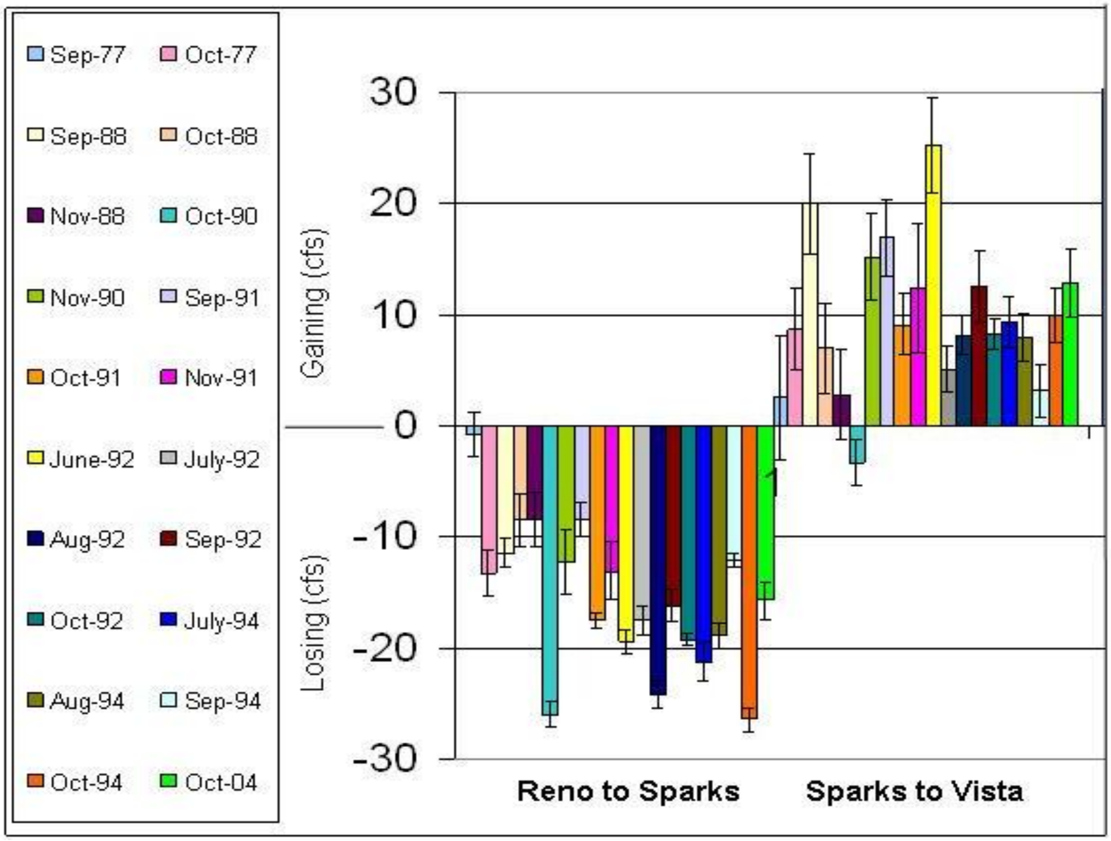

Figure 4.3 Monthly reach seepage and associated errors during historically low flows.

4.2 Thermal Analysis

4.2.1 Validation of Temperature Data

Raw streambed temperatures and ambient air temperatures are illustrated in Figures 4.4 and 4.5. Historical daily mean ambient air temperatures were measured at the Reno-Tahoe International Airport and obtained from the WRCC. Streambed temperatures in the summer were about 10 to 12 degrees higher than in the spring, and ranged from 13 to 22 degrees Celsius (see Figure 4.5). Diurnal temperature fluctuations were smaller in the spring (0.5 to 3 degrees Celsius) than during the summer (1-3.5 degrees). During Phase 2 groundwater temperatures in AGMW 12 (adjacent to the river at the UNR Agricultural Main Station) was consistently at 13 degrees, while at AGMW 16 further away groundwater temperatures remained at 11.3 degrees (Appendix E).

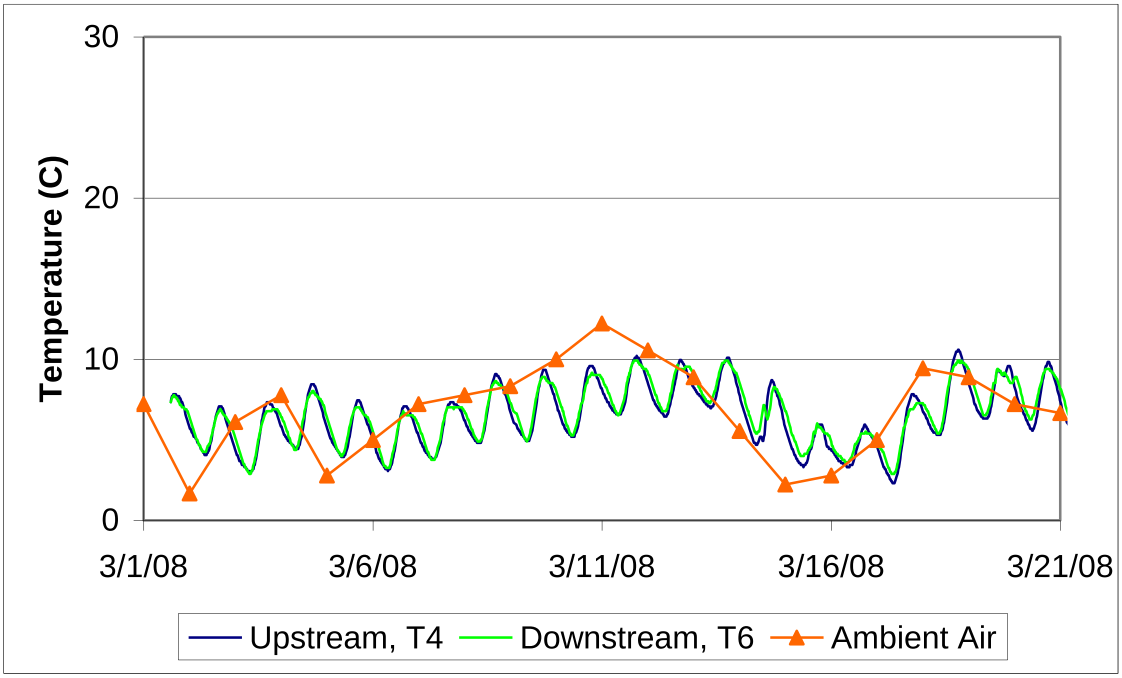

Figure 4.4 Phase 1 (early spring) streambed temperatures at T4 to T6 sensor locations.

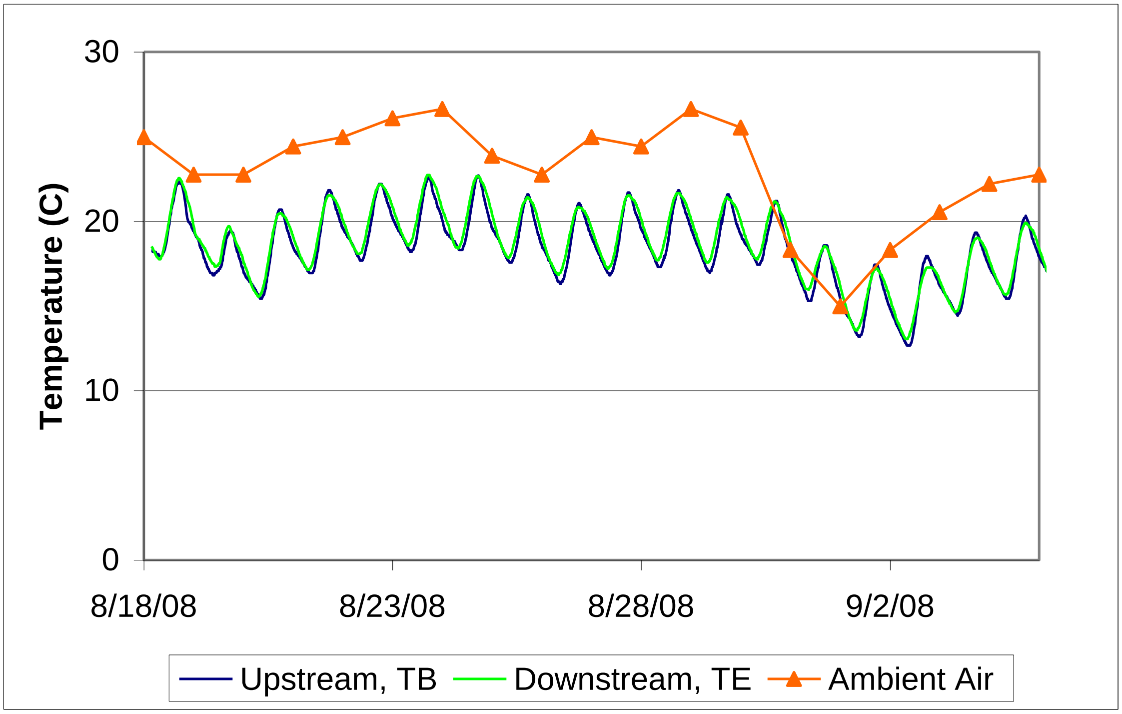

Figure 4.5 Phase 2 (late summer) streambed temperatures at TB and TE locations.

Phase 1 streambed temperatures on March 8, 2008, at different locations along the Truckee River are shown in Figures 4.6 and 4.7. Data from two thermistors were collected at site T3, one at T4, two at T5, and one at T6. The difference in temperature between T3 and T4 did not change in the afternoon, suggesting that net heat flux remained spatially consistent between these thermistors. Diurnal variation and a 2°C decrease in temperature were observed over the twenty-four hour period. This was part of a larger weekly decrease in average temperature which was presented in Figures 4.4 and 4.5.

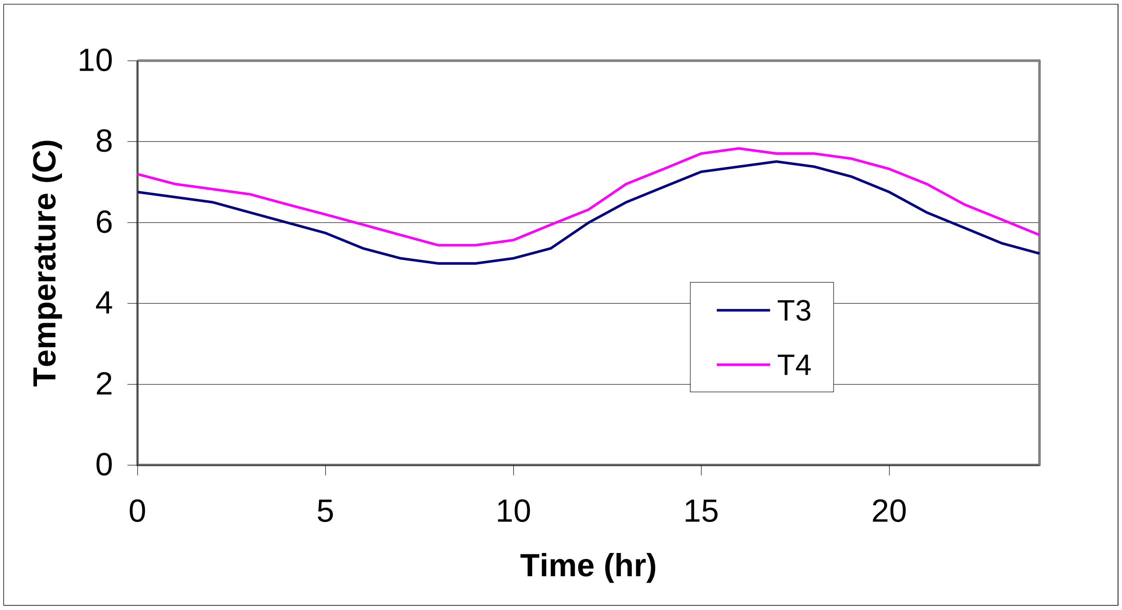

Figure 4.6 River temperature increases from the Transfer Station to Glendale in Phase 1.

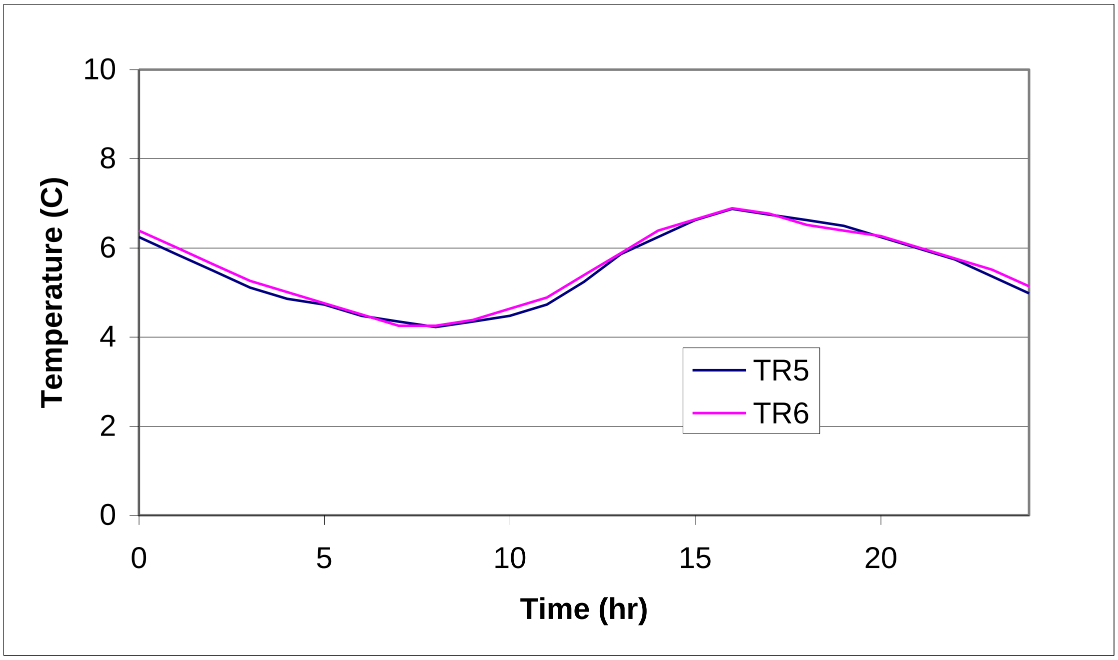

Figure 4.7 Temperatures along the UNR Agricultural Main Station, Phase 1.

Prior to applying temperature measured by the thermistors to the thermal analysis, reliability of the data was checked. On average, streambed temperature increased downstream along the UNR Agricultural Main Station, as was expected during Phase 1

(Figure 4.8). Thermistor T5 (#OB8) was 1.5 kilometers upstream of T6 (#473). Though Pioneer Ditch merges with the river just above T6, no discharges occurred because it was too early in the season for irrigation diversions. Since thermistor accuracy was calibrated to +/- .05°C, the difference in downstream temperature occurs outside the range of standard error (Figure 4.8) and was considered real. More graphical representations for differences in streambed temperature for both Phases are in Appendix F. Yet not all changes in downstream temperature illustrated in Appendix F were consistently larger than the range of standard error (i.e. T1 to T2). There is significantly less difference in temperature between the thermistors during the summer, whereas spring streambed temperatures showed a marked increase (up to 1 degree Celsius) downstream (Appendix F). Diurnal changes in the difference between streambed temperatures may indicate a significant influence from net heat flux (Figure 4.8 and Appendix F).

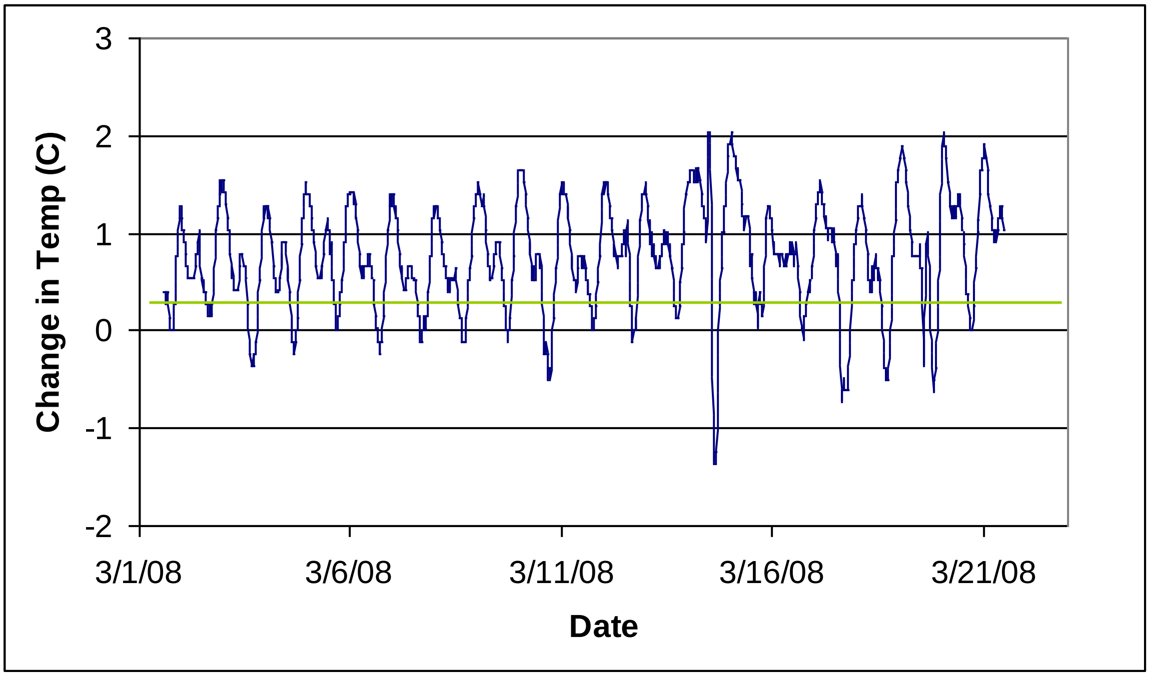

Figure 4.8 Difference in temperature between sensors 473 (T5) and OB8 (T6), Phase 1. Line indicates compounded standard error of 0.1 degrees Celsius.

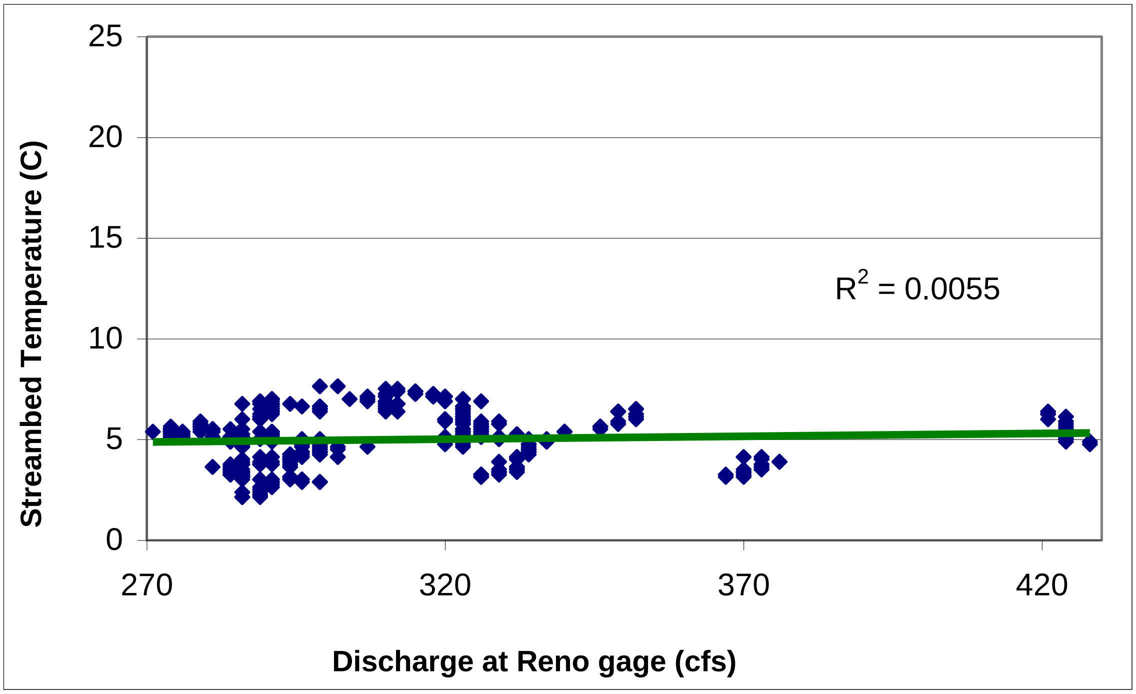

Figure 4.9 Phase 1 (March 1 to 21, 2008) discharge at Reno gage versus nighttime temperatures at T1.

Temperature data was plotted against flow for both Phases (Figures 4.9 and 4.10). Streambed temperature is independent of river flow, as was suggested by previous research (Figures 4.9 and 4.10) (Peterson, 2002). There is no apparent correlation between flow and night temperatures in either spring or summer deployments. Hence the change in downstream temperature may be a function of groundwater advection or surface heat flux from meteorological conditions.

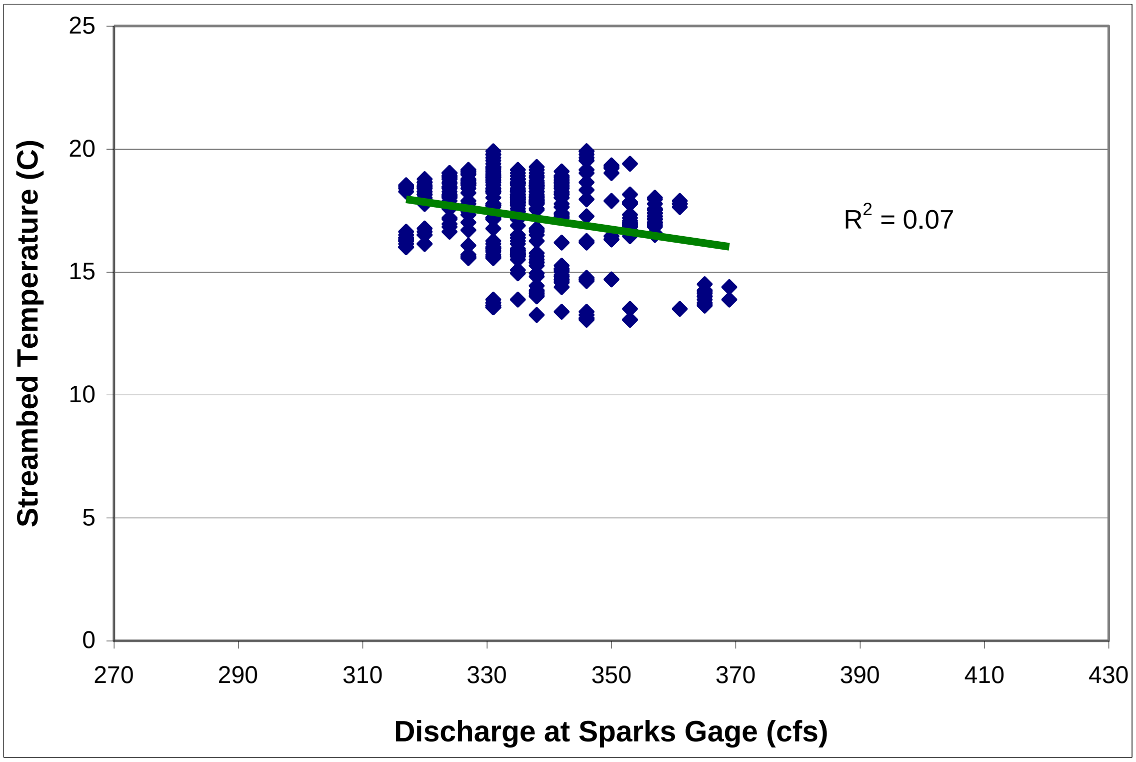

Figure 4.10 Phase 2 (August 18 to September 5, 2008) discharge at Sparks gage versus nighttime temperatures at TE.

4.2.2 Thermal Analysis Results

Gage-recorded tributaries between all thermistors during Phase 1 in early spring were non-existent. During Phase 2 in the late summer, temperature differences between Pioneer Spill and the Truckee River should be insignificant because Pioneer Spill contributed only 7 cfs (2% of total discharge measured at Sparks gage) to the Truckee River between thermistors TC and TE. No data exists from thermistors downstream of North Truckee Drain or Steamboat Ditch so those surface influents are not relevant to the extent of the thermal analysis. Hence streambed temperature changes were not significantly influenced by surface water inflows and should not have an adverse affect on thermal analysis results.

Groundwater temperatures were obtained from WCDWR, and mean values (from a time period respective to each deployment period) from multiple monitoring wells were applied to each reach for both the thermal analysis and SSTEMP application. Table 4.1 presents mean groundwater temperatures for each reach, and representative monitoring wells.

Table 4.1 Groundwater Temperatures.

Mean T (°C)	Reach	Relevant Monitoring Wells (MW)	DTW (m)	MW Distance to River (m)
14.95	T1-T2	MW7NS, WMMW3	4.3, 15.6	30.3, 20.4
14.7	T2-T3	WMMW3	15.6	20.4
14.8	T3-T4	CTM21S	8.4	115.0
15.25	T4-T5	CTM20S, USGSAg	2.3, 3.1	89.6, 149.4
14.35	T5-T6	UNRAg 25, 36	3.1, 4.3	59.9, 53.9
14.3	TB-TC	21StMWS	6.6	33.0
16.95	TC-TE	CTM20S, USGSAg, UNRAg 25, 36, 12	2.5, 3.3, 3, 5, 5	89.6, 149.4, 59.9, 53.9, 25.3
15.1	T3-T5	CTM21S, CTM20S, USGSAg	8.4, 2.3, 3.1	115.0, 89.6, 149.4

Fluxes estimated from the thermal analysis ranged from 0.6 to 80 cfs (gaining). The estimated groundwater fluxes calculated using the thermal analyses were smaller in August than the fluxes estimated during March. Phase 1 fluxes were estimated at 15-80 cfs between thermistors T3-T5 (roughly equivalent to Reach 1) and almost 20 cfs between T5-T6 (within Reach 2) (Table 4.2 and Figures 4.11 and 4.12). Phase 2 estimated groundwater fluxes between TB-TC (equivalent to Reach 1) were no more than 10 cfs, and about 5-50 cfs between TC-TE (equivalent to Reach 2) (Figures 4.13 and 4.14). Reach 1 estimated maximum flux during Phase 1 (80 cfs) was not considered to represent existing conditions because it disagrees with standard hydraulics (that is, the potential for groundwater discharge through the streambed should decrease with a rise in stage, yet results inferred that estimated gains increased with higher river flows). Or, less likely, rise in groundwater elevation was faster than rise in river stage. SSTEMP estimated fluxes were also relatively high for that day (Appendix K).

Stream budgets for thermistor Phases 1 and 2 were calculated for comparison to fluxes simulated by the thermal analysis. Table 4.2 and Figures 4.11 to 4.14 illustrate fluxes to and from the river for each reach. North Truckee Ditch can not be accounted for because no flows have been recorded since 2002, though water has been in the ditch (written communication, Chris Benedict). Recorded flows prior to 2002 averaged less than 1 cfs. If North Truckee Ditch was accounted for and flows were comparable, calculated losses from the river would decrease 4.3% to 17%, decreasing average losses 7% from -15 cfs to -14 cfs in Reach 1 during Phase 2.

Table 4.2 Potential groundwater flux estimated by the thermal analysis and the stream budget.

		Groundwater Flux		
		Mean	Max	Min
Phase 1	Reach 1 Thermal Analysis	50.9	80	15
	Reach 1 Stream Budget	-0.6	3.5	-6.4
	Reach 2 Thermal Analysis	16.5	20	0.6
	Reach 2 Stream Budget	-17.1	8.7	-36.7
Phase 2	Reach 1 Thermal Analysis	2.6	10	0.6
	Reach 1 Stream Budget	-15.1	-6.0	-23.0
	Reach 2 Thermal Analysis	10.2	50	4.5
	Reach 2 Stream Budget	13.5	18.6	4.1

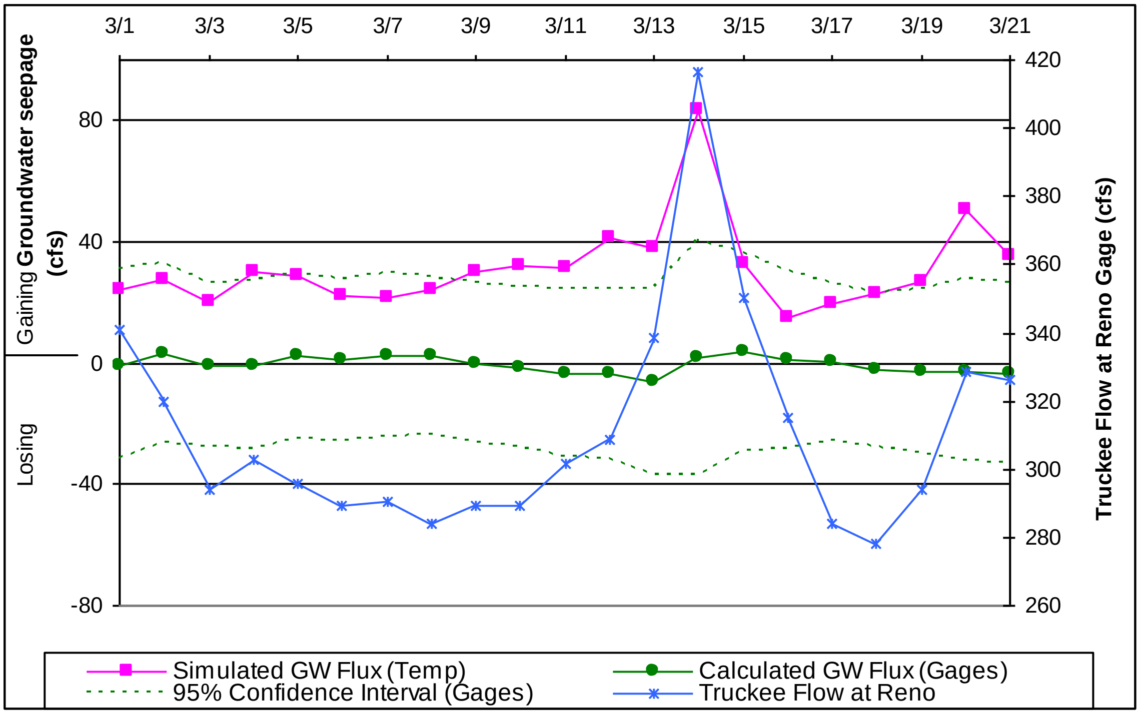

Figure 4.11 Reach 1 (Reno-Sparks) estimated (T3-T5) seepage for Phase 1.

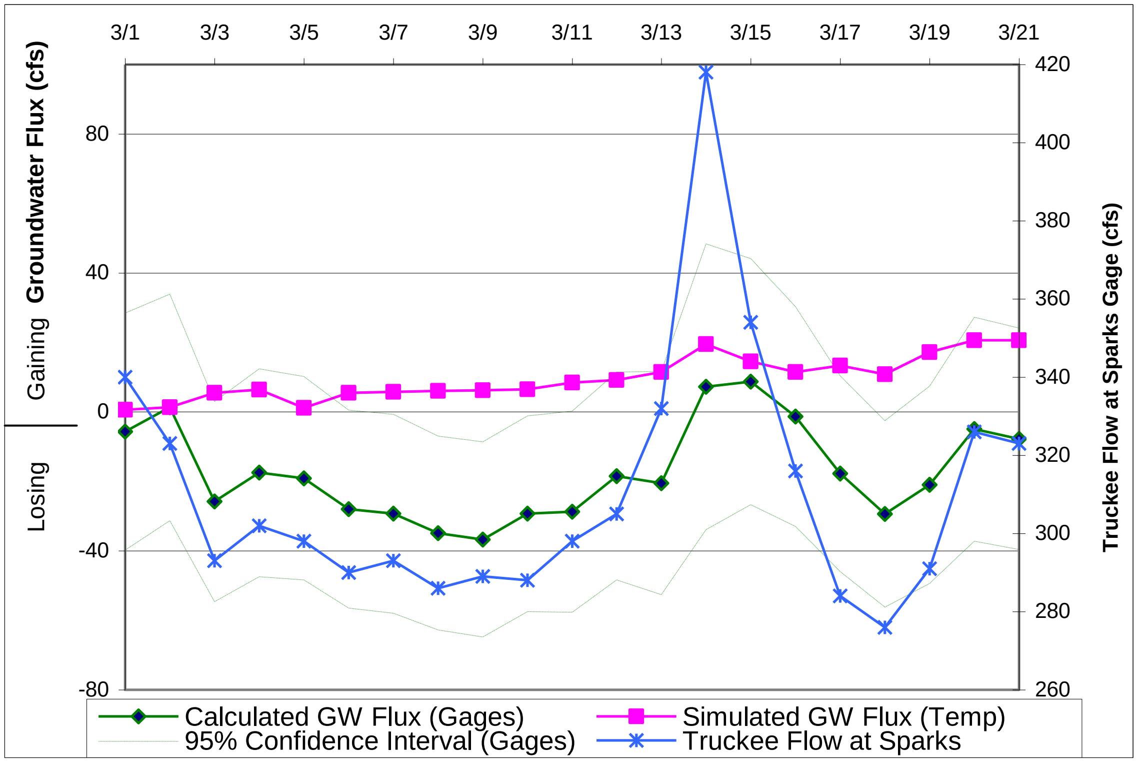

Figure 4.12 Reach 2 (Sparks-Vista) estimated (T5-T6) seepage for Phase 1.

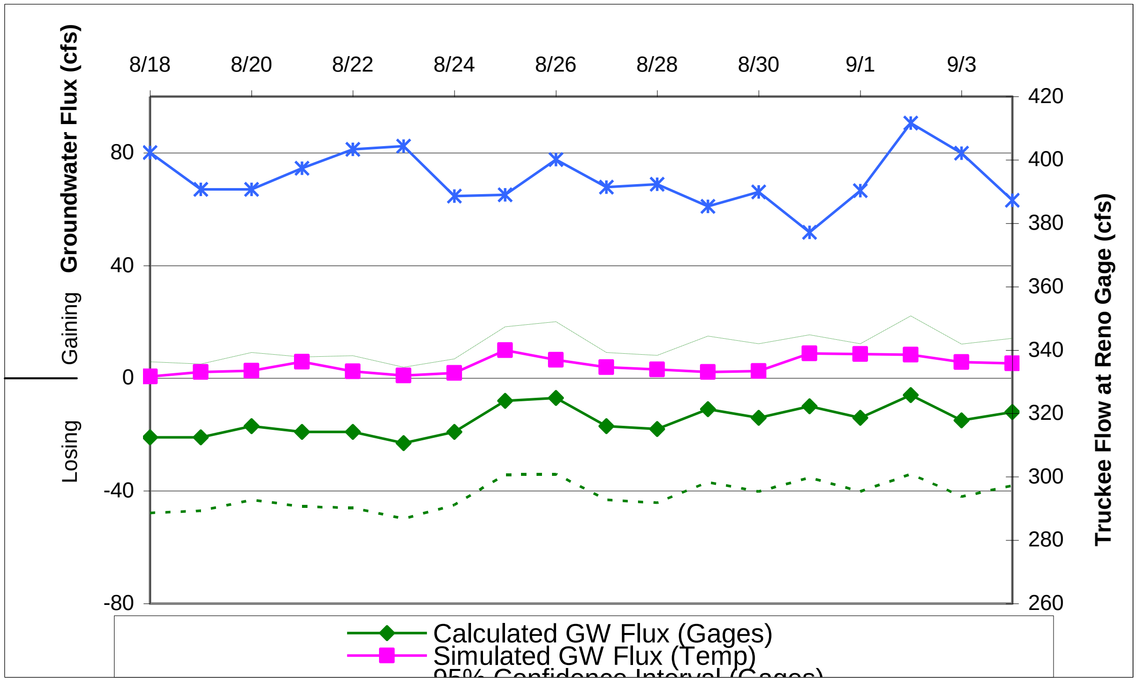

Figure 4.13 Reach 1 (Reno-Sparks) estimated (TB-TC) seepage for Phase 2.

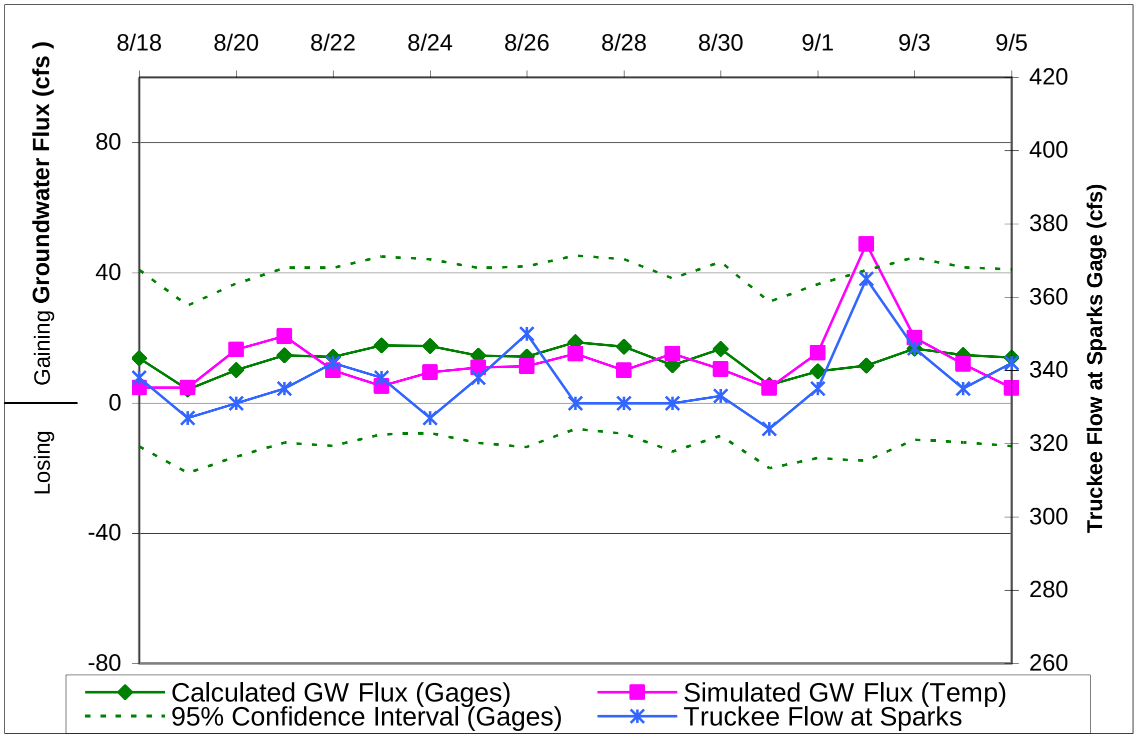

Figure 4.14 Reach 2 (Sparks-Vista) estimated (TC-TE) seepage for Phase 2.

Table 4.3 tabulates flows during Phases 1 and 2, with comparisons to historical flows. Average flow measured at Reno and Sparks were larger in late summer (Phase 1) than early spring (Phase 2), though it was expected form historical data that flows would be higher in early spring (Table 4.3). Mean flows measured at all gages in Phase 1 are significantly lower than historical mean flows at the time (Table 4.3). Flow is lower at Vista than Reno during Phase 2, which is not uncommon that time of year. Maximum flows in 2008 occurred during May, whereas minimum flows occurred during December.

Table 4.3 Measured flows during both Phases, compared to historical flows.

	Phase 1 Flow (cfs)			Historical March			Phase 2 Flow (cfs)			Historical Aug/Sept		
Gage	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
Reno	312	462	266	918	9,140	96	396	452	358	299	882	0.4
Sparks	311	418	276	962	10,030	90	336	385	286	225	742	0
Vista	378	550	281	1,068	11,400	143	372	452	254	376	1200	42

A scatter plot illustrates observed versus simulated downstream temperature using SSTEMP when no groundwater accretion was applied (Figure 4.15). Sensitivity coefficients for each variable’s influence on groundwater flux used in daily sensitivity analyses are illustrated in Appendix H. Inflow temperature and groundwater temperature consistently had the largest sensitivity coefficients (Appendix H). Hence, according to the results in Appendix H, omitting meteorological parameters from Equation 12 did not affect estimated groundwater flux. Estimated groundwater fluxes using the mixing model and SSTEMP are provided in Appendix I.

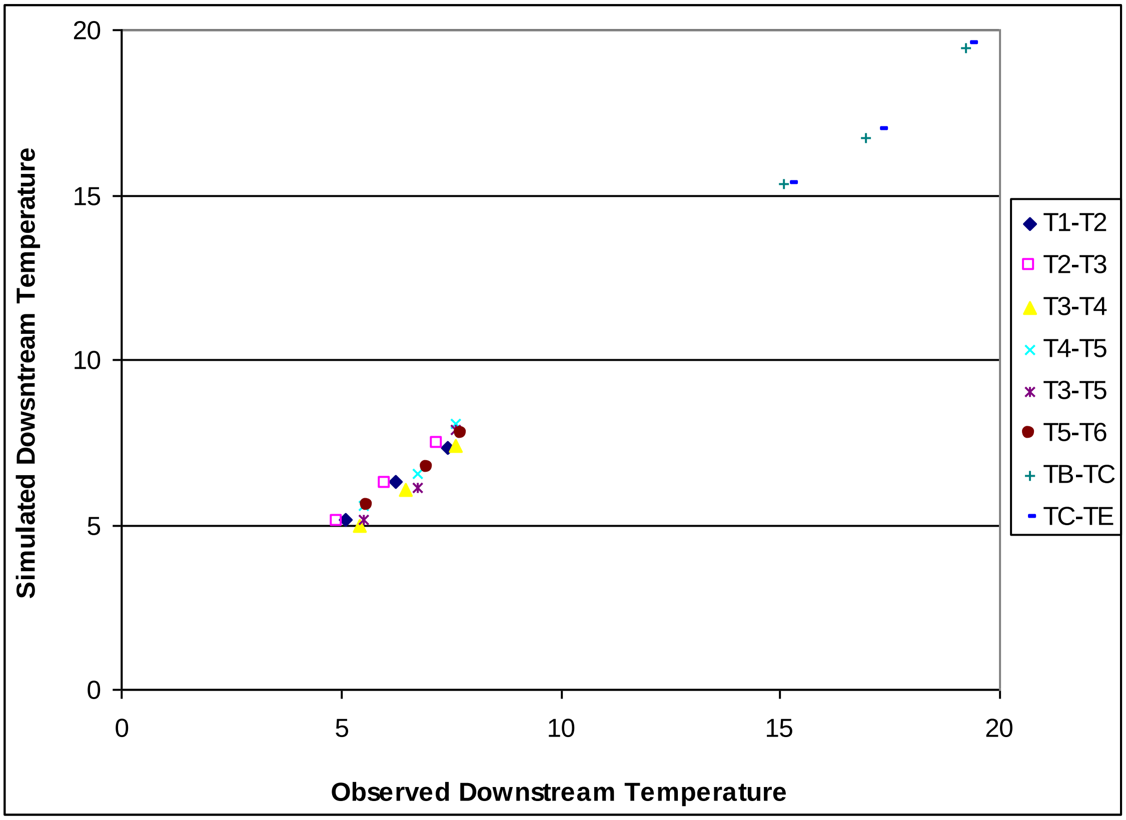

Figure 4.15 Observed versus SSTEMP simulated downstream temperature.

Heat flux parameters that are influential to downstream temperature were also calculated by SSTEMP. They varied from each reach due to stream characteristics, and parameters in the same reach varied daily (though values were the same magnitude) due to meteorological conditions. Friction, for example, was larger at long reaches (16.2 to 18.0 joules/m^{2}s at TC-TE) and steep reaches (23.3 to 34.9 joules/m^{2}s at T2-T3). Whereas friction calculated for a short reach (TB-TC) ranged from 2.5 to 2.7 joules/m^{2}s. Net radiation was the key parameter for simulating downstream temperature, and varied significantly from day to day. In reach T3-T4 net radiation ranged from 35.4 to 130.4 joules/m^{2}s, in reach T5-T6 net radiation ranged from 12.6 to 115.0 joules/m^{2}s, and in reach TB-TC net radiation ranged from -51.8 to +113.1 joules/m^{2}s.

4.3 River Stage versus Groundwater Levels

Water levels in monitoring wells along the Truckee River are below the river’s stage elevation (indicative of a potentially losing reach) through much of the Central Truckee Meadows (Figure 4.16). Water levels in monitoring wells (except UNRAG25) down gradient from the 1336m contour are equivalent to, or greater than the Truckee River’s stage elevation, which is indicative of a potentially gaining reach. This is just a snapshot of one point in time, and it is not suggested that this condition is present year round. Hidden Valley Production Well (HV3) pumped over 20 million gallons in June 2008, and HV5 pumped about 12 million gallons (Table 4.4). This may have created a downward vertical gradient in the vicinity of HV3, which could be why potentiometric contours imply a losing river (concave upstream) up to the Sparks gage in Figure 4.16.

Table 4.4 Hidden Valley Production Wells at 1340 meter contour in Figure 4.16.

	Pumping, Million Gallons			
	May-10	**Jun-08**	**Jul-08**	**Aug-08**
HV3	13.693	21.37	18.971	18.413
HV4	0.003	0	0	0.003
HV5	3.256	12.053	9.512	14.266

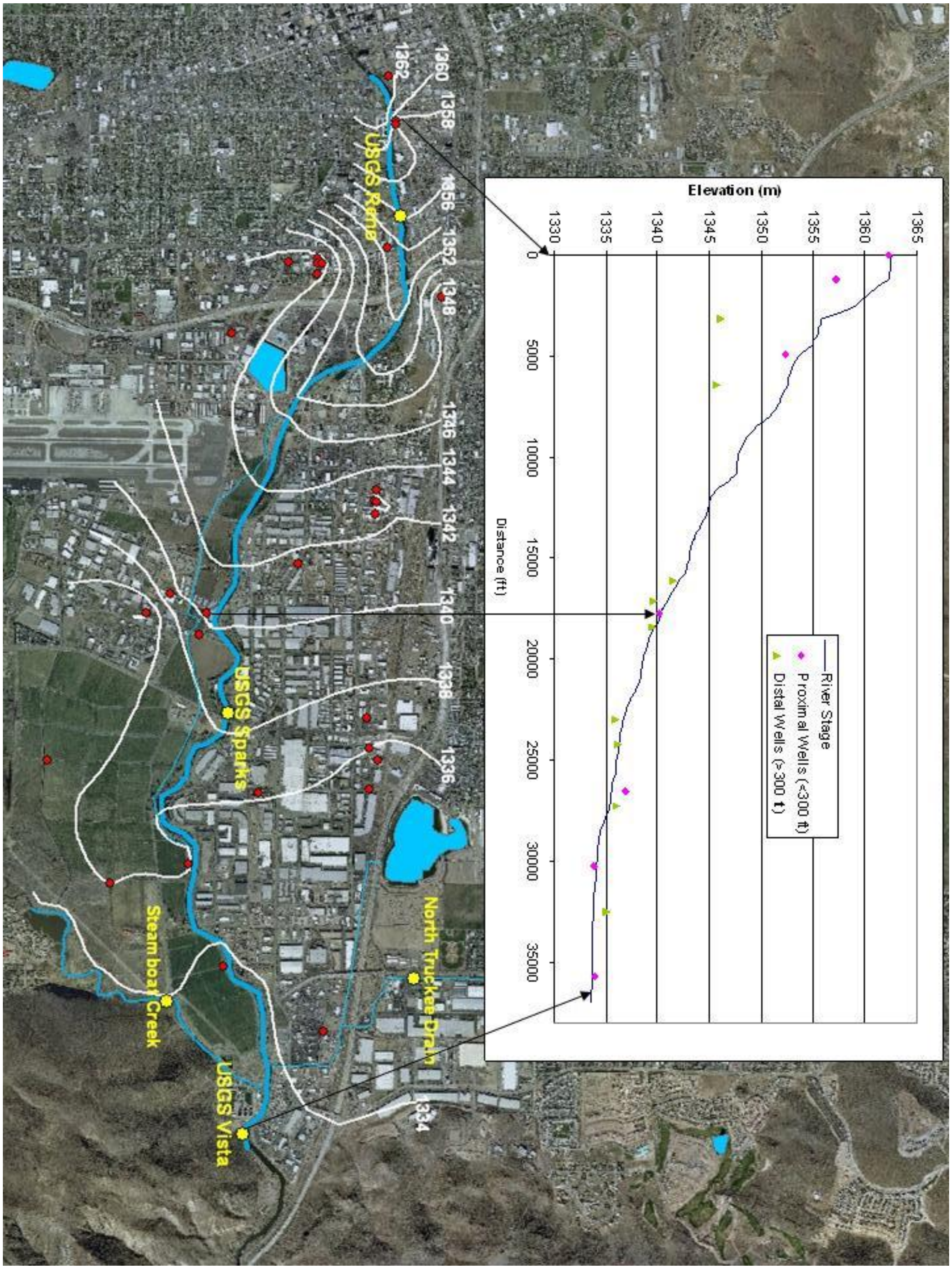

Figure 4.16 River stage profile, monitoring wells and potentiometric surface, July 2008.

Potential groundwater flux during the LIDAR flight of seven days was calculated using the same methodology from the stream budget. Reach 1 was losing approximately 6 cfs (2 cfs per mile), and Figure 4.17 suggests that, according to depletions in the Stream Budget, Reach 2 may also have been losing 3-25 cfs (1-9 cfs per mile). Negative flux calculated in Reach 2 disagrees with results seen in Figure 4.16 Though a positive flux for Reach 2 is possible within a 95% confidence interval (Figure 4.17).

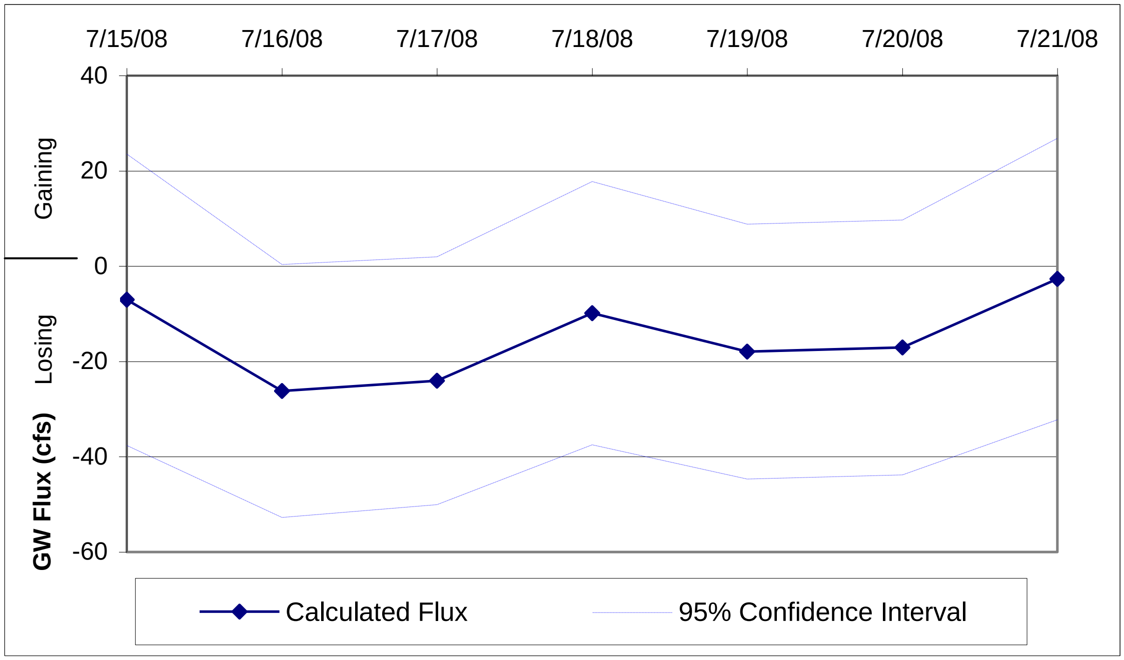

Figure 4.17 Reach 2 calculated groundwater flux during the LIDAR flight.

Temporal changes in shallow water level were compared to nearby river stage elevations (Figures 4.18 to 4.21). RETRACP2 is 88 meters from the Truckee River's thalweg, WMMW3 is 30 meters from the Truckee River's thalweg, CTM20S is 100 meters from the Truckee River's thalweg, and UNRAG 25 is 65 meters from Truckee River's thalweg. Water level in RETRACP2 changes seasonally above and below river stage (Figure 4.18). Water level in WMMW3 is consistently below river stage (Figure

4.19). Water levels in Figures 4.20 and 4.21 are, for the most part, above river stage elevation.

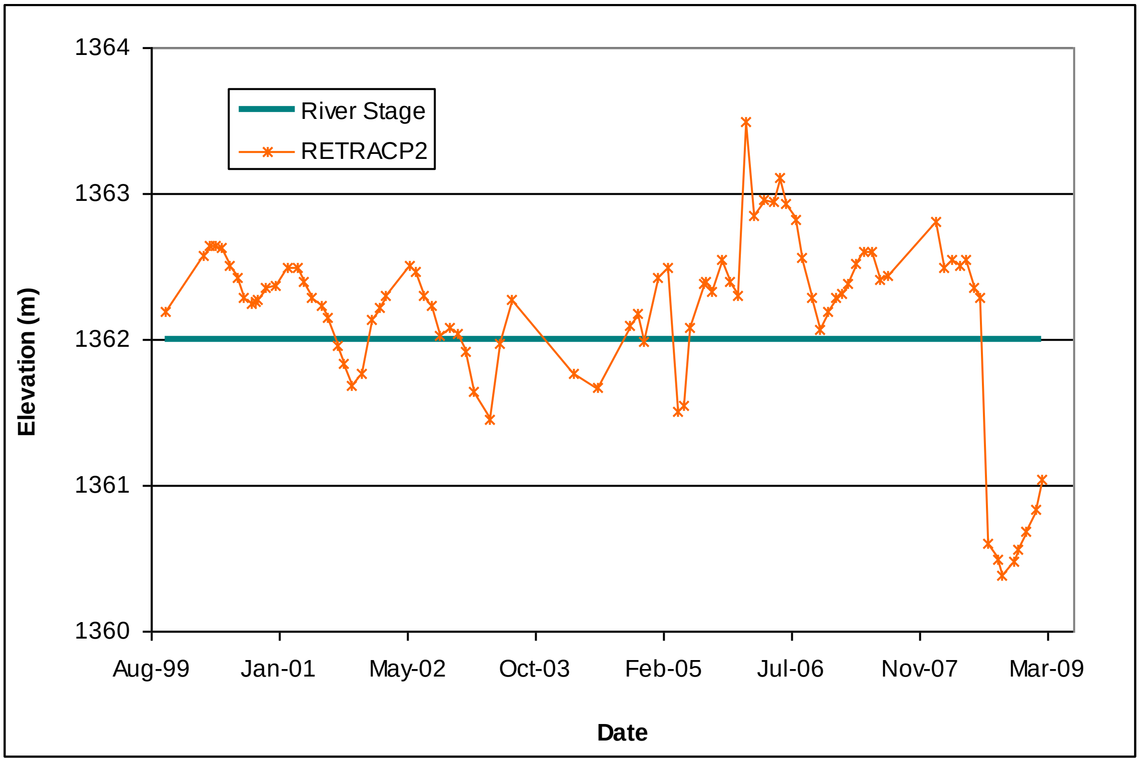

Figure 4.18 RETRACP2 water level and nearby river stage elevation.

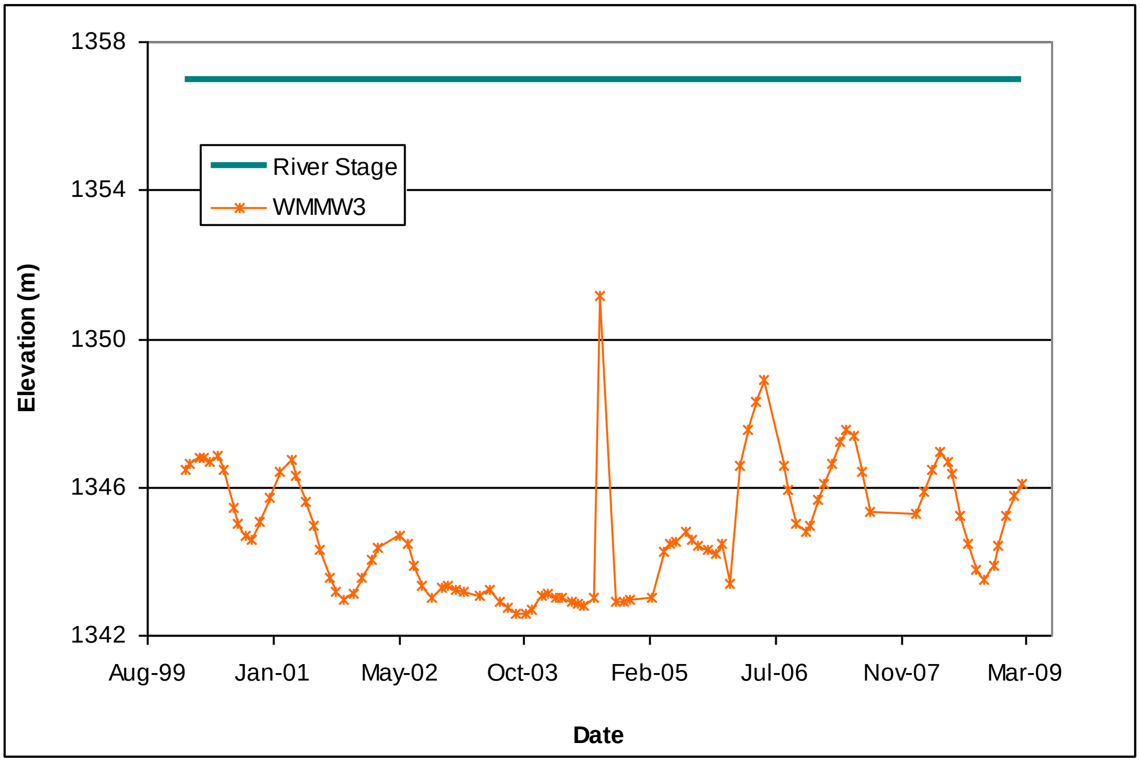

Figure 4.19 WMMW3 water level and nearby river stage elevation.

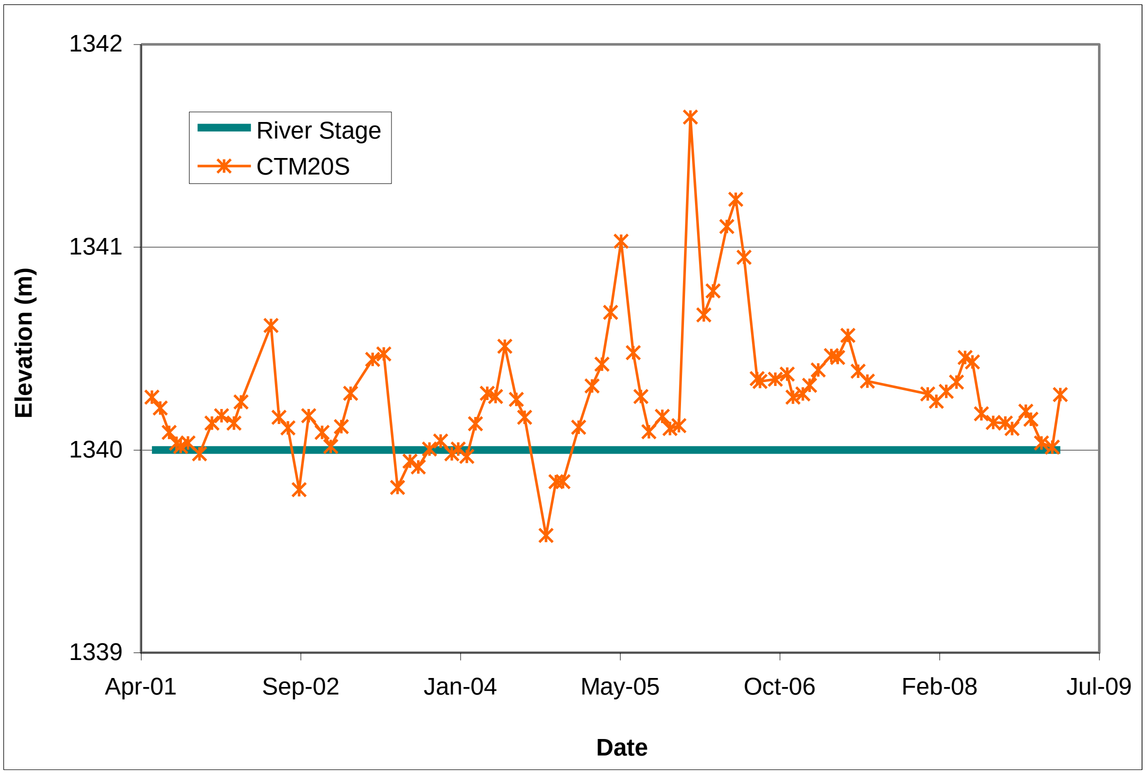

Figure 4.20 CTM20S water level and nearby river stage elevation.

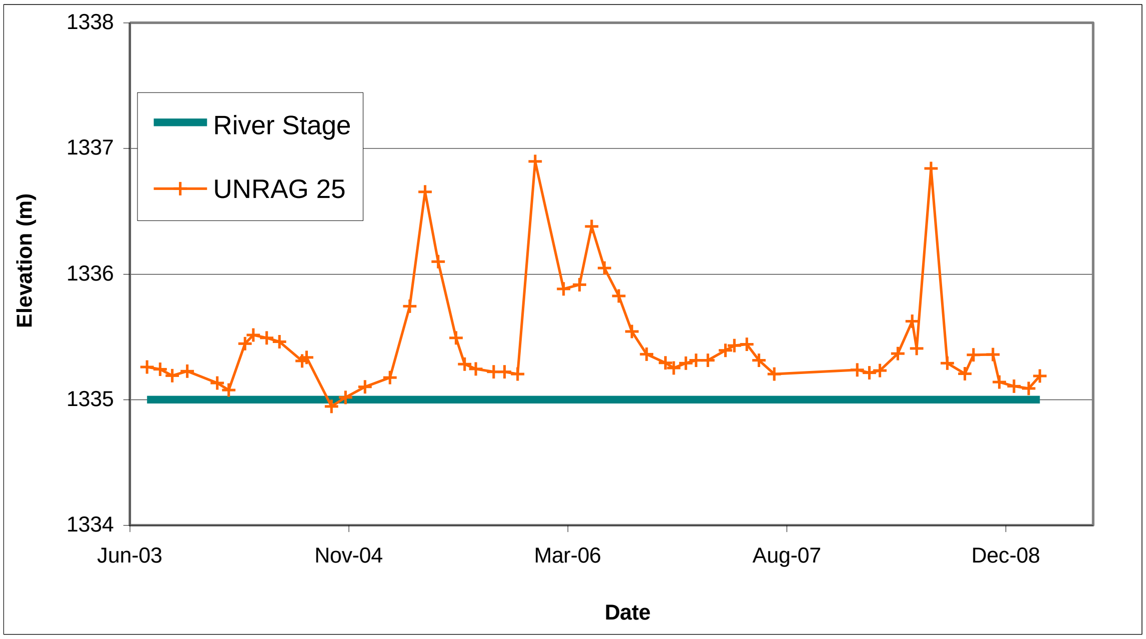

Figure 4.21 UNRAG 25 water level and nearby river stage elevation.

4.4 Groundwater Trends

4.4.1 Hydrographs

Hydrographs for 77 wells in the study extent were compiled in an effort to find regional patterns. Depth to groundwater data was measured monthly by WCDWR, while data from CTM21S was collected by a transducer installed by WCDWR. Fifteen of those hydrographs are plotted on Plate 1. There is a combination of monitoring wells in both the deep and shallow zones of the aquifer system, and some shallow zone monitoring wells are potentially connected hydraulically to the Truckee River because their hydrographs show responses to changes in river discharge (though this could also be seasonal response to changes in recharge and pumping). All the agricultural monitoring wells are among those that show reactions to changes in Truckee River flow, along with:

HV4M (right at the river), USGSAG, GlobalMW1, CTM20S, SSFS207, Apollo, and CTM13S (though not all hydrographs for the aforementioned wells are on Plate 1). Several hydrographs are detailed in the following paragraphs.

An upward vertical gradient in the groundwater occurs at the USGS Tracy monitoring well (Figure 4.22). The shallow screened interval is 16 to 26 feet below the measuring point, and the deep screened interval is 151 to 161 feet below the measuring point. No depth-to-water-level data was available from August to December of 2007.

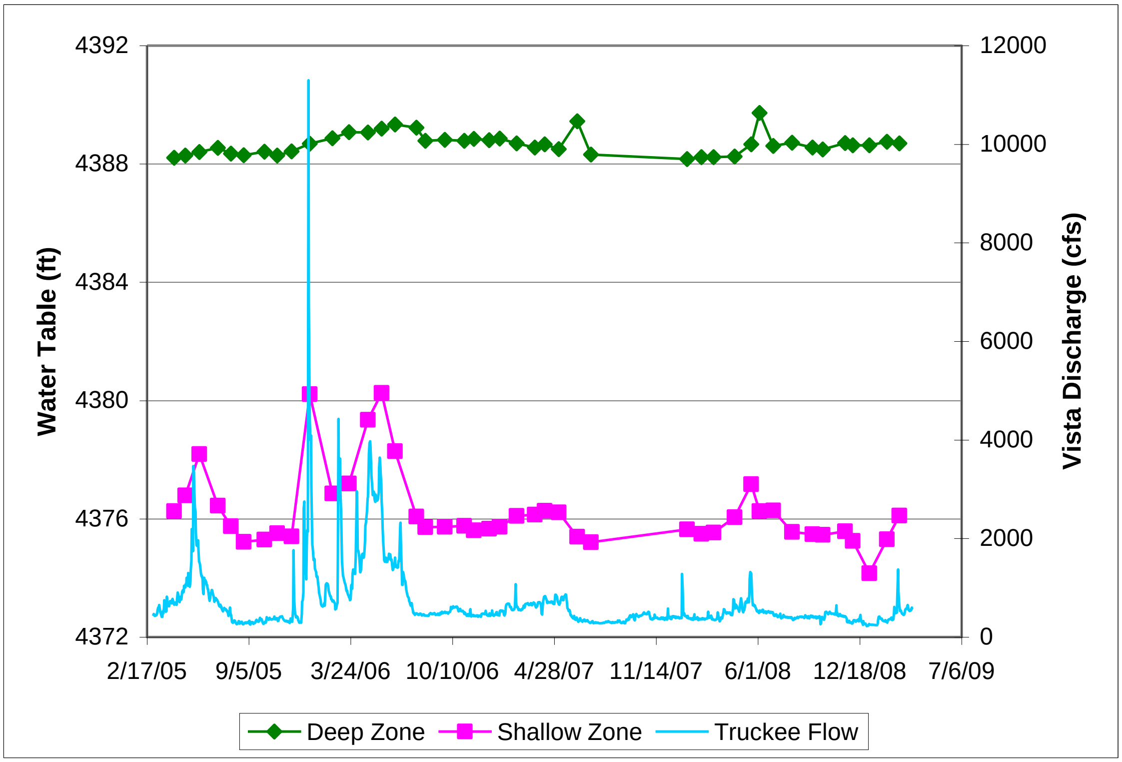

Figure 4.22 Tracy MWD and Tracy MWS (near Vista Gage) and Truckee River flow.

Downward vertical gradients are not uncommon, either under ambient conditions or in response to pumping. A downward vertical gradient occurs during pumping in the Central Truckee Meadows at 21st ST (Figure 4.23) and also occurs at monitoring wells CTM72, CTM73, CTM74, CTM75, CTM76, and Poplar1. This agrees with previous work which stated a downward vertical gradient exists in downtown Reno (CDM, 2002). Yet when pumping ceases and injection commences, an upward vertical gradient occurs in these same wells. The 21st ST monitoring wells in the deep zone of the aquifer do not react significantly to changing flows in the Truckee River (Figure 4.23). Deep monitoring wells share a similar screened interval as the nearby Kietzke production well.

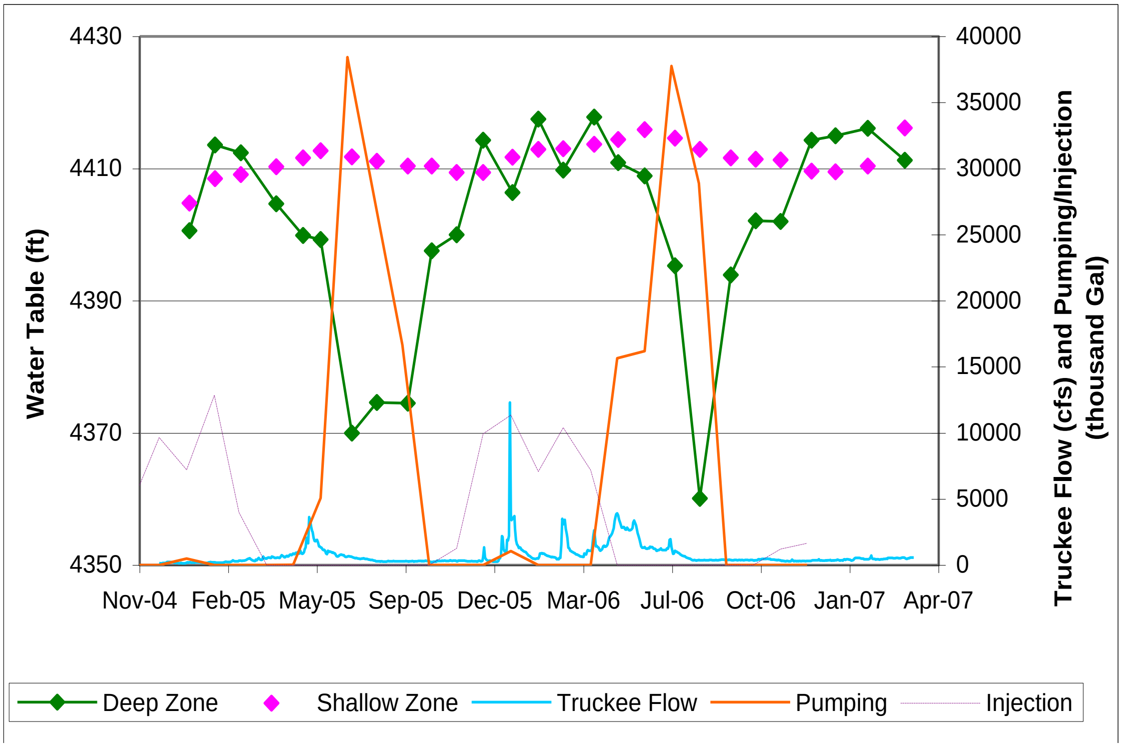

Figure 4.23 21st STMW monitoring wells in both the deep and shallow zones of the aquifer system in the Central Truckee Meadows.

Water levels are monitored at wells MW7NS, MW8ND, and RETRACP2 west of the Virginia Lake Fault Zone (VLFZ), and lie on both sides of the Truckee River (Figure 4.24). Water levels in shallow wells MW7NS and RetracP2 show some correlation to river flow (measured at the USGS Reno gage) since their depth to water is 6.5 feet and 5 feet, respectively, below average river stage.

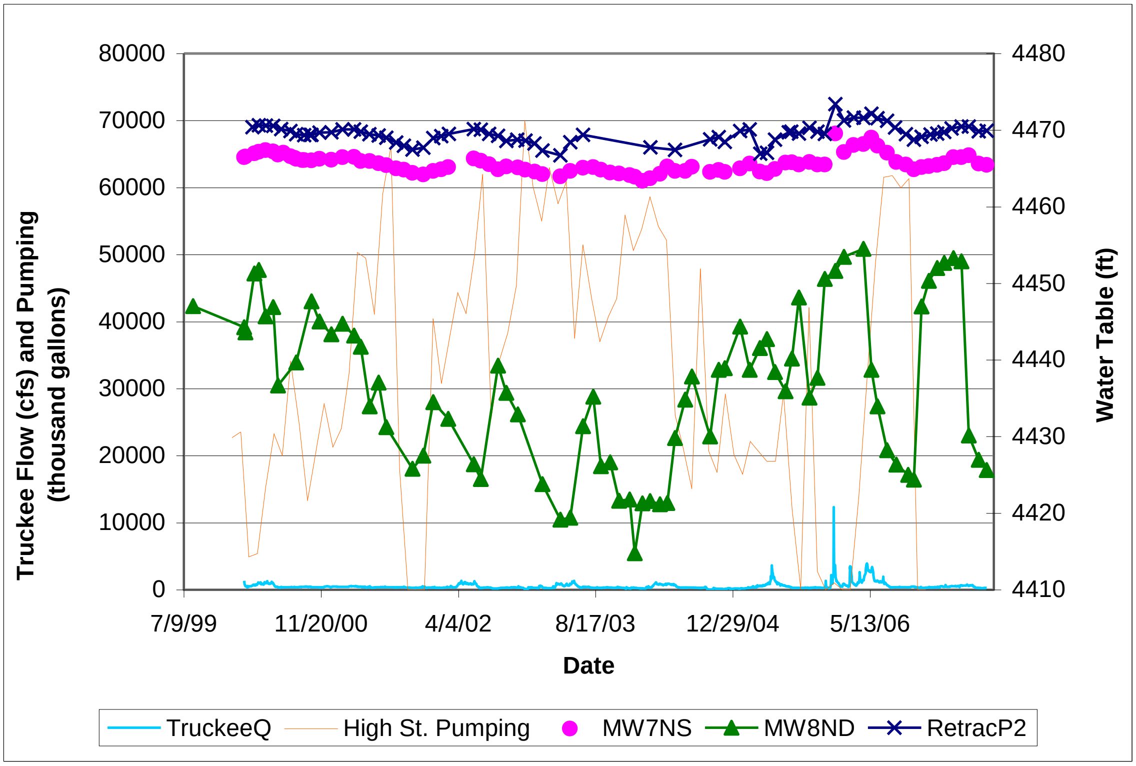

Figure 4.24 Hydrographs for MW7NS, MW8ND, and RetracP2 west of VLFZ.

4.4.2 Potentiometric Surface

Figures 4.25 to 4.28 are potentiometric maps of the eastern Truckee Meadows along the river corridor. Total municipal production and recharge during and prior to these potentiometric surfaces are listed in Appendix J. During June 2005 the potentiometric contours in Figure 4.25 indicate that Reach 1 was potentially losing (because contours are convex downstream) and Reach 2 may not be experiencing any flux (because contours at this resolution are perpendicular to the river). During September 2005 the potentiometric contours in Figure 4.26 also indicate that Reach 1 was potentially losing and Reach 2 may have been neutral. Similar amounts of pumping occurred in both June and September of 2005 (Appendix J). During December 2005 the potentiometric contours in Figure 4.27 continue to indicate that Reach 1 was potentially losing and Reach 2 may have been neutral, although six municipal wells (Appendix J) were used to recharge the aquifer during that time. During March 2006 the potentiometric contours in Figure 4.28 indicate that Reach 1 may have been neutral and Reach 2 was potentially gaining (because contours are concave downstream). Five municipal wells were also injecting to the aquifer in March 2006. The steepest gradient in Figures 4.25 to 4.28 was located in the vicinity of the VLFZ.

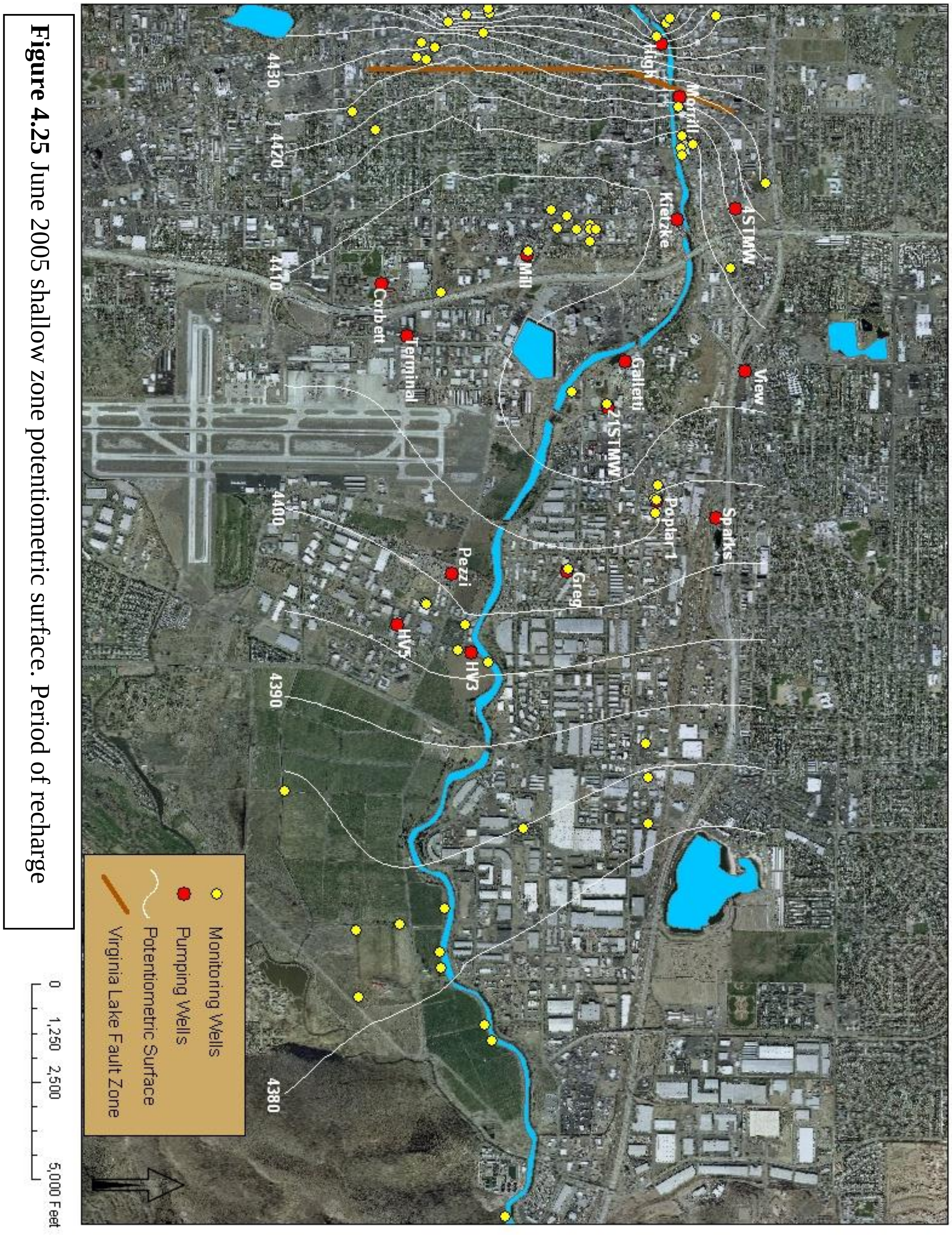

Figure 4.25 June 2005 shallow zone potentiometric surface. Period of recharge

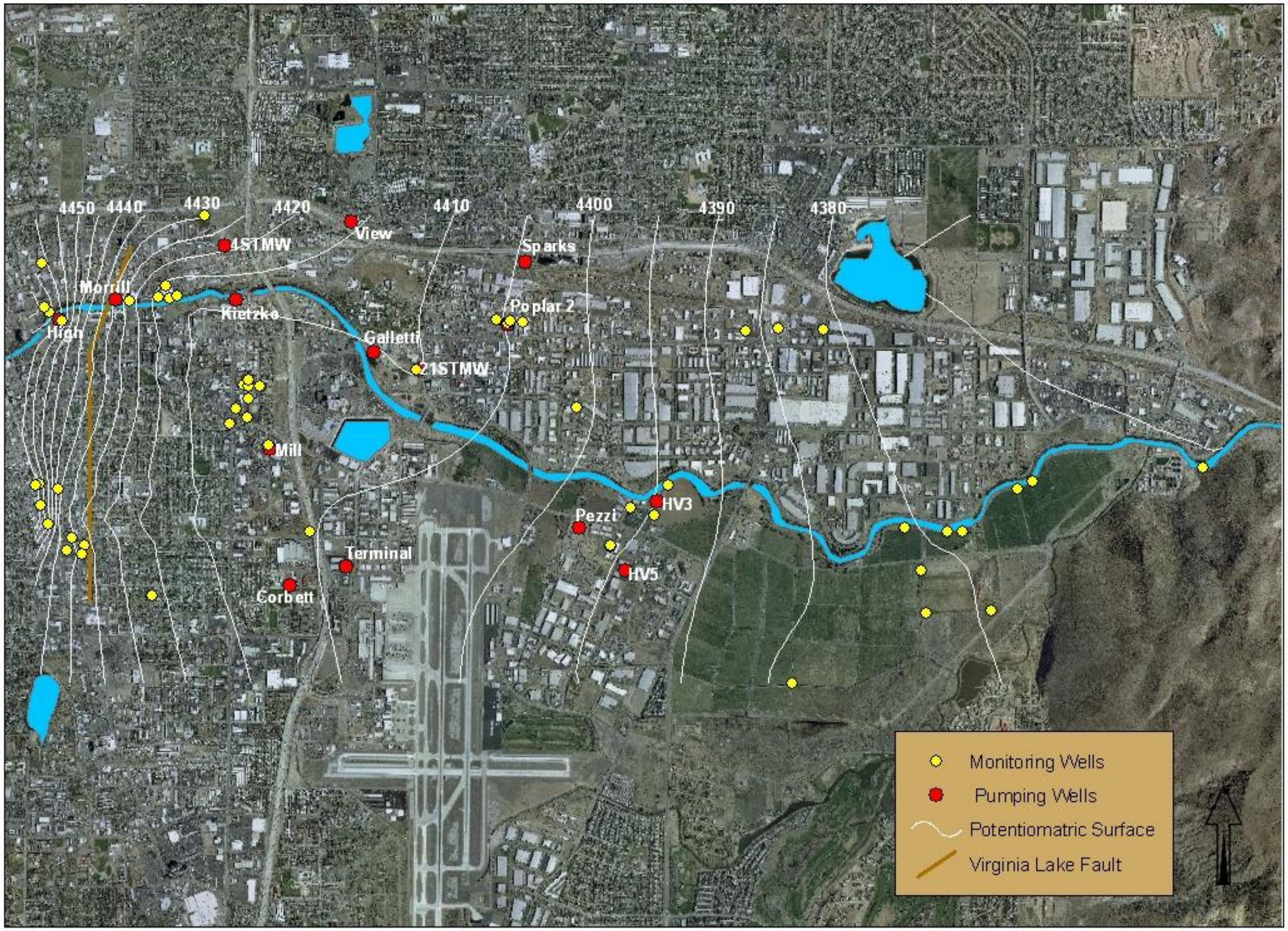

Figure 4.26 September 2005 shallow zone potentiometric surface. Period of recharge

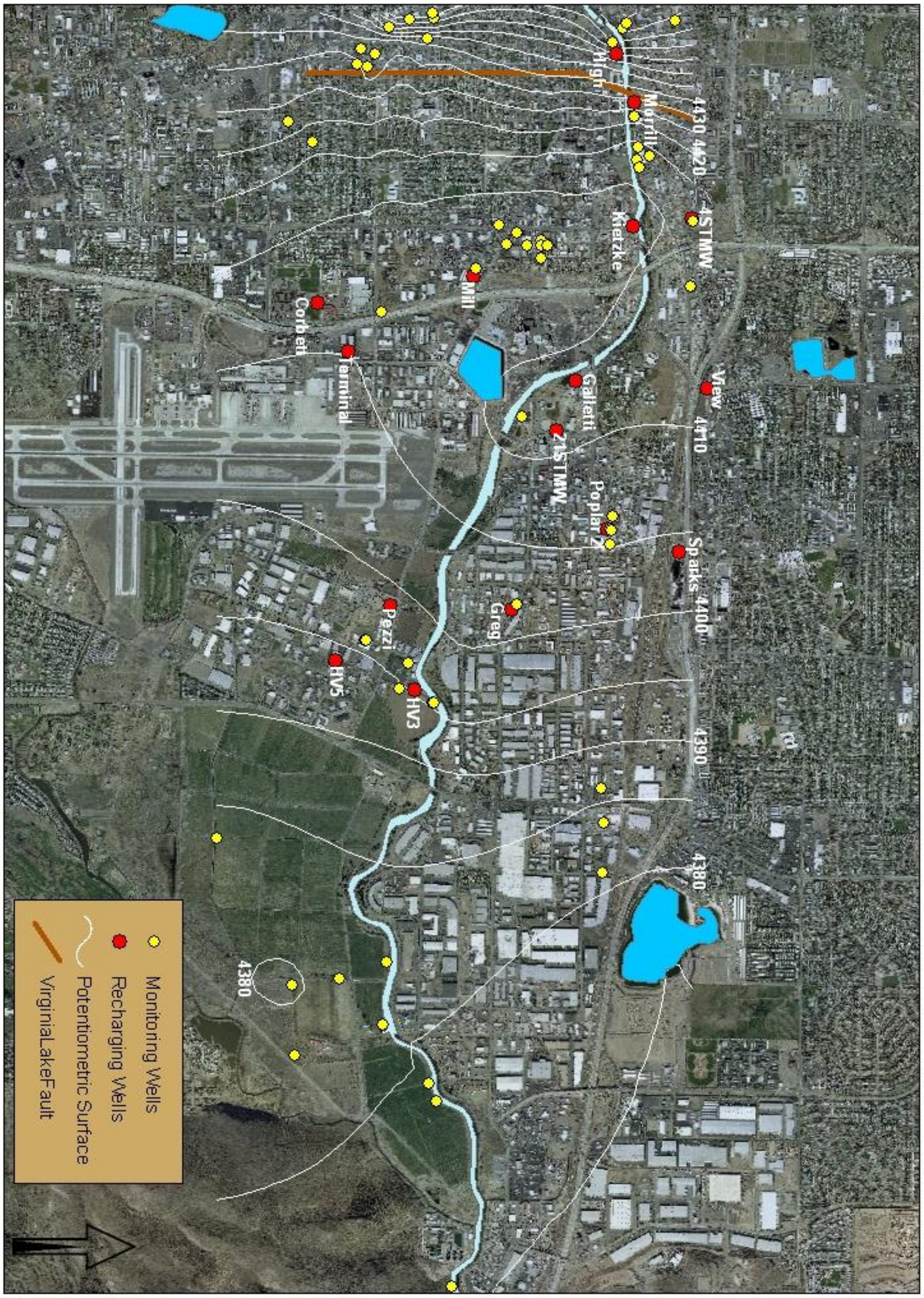

Figure 4.27 December 2005 shallow zone potentiometric surface. Period of recharge

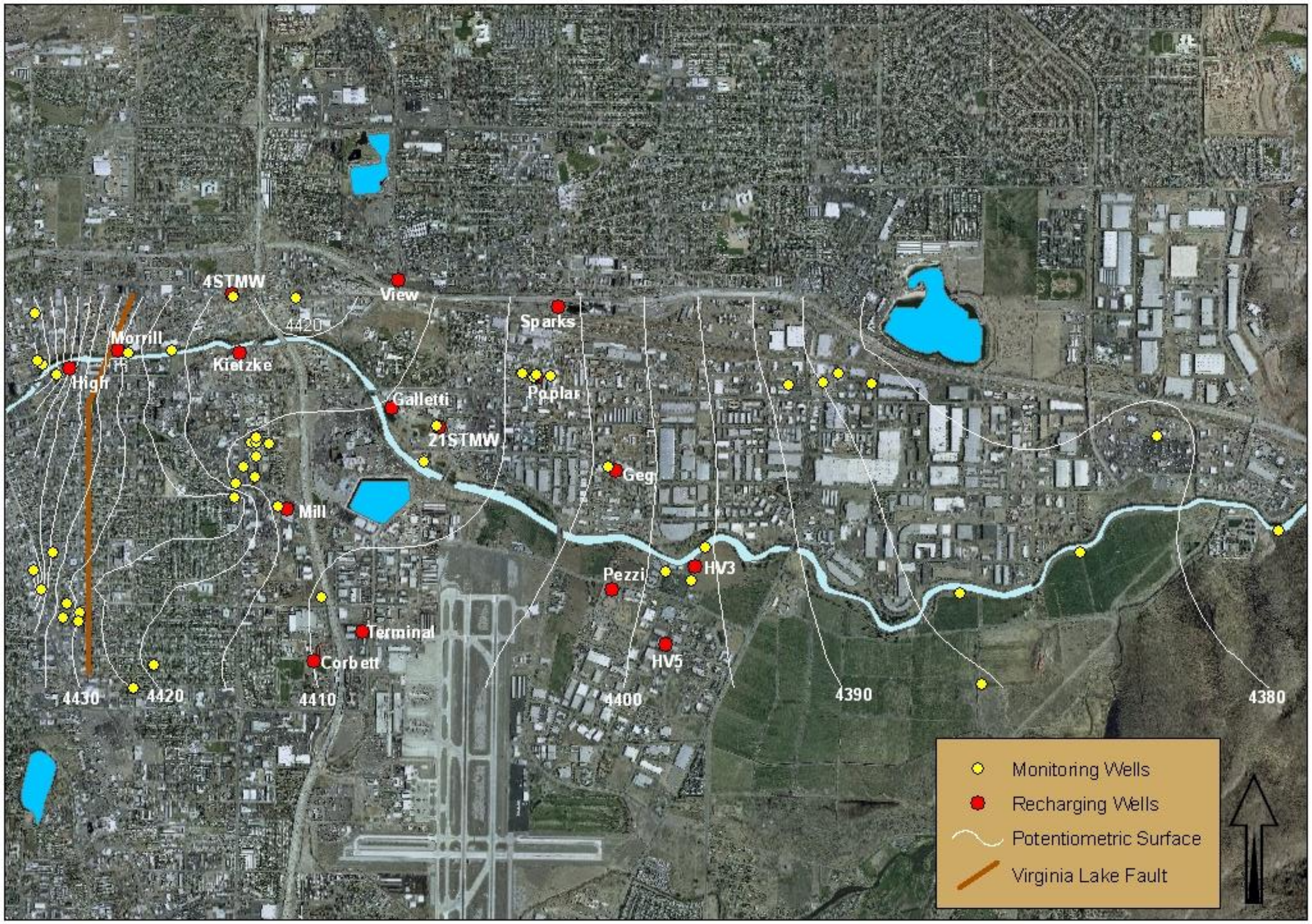

Figure 4.28 March 2006 shallow zone potentiometric surface. Period of recharge

Chapter 5 Discussion, Conclusions and Recommendations

5.1 Discussion

Stream budget results may be the most reliable of the methods used because it applies the theory of mass (or volume) conservation (Becker, 2004). Results indicate that during low flows, the eastern section of the study area is a gaining reach, while the western section (Central Truckee Meadows) is a losing reach (Appendix B and Figure 4.3). Although uncertainties are present in the stream budget calculations, results agree with previous research; essentially the river appears to be mostly losing from the Reno gage to the Sparks gage, and mostly gaining from the Sparks to Vista gages. Results for Reach 1 agree with previous work which concluded that losses to groundwater occurred mostly in the central Truckee Meadows. Daily groundwater seepage to the aquifer estimated by the stream budget for Reach 1 ranges from 1 to 16 cfs, losing an average of 5 cfs per mile. During low flows Reach 2 has an average gain of 10 cfs, with the river gaining an average 4 cfs per mile. Though data clearly show Reach 2 as gaining, the spatial resolution of the measurements is not sufficient to hypothesize whether groundwater discharge into the river occurs at point sources, or is equally distributed (diffuse) along the this reach of the Truckee River.

The key data used in the stream budget was flow at the USGS gages. If measured flow at the gages is biased, how does that affect calculated groundwater flux? If measured flow at the Sparks gage is biased higher than actual flow, then one of two conditions would occur. One condition is that groundwater flux calculated for Reach 1 would always be positive and groundwater flux calculated for Reach 2 would always be negative (not observed in our data). Another condition is that the magnitude of calculated groundwater flux would be minimized (could be supported by our data). Yet if measured flow at the Sparks gage is biased lower than actual flow, then one of the following conditions would occur. One condition is that groundwater flux in Reach 1 would always be negative, and groundwater flux in Reach 2 would always be positive (supported by our data). The other condition is that the magnitude of calculated groundwater flux would be maximized (could also be supported by our data). Unfortunately, with available data, it can not be discerned whether the Sparks gage is biased high or low.

According to the thermal analysis, Phase 1 (early spring) data indicates that groundwater was discharging to the river between sensors T3-T5 (Figure 4.11), and T5-T6 (Figure 4.12). During Phase 2 (late summer) data shows the river was gaining between TC-TE (Figure 4.13). Estimated groundwater flux was smaller in later summer than in early spring, and may be contributed to seasonal changes in flow regime and/or municipal pumping. Groundwater flux estimated by the thermal analysis mostly falls within the 95% confidence interval of calculated flux from the stream budget (with the exception of a flux of 80 cfs on March 14 at T3-T5 that coincides with a spike in river flow) (Figure 4.11). This anomalous flux estimated at 80 cfs for T3-T5 is not believed to represent existing conditions because it disagrees with standard hydraulic theory (potential gains should not increase with higher river flows). Perhaps this issue arises because the thermal analysis does not account for a lag time between change in discharge and flux into the river. Also, perhaps the thermal analysis is very sensitive to sharp increases in river flow (has a high sensitivity coefficient in SSTEMP). Yet fluxes estimated by SSTEMP on March 15 were also relatively higher than other daily groundwater fluxes.

There were some shortcomings of the thermal analysis method and the thermal mixing equation (11). One shortcoming is that it cannot accommodate stream loss. Also, gains were estimated by the thermal analysis during late summer in Reach 1, which most likely was expected to be losing at that time. Streamflow may have not been low enough for the thermal analysis to reliably identify any temperature differences associated with groundwater discharge. Lower flows were hoped for, but measured flows at each gage were about average (Table 4.2), and the amount of expected groundwater flux was small (10-20%) compared to total river discharge. Finally, bank storage might have contributed to some extra flow in the river. There was a large spike in discharge in the Truckee River two months prior to the first thermistor deployment. Water stored in the river banks may have slowly seeped back into the river during Phase 1 (though there is no way to quantify this, or know if it was influential to the results).

In Reach 2 during Phase 2 Pioneer Ditch contributed 2% to total river flow while estimated groundwater flux from the thermal analysis potentially contributed, on average, 3% to total river flow (Tables 4.1 and 4.2, and Figure 4.13). Temperature in Pioneer Ditch was not measured, though it is something that should have been addressed in the experimental design because it may have influenced results from the thermal mixing equation (11). Due to the larger ratio of surface water to volume of discharge in Pioneer Ditch, it is likely that temperature in Pioneer Ditch was higher than the Truckee River at the point of confluence. Groundwater temperature (Appendix E) was lower than the average river temperature during Phase 2 (range of 12 to 25°C) (Taylor, 1998), so

Pioneer Ditch could have balanced out the change in temperature if their difference from the mean river temperature was similar.

Figures 4.4 and 4.5 reveal that streambed temperatures were influenced by ambient air temperature and solar radiation. Therefore the SSTEMP model was applied to address any possible issues of ignoring other sources of thermal energy from the simplified thermal mixing equation (11). According to the SSTEMP sensitivity analysis, ignoring meteorological parameters did not significantly affect results for the thermal analysis because only upstream temperature and groundwater temperature had large sensitivity coefficients (Appendix H). SSTEMP is unreliable when estimating downstream temperatures less than 4°C (Bartholow, 2000). The lowest temperature estimated was 4.73°C on March 2 at Reach T3-T5, so estimating low temperatures downstream was not an issue. Therefore the thermal analysis was considered site appropriate for this section of the Truckee River.

River stage versus nearby shallow water levels reveals where the Truckee River was potentially gaining or losing. During July 2008 the water table was concurrent and/or above river stage east of McCarran Blvd (Figure 4.16), indicating potential groundwater flow to the river. West of that locale river stage is higher than nearby water levels (Figure 4.16), indicating potential river seepage to the aquifer system. Shallow zone groundwater levels measured in August 2008 decreased 0.3 to 2 feet, including locations with downward vertical gradients (water table was below river stage). These results could indicate a change from one hydrogeologic regime to another, or that there may be a stronger correlation to seasonal irrigation and pumping than to potential gradients between river stage and shallow water level.

The negative groundwater flux calculated in July 2008 (Figure 4.17) disagrees with results from the river stage and proximal shallow water levels (Figure 4.16). It is possible that this reach is in the process of switching seasonal flow regimes; from a gaining to a losing reach because there is lag time between river infiltration (interpreted from the negative stream budget) and when a rise in groundwater level is recorded.

Trends in the shallow potentiometric surface (Figures 4.25 to 4.28) reveal that Reach 1 is potentially losing (possibly as a result of pumping) from June 2005 to December 2005, while Reach 2 is relatively neutral at that time. In March 2006 (while municipal wells are injecting water into the aquifer), Reach 1 appears to be neutral and Reach 2 is gaining. Appendix J demonstrates that pumping is typical from June to September, and artificial recharge is common from November to April. The steepest gradient in Figures 4.25 to 4.28 was located in the vicinity of the VLFZ. Despite varying pumping regimes, this fault zone appears to have some influence on groundwater in the Central Truckee Meadows.

The main hydrogeologic regime of the eastern Truckee Meadows is characterized by the Truckee River contributing water to the adjacent shallow aquifer, followed downstream by the adjacent shallow aquifer contributing groundwater to the river. Localities on smaller spatial scales may divert from the established hydrogeologic regime during periods of pumping or artificial recharge. Any of the aforementioned methods used to ascertain this hydrogeologic scenario could be applied to other locations where groundwater interactions with a stream are taking place.

5.2 Conclusions

Stream budget results conclude that during low flows, the eastern section of the study area is a gaining reach, while the western section (Central Truckee Meadows) is a losing reach (Figure 4.3 and Appendix B). These results are reliable and agree with previous research. The stream budget computed smaller fluxes than the thermal analysis, with the exception of Reach 2 during the late summer of 2008.

Results from the thermal analysis suggest that during the Phase 1 deployment reaches T3-T5 and T5-6 were gaining (mean fluxes of 50.9 and 16.5 cfs, respectively), and during the Phase 2 deployment fluxes estimated for reach TB-TC were small (mean of 2.6 cfs) and reach TC-TE was likely gaining (mean flux of 10.2 cfs). According to SSTEMP, upstream temperature and groundwater temperature had the most influence on downstream temperature. Yet it is still advisable to incorporate meteorological parameters when modeling a stream’s thermal energy budget.

The river stage’s relation to the adjacent water table changes as it flows through central and eastern Truckee Meadows (Figure 4.16). Though this method could not directly quantify groundwater flux to the river, it is an indication that the Truckee River changes seepage regimes between the Central Truckee Meadows and the UNR Agricultural Main Station; from infiltrating to the aquifer below, to groundwater discharging to the river.

Potentiometric maps reveal a losing reach in downtown Reno, while suggesting a gaining reach at the UNR Agricultural Main Station (Figures 4.25 to 4.28). These potentiometric maps also indicate pumping does not affect the water table as significantly as water levels in deep zones of the aquifer (Figure 4.23), suggesting that the Truckee River is not always directly influenced by production wells.

5.3 Recommendations

TROA Ruling 6035 signed by the State Engineer in March 2010 stated that consumptive use (ET) in the Truckee Meadows is 2.5 acre-ft/year per acre. It is recommended that current crop and riparian acreage should be estimated in order to compute a modern ET for the Truckee Meadows. This information would have been helpful in comparing past and present groundwater budgets.

Surface water diversions and confluences are not monitored well enough for a river that is 100% appropriated. It is recommended that one locality should exist to retrieve all data in a digital format for surface flows, as opposed to partial data being stored by three separate agencies (USGS, Nevada Water Master, and TMWA). Hence significant uncertainties concerning results from the Stream Budget arose from poor book-keeping of Truckee River diversions and surface water influents.

There is a lack of data regarding the deeper aquifer between East McCarran and Vista. It is recommended that deep monitoring wells be completed near the Truckee River in this vicinity to acquire hydraulic properties for the deeper aquifer.

Using an approach and methodology appropriate to the problem, achievable in a reasonable amount of time, and with the resources and money available are key aspects to a well designed experiment. For example, peizometers or a distributed temperature sensor (DTS) could have been a more appropriate tool for identifying groundwater fluxes to and from the river, if it were not due to the urban environment and tall peizometers visible above the water. Yet different methods were used and unfortunately much temperature data was never retrieved due to theft. It was not possible to directly spatially compare groundwater seepage calculated by the stream budget with the seepage estimated by the thermal analysis. This arises from different geographical locations of USGS stream gages and the thermistors deployed for this study. More thermistors could be deployed at each stream gage to address this issue, but at the risk of losing more data due to theft of the thermistors. Therefore improved site appropriate methods are seen as a better alternative before commencing with additional groundwater modeling. A well designed and applied experiment is crucial for defining a conceptual model for very complex groundwater systems.

I recommend that a scientist always verifies a method works and is appropriate before following through with a time-consuming analysis. Calculations should have been done to find the threshold below which flows must be in order to see a change in temperature attributable to groundwater influx prior to deploying thermistors for the thermal analysis. A final item that should have done differently was to create quarterly potentiometric maps for 2008 (instead of 2005 and 2006 in Figures 4.25 to 4.28). This period would have been more pertinent to the deployment periods for the thermal analysis.

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Appendix A. USGS stream Gages

	Gauge #	Lat	Long	Elevation	description
Reno	10348000	39^o 31' 49"	119^o 47' 40"	4,445	644 meters upstream of Kietzke
Sparks	10348200	39^o 31' 03"	119^o 44' 30"	4,382	166 m upstream of East McCarran
Vista	10350000	39^o 31' 14"	119^o 42' 00"	4,369	425 m downstream of SB creek influence
North Truckee Drain	10348245	39^o 34' 08"	119^o 43' 32"	4,410	1800 m upstream of influence w/ Truckee R.
Steamboat Creek at Clean Water Way	10349980	39^o 30' 47"	119^o 42' 41"	4,375	1200 m upstream of influence w/ Truckee R.

Appendix B. Daily calculated seepage rates (flux) at low flows.

	Reach 1				**Reach 2**			
Date	upstream flow	flux (cfs)	flux (cfs/mile)	flux (cfs/km)	upstream flow	flux (cfs)	flux (cfs/mile)	flux (cfs/km)
9/21/77	50	8.8	2.7	1.8	39	0.5	0.2	0.12
9/22/77	41	-1.8	-0.6	-0.4	33	3.5	1.3	0.80
9/23/77	41	-3.3	-1.0	-0.7	32	10.0	3.7	2.3
9/24/77	41	-2.3	-0.7	-0.5	33	-0.5	-0.2	-0.10
9/25/77	30	-0.3	-0.1	-0.06	24	0.5	0.2	0.12
9/26/77	29	-2.9	-0.9	-0.6	22	2.3	0.9	0.53
9/27/77	30	-3.9	-1.2	-0.8	22	1.0	0.4	0.24
10/8/77	50	-21	-6	-4.3	22	3.3	1.2	0.74
10/9/77	34	-13	-4	-2.7	15	11.8	4.3	2.7
10/10/77	36	-8	-2	-1.6	16	9.8	3.6	2.2
10/11/77	41	-17.5	-5	-3.6	17	2.2	0.8	0.49
10/12/77	38	-18.9	-6	-3.9	15	1.5	0.5	0.33
10/13/77	32	-15.3	-5	-3.1	9.7	0.36	0.1	0.08
10/14/77	24	-7.7	-2	-1.6	9.8	9.0	3.3	2.1
10/15/77	27	-20.2	-6	-4.1	0.5	22.3	8.2	5.1
10/16/77	26	-11.8	-4	-2.4	8.5	8.3	3.0	1.9
10/17/77	24	-11.3	-3	-2.3	7.7	11.1	4.1	2.5
10/18/77	25	-10.9	-3	-2.2	9.3	8.5	3.1	1.9
10/19/77	27	-21.5	-7	-4.4	0.5	20.3	7.4	4.6
10/20/77	33	-20.4	-6	-4.2	9.2	8.6	3.2	2.0
10/21/77	34	-6.2	-2	-1.3	23	4.8	1.8	1.1
9/21/88	37	-15	-5	-3.1	22	22.1	8.1	5.0
9/22/88	17	-10	-3	-2.0	7.4	15.8	5.8	3.6
9/23/88	20	-12	-4	-2.4	8	1.6	0.6	0.36
9/24/88	43	-18	-6	-3.7	25	17.1	6.3	3.9
9/25/88	36	-23	-7	-4.7	13	27.1	9.9	6.2
9/26/88	39	-17	-5	-3.5	22	22.0	8.0	5.0
9/27/88	24	-4	-1	-0.8	20	26.6	9.8	6.1

9/28/88	24	-6	-2	-1.2	18	19.5	7.1	4.4
9/29/88	18	-3	-1	-0.6	15	26.6	9.8	6.1
9/30/88	21	-6.9	-2	-1.4	14	21.5	7.9	4.9
10/1/88	40	-3	-1	-0.6	37	-10.6	-3.9	-2.4
10/2/88	37	-7	-2	-1.4	30	-2.1	-0.8	-0.48
10/3/88	31	-10	-3	-2.0	21	3.0	1.1	0.67
10/4/88	30	-6	-2	-1.2	24	11.0	4.0	2.5
10/5/88	17	-16.5	-5	-3.4	0.5	20.1	7.3	4.6
10/6/88	20	-19.5	-6	-4.0	0.5	16.5	6.0	3.8
10/7/88	23	-10	-3	-2.0	13	4.1	1.5	0.94
10/8/88	40	-7	-2	-1.4	33	-3.0	-1.1	-0.68
10/9/88	42	-6	-2	-1.2	36	-0.9	-0.3	-0.21
10/10/88	41	-5	-2	-1.0	36	-0.66	-0.2	-0.15
10/11/88	30	-7	-2	-1.4	23	18.5	6.8	4.2
10/12/88	31	-10	-3	-2.0	21	20.1	7.4	4.6
10/13/88	34	-10	-3	-2.0	24	17.6	6.4	4.0
10/14/88	41	-7	-2	-1.4	34	5.3	1.9	1.2
10/15/88	41	-9	-3	-1.8	32	5.9	2.2	1.3
10/16/88	51	-9	-3	-1.8	42	-0.03	-0.01	-0.01
10/17/88	47	-8	-2	-1.6	39	-0.56	-0.2	-0.13
10/18/88	44	-2	-1	-0.4	42	3.3	1.2	0.76
10/19/88	29	-7	-2	-1.4	22	13.5	4.9	3.1
10/20/88	15	-6.4	-2	-1.3	8.6	15.5	5.7	3.5
10/21/88	33	-13	-4	-2.6	20	9.3	3.4	2.1
10/22/88	40	-8	-2	-1.6	32	7.7	2.8	1.7
11/3/88	40	-9	-3	-1.8	31	5.4	2.0	1.2
11/4/88	48	-8	-2	-1.6	40	1.4	0.5	0.3
11/5/88	49	-6	-2	-1.2	43	4.5	1.7	1.0
11/6/88	49	-8	-2	-1.6	41	14.3	5.3	3.3
11/7/88	35	-8	-2	-1.6	27	-1.6	-0.6	-0.37
11/8/88	45	-9	-3	-1.8	36	4.3	1.6	0.97
11/9/88	27	-9	-3	-1.8	18	11.7	4.3	2.7
11/10/88	30	-10	-3	-2.0	20	-3.1	-1.1	-0.71
11/11/88	32	-11	-3	-2.2	21	-8.6	-3.2	-2.0

11/12/88	43	-6	-2	-1.2	37	-0.4	-0.1	-0.09
9/29/90	41	-13.9	-4.3	-2.8	27.0	0.7	0.3	0.16
9/30/90	42	-32.7	-10.1	-6.7	9.2	-13.3	-4.9	-3.0
10/1/90	40	-31.2	-9.6	-6.4	8.8	-16.5	-6.0	-3.7
10/2/90	28	-19.3	-5.9	-3.9	8.7	-15.1	-5.5	-3.4
10/3/90	33	-32.5	-10.0	-6.6	0.5	1.9	0.7	0.44
10/4/90	25	-18.7	-5.7	-3.8	6.3	-8.2	-3.0	-1.9
10/5/90	26	-18.9	-5.8	-3.9	7.1	-12.7	-4.6	-2.9
10/6/90	27	-26.6	-8.2	-5.4	0.4	-3.8	-1.4	-0.9
10/7/90	28	-15.0	-4.6	-3.1	13.0	0.1	0.03	0.02
10/8/90	33	-32.5	-10.0	-6.6	0.5	13.0	4.8	3.0
10/9/90	41	-40.5	-12.5	-8.3	0.5	13.4	4.9	3.0
10/10/90	38	-37.5	-11.5	-7.7	0.5	0.3	0.1	0.07
10/11/90	33	-25.0	-7.7	-5.1	8.0	-17.0	-6.2	-3.9
10/12/90	36	-35.6	-10.9	-7.3	0.4	5.8	2.1	1.3
10/13/90	24	-11.0	-3.4	-2.2	13.0	2.6	0.9	0.6
10/14/90	33	-26.1	-8.0	-5.3	6.9	-4.0	-1.5	-0.9
11/3/90	49	-14	-4	-2.9	35	19.4	7.1	4.4
11/4/90	49	-20	-6	-4.1	29	8.8	3.2	2.0
11/5/90	48	-17	-5	-3.5	31	9.9	3.6	2.2
11/6/90	45	-7	-2	-1.4	38	13.9	5.1	3.2
11/7/90	48	-9	-3	-1.8	39	18.3	6.7	4.2
11/8/90	43	-11	-3	-2.2	32	17.3	6.3	3.9
11/9/90	43	-11	-3	-2.2	32	21.3	7.8	4.8
11/10/90	39	-12	-4	-2.4	27	9.4	3.5	2.1
11/11/90	35	-13	-4	-2.7	22	11.1	4.1	2.5
11/12/90	42	-13	-4	-2.7	29	7.4	2.7	1.7
11/13/90	41	-12	-4	-2.4	29	22.6	8.3	5.1
11/14/90	41	-11	-3	-2.2	30	18.5	6.8	4.2
11/15/90	40	-13	-4	-2.7	27	13.0	4.8	3.0
11/16/90	40	-13	-4	-2.7	27	22.0	8.0	5.0
11/17/90	39	-11	-3	-2.2	28	18.5	6.8	4.2
11/18/90	37	-8	-2	-1.6	29	10.5	3.8	2.4

11/19/90	42	-13	-4	-2.7	29	22.4	8.2	5.1
11/20/90	49	-12	-4	-2.4	37	21.1	7.7	4.8
11/21/90	47	-12	-4	-2.4	35	11.3	4.1	2.6
11/22/90	45	-13	-4	-2.7	32	19.4	7.1	4.4
11/23/90	45	-12	-4	-2.4	33	9.9	3.6	2.2
11/24/90	43	-12	-4	-2.4	31	9.6	3.5	2.2
9/12/91	42	-14.3	-4.4	-2.9	16.0	24.2	8.9	5.5
9/13/91	41	-14.3	-4.4	-2.9	15.0	10.5	3.8	2.4
9/14/91	32	-19.9	-6.1	-4.1	0.4	11.2	4.1	2.6
9/15/91	33	-13.5	-4.2	-2.8	7.8	10.1	3.7	2.3
9/16/91	42	-17.3	-5.3	-3.5	13.0	3.3	1.2	0.75
9/17/91	40	-14.3	-4.4	-2.9	14.0	20.1	7.4	4.6
9/18/91	19	0.3	0.1	0.06	7.6	19.6	7.2	4.5
9/19/91	17	0.8	0.2	0.16	6.1	22.9	8.4	5.20
9/20/91	17	0.2	0.1	0.04	5.5	21.1	7.7	4.79
9/21/91	17	-0.2	-0.1	-0.04	5.1	20.5	7.5	4.66
9/22/91	22	-5.0	-1.5	-1.0	5.3	30.5	11.2	6.93
9/23/91	29	-10.6	-3.3	-2.2	6.7	17.6	6.5	4.01
9/24/91	31	-12.4	-3.8	-2.5	6.9	19.1	7.0	4.33
9/25/91	34	-12.8	-3.9	-2.6	9.5	21.6	7.9	4.90
9/26/91	27	-9.2	-2.8	-1.9	6.1	15.8	5.8	3.60
9/27/91	27	-6.1	-1.9	-1.25	9.2	13.2	4.8	3.01
9/28/91	25	-4.4	-1.4	-0.9	8.9	18.9	6.9	4.31
9/29/91	21	-3.8	-1.2	-0.8	5.5	7.5	2.8	1.71
9/30/91	21	-3.3	-1.0	-0.7	6.0	13.7	5.0	3.11
10/1/91	21	-16.8	-5.2	-3.4	4.2	20.7	7.6	4.70
10/2/91	22	-15.6	-4.8	-3.2	6.4	28.5	10.4	6.48
10/3/91	18	-13.6	-4.2	-2.8	4.4	18.8	6.9	4.28
10/4/91	20	-15.8	-4.9	-3.2	4.2	17.3	6.4	3.94
10/5/91	20	-15.2	-4.7	-3.1	4.8	11.8	4.3	2.69
10/6/91	20	-15.0	-4.6	-3.1	5.0	11.9	4.4	2.71
10/7/91	25	-19.1	-5.9	-3.9	5.9	8.6	3.1	1.95
10/8/91	27	-20.8	-6.4	-4.2	6.2	5.0	1.8	1.13
10/9/91	24	-19.2	-5.9	-3.9	4.8	-0.29	-0.1	-0.07

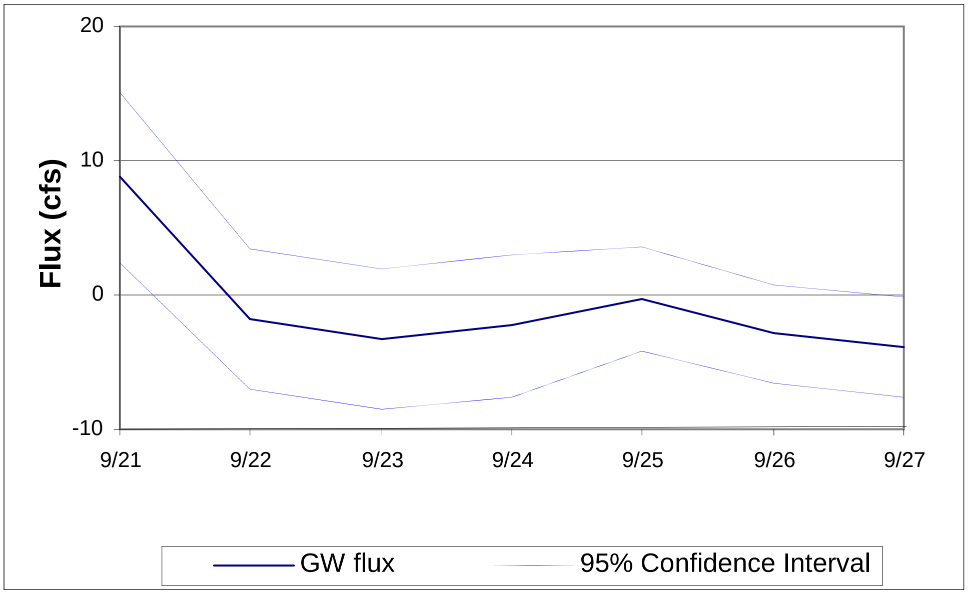
10/10/91	24	-19.6	-6.0	-4.0	4.4	-0.43	-0.2	-0.10
10/11/91	21	-17.5	-5.4	-3.6	3.5	-0.86	-0.3	-0.20
10/12/91	21	-17.9	-5.5	-3.6	3.1	4.2	1.5	0.95
10/13/91	20	-17.1	-5.3	-3.5	2.9	12.7	4.7	2.89
10/14/91	22	-19.9	-6.1	-4.1	2.1	10.4	3.8	2.36
10/15/91	20	-17.4	-5.3	-3.5	2.6	8.1	3.0	1.84
10/16/91	23	-21.0	-6.5	-4.3	2.0	15.3	5.6	3.48
10/17/91	20	-18.4	-5.7	-3.7	1.6	5.5	2.0	1.24
10/18/91	18	-16.4	-5.0	-3.3	1.6	6.4	2.4	1.46
10/19/91	22	-20.1	-6.2	-4.1	1.9	7.5	2.7	1.69
10/20/91	21	-18.6	-5.7	-3.8	2.4	10.3	3.8	2.34
10/21/91	19	-17.0	-5.2	-3.5	2.0	6.2	2.3	1.40
10/22/91	21	-19.3	-5.9	-3.9	1.7	8.6	3.1	1.95
10/23/91	22	-17.5	-5.4	-3.6	4.5	4.8	1.8	1.10
10/24/91	23	-15.0	-4.6	-3.1	8.0	2.7	1.0	0.62
10/25/91	22	-15.8	-4.9	-3.2	6.2	4.2	1.5	0.96
10/31/91	49	-11	-3.4	-2.2	38	9.4	3.4	2.13
11/1/91	46	-12	-3.7	-2.4	34	24.5	9.0	5.56
11/2/91	47	-14	-4.3	-2.9	33	19.3	7.1	4.39
11/3/91	47	-10	-3.1	-2.0	37	11.4	4.2	2.59
11/4/91	43	-10	-3.1	-2.0	33	6.8	2.5	1.53
11/5/91	43	-11	-3.4	-2.2	32	7.9	2.9	1.80
11/6/91	42	-13	-4.0	-2.7	29	9.3	3.4	2.12
11/7/91	40	-18	-5.5	-3.7	22	11.3	4.1	2.57
11/8/91	46	-19	-5.8	-3.9	27	11.7	4.3	2.66
6/16/92	37	-10.0	-3.1	-2.0	19.0	54.3	19.9	12.3
6/17/92	32	-17.7	-5.5	-3.6	7.2	32.7	12.0	7.4
6/18/92	40	-26.5	-8.1	-5.4	0.5	38.0	13.9	8.6
6/19/92	33	-18.0	-5.6	-3.7	7.1	26.3	9.6	6.0
6/20/92	29	-24.7	-7.6	-5.0	4.2	16.3	6.0	3.7
6/21/92	18	-15.1	-4.7	-3.1	2.8	26.9	9.9	6.1
6/22/92	24	-21.5	-6.6	-4.4	2.4	24.1	8.8	5.5
6/23/92	18	-14.5	-4.5	-3.0	3.4	12.1	4.4	2.7
6/24/92	22	-17.9	-5.5	-3.7	4.0	24.1	8.8	5.5

6/25/92	27	-24.1	-7.4	-4.9	2.8	12.9	4.7	2.9
6/26/92	26	-23.4	-7.2	-4.8	2.5	9.9	3.6	2.3
7/21/92	48	-22.9	-7.1	-4.7	15.0	1.2	0.4	0.3
7/22/92	33	-18.7	-5.8	-3.8	7.7	1.3	0.5	0.3
7/23/92	28	-14.8	-4.6	-3.0	5.0	2.4	0.9	0.5
7/24/92	22	-9.5	-2.9	-1.9	4.2	5.9	2.2	1.3
7/25/92	25	-11.9	-3.7	-2.4	3.5	6.7	2.5	1.5
7/26/92	33	-17.7	-5.5	-3.6	5.2	4.6	1.7	1.0
7/27/92	38	-20.0	-6.2	-4.1	5.9	7.5	2.7	1.7
7/28/92	32	-17.8	-5.5	-3.6	5.5	5.8	2.1	1.3
7/29/92	30	-18.7	-5.8	-3.8	5.1	7.6	2.8	1.7
7/30/92	28	-22.6	-7.0	-4.6	5.3	7.2	2.6	1.6
7/31/92	22	-18.2	-5.6	-3.7	3.7	6.2	2.3	1.4
8/1/92	27	-23.8	-7.3	-4.9	3.1	7.8	2.9	1.8
8/2/92	25	-22.9	-7.0	-4.7	2.0	5.0	1.8	1.1
8/3/92	32	-30.8	-9.5	-6.3	1.1	7.0	2.6	1.6
8/4/92	26	-22.0	-6.8	-4.5	3.9	7.5	2.8	1.7
8/5/92	25	-24.6	-7.6	-5.0	0.3	8.7	3.2	2.0
8/6/92	32	-31.4	-9.7	-6.4	0.5	7.1	2.6	1.6
8/7/92	30	-27.1	-8.3	-5.5	2.8	2.7	1.0	0.6
8/8/92	28	-26.0	-8.0	-5.3	1.9	5.6	2.1	1.3
8/9/92	25	-24.6	-7.6	-5.0	0.3	6.9	2.5	1.6
8/10/92	29	-28.8	-8.9	-5.9	0.1	9.5	3.5	2.2
8/11/92	20	-18.6	-5.7	-3.8	1.3	10.6	3.9	2.4
8/12/92	24	-23.7	-7.3	-4.8	0.2	11.3	4.1	2.6
6/24/94	31	-22.6	-7.0	-4.6	8.3	14.2	5.2	3.2
6/25/94	40	-21.7	-6.7	-4.4	7.2	11.1	4.1	2.5
6/26/94	46	-20.9	-6.4	-4.3	13.0	9.2	3.4	2.1
6/27/94	41	-29.5	-9.1	-6.0	0.5	26.0	9.5	5.9
6/28/94	39	-19.6	-6.0	-4.0	9.3	17.7	6.5	4.0
6/29/94	34	-16.7	-5.2	-3.4	7.4	20.8	7.6	4.7
6/30/94	31	-19.0	-5.9	-3.9	2.5	17.0	6.2	3.9
7/1/94	31	-20.4	-6.3	-4.2	1.5	8.8	3.2	2.0

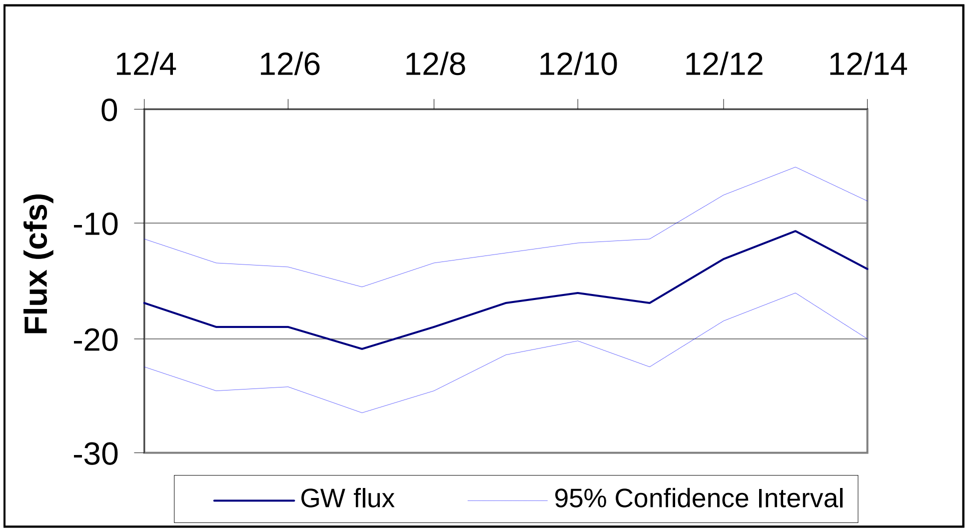
7/2/94	32	-21.2	-6.5	-4.3	1.8	6.3	2.3	1.4
7/3/94	31	-20.6	-6.3	-4.2	1.5	7.3	2.7	1.7
7/4/94	31	-17.1	-5.3	-3.5	5.1	6.6	2.4	1.5
7/5/94	31	-17.1	-5.3	-3.5	5.4	17.3	6.3	3.9
7/6/94	34	-24.2	-7.5	-4.9	1.7	16.7	6.1	3.8
7/7/94	33	-24.5	-7.5	-5.0	0.8	5.4	2.0	1.2
7/29/94	37	-24.6	-7.6	-5.0	4.70	9.1	3.3	2.1
7/30/94	27	-19.9	-6.1	-4.1	0.34	8.9	3.2	2.0
7/31/94	33	-23.2	-7.1	-4.7	1.70	6.4	2.3	1.5
8/1/94	31	-15.3	-4.7	-3.1	6.60	7.2	2.6	1.6
8/2/94	31	-21.2	-6.5	-4.3	1.10	5.8	2.1	1.3
8/3/94	33	-24.2	-7.5	-4.9	0.38	8.1	3.0	1.8
8/4/94	30	-26.7	-8.2	-5.4	0.02	4.9	1.8	1.1
8/5/94	28	-21.3	-6.6	-4.3	0.10	7.2	2.6	1.6
10/16/94	33	-26.7	-8.2	-5.4	6.3	7.7	2.8	1.8
10/17/94	32	-22.4	-6.9	-4.6	9.6	11.0	4.0	2.5
10/18/94	33	-19.0	-5.8	-3.9	14.0	7.7	2.8	1.7
10/19/94	31	-22.8	-7.0	-4.6	8.2	11.2	4.1	2.6
10/20/94	30	-25.5	-7.8	-5.2	4.5	10.5	3.9	2.4
10/21/94	29	-26.2	-8.1	-5.3	2.8	14.7	5.4	3.4
10/22/94	29	-28.3	-8.7	-5.8	0.6	9.8	3.6	2.2
10/23/94	29	-27.7	-8.5	-5.6	1.3	8.7	3.2	2.0
10/24/94	28	-26.8	-8.2	-5.5	1.2	13.9	5.1	3.2
10/25/94	31	-29.2	-9.0	-6.0	1.8	8.9	3.3	2.0
10/26/94	27	-25.9	-8.0	-5.3	1.1	13.7	5.0	3.1
10/27/94	29	-28.5	-8.8	-5.8	0.5	9.6	3.5	2.2
10/28/94	26	-25.8	-7.9	-5.3	0.2	11.2	4.1	2.5
10/5/04	49	-17.0	-5.2	-3.5	32.0	19.7	7.2	4.5
10/6/04	41	-17.0	-5.2	-3.5	24.0	11.1	4.1	2.5
10/7/04	35	-15.0	-4.6	-3.1	20.0	17.2	6.3	3.9
10/8/04	34	-17.0	-5.2	-3.5	17.0	10.1	3.7	2.3
10/9/04	25	-15.7	-4.8	-3.2	9.3	12.8	4.7	2.9

10/10/04	29	-28.5	-8.8	-5.8	0.5	20.4	7.5	4.6
10/11/04	39	-12.0	-3.7	-2.4	27.0	9.8	3.6	2.2
10/12/04	24	-23.5	-7.2	-4.8	0.5	21.4	7.8	4.9
10/13/04	25	-12.0	-3.7	-2.4	13.0	8.2	3.0	1.9
10/14/04	32	-11.0	-3.4	-2.2	21.0	8.3	3.0	1.9
10/15/04	26	-10.0	-3.1	-2.0	16.0	9.4	3.4	2.1
10/16/04	32	-11.0	-3.4	-2.2	21.0	7.8	2.9	1.8
10/17/04	44	-15.0	-4.6	-3.1	29.0	11.0	4.0	2.5
Average		-15.76	-4.85	-3.22		10.32	3.78	2.35
Median		-15.64	-4.81	-3.19		9.48	3.47	2.16
Max Gain		8.80	2.71	1.80		54.29	19.89	12.34
Max Loss		-40.47	-12.45	-8.26		-17.02	-6.23	-3.87

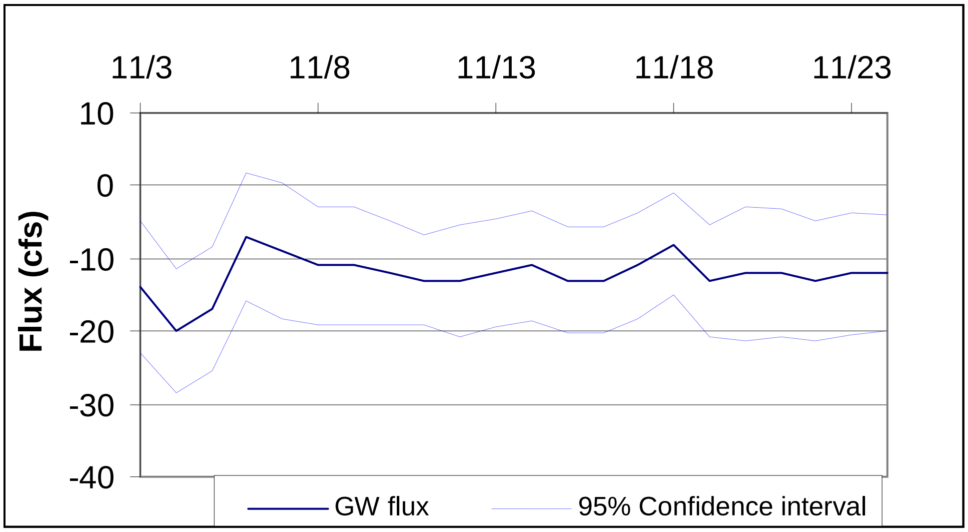
Appendix C. Selected dates of calculated groundwater seepage using the stream budget method during low flows.



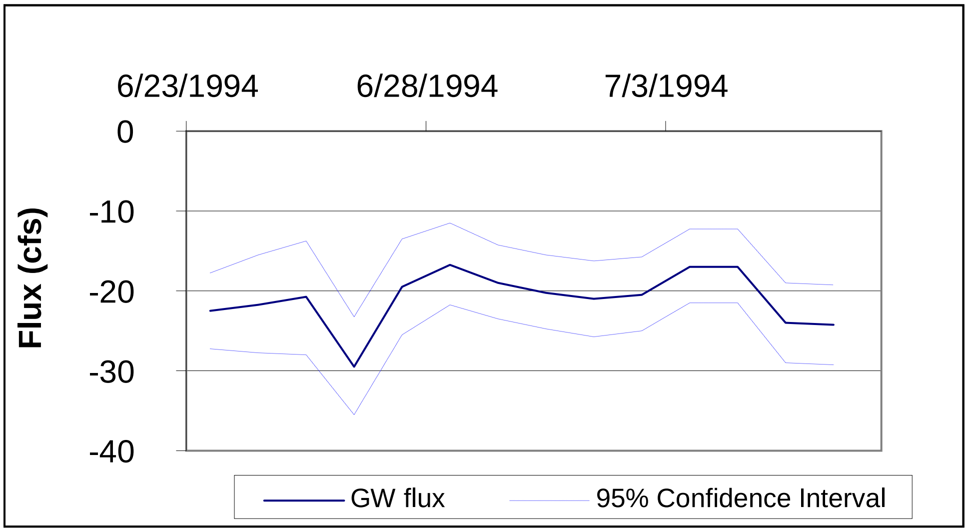
Reach 1 calculated groundwater flux during low flows in September, 1977.



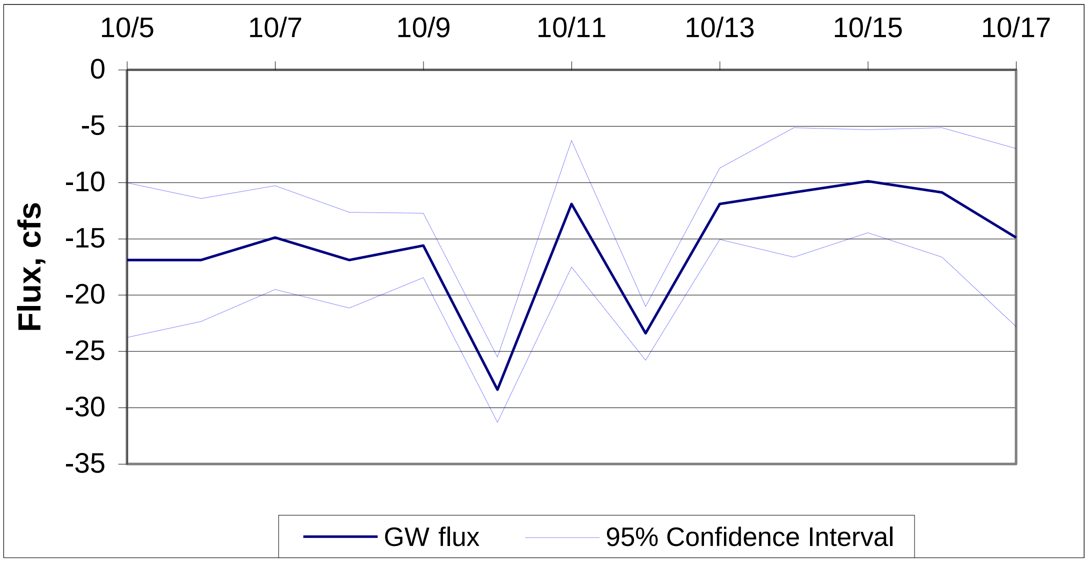
Reach 1 calculated groundwater flux during low flows in December 1977.



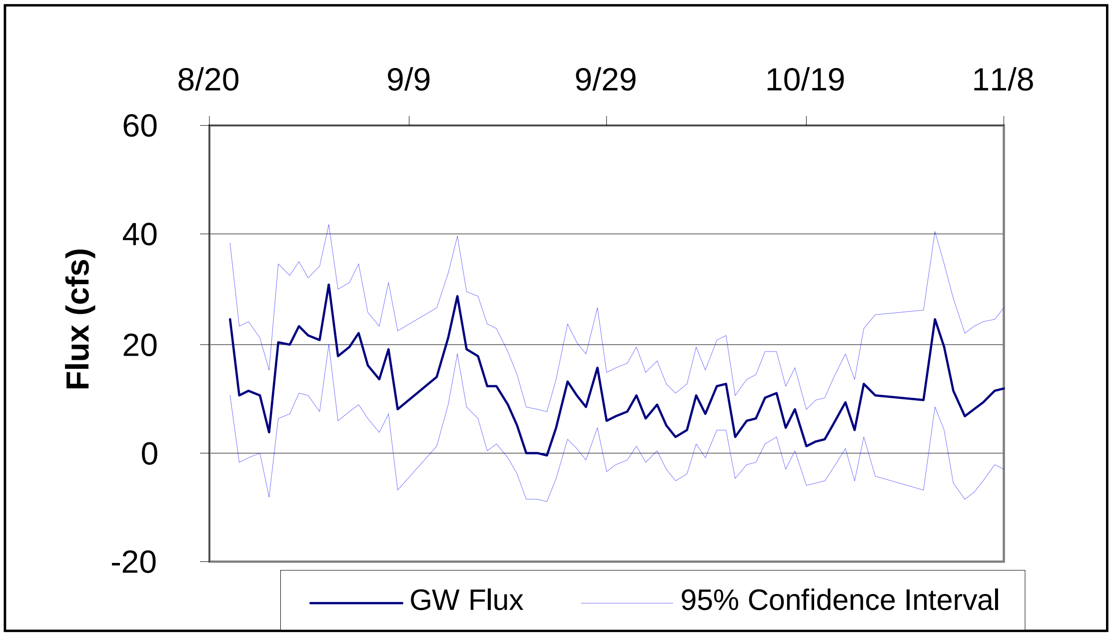
Reach 1 calculated groundwater flux during low flows in November, 1990.



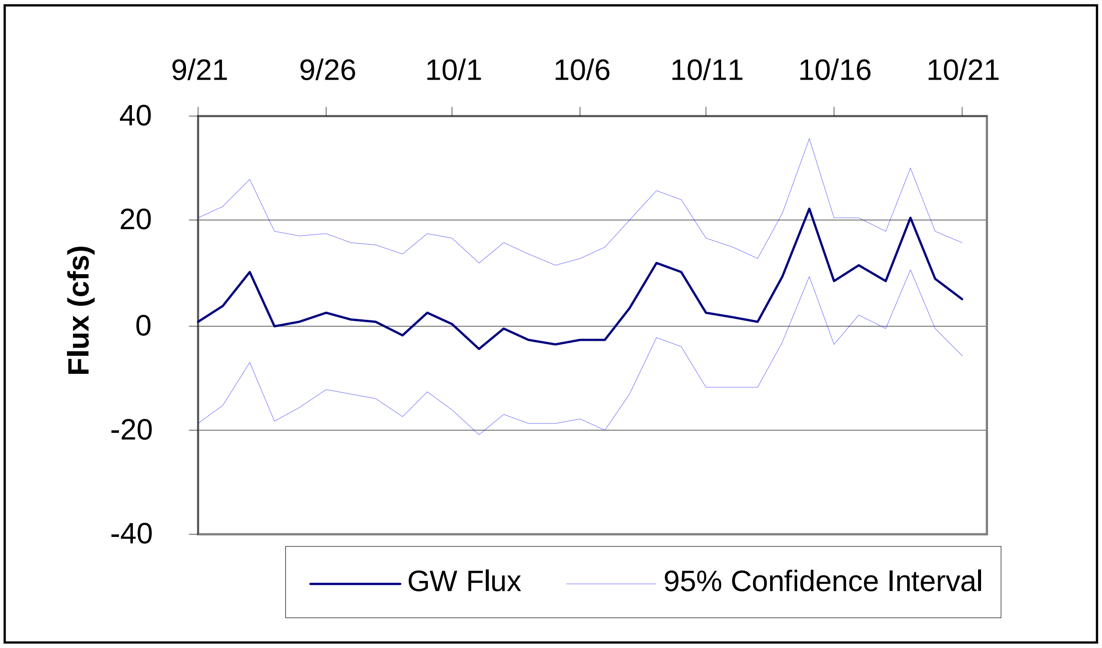
Reach 1 calculated groundwater flux during low flows in summer, 1994.



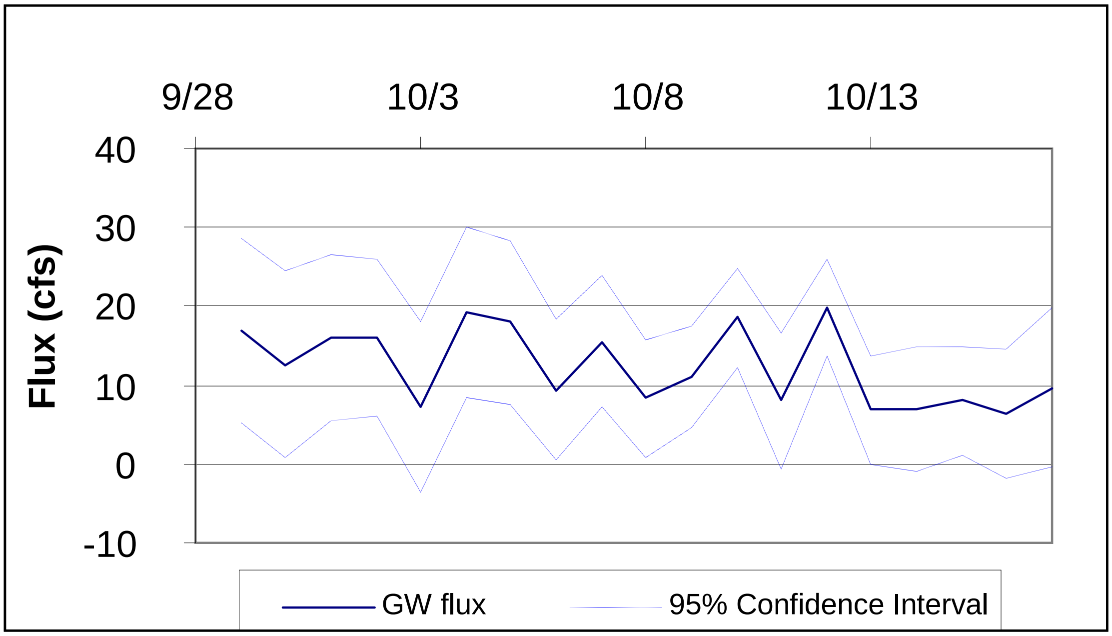
Reach 1 calculated groundwater flux during low flows in October 2004.



Reach 2 calculated groundwater flux during low flows in fall 1991.



Reach 2 calculated groundwater flux during low flows in fall 1977.

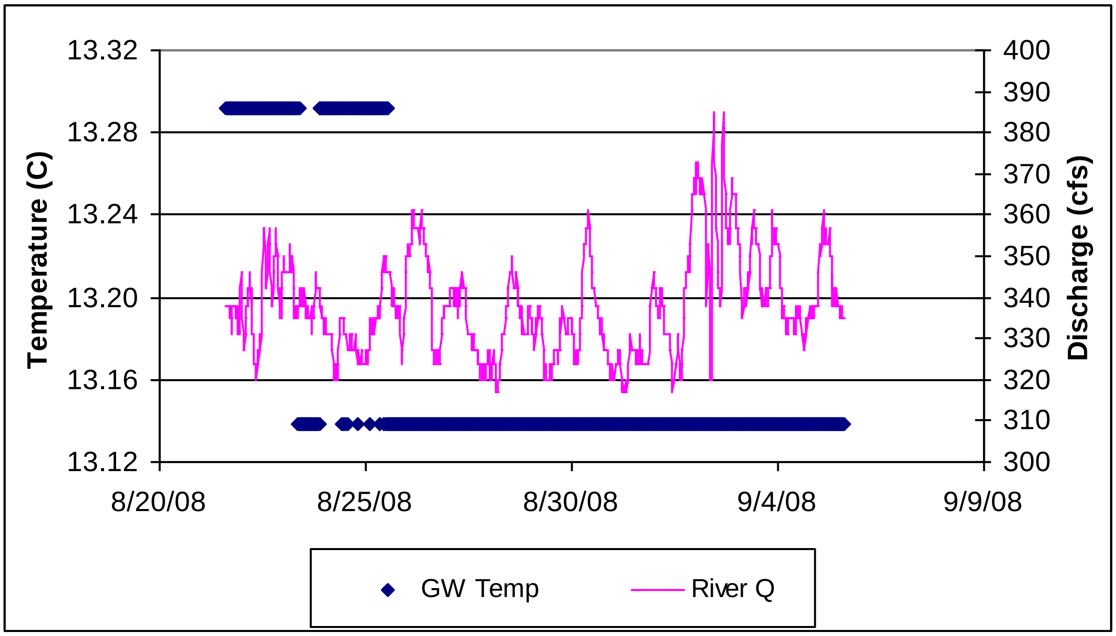


Reach 2 calculated groundwater flux during low flows fall 2004.

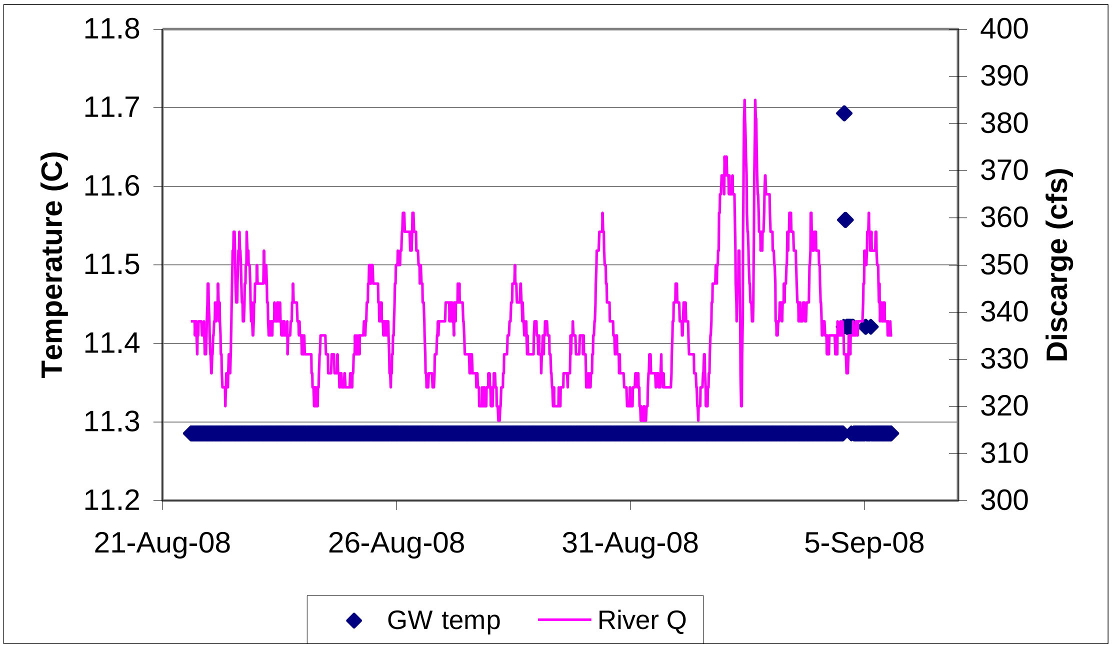
Appendix D. Thermistor locations and regression equations.

Location	ID #	Location Summary	Streambed Description	Regression Equation	River Distance (km)	Stage (inches)
T1	F58	Brodhead Park, Reno	Boulders	1.0028x + 0.3885	0	20.5
T2	DEB	Kirman/Sutro Bridge	Boulders	1.0255x + 0.4881	0.56	24
T2	F57	Kirman/Sutro Bridge	Boulders	1.008x + 0.6827	0.56	24
T3	DC9	Downstream of Waste Transfer Station	Boulders & gravel	1.0111x + 0.5147	0.91	36
T3	FF3	Downstream of Waste Transfer Station	Boulders & gravel	1.0101x + 0.4274	0.91	36
T4	376	Galletti Park	Sand & macrophytes	1.0048x + 0.5408	2.4	> 48
T5	473	Spice Island Park, Sparks	Sand & gravel	1.0102x + 0.1827	7.46	33
T6	OB8	Franklin Way	Sand & gravel	1.0051x + 0.6102	9.06	42
TB	AF4	Galletti Park	Sand & macrophytes	1.2682x - 3.1324	2.4	> 48
TB	BC2	Galletti Park	Sand & macrophytes	1.003x + 0.6415	2.4	> 48
TC	473	Near Grand Sierra Resort	Gravel & macrophytes	1.028x + 0.0338	7	45
TE	DC9	Upstream of North Truckee Drain	Sand & silt	1.0111x + .5147	10	36
TE	DEB	Upstream of North Truckee Drain	Sand & silt	0.9981x + 0.7436	10	36

Appendix E. Groundwater Temperature in Agricultural wells.

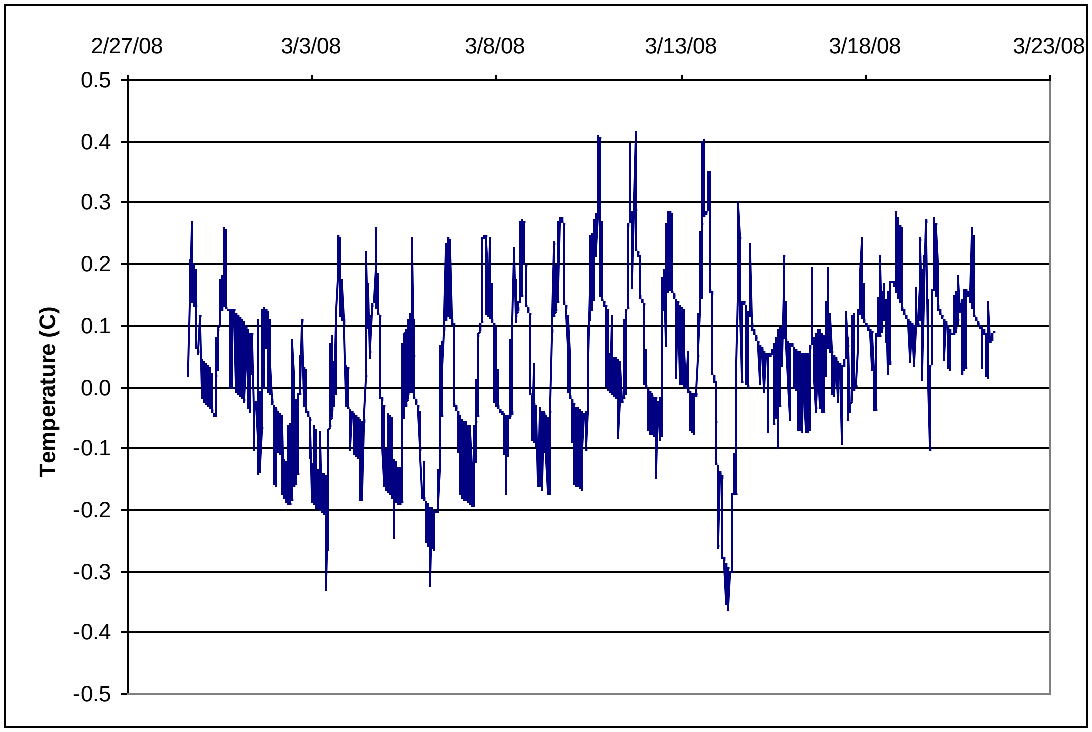


Groundwater temperature at AgMw12 and river discharge at USGS Sparks gage.

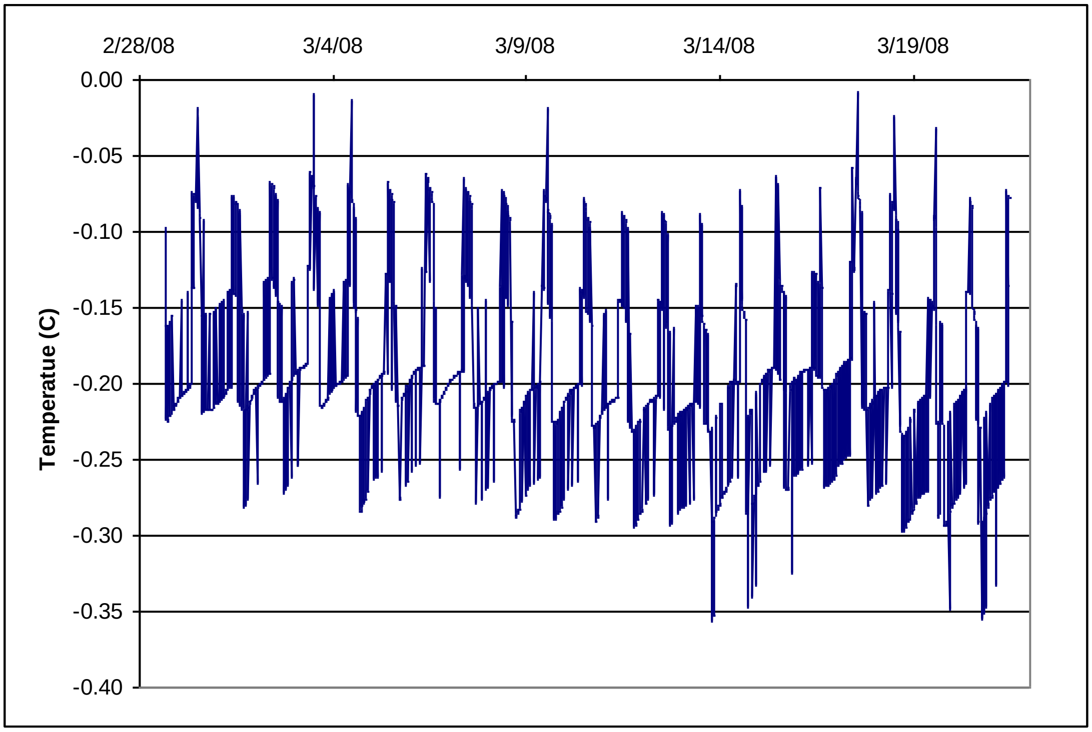


Groundwater temperature at AgMw16 and river discharge at USGS Sparks gage.

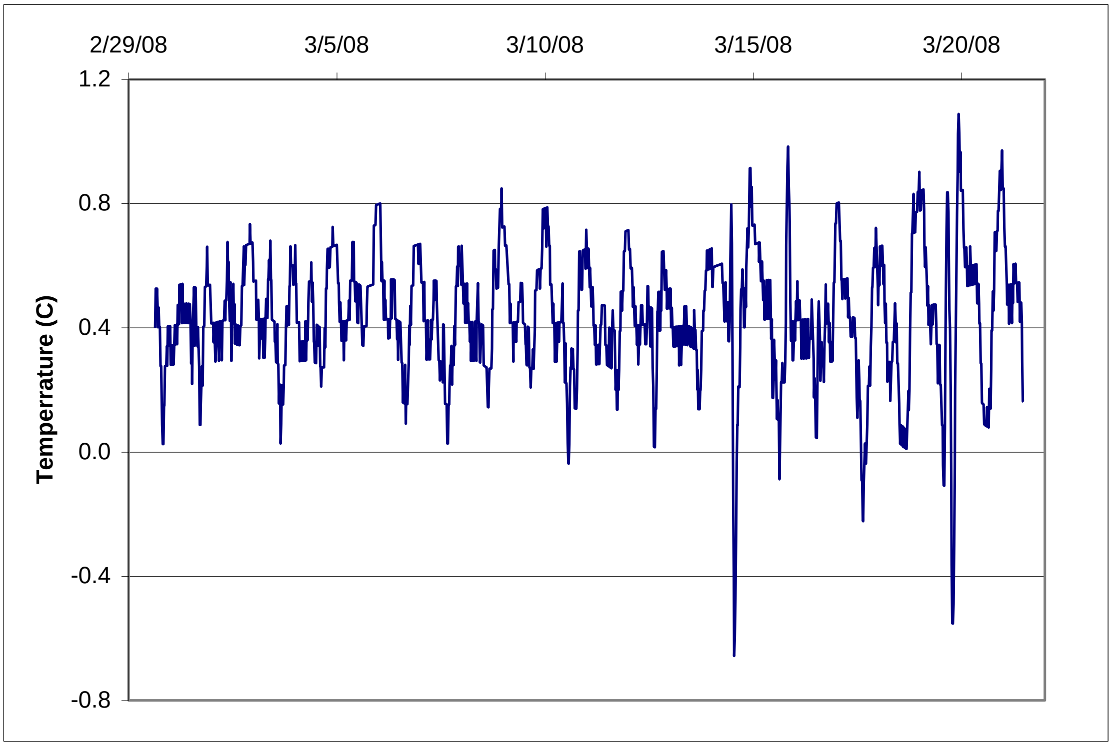
Appendix F. Differences in streambed temperature between sensors.



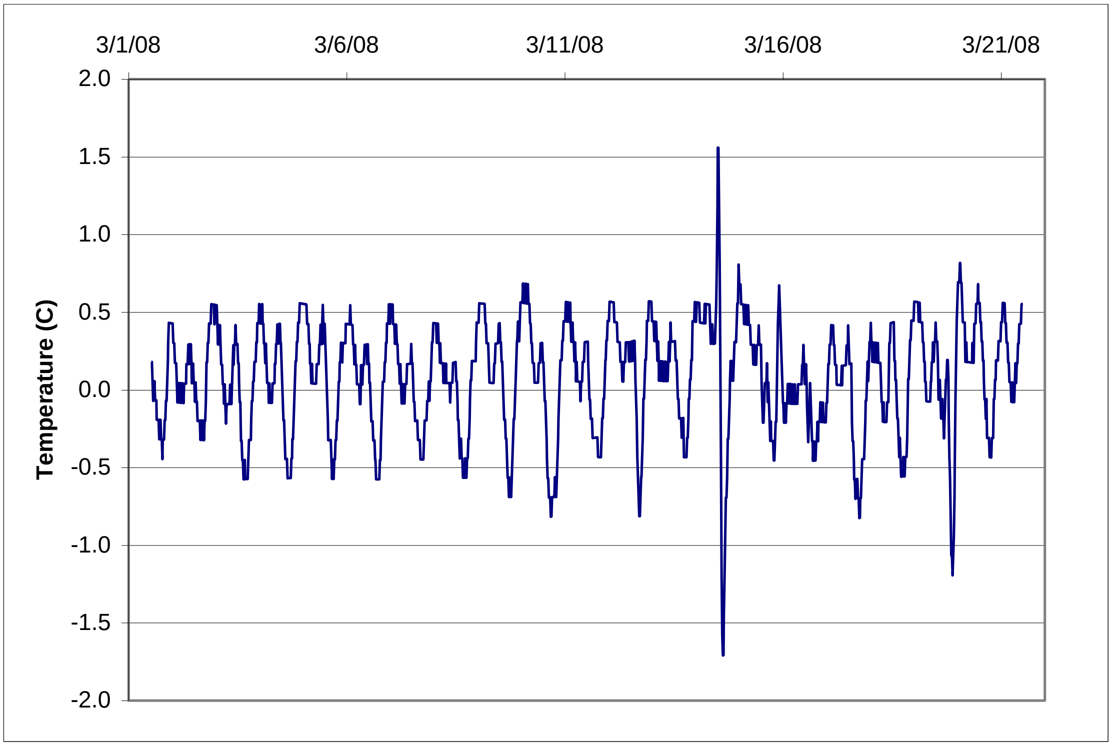
Differences in streambed temperature between thermistors T1 and T2.



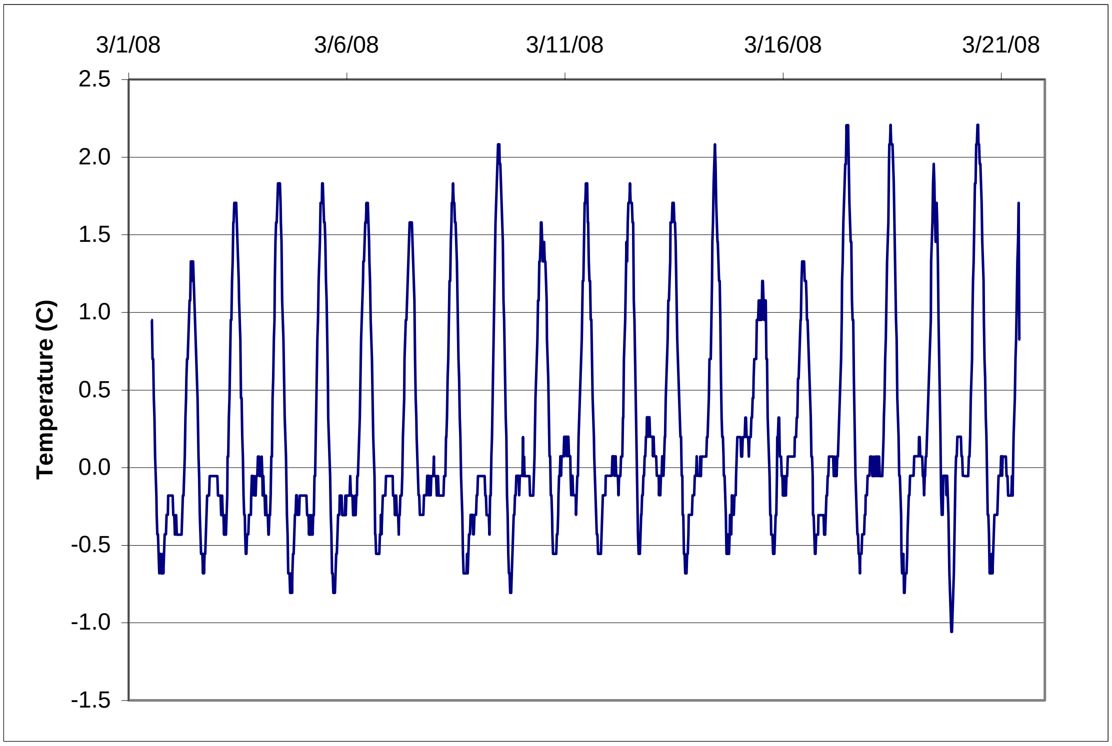
Differences in streambed temperature between thermistors T2 and T3.



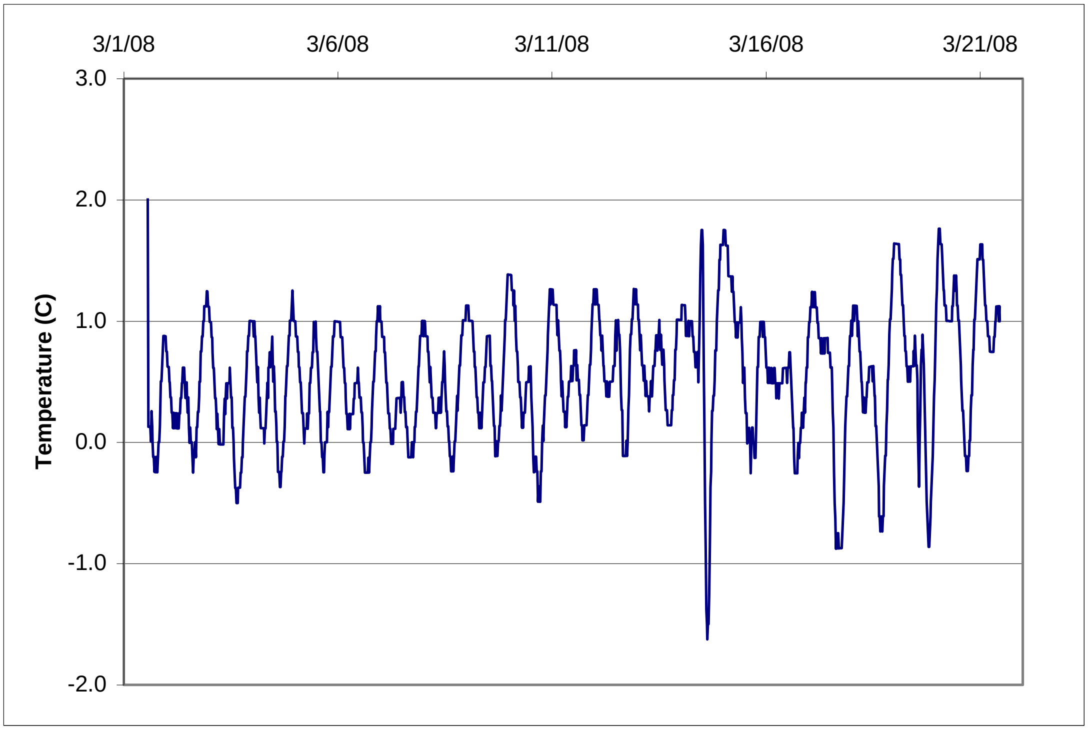
Differences in streambed temperature between thermistors T3 and T4.



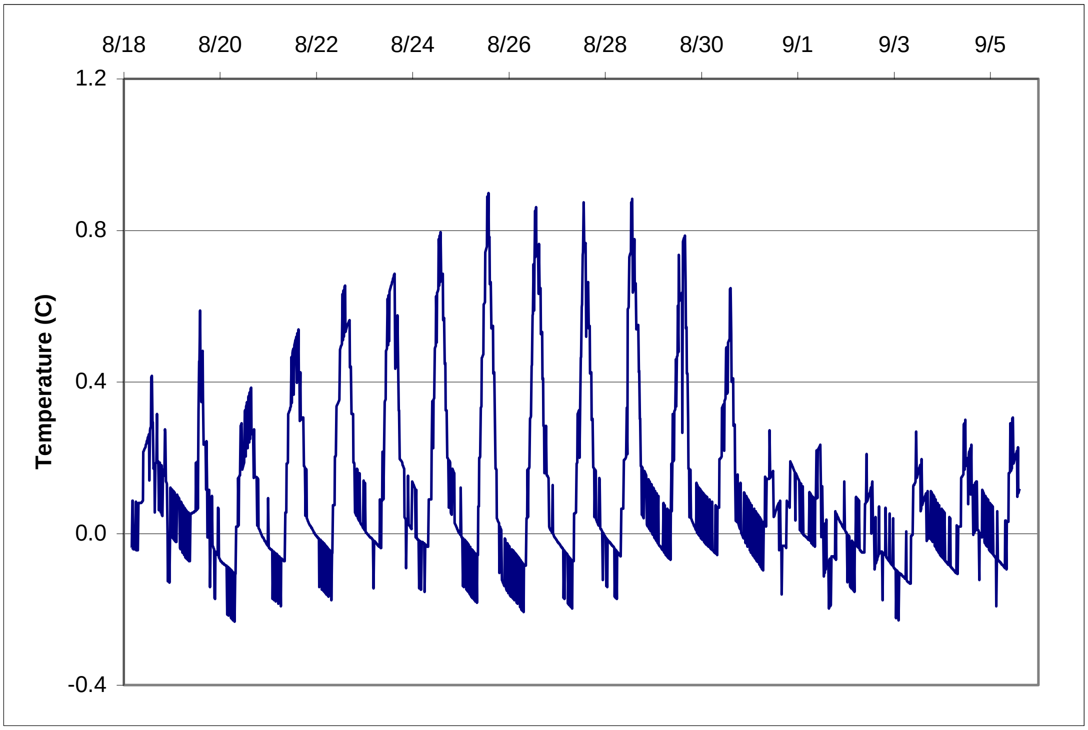
Differences in streambed temperature between thermistors T4 and T5.



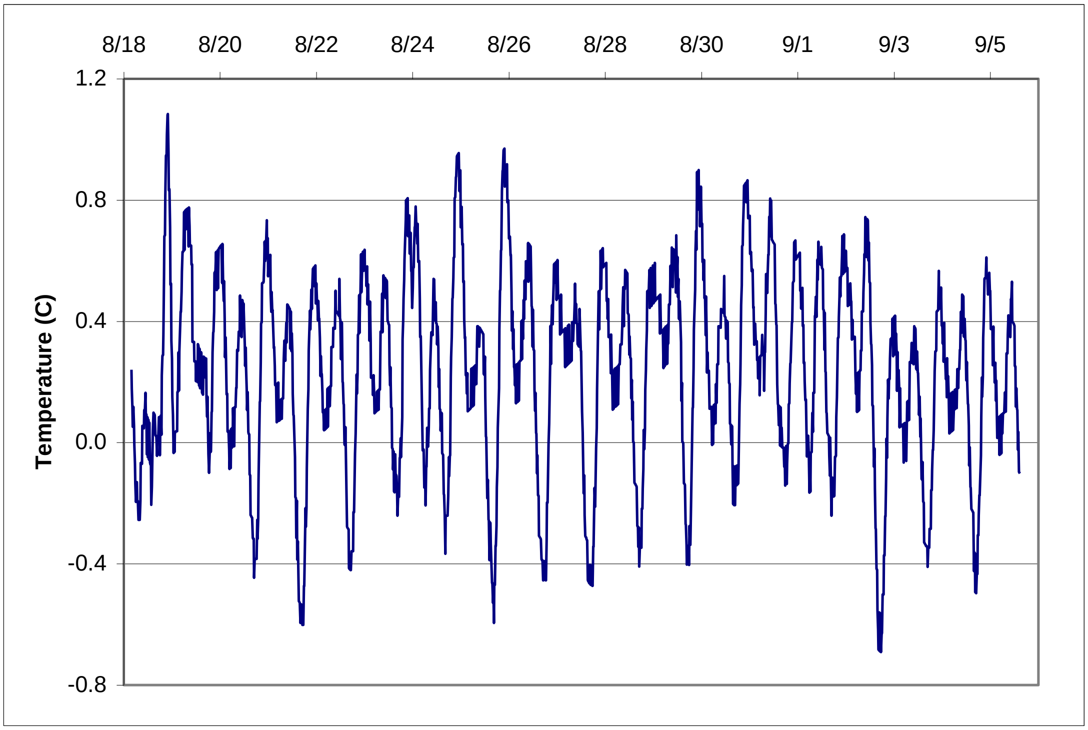
Differences in streambed temperature between thermistors T4 and T6. Differences between T5 and T6 are presented in Figure 3.7.



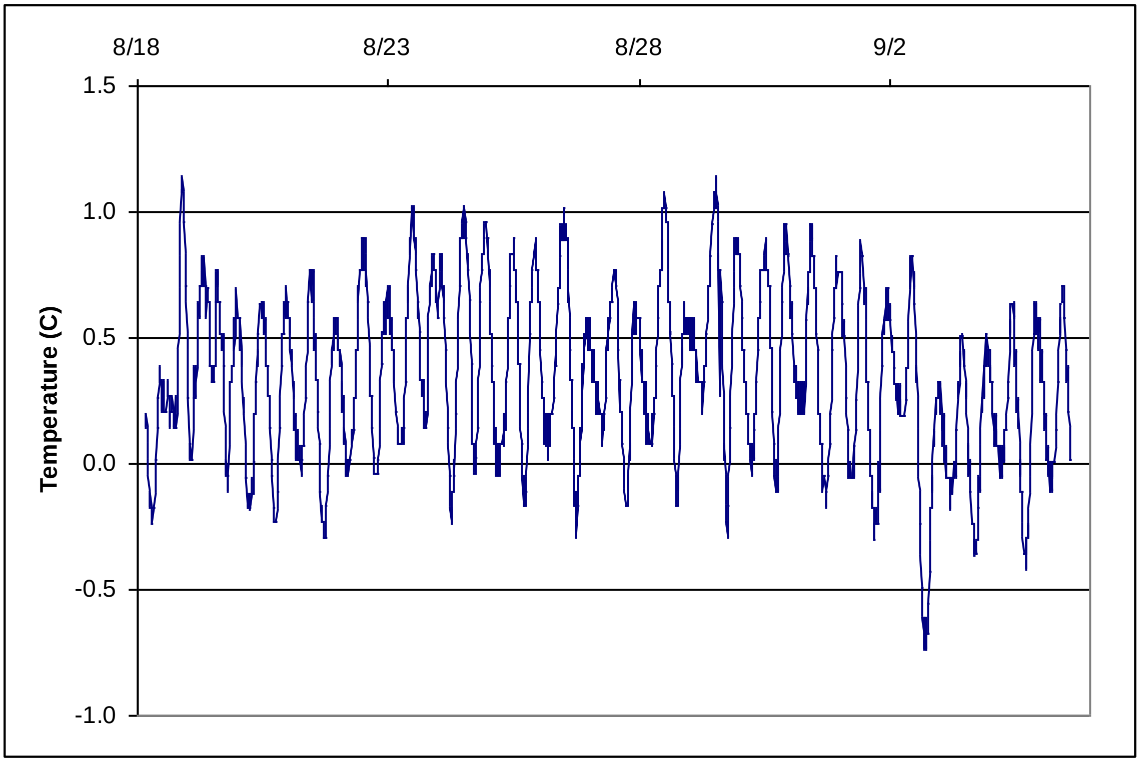
Differences in streambed temperature between thermistors T1 and T6.



Differences in streambed temperature between thermistors TB and TC.

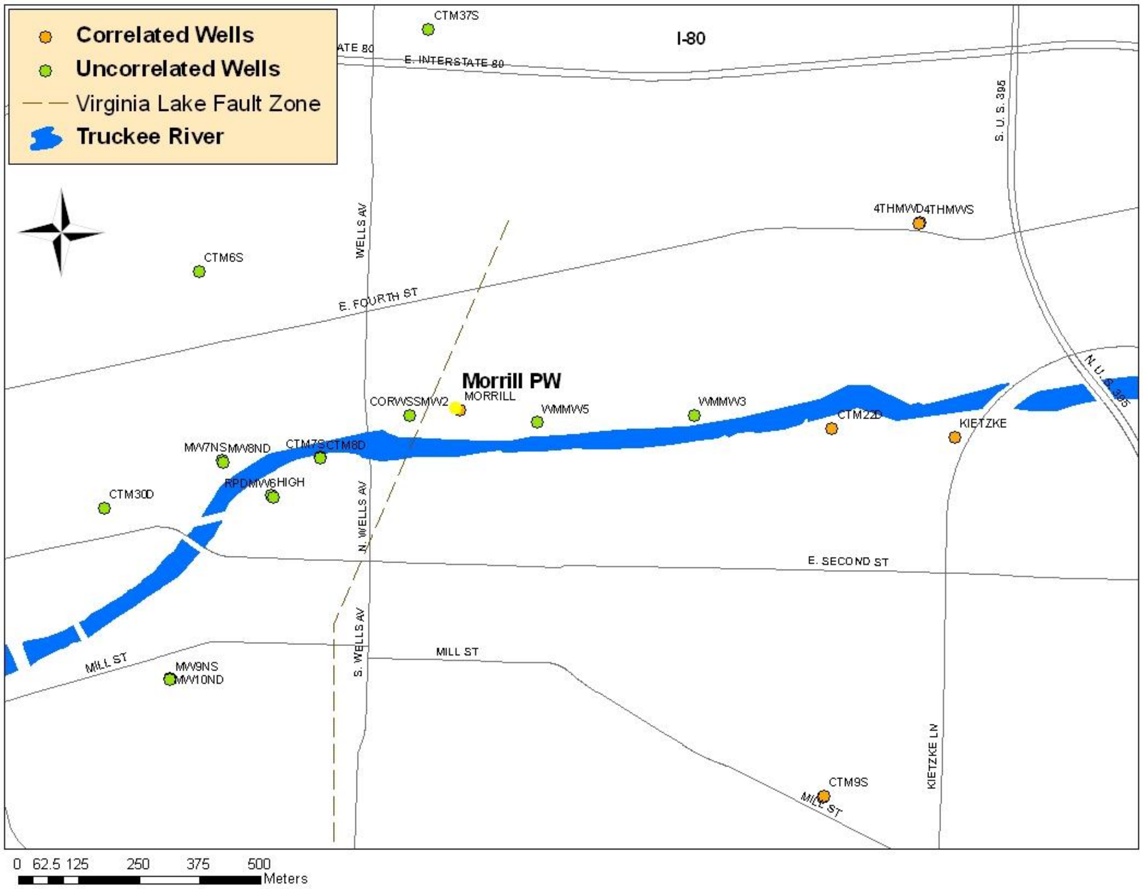


Differences in streambed temperature between thermistors TC and TE.

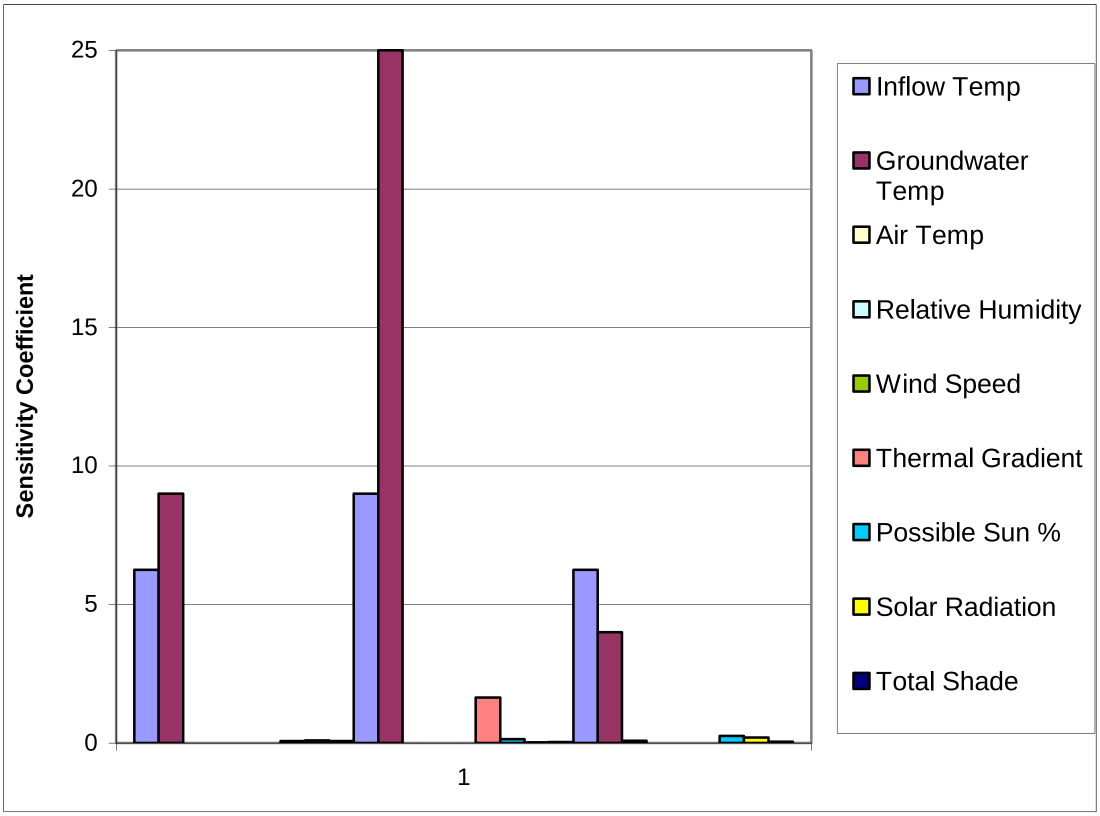


Differences in streambed temperature between thermistors TB and TE.

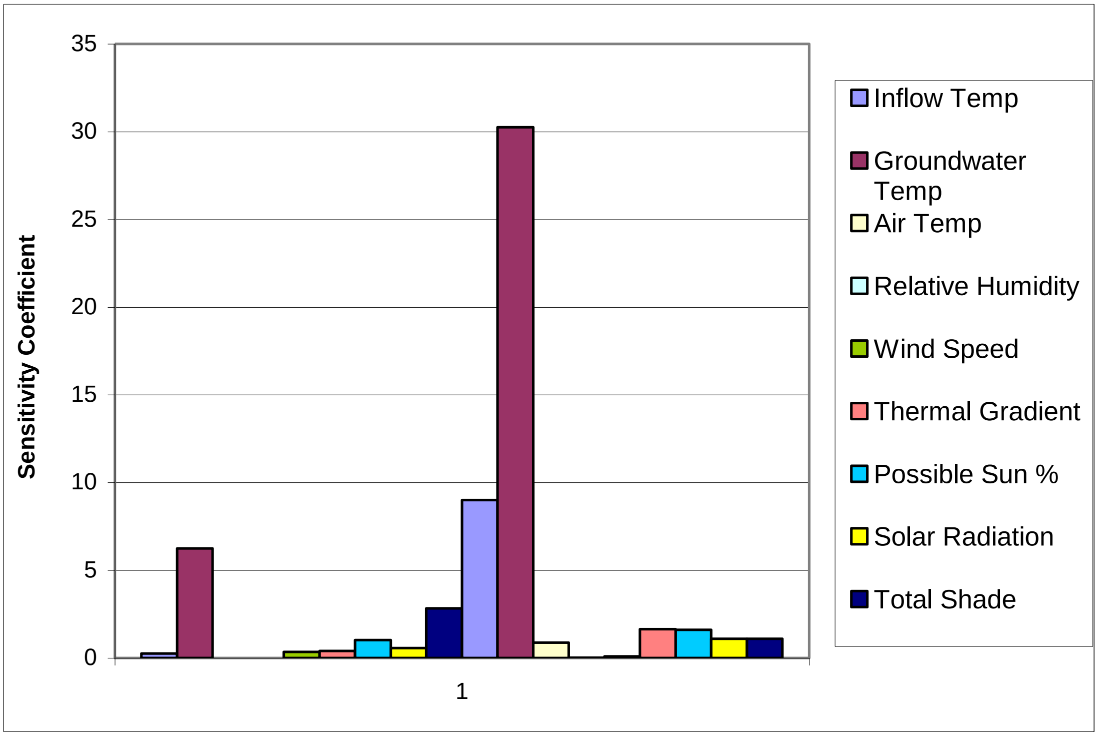
Appendix G. Wells monitored during Morrill PW aquifer test in spring 2007.



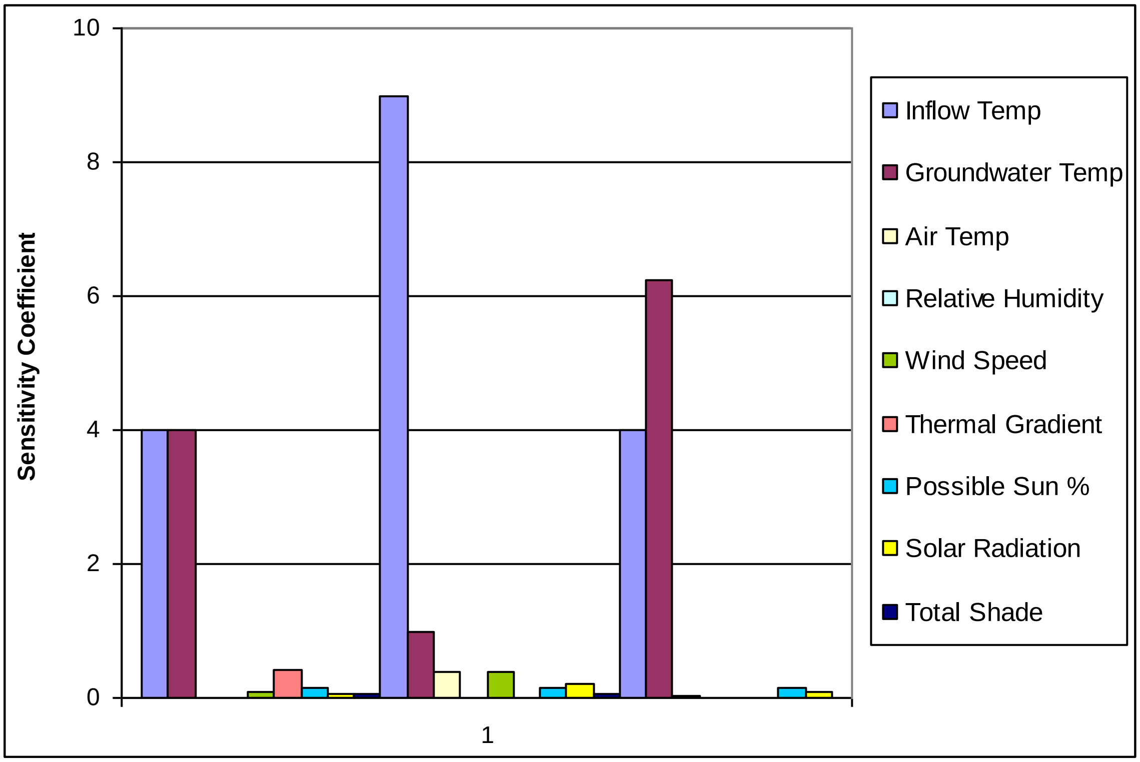
Appendix H. Sensitivity coefficients for variables used in SSTEMP.



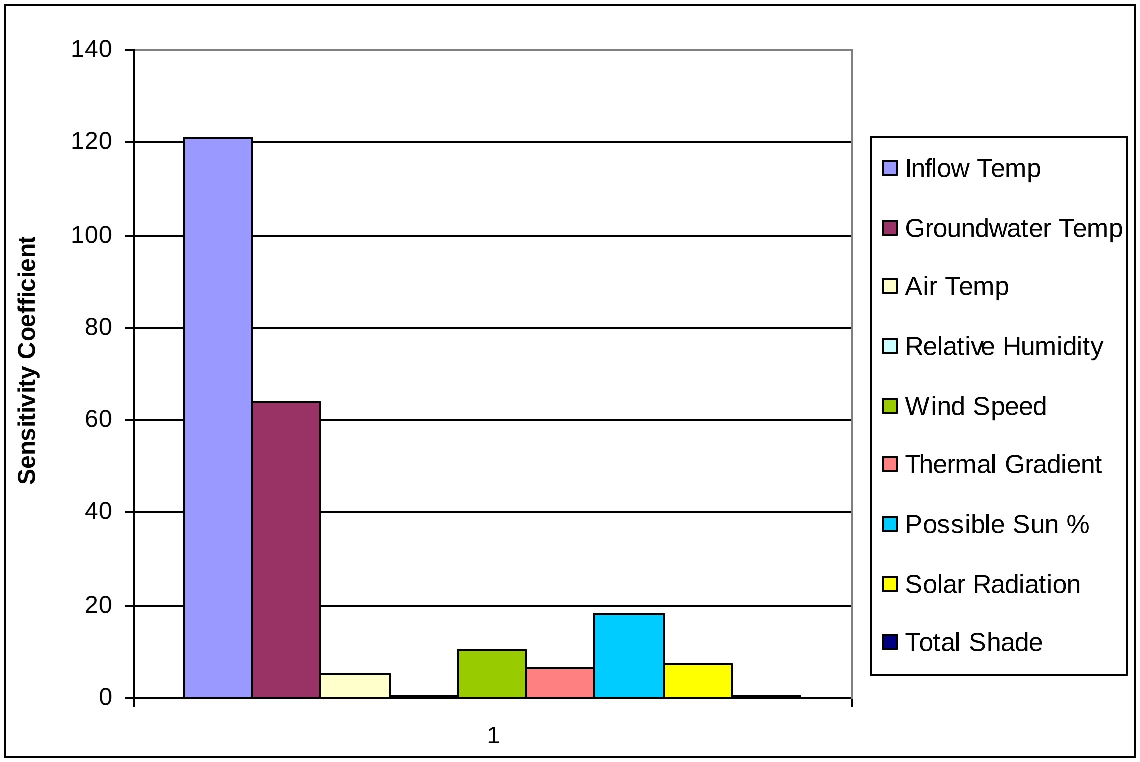
Reach T3-T4 sensitivity coefficients on March 2, 14 and 18, 2008.



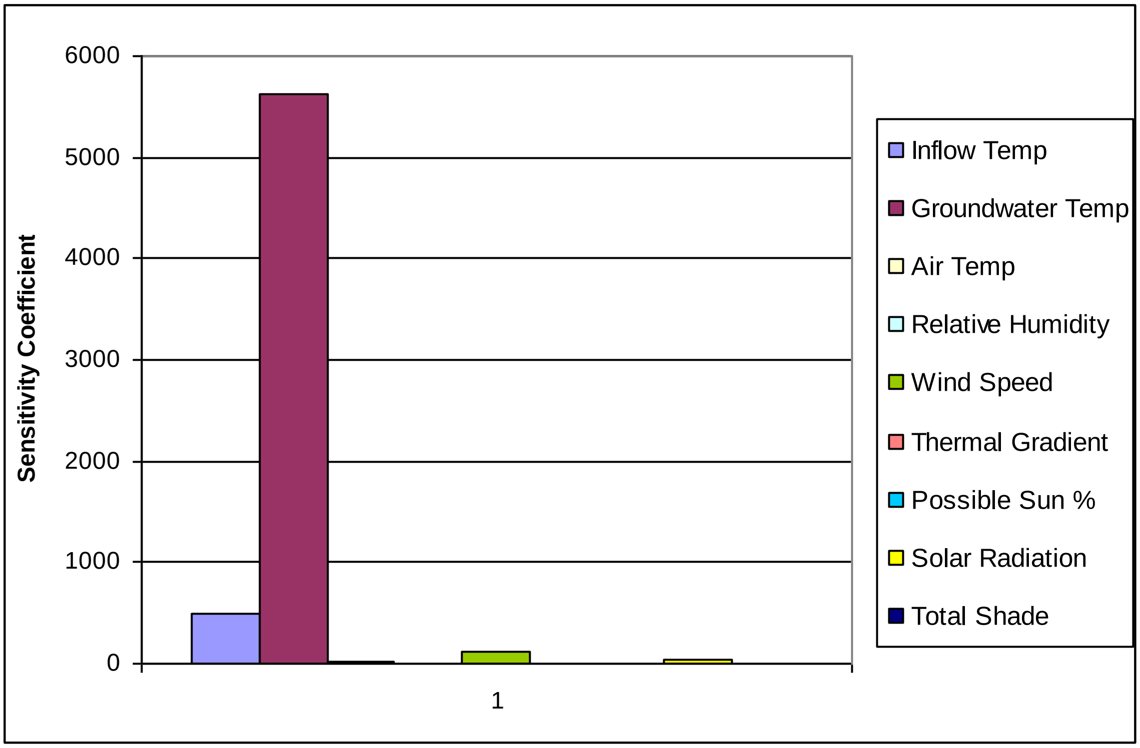
Reach T3-T5 sensitivity coefficients on March 2, 14 and 18, 2008.



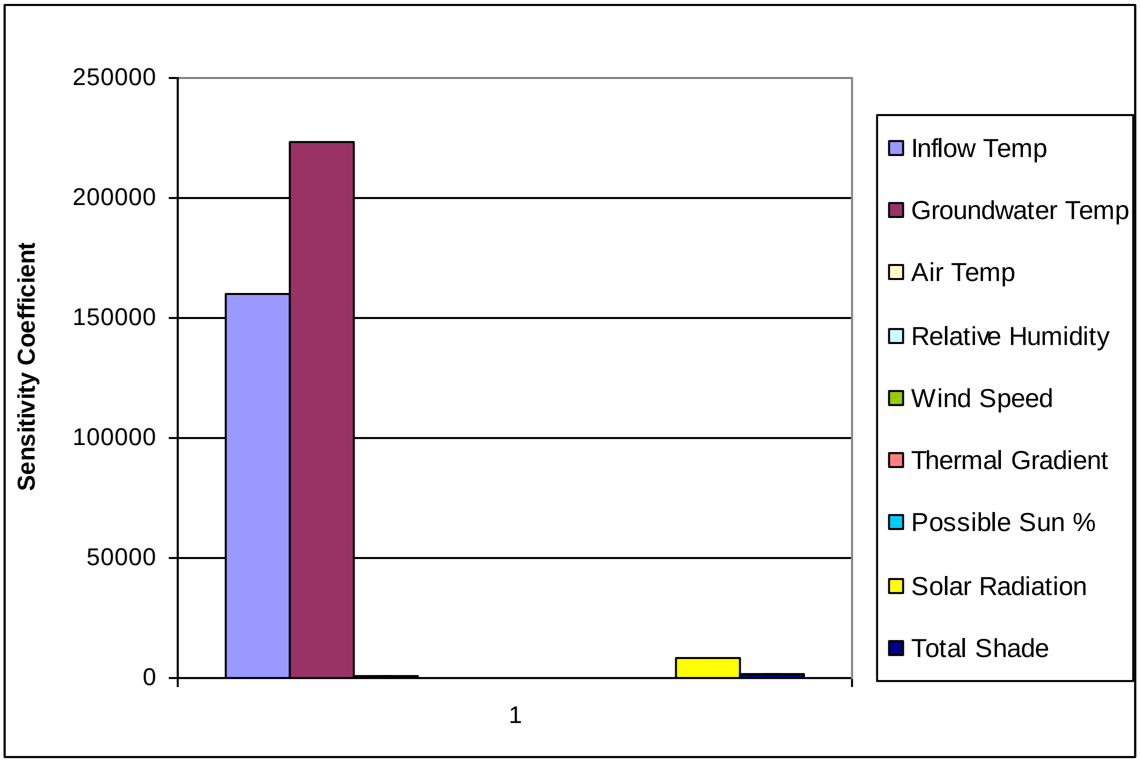
Reach T5-T6 sensitivity coefficients on March 2, 14 and 18, 2008.



Reach TB-TC sensitivity coefficients on August 21, 2008.



Reach TB-TC sensitivity coefficients on August 31, 2008.



Reach TB-TC sensitivity coefficients on September 2, 2008.

Appendix I. Estimated groundwater fluxes (cfs) using the mixing model and SSTEMP. No values exist where groundwater flux was not applicable for SSTEMP.

	T3-T4 Mixing Model	T3-T4 SSTEMP	T5-T6 Mixing Model	T5-T6 SSTEMP	T3-T5 Mixing Model	T3-T5 SSTEMP
3/2/2008	13.67	14 to 20	1.29	0.75 to 3.5	27.22	12 to 17
3/14/2008	24.97	20 to 33	19.47	9.5 to 14.5	83.74	28 to 38.5
3/18/2008	11.69	6.5 to 11	10.82	0.5 to 2.5	22.6	NA

	TB-TC Mixing Model	TB-TC SSTEMP	TC-TE Mixing Model	TC-TE SSTEMP
8/21/2008	5.873	49 to 72	20.53	30 to 48
8/31/2008	8.830	NA	4.64	108 to 145
9/2/2008	8.350	58 to 90	48.83	NA