THESIS

EFFECTS OF CONJUNCTIVE USE ON STREAMFLOW AT THE TAMARACK STATE WILDLIFE AREA, NORTHEASTERN COLORADO

Submitted by

Erin Donnelly

Department of Ecosystem Science and Sustainability

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2012

Master's Committee:

Advisor: John Stednick

Michael Ronayne
Thomas Sale
Stephanie Kampf

ABSTRACT

EFFECTS OF CONJUNCTIVE USE ON STREAMFLOW AT THE TAMARACK STATE WILDLIFE AREA, NORTHEASTERN COLORADO

The Tamarack Recharge Project in northeastern Colorado is intended to augment the streamflow of the South Platte River by 10,000 acre-feet between April and September to increase aquatic habitat for four federally threatened or endangered bird and fish species in Nebraska. The project goal is to retime surface water flows by pumping unappropriated alluvial groundwater into a recharge pond where it infiltrates and returns to the river at critical low flow periods. Retimed surface water flow will help maintain critical habitat for native aquatic species by increasing streamflow without harming water rights holders.

To evaluate the effects of this managed groundwater recharge on streamflow in the South Platte River, the hydrologic environment was characterized and quantified through streamflow monitoring, water table elevation mapping, and a groundwater tracer study.

Stream discharge measurements were taken at 4 cross sections on the South Platte River. Two cross sections were considered upgradient of the recharge pond and two were downgradient of the recharge pond. The mean flow of the upstream cross sections was 2.64 cubic meters per second (cms) compared to 2.66 cms at the downstream cross sections, which was not a significant difference.

A fluorescein tracer study was used to estimate groundwater travel times and hydraulic conductivity. Based on the arrival time of the breakthrough curve at different piezometers, the mean hydraulic conductivity was estimated to be 331 m/d. Using this value, the estimated return time to the South Platte River at 4 cross sections ranged from 92 to 534 days.

Measurements of discharge and water table elevations suggesting that Tamarack Project did not produce a measureable increase in streamflow in the South Platte River during the target period are not indicative of project functionality. The annual volume of water pumped into the recharge pond was 1% of the annual yield of the South Platte River. While the volume of return flows did not produce measureable results in the river, data from the tracer study and in-stream vertical hydraulic gradient data indicate a gaining stream condition during the fall and a losing stream during the winter and early spring. Potential source(s) of groundwater discharging to the stream include the recharge pond and irrigation return flows and warrant further study.

ACKNOWLEDGEMENTS

I gratefully acknowledge Dr. John Stednick and Dr. Michael Ronayne for their knowledge, guidance, and willing involvement throughout this project. I also extend my thanks to Dr. Thomas Sale and Dr. Stephanie Kampf for serving as committee members and offering additional advice and constructive criticism. Dr. Mary Meyer also provided valuable statistics information.

This research was funded by Colorado Parks and Wildlife through the Species Conservation Fund. I also thank Ryan Fitzpatrick, Jeff Mekelburg, and Levi Kokes of Colorado Parks and Wildlife for providing additional support, materials, and access to the Tamarack State Wildlife Area.

Finally, I extend sincere appreciation to Spencer Shumate, Ariann Maggart, Kate Condon, Reese Lonsert, Jason Roudebush, and Megan Moore for their help in the field. Without them, data collection would not have been possible.

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INTRODUCTION

The State of Colorado faces the difficult problem of increasing competition for water from expanding urban centers, traditional agriculture, and non-consumptive uses raised by environmental concerns (Fredericks and others 1998). Colorado is considered a semi-arid environment, characterized by low precipitation and high potential evapotranspiration. As a result, rapid human population growth and heavy agricultural activity during the past century have strained water resources in the region (Blomquist and others 2004). Shortages of surface water supply often initiate the development and use of groundwater (Safavi and others 2010). Conjunctive use is the management of ground and surface water resources in an effort to maximize total water supply. The benefits of a conjunctive use system exist because of the nature of the resources. Surface water has lower delivery and extraction costs, but is subject to variability in supply. Groundwater, though more reliable, is more expensive to pump (Montazar and others 2010). The challenge with conjunctive use is to understand the response of both surface and groundwater systems to avoid major water deficits.

The Prior Appropriation Doctrine regulates water use in the majority of Southwestern states. The doctrine allocates water based on seniority, or “first in time, first in right.” The first person to use the water acquires a senior right to its future use against later, or junior, appropriators (Leaf 2005). The Doctrine also applies to tributary groundwater that is hydrologically connected to surface water systems (Blomquist and others 2004). However, water law governing groundwater is more difficult to administer due to the complexity of groundwater movement in unconfined, heterogeneous, aquifers (Gehman and others 2009). In Colorado, the urban and agricultural areas are located in the arid plains east of the Rocky

Mountains. Water demand is met through a combination of native surface flows, surface water projects, and groundwater.

The South Platte River is the major water supply for northeastern Colorado (Strange and others 1999). The river originates in Park County Colorado, where it flows 725 km east through Denver and travels northeast into Nebraska into the Platte River. Downstream from Denver, the South Platte River is underlain by an alluvial aquifer that ranges from 20-200 feet in thickness. The unconfined aquifer is estimated to hold approximately 8.3 million acre feet in storage (Freeman 2010).

The South Platte River system has a snow-melt hydrograph, meaning peak run-off occurs in late spring. However, the largest water demand occurs during the summer growing season when the river naturally runs low (Beckman 2007). As a result, the South Platte River Basin has become a complex system of canals, diversions and other hydrologic modifications that has been described as an elaborate plumbing system (Strange and others 1999). And while approximately 70% of off-stream water is used for irrigated agriculture on the eastern plains, nearly two-thirds of the population of Colorado lives on the Front Range (Strange and others 1999). As growth continues along the Front Range, water managers must find ways to meet the demand.

Flow regulation may adversely affect riparian and aquatic species (Kinzel and others 2009). Currently in the Platte River Basin, three species are listed as federally endangered including the pallid sturgeon, whooping crane, and interior least tern while the piping plover is listed as threatened (US Bureau of Reclamation Service 2006). Several state threatened and endangered minnow species are also listed on the lower South Platte River in Colorado including the brassy, plains, and suckermouth minnow, northern redbelly dace and common shiner (Colorado Division of Wildlife 2011). To meet the required terms of the Endangered Species

Act, as well as meet agricultural and municipal demands, Colorado entered into the Three States Cooperative Agreement of 1997 with Wyoming, Nebraska, and the Department of the Interior (US Bureau of Reclamation Service 2006). By 2006 the Platte Recovery and Implementation Program was established to address issues related to the Endangered Species Act in Central Nebraska through management of certain land and water resources following the principle of adaptive management. The three main goals of the group are to 1) increase flows in the Central Platte River Basin during times of high demand 2) enhance, restore, and protect habitat for the three listed bird species and 3) accommodate new water-related activities. The goal of this statute is to increase in-stream flows that are thought to increase habitat for threatened and endangered species, as well as accommodate new water-related activities (Colorado Division of Water Resources 1999).

The US Fish and Wildlife Service (USFWS) analyzed 50 years of flow data on the Platte River (1943-1994) to quantify the shortage of critical habitat and concluded that there was a 417,000 acre-feet water deficit per year (Freeman 2010). In addition to volume, the USFWS placed a high priority on pulse flows, or flows of large magnitude. Pulse flows during late spring and early summer maintain the physical and biological integrity of the river by scouring vegetation and moving sediment to maintain a shallow, wide and braided planform (Johnson 1994). Furthermore, the pulse flows should coincide with the timing of the historic peak flow between 20 May-20 June (Freeman 2010).

Habitat suitability criteria, also known as habitat suitability indices (HSI), have been developed for several fish species over a variety of stream systems. Habitat criteria for a particular species are usually specified in terms of water depth, current velocity, and substrate type (Hubert and Rahel 1989). Habitat data are used to model aquatic habitat as a function of stream discharge, such as the Instream Flow Incremental Methodology (IFIM) model used by the USFWS (Conklin and others 1996). By increasing stream flow during the critical periods, the Tamarack Project is predicted to increase habitat for aquatic species.

Under the Three States Cooperative Agreement, Colorado agreed to deliver 10,000 acre-ft of water to the Nebraska border between April and September. This is accomplished in part by the Tamarack Ranch Project, located on the lower South Platte River in Colorado. The project aims to augment surface water flows in the river during critical low flow periods. This maintains critical habitat for aquatic species without harming water rights holders (Freeman 2010).

Managed groundwater recharge

Flow augmentation projects utilizing managed groundwater recharge serve as a management tool for the conjunctive use of groundwater and surface water (Watt 2003). Managed groundwater recharge projects, or the practice of augmenting water supplies, may also be called managed aquifer recharge (MAR), groundwater banking, aquifer replenishment, and artificial recharge. Artificial recharge systems may serve to store water, improve water quality through geopurification, reduce saltwater intrusion or land subsidence, and augment groundwater resources (Bouwer 2002).

Reclaimed water will likely become a large portion of source water in the future. Utilizing artificial recharge water raises water quality concerns, especially when water is used as a drinking source, so it is important to understand the fate and transport of potential contaminants near recharge sites. Results of detailed water quality studies near MAR operations have shown that the most important hydrologic parameters are travel time and distance, as a large number of potential contaminants (organic compounds and microorganisms) are naturally removed or become inactive with time and distance in the subsurface (McDermott and others 2008).

Surface artificial recharge of groundwater requires a permeable topsoil and a semi-permeable to permeable soil in the unsaturated zone to provide sufficient lateral flow (Kumar and others 2009). There are a number of different designs, including injection wells and recharge ponds (McDermott and others 2008). Fundamental issues concerning the effectiveness of managed groundwater recharge projects include the hydrogeology and engineering considerations of site evaluation, recharge method and clogging, source water supply, water quality, and the potential impairment of the aquifer and native groundwater supply (McDermott and others 2008).

Field studies investigating alluvial exchange have used tracers as a method to estimate residence and travel times within an aquifer. Stable isotopes oxygen 18, deuterium, tritium, and chloride have been used in various semi-arid and arid regions (Kumar and others 2009). These tracers are useful in understanding the origin of water, particularly groundwater recharge (Zhang and others 2010). Other studies have used SF6 (sulfur hexafluoride) where initial and mean arrival times of the tracer can be determined by evaluating plots of concentration vs. time, commonly called the breakthrough curve (Clark and others 2005; McDermott and others 2008).

Several techniques exist for quantifying groundwater recharge. The method depends on the goals of the recharge study, available data, and space/time scales. The different methods are generally divided into 3 groups including physical estimates (water budget, hydrograph separation, etc), tracer studies (isotopes and dyes), and numerical modeling (Scanlon and others 2002).

The effectiveness of artificial recharge systems depends largely on the nature of the groundwater-surface water interaction. This interaction is influenced by geology, climate, and topography. Groundwater moves along flow paths as part of a flow system. The flow system can be divided into local, intermediate, and regional systems. Local systems refer to water that discharges into a pond or stream, whereas a regional flow system discharges into major rivers, lakes, or oceans. An intermediate flow system is driven by topographic differences between the recharge and discharge areas (Sophocleous 2002). Areas with high topographic relief have dominant local flow systems, while flat areas have dominant intermediate and regional flow systems.

The river-aquifer interface (RAI) can strongly influence discharge and recharge processes. This stems from the fact that this area often has significantly different physical properties than the surrounding aquifer (Tellam and Lerner 2009). Differences in sediment deposition in the active channel can lead to layers of low resistivity and hydraulic conductivity in a course alluvial system (Heeren 2010).

Gravity is the force that drives groundwater through aquifers. Groundwater possesses potential energy, which it converts into thermal and kinetic energy as it flows downslope (Kasenow 1997). Groundwater studies measure groundwater in terms of head, which is the elevation of water in a well relative to some datum (usually sea level). Total head is the measure of elevation head, pressure head, and velocity head. This is summarized in the Bernoulli equation, which states that under conditions of steady flow, the total energy of an incompressible fluid is constant at all positions along a flow path in a closed system (Sterret 2007):

$$H = \frac{P}{\gamma} + \frac{V^2}{2g} + z \tag{1}$$

Where H= total head; γ= specific weight of water; V= velocity of flow; g= acceleration of gravity; z= elevation above a certain datum. Because groundwater generally moves at a slow rate, the velocity term is much smaller than the other terms, and is considered negligible. Dropping the velocity term gives:

$$H = \frac{P}{\gamma} + z \tag{2}$$

For a fluid at rest, the pressure term is equal to the weight of the water per unit cross sectional area:

$$P = \gamma hp \tag{3}$$

Where hp= pressure head. Substituting Equation 3 into Equation 2 gives:

$$H = z + hp \tag{4}$$

meaning that the total hydraulic head (H) is equal to the elevation head and the pressure head (Fetter 2001).

Groundwater studies often utilize piezometers and water table wells. Water table wells measure the static water level. Piezometers are pipes inserted into the ground with openings at the top and bottom so that water can only enter the piezometer at that particular depth. Piezometers measure the hydraulic head at a specific point in the aquifer (Fetter 2001). A group of piezometers at differing depths, or nested piezometers, can be used to determine the vertical hydraulic gradient. For an unconfined aquifer, the potentiometric and static water level are equal.

The recharge process involves the growth of a groundwater mound below the spreading basin (Freeze and Cherry 1979). The magnitude and timing of return flows from managed groundwater recharge depend on the alluvium properties and the distance between the recharge area and the river (Watt 2003). These values are rarely static. The rate of alluvial exchange for areas such as the South Platte vary temporally and spatially (Sjodin and others 2001). The time of year determines discharge rates (with highest flows in the spring from snowmelt runoff) and pumping rates. Exchange will differ from reach to reach due to differences in irrigation return flows and differences in alluvium and channel morphology (Sjodin and others 2001; Kumar and others 2009).

Groundwater pumping can have significant effects on groundwater and surface water movement in unconfined aquifers. Pumping can increase the hydraulic gradient in the area surrounding the well, which increases groundwater velocity and may alter flow direction (Anderson and Woessner 2002). The magnitude of stream/aquifer interaction during pumping depends on streambed hydraulic conductivity, as streambed conductivity can be up to three orders of magnitude lower than aquifer conductivity (Fox 2004).

There has been extensive research on the development of groundwater mounds below waste disposal ponds and sanitary landfills. In studies where model predictions did not match field data predictions of groundwater movement, the difference was attributed to the buildup of silt and clay in the spreading basin, and/or growth of microbial organisms that clog the soil pores (Freeze and Cherry 1979). Other studies ascribed the difference to the role of the unsaturated zone in groundwater movement, as models generally neglect flow behavior in the unsaturated zone (Anderson and Woessner 2002).

Several methods exist for quantifying the impact of pumping and recharge on the timing and volume of river depletions. The mathematical flow equation for two dimensional flow in an unconfined aquifer is defined as:

$$S = \frac{\left(T\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) + Q\right)}{\frac{\partial h}{\partial t}} \tag{5}$$

Where T=transmissivity (L^2/t); h= potentiometric head (L); Q= net groundwater withdrawal per unit area (L/t); S= storage coefficient (L^{-1}); and t= time.

The three most common methods for solving the flow equation are the Glover method, the Stream Depletion Factor (SDF) method, and finite difference numerical methods (Fredericks and others 1998). These analytical and numerical methods, respectively, estimate transient stream depletion in unconfined aquifers due to ground water pumping and measure stream accretions from managed groundwater recharge projects (Miller and others 2007).

Water rights decisions are based on analytical solutions that often oversimplify physical conditions (Fox and others 2002). The Colorado "Amended Rules and Regulations for the South Platte" of 1974 states that all effects of ground water pumping and stream accretion should be measured with the Glover formula, or other accepted engineering formula. However the Glover method assumes an ideal aquifer, or one that has a fully penetrating stream, permeable streambed, and a semi-infinite, homogeneous isotropic aquifer (Jenkins 1968).

The Glover method is based on Theis (1941) for confined aquifers:

$$q = \left(\frac{2}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(-\alpha \sec^2 u\right) du\right) Q$$

(6)

Where q=discharge contributed by a stream (m^3/s); α= a2S/(4Tt) (dimensionless); a=effective distance between pumping well and recharging stream (m); S= aquifer storage coefficient (dimensionless); T= transmissivity (m^2/s); t= time since the start of pumping (s).

The Glover equation expresses Equation 4 as a complementary error function. It was developed for confined aquifers, but can be used for unconfined provided that the ratio of drawdown to saturated thickness does not exceed 25%, and the storage coefficient remains constant. The Glover equation relates the stream depletion rate (q) to the aquifer pumping rate (Q) (Glover and Balmer 1954):

$$q = \left(erfc\left(\sqrt{\frac{a^2 S}{4tT}} \right) \right) Q$$

(7)

Integrating Equation 7 gives:

$$v = \left(\left(\frac{a^2}{\frac{2tT}{S}} + 1 \right) erfc\left(\frac{a}{\sqrt{\frac{4tT}{S}}} \right) - \left(\frac{a}{\sqrt{\frac{4tT}{S}}} \right) \left(\frac{2}{\sqrt{\pi}} \right) exp\left(-\frac{a^2}{\frac{4tT}{S}} \right) \right) Qt$$

(8)

This relates cumulative stream depletion volume (v) to cumulative pumped volume (Qt).

Since 1985, the predominant method for measuring net stream effects on the South Platte River has been the SDF method using United States Geological Survey (USGS) maps to account for non-ideal conditions, such as non-permeable boundary layers (Miller and others 2007). The SDF was developed by Jenkins (1968) to quantify stream depletion by wells in non-ideal aquifers (Bredehoeft and Kendy 2006). SDF has units of days and represents the lag time for recharge to return to the river. Mathematically the SDF represents the time when the cumulative stream depletion volume is 28% of the cumulative pumped volume. The SDF method calculates return flow to the river based on Glover's analytical solution for a well near a stream, but uses a numerical groundwater model to account for varying aquifer properties and boundary conditions (Miller and others 2007).

In a mathematically ideal aquifer, the SDF is determined by:

$$SDF = \frac{a^2}{\frac{T}{S}} \tag{9}$$

Where a= distance from the pumped well to the stream; T= transmissivity (L^2/t); S= specific yield of the aquifer. Plugging Equation 8 into Equation 6 and 7 gives:

$$q = \left(erfc\left(\sqrt{\frac{SDF}{4t}}\right)\right) Q \tag{10}$$

And:

$$v = \left(\left(\frac{SDF}{2t} + 1\right) erfc\left(\sqrt{\frac{SDF}{4t}}\right) - \left(\sqrt{\frac{SDF}{4t}}\right)\left(\frac{2}{\sqrt{\pi}}\right) exp\left(-\frac{SDF}{4t}\right)\right) Qt \tag{11}$$

Analytical models predict system changes based on mathematical, or analytical, equations. In groundwater models, they generally assume a homogeneous porous medium and one or two-dimensional flow. With the exception of well hydraulics, analytical solutions are not adequate in predicting aquifer behavior in heterogeneous conditions (Freeze and Cherry 1979). Therefore, numerical models are often used because they can account for more variability

(Anderson and Woessner 2002). However numerical models of stream/aquifer systems require estimates of leakance or conductance, which is a function of the streambed hydraulic conductivity (Fox and others 2002).

Considerable research has focused on improving analytical models for stream/aquifer interaction during pumping. More recent advances in groundwater modeling use analytical solutions that can include the effects of the streambed layer and stream partial penetration (Fox 2004).

Water Development in the South Platte River Basin

The South Platte River Basin is a heavily studied area due to the high demand for water as well as the number of hydrologic modifications that have been made to the river. Water development began in the 1840's with irrigation canals and ditches (Strange and others 1999). Flows were quickly over-appropriated during the summer months due to the discovery of gold near Golden in 1858 (Johnson 1994). Between 1885 and 1930, several off-channel reservoirs were built to catch spring runoff to meet the demand during the summer months. Groundwater pumping and trans-basin diversions began in 1930 (Strange and others 1999).

The flow record for the South Platte River begins in 1901 in Kersey, several decades after water development began (Johnson 1994). While there are no flow records that pre-date water development in the South Platte, records over the past century show significant alterations in flow regime (Kinzel and others 2009). For example, during the 1920's irrigation return flows significantly increased summer base flows in the South Platte, shifting the river from a losing to a gaining stream (Strange and others 1999; Watt 2003).

The South Platte River was historically a wide braided channel with sparse vegetation and a highly mobile floodplain (Strange and others 1999; Kinzel and others 2009). Various anthropogenic influences, most notably reduced peak and annual flows, have altered vegetative and aquatic species composition and hydrologic processes (Johnson 1994; Strange and others 1999). Serial aerial photographs reveal significant changes in channel morphology over the past century (Kinzel and others 1999). The channel transformed from a braided into a meandering, anastomosed, and narrowed planform. The disappearance of scouring flows allowed vegetation to grow along channel banks and sand bars that has stabilized the floodplain. The changes in channel morphology and bed material size decreased habitat availability for native aquatic species (Warner 1986).

Woodland expansion in the South Platte began in 1900. By 1930, vegetation occupied most of the former channel area of the North and South Platte Rivers and was expanding into the Platte River. The rate of woodland encroachment is determined by three factors including early summer flows, summer drought, and ice (Johnson 1994).

Current hydrologic characteristics in the South Platte are dependent on land and water use. Upstream of Denver, most of the flow is diverted for municipal use, or stored in water-supply reservoirs (Johnson 1994). As a result, the water downstream of Denver is predominately wastewater effluent, with the exception of high-flow periods in the spring (Strange and others 1999). Further east, the stream is comprised of groundwater return flows from agricultural areas. There are currently 60 off-channel reservoirs, with a total storage capacity of 2,756,425 acre-ft (Johnson 1994). Eight major trans-basin diversions provide an additional 377,396 acre-ft to the South Platte River Basin (CWCB 2006), which is approximately 25% of the total annual flow (Johnson 1994).

The South Platte River Compact of 1923 between Colorado and Nebraska mandates that if the river drops below 4 cms (120 cfs) at the CO-NE border between April 1st and October 15th, Colorado must cease all diversions to water rights holders junior to June 14, 1897 (Bennett and Howe 1998). Flows are not regulated by this statute for the remainder of the year.

Groundwater pumping from the South Platte alluvial aquifer was started by farmers with low priority to surface water rights. By the late 1960's, sustained groundwater pumping resulted in a decrease in water table elevations and decreased seepage into the river (Warner 1986). This prompted the passage of the Groundwater Management Act of 1965, which provided a template for governing groundwater in Colorado (Blomquist and others 2004). The passage of the Water Rights Determination Act followed shortly after in 1969. This Act integrated groundwater in existing surface water adjudication and administration system, as well as provided incentives for stream augmentation. Augmentation serves as a tool for junior water rights holders to protect their water from senior holders (Blomquist and others 2004).

Artificial recharge in the Lower South Platte Basin started in the 1970's in Logan County. The South Platte Ditch was the first ditch company to develop and utilize re-regulated flow accretions to the South Platte River resulting from artificial recharge into an off-ditch recharge basin. Currently, there are numerous ditch and reservoir companies, municipalities, water districts, and private individuals that average over 40,000 acre feet of annual diversions to recharge in annual river accretions of 14,000 acre-feet (Leaf 2005).

In 1975 the State Engineer instituted additional regulations specifically for groundwater in the South Platte Basin, stating that water users could continue to pump groundwater if they developed a successful augmentation plan (Warner 1986), which prompted the start of water user organizations such as the Ground Water Appropriators of the South Platte (GASP). GASP is a river augmentation organization that initially used membership fees from junior well owners to lease shares of water from ditch companies and reservoirs, and irrigation credits from irrigation districts (Blomquist and others 2004). This allowed junior water rights holders to pump out of priority without harming senior appropriators (Freeman 2010). However, the drought of 2002 prompted a court case in which the Supreme Court ruled that augmentation plans must be filed with a water court (Blomquist and others 2004).

Tamarack State Wildlife Area

Per the Three States Agreement, the Tamarack Ranch project aims to increase streamflow in the South Platte by 10,000 acre-ft between April and September (Freeman 2010). The Tamarack Project is managed by the South Platte Lower River Group (SPLRG). The group is a coalition of water users and governmental agencies formed to preserve existing water uses and enhance streamflow and water-related wildlife habitat. The major focus of the coalition is to identify and develop managed groundwater recharge projects, using the Tamarack site as a pilot project (Colorado Division of Water Resources 1999). Recharge sites are chosen based on their capacity for wetland habitat preservation or creation, as well as their ability to enhance in-stream flows. Sites that are effective in increasing in-stream flow volume receive credit in the Platte Basin Endangered Species Program (USGS 2002).

The Tamarack project utilizes 10 wells to pump unappropriated groundwater from the alluvium adjacent to the South Platte River during winter and early spring months into a recharge pond located approximately 1500 m away from the river (Miller and others 2007). The water infiltrates the soil and returns to the river at a later date. The stream depletion factor (SDF) for Tamarack ranges between 60 to 270 days, though the uncertainty in the SDF can run as high as

30% in narrow aquifers like the South Platte if boundary effects are not correctly estimated (Miller and others 2007).

There has been a growing demand for an upgrade in current technology to manage conjunctive use in the South Platte River Basin (Garcia 2001). Decision support systems (DSS) is a computer based system that allows water managers to use data and models to solve problems (Fredericks and others 1998). Northern Colorado Water Conservancy District (NWCD) uses the Integrated Decision Support Group - Alluvial Water Accounting System (IDS-AWAS) to calculate river depletions using the effective SDF option at the Tamarack site. However, they will transition to the Glover alluvial aquifer or Unit Return Flow (URF) option with factors developed from the Colorado Division of Wildlife (CDOW) Modflow model (Personal communication, 2010, John Altenhofen of NWCD).

The Lower South Platte River Basin has been heavily studied over recent decades. Several studies have examined the effects of managed groundwater recharge on surface water quantity and quality on the lower South Platte River at the Tamarack site since the State of Colorado owns both the land and the water rights (Freeman, 2010). The two main components of the Tamarack study area are the surface water in the South Platte River and the groundwater in the alluvial aquifer (Fox 2004). Field investigations, analytical models, and numerical models have all been used to estimate residence times in the aquifer and travel direction.

An artificial recharge experiment was carried out at the Tamarack Ranch in 1979, which found high infiltration rates that in turn increased the rate at which groundwater storage was recharged (Warner 1986). The USGS developed a calibrated groundwater flow model in 1985 for the Tamarack to predict the effects of increased groundwater pumping, artificial recharge, and river diversions (Burns 1985).

Measuring changes in gravity over time was used to estimate variations in groundwater mass associated with a rise or fall in the water table at the Tamarack site (Gehman and others 2009). Negative gravity differences were found between the base site and pumping sites, while positive gravity differences were found at the recharge pond. These differences correlated well with changes in groundwater mass. Gravity data was used to estimate specific yield (S_y) of the aquifer and water table changes.

Another study utilized electrical resistivity to delineate three stratigraphic layers with distinct geophysical characteristics (Poceta 2005). The layers include eolian sand, alluvium, and bedrock. One survey line suggested the presence of a paleo-channel that may influence groundwater flow.

The predictive performance of analytical solutions for unsteady stream depletion were analyzed using field data from a stream/aquifer test at the Tamarack site (Fox 2004). The estimated drawdown, aquifer transmissivity, and streambed conductivity from a pumping test were compared to four different analytical solutions (Hunt 1999; Butler and others 2001; Fox and others 2002; Hunt 2003). Measured drawdown, transmissivity, and conductivity obtained from the four models matched field estimates of these parameters with the exception of early time drawdown response. Hunt (2003) was the only model to accurately predict the delayed yield response. However for long-term water management, the analytical solutions predicted by Fox (2002), Hunt (1999), and Butler (2001) would be appropriate since delayed yield effects are not a concern (Fox 2004).

Water quality analysis has been used to illustrate groundwater movement at the Tamarack site. One study found that groundwater chemistry varies over time and space. The chemistry of the alluvial aquifer of the lower South Platte is predominately calcium and bicarbonate while the river is predominately sodium/calcium and sulfate (Watt 2003). As the Tamarack project continues to pump, the study predicts that alluvial aquifer water quality will be further influenced by surface water quality. Another study used the distinct chemical signatures of groundwater and surface water to quantify the amount of mixing between the two source waters (Beckman 2007).

Despite this research at the Tamarack site, the hydrology of the area, especially the dynamic interaction between surface and subsurface flow, remains relatively unknown. To evaluate the effects of managed groundwater recharge on surface water volume, the hydrologic/hydrogeologic environment must be better characterized.

HYPOTHESIS

The Tamarack Project produces a measureable increase in streamflow in the South Platte River between April and September.

STUDY OBJECTIVES

To determine if there is a measurable increase in streamflow due to managed groundwater recharge, the following five objectives were accomplished (Table 1):

1. Physically measured streamflow rates at four cross-sections on the South Platte River within the Tamarack State Wildlife Area during periods of pumping and non-pumping to determine streamflow augmentation.
2. Surveyed the channel morphology at these four cross-sections during periods with and without flow augmentation to measure any changes in stream depth.
3. Used nested piezometers at four cross-sections and water table elevations from existing piezometers to measure vertical and horizontal groundwater gradients.
4. Conducted a fluorescein tracer study to characterize groundwater movement. Dye was placed in the recharge pond and monitored in a network of piezometers to estimate groundwater travel time.
5. Measured the vertical hydraulic gradient at four cross sections within the streambed to quantify groundwater contribution to streamflow.

Table 1: Timeline for study objectives

Objective	Timeline
1. Streamflow	September 2010 – September 2011
2. Channel morphology	September 2010 – November 2010
3. Groundwater flow	April 2010 – March 2012
4. Groundwater tracer study	May 2011 – September 2011
5. Groundwater contribution to streamflow	September 2011 – March 2012

MATERIALS AND METHODS

Site description

The Tamarack Recharge Project began in 1997 (Watt 2003). The Tamarack Ranch is state-owned land within the South Platte River Basin located in Logan County near Crook, Colorado (CO), approximately 50 km northeast of Sterling, CO (Figure 1). The site consists of 22 piezometers, a minnow stream, and two recharge ponds (Miller and others 2007) (Figure 2). The physical pond location was chosen based on the stream depletion factor (SDF) of 70-90 days (Figure 3) (Hurr and Schneider 1972). The ponds are full during times of pumping, which generally operate from December to April (Table 2).

The South Platte River at Tamarack is a braided stream with alluvial deposits of clay, silt, sand, and gravel. Past studies showed that changes in stream stage produced a subsequent change in water table height, suggesting the alluvial aquifer is highly connected to the streambed (Sjodin 1998).

The hydrogeology of the Tamarack site is complex. Tamarack is underlain by Oligocene-aged Brule Shale that consists of fine sand, silt and clay, and channel deposits of gravel and sand (Poceta 2005). The South Platte alluvium is a highly conductive sand with some reporting hydraulic conductivities of 60-200 m/d (Johnson 1994; Fox 2004; Miller and others 2007). The alluvium depth ranges from 1 m at the river valley edge to 100 m underneath the river (Beckman 2007; Gehman and others 2009). The alluvium covers approximately one-third of the northern part of the site. The southern two-thirds of the site is composed of vegetated eolian sand dunes (Gehman and others 2009).

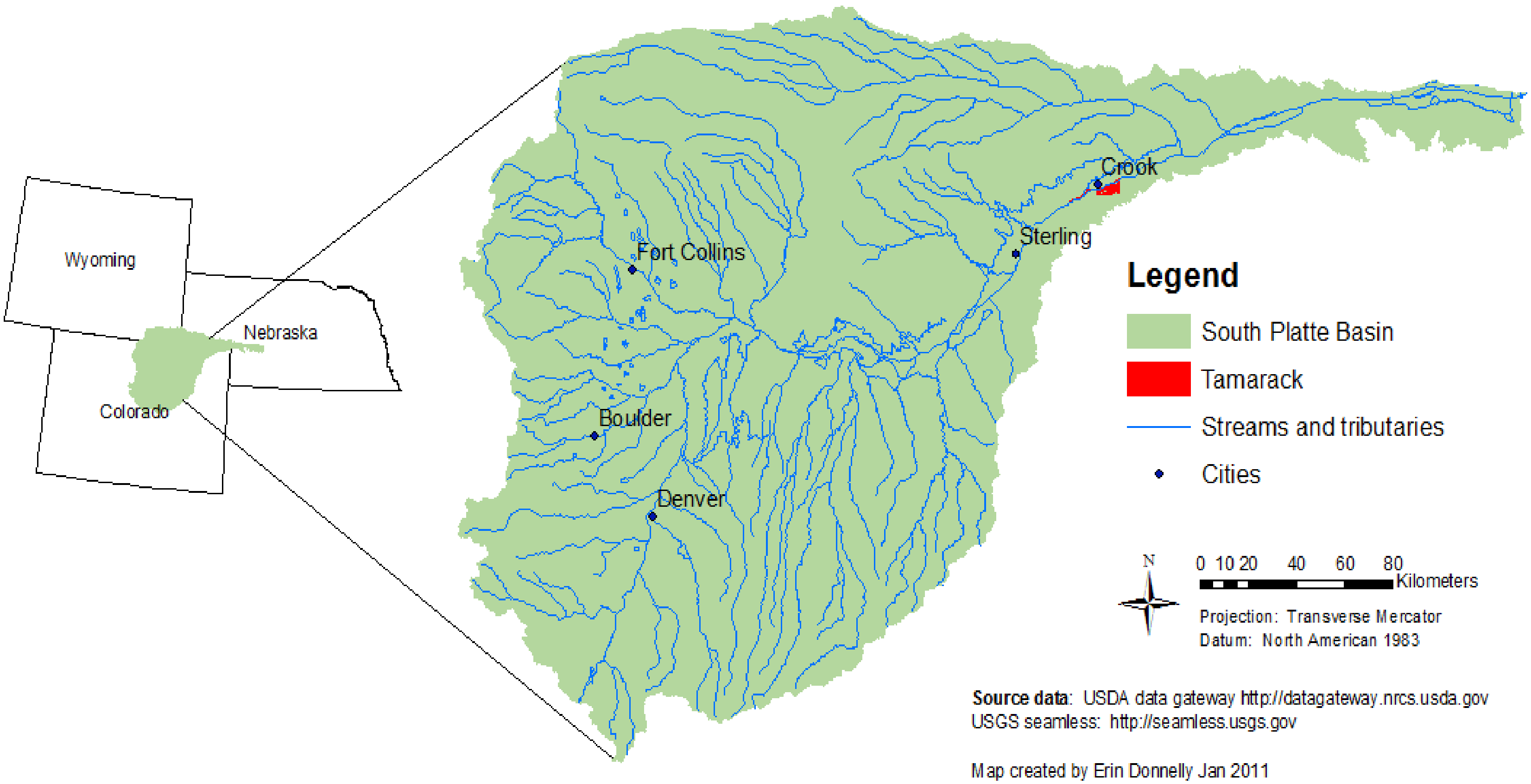

Figure 1: Location of Tamarack State Wildlife Area

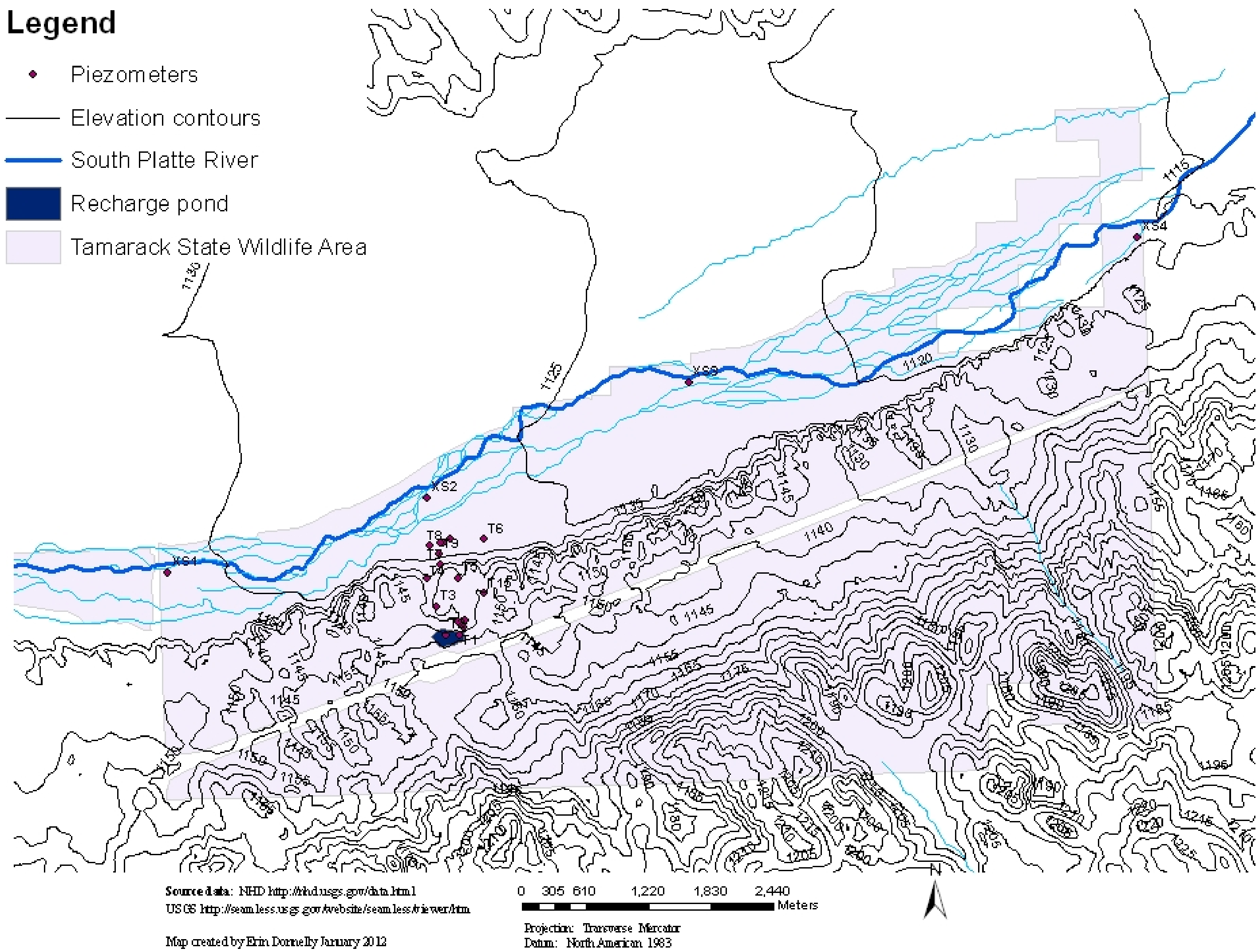

Figure 2*:* East side of Tamarack State Wildlife Area

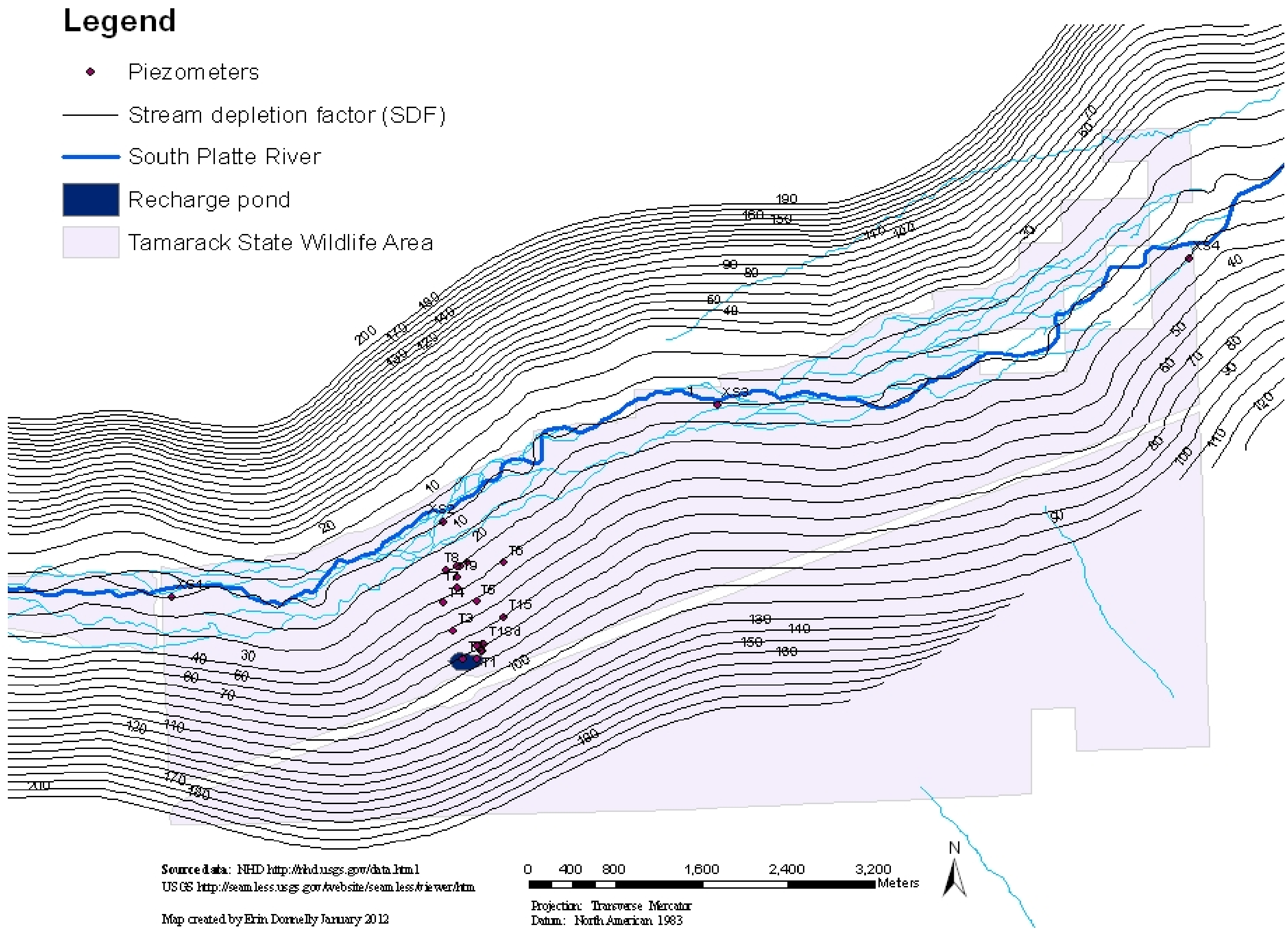

Figure 3: Stream depletion factor values of the Tamarack State Wildlife Area. The SDF values near the recharge pond are between 70 and 90 days.

Table 2: Pumping volumes by year and month into the Tamarack recharge pond (acre-feet) (Personal communication, 2010, John Altenhofen of Northern Colorado Water Conservancy District; Personal communication, 2012, Levi Kokes of Colorado Parks and Wildlife).

Water Year	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug	Sept	Total
1997	N/A	N/A	N/A	0	190.6	210.2	197.1	62	232.5	93.4	0	0	985.8
1998	6.3	0.0	0.0	76.3	175.3	211.8	200.7	205.8	199.7	8.7	0.0	0.0	1084.4
1999	0.0	0.0	0.0	0.0	133.1	207.0	172.1	209.9	215.8	179.1	0.0	0.0	1116.9
2000	0.0	0.0	0.0	191.4	584.1	565.9	518.2	413.4	0.0	0.0	0.0	0.0	2272.9
2001	15.2	0.0	0.0	290.6	533.1	610.9	580.5	501.1	374.8	91.5	0.0	0.0	2997.7
2002	0.0	0.0	0.0	98.5	404.7	476.7	187.5	0.0	0.0	0.0	0.0	0.0	1167.4
2003	0.0	0.0	0.0	74.0	347.9	342.6	0.0	0.0	0.0	0.0	0.0	0.0	764.5
2004	40.2	0.0	200.0	254.2	392.9	403.5	0.0	0.0	0.0	0.0	0.0	0.0	1290.8
2005	59.3	119.0	0.0	0.0	108.6	455.6	0.0	0.0	0.0	0.0	0.0	0.0	742.5
2006	0.0	269.3	96.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	365.5
2007	0.0	0.0	99.8	0.0	0.0	344.2	0.0	0.0	0.0	0.0	0.0	0.0	444.0
2008	0.0	0.0	0.0	417.7	572.4	593.6	202.7	0.0	0.0	0.0	0.0	0.0	1786.4
2009	0.0	0.0	189.0	527.0	457.5	517.6	530.7	6.7	0.0	0.0	0.0	0.0	2228.5
2010	0.0	0.0	551.1	547.5	387.1	528.3	0.0	0.0	0.0	0.0	0.0	0.0	2014.0
2011	0.0	0.0	539.8	696.2	649.4	668.0	241.1	124.0	0.0	0.0	0.0	0.0	2918.5
2012	0.0	0.0	803.1	679.4	676.9	716.4	575.9	N/A	0.0	0.0	0.0	0.0	3451.6

Previous studies identified the presence of a paleo-channel running parallel to the active channel. A depth to bedrock contour map of the Tamarack Area identifies the presence of the channel (Hurr and Schneider 1972; Poceta 2005) (Figure 4). The channel, which is 40-45 m deeper than the adjacent bedrock, may be a former channel of the South Platte River (Burns 1985). However, the dimensions of the channel are difficult to define because they are based on only 15 well logs on two transect lines located eight km apart (Poceta 2005).

Since 1997, water table elevations have been measured from a network of 22 piezometers and two abandoned irrigation wells, and water quality samples have been collected from the recharge pond, four sites along the South Platte River, and two sloughs. The piezometers are separated into three groups based on their stratigraphy of eolian sand, alluvium, and shale (Table 3). The piezometers are of variable depth and occasionally screening intervals (wells). They were not designed for this study specifically, but were rather placed for initial groundwater modeling efforts.

Streamflow and stream depth

Streamflow and stage were measured at four stream cross sections (XS1-XS4) on the South Platte River between Crook and Red Lion, CO (Figure 2). Data from cross sections 1 and 2, which were considered upgradient of return flows, were compared to downgradient cross sections 3 and 4 to determine augmentation. Cross sections 1 and 2 were chosen as the control based on previous studies that showed flowpaths of the return water did not affect the South Platte River upgradient of the recharge pond (Beckman 2007). Cross section sites were chosen on straight, single channel portions of the river that were free of backwater effects. Cross

Table 3: Monitoring well information (personal communication, Pete Conovitz, Colorado Parks and Wildlife, 2010). See Figure 2 for piezometer locations.

Sample group	Site name	Total depth (m)
Shale piezometers	T13d	60.7
Eolian sand piezometers	T3	10.2
	T13s	13.4
	T15	9.5
	T16	10.5
	T17s	13.1
	T18s	14.2
	T19	13.2
Alluvium piezometers	T17d	21.2
	T18d	19.6
	T5	7.3
	T6	4.0
	T8	4.4
	T9	3.9
	T11	4.5
	T12	11.4

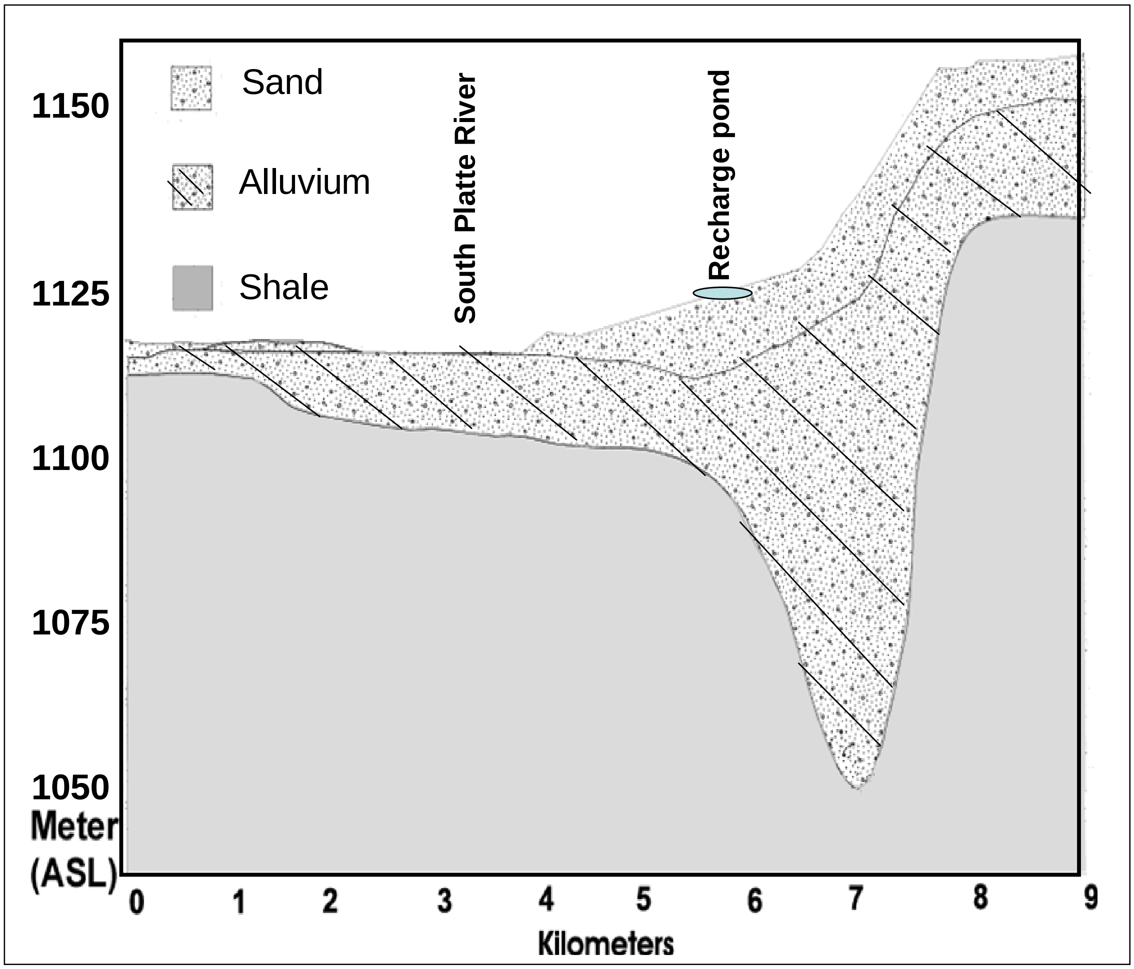

Figure 4: Geologic cross section of Tamarack Ranch based on eight boring logs east of Tamarack Ranch. Approximate location of recharge pond and South Platte River are shown on map. Vertical exaggeration is 40:1. (From Poceta 2005).

sections were also chosen based on accessibility and homeogeneity (no major obstructions) of the cross sectional profile. Streamflow measurements were conducted using USGS streamflow gauging techniques to determine instantaneous streamflow rates (Buchanan and Somers 1969). Discharge was measured with the FlowTracker® by SonTek. Stream depth was measured at each cross section with channel surveys using Leica® total station equipment. Horizontal measurements were taken at 0.35 m intervals, while vertical measurements were taken at 0.01 m intervals.

A Student's t test was used to identify statistical differences between the cross sections upstream and downstream of the recharge pond. Variance was estimated using:

$$s^2 = \left(\frac{1}{n-m}\right) \sum_{d=1}^{6} \sum_{j=1}^{2} \sum_{i=1}^{2} (Y_{dji} - \hat{Y}_{dji}) \tag{12}$$

Where s^2=variance; n= number of terms; m=number of means; d=date; j= sample group; i=replicate; Y= discharge value. This equation subtracts the average upstream and downstream discharge from the cross section-specific discharge for each measurement date. These values are summed and multiplied by the number of means subtracted from the number of terms. The variance was used to calculate the t value for n degrees of freedom:

$$t(n\ degrees\ of\ freedom) = \frac{\left(\hat{Y}_{1d} - \hat{Y}_{2d}\right)}{s} \tag{13}$$

Where t= t-value; $\hat{Y}_{1d}$= average upstream discharge; $\hat{Y}_{2d}$= average downstream discharge. The null hypothesis (H_o) is that there is no significant difference between the means of the upstream and downstream variable (Personal communication, 2012, Dr. Mary Meyer of Colorado State University).

Groundwater flow

Groundwater flow direction was determined through groundwater elevation data measured from nested piezometers over time. In addition to the network of existing piezometers on the Tamarack State Wildlife Area, another 3 piezometers were installed at the 4 river cross sections. In-Situ Troll 500® loggers were launched at each cross-section to measure instantaneous water levels. Water table elevations were compared to in-channel surface water elevations to determine the vertical hydraulic gradient and groundwater flow direction.

To install the nested piezometers, a borehole was drilled at each cross-section using a hollow stem auger drill rig to depths of approximately 5, 10, and 15 m. A 0.2 m layer of clean sand was placed at the base. PVC pipe with a diameter of 6.4 cm (2.5 in) and depths screened at 0.3 m were placed in each piezometer. Steel casing of 7.6 cm (3 in) diameter was placed around the PVC and sealed with concrete from the surface to a depth of approximately 0.6 m.

Groundwater tracer study

A fluorescein tracer study was used to estimate groundwater travel time to the river and quantify groundwater contribution to streamflow. Fluorescein was chosen for this study based on the substrate, water quality, and desired detection limits at the Tamarack State Wildlife Area. Fluorescein (color index number 45350), also known as acid yellow 73, is an anionic compound, which is less subject to adsorption onto substrate material than cationic dye. A 75% "as sold mixture" was used, meaning a cornstarch diluent was added by the manufacturer to make it easier to dissolve the dye mixture into water (Aley 2002). The detection limit of fluorescein dye in water using a synchronous scan protocol with a bandwidth separation of 17 nm, an excitation slit of 5 nm, and an emission slit of 3 nm is 0.0005 ppb (Aley 2002).

Nine kg of fluorescein were released into the recharge pond on May 3rd, 2011. The amount was chosen based on the recommended amount for a volume of 2 acre feet and a travel distance of approximately 1200 m (Personal communication, 2010, Thomas Aley, Ozark Underground Laboratory). The initial concentration of fluorescein was estimated at 4 parts per million (ppm). Tracer sampling was conducted with water samples, activated carbon samplers placed within piezometers, and surface water samples from the South Platte River. Carbon samplers contained 4.25 grams of Barnebey and Sutcliffe Type AC Activated Carbon. They continuously adsorb and accumulate dye and allow for greater detection limits than water samples. Ozark Underground Laboratory ran all dye analyses.

The tracer was placed on May 3rd, 2011 after the recharge pumps had been turned off. However the pumps ran from April 27th to May 4th, 2011 to fill the minnow ponds. As a result, the groundwater flow conditions during the tracer study may not represent the flow conditions during normal recharge periods.

A total of 11 piezometers were sampled for fluorescein dye based on well depth and location. The piezometers were divided into upper eolian, middle alluvium, and lower alluvium groups based on their respective distances from the recharge pond. The upper eolian sand piezometers (T13d, T19, T17d, and T18d) were sampled four times between May 5th and May 16th, 2011. On May 19th, the sampling protocol expanded to the middle alluvium piezometers (T5, T9, and T12). Sampling of the upper eolian and middle alluvium piezometers continued through July 15th, 2011. Sampling of the lower alluvium piezometers (XS1, XS2, XS3, and XS4) began on June 9th and continued through September 28th, 2011. The 7 piezometers in the upper eolian and middle alluvium were pre-existing while the 4 piezometers in the lower alluvium were installed as part of this research.

Data from the fluorescein tracer study were used to estimate the horizontal hydraulic conductivity (K_h) of the substrate. Hydraulic conductivity was estimated using Darcy's Law (Sterret 2007):

$$q = -Kh\left(\frac{dh}{dl}\right) \tag{14}$$

Where q= the volumetric flow rate perpendicular to the direction of groundwater flow, also referred to as specific discharge or Darcy flux velocity (m/d); K_h= horizontal hydraulic conductivity (m/d); dh= difference in hydraulic head (m); dl= distance along the flow path (m). The Darcy flux (q) and hydraulic gradient were estimated using tracer data and well locations. Rearranging Darcy's Law to solve for K gives:

$$-Kh = \frac{q}{\left(\frac{dh}{dl}\right)} \tag{15}$$

The difference in head values (*dh*) was found by taking the elevation at the center of the recharge pond and subtracting the measured head values for each well. The *dl* variable was determined by inserting GPS-derived northing and easting well location data into the Pythagorean theorem.

The Darcy flux (q) is related to the average linear velocity (v_x) by the effective porosity $\eta_{e,}$ or the porosity through which flow can occur (Fetter 1999):

$$Vx = \frac{Kh}{ne} * \frac{dh}{dl} \tag{16}$$

The average linear velocity (v_x), or the rate at which the flux of water across the unit cross-sectional area of pore space occurs, was estimated using:

$$Vx = \frac{d}{t}$$

(17)

Where d = distance from the recharge pond (m); t= time (days). Peak arrival time was estimated from the fluorescein breakthrough curves. The average linear velocity (v_x) calculated in equation 4 was multiplied by the effective porosity to find the Darcy flux (q). Equation 2 was used to find the range of hydraulic conductivities at each piezometer over the sampling period.

Groundwater contribution to streamflow

PVC pipes were inserted 0.5 m into the streambed at the four river cross sections to determine the vertical hydraulic gradient. Darcy's Law was used to determine the vertical flow per unit length:

$$Q = Kv * \left(\frac{hg - hs}{m}\right) w$$

(18)

Where K_v = the vertical hydraulic conductivity; h_g = groundwater head; h_s = surface water head; m = the length below the streambed; w = stream width.

For this analysis it was assumed that the vertical hydraulic conductivity (K_v) was lower than the horizontal hydraulic conductivity (K_h) determined in Equation 15. Previous modeling of South Platte River aquifers report an anisotropy ratio of 9.9 (Paschke 2011). The vertical hydraulic conductivity was estimated by dividing the average horizontal hydraulic conductivity by the anisotropy ratio:

$$Kv = \frac{Kh}{9.9}$$

(19)

The variation in groundwater contribution to streamflow (Q) was determined with the following equation:

$$s^2 = VAR(K_v dw)VAR\left(\frac{hg - hs}{m}\right) + E(K_v dw)^2 VAR\left(\frac{hg - hs}{m}\right) + E\left(\frac{hg - hs}{m}\right)^2 VAR(K_v dw)$$

(20)

Where VAR= the estimated variance; d= distance; w = width; E=the expected value (Dr. Mary Meyer, 2012, Colorado State University, personal communication). This assumes that K_v and (hg-hs/m) are independent terms. This equation was based on the assumption that

$$VAR(x) = E\left[\left(x - E(x)\right)^2\right] = E(x^2) - E(x)^2$$

(21)

Where x is the actual value, and E(x) is the expected value, or mean, of x (Personal communication, 2012, Dr. Mary Meyer of Colorado State University).

RESULTS

Streamflow

Streamflow over most of the 2011 water year was unusually high compared to historical levels (Figure 5). Streamflow greater than 6 cubic meters per second (cms) created unsafe wading conditions. As a result, discharge was not measured during some of the months of interest. Discharge measurements were taken on six separate dates (Figure 6). The average streamflow for the upstream cross sections (cross sections 1 and 2) was 2.64 cms, while the average streamflow for the downstream cross sections (3 and 4) was 2.66 cms (Table 4). While the average streamflow for downstream cross sections was larger than the upstream average, individual measuring dates did not consistently display these results. Upstream cross sections had a larger discharge than downstream cross sections on half of the measuring dates.

Individual discharge measuring dates were used to estimate the unbiased variance in streamflow data. This was used to find the degree of significance, or p-value of the difference. Only streamflow measured on October 28th 2010 and September 7th 2011 showed a significant difference (p-value < 0.05) in flow between upstream and downstream cross sections (Table 5). On September 7th, the flow of the upstream cross sections was significantly higher than downstream cross sections.

The percent difference in discharge between the Colorado Division of Water Resources (CDWR) gage at Crook (located at cross section 1) and the discharge measured in the field with the FlowTracker® varied by date and cross section. The overall percent difference increased with increasing distance from cross section 1 (Table 6), suggesting that streamflow increased with increasing distance from cross section 1. The percent difference was larger in the downstream

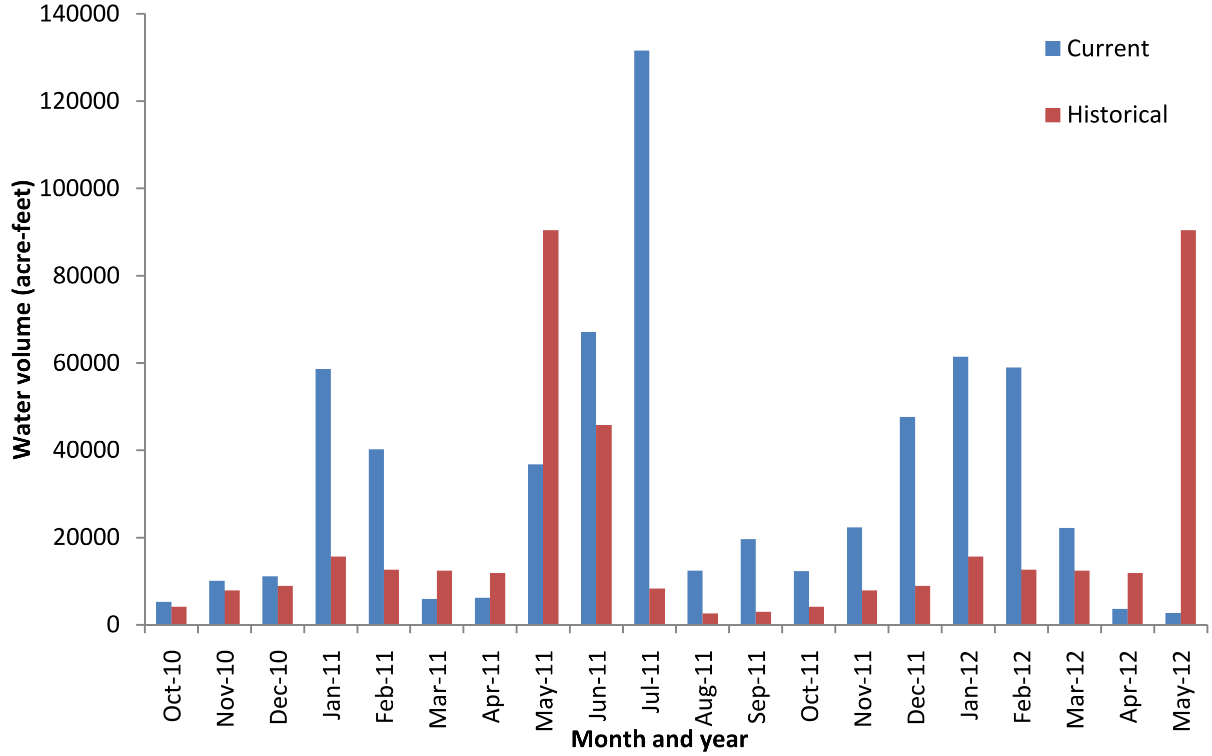

Figure 5: South Platte monthly stream volume at Crook, CO from October 2010 through May 2012 (Colorado Division of Water Resources 2012) compared to historical values (United States Geological Survey 2012).

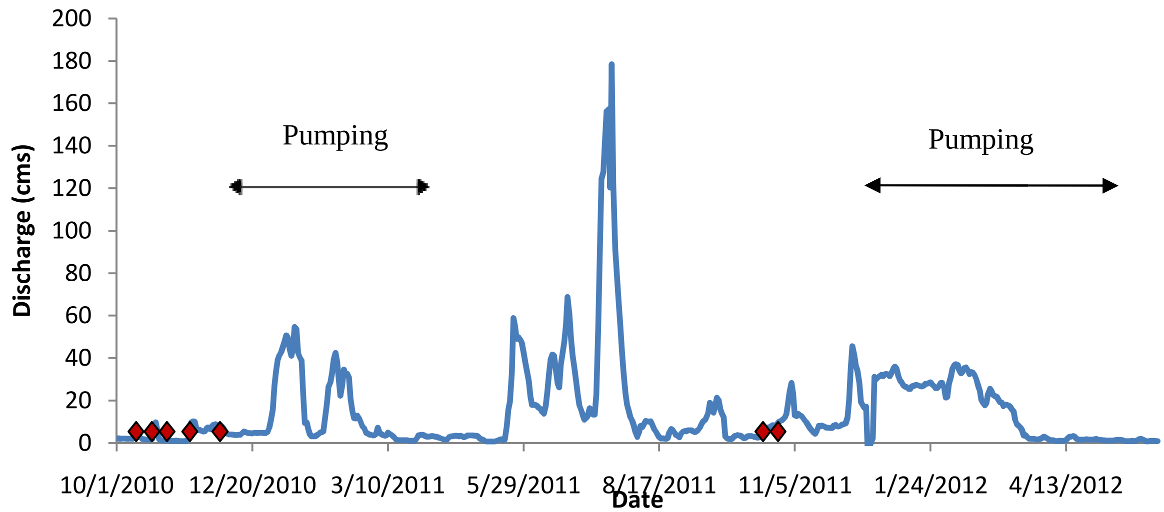

Figure 6: Discharge measurements on 6 dates (10/7, 10/14, 10/28, 11/4 of 2010 and 9/7 and 9/28 of 2011) on the South Platte River plotted against the hydrograph from 10/1/2010 to 6/6/2012 (Colorado Division of Water Resources 2012).

Table 4: Measured discharge rates for the Colorado Division of Water Resources (CDWR 2012) and the four cross sections. The flow volume for cross sections 1 and 2 were averaged and compared to the average of cross sections 3 and 4 to determine if there was a significant increase in flow in the downstream cross sections due to artificial groundwater recharge.

	Discharge at CDWR Crook gage (cms)	**Measured upstream discharge (cms)**			**Measured downstream discharge (cms)**		
Date		XS1	XS2	Average	XS3	XS4	Average
10/7/2010	1.99	2.73	2.21	2.47	2.01	2.01	2.01
10/14/2010	3.09	2.98	2.99	2.99	2.97	2.92	2.95
10/28/2010	1.24	0.28	0.76	0.52	1.37	1.51	1.44
11/4/2010	0.89	0.67	1.00	0.84	1.05	1.20	1.13
9/7/2011	5.04	5.70	N/A	5.70	4.90	4.79	4.85
9/28/2011	1.79	3.04	3.61	3.33	3.24	3.95	3.60
Average	**2.34**			**2.64**			**2.66**

Table 5: Results of a t test for the discharge measurements on 6 measuring dates. p-values less than 0.05 are considered significant.

Date	**Upstream average**	**Downstream average**	**Variance**	**Degrees of freedom**	**t-value**	**p-value**	**Significant**
10/7/2010	2.47	2.01	0.261	11	1.7	0.106	No
10/14/2010	2.99	2.95			0.15	0.881	No
10/28/2010	0.52	1.44			-3.54	0.005	Yes
11/4/2010	0.84	1.13			-1.12	0.290	No
9/7/2011	5.7	4.85			3.78	0.008	Yes
9/28/2011	3.33	3.6			-1.04	0.323	No
Average	**2.64**	**2.66**			**-0.08**	**0.949**	**No**

Table 6: Percent difference of discharge measurements of the four cross sections compared to the reported discharge at the Crook gage.

Date	**XS1**	**XS2**	**XS3**	**XS4**
Average	**2.4**	**16.6**	**17.3**	**27.9**

cross sections compared to the cross sections upgradient of the recharge pond, suggesting there was some additional input of water.

While the difference between streamflow in the upstream and downstream cross sections was not significant, the percent difference in flow between the CDWR gage and downstream cross sections suggests that stream accretion may have occurred at downstream cross sections.

Stream depth

The planforms of the four river cross sections showed high bank angles on all measuring dates, suggesting an incised channel (Figure 7). Because the flows on the five measuring dates were not large enough to overtop the banks to expand laterally, an increase in flow produced an increase in depth.

The profile of cross section 1 from Oct 14th, 2010 showed a deep pool on the river-right side (Figure 7). The depth of this pool decreased over time to a more uniform stream depth, which suggests sediment movement.

The cross sectional profile of cross section 2 did not show significant channel change over time (Figure 7). However, on November 4th, 2010 the lowest flow of the 4 sampling dates, sediment appeared to accumulate in the middle of the streambed, which may separate the channel during lower streamflow conditions.

The cross sectional profile of cross section 3 showed the greatest channel change over time (Figure 7). Over the course of the 4 sampling dates, the deep section at horizontal location 5008 on October 7th filled by Nov 4th. Braiding started to occur on the river-left side of the channel, as indicated by the partially exposed sandbed on Nov 4th.

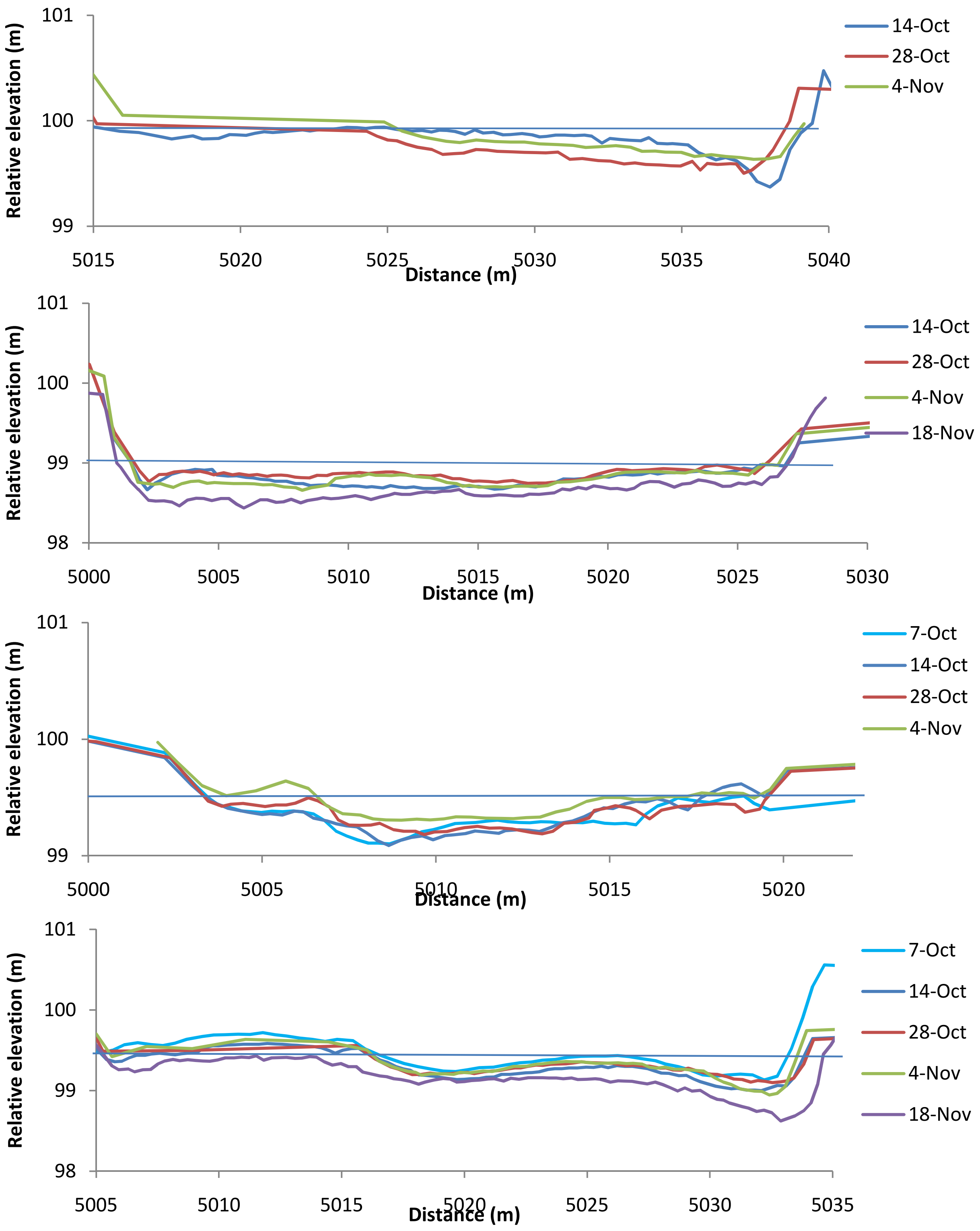

Figure 7: Measured bed surface for 5 dates in 2010 for cross sections 1-4. The blue horizontal line represents the river stage. Cross section 1 is the top-most figure. The horizontal measurements were taken at 0.35 m (1 foot) intervals with Leica® total station equipment while the vertical measurements were taken at 0.01 m intervals.

Table 7: Cross sectional area (m^2) recorded by Sontek® equipment. Cross sectional area increased with an increase in discharge. Cross sections were not surveyed on dates where the flow conditions were unsafe for sampling.

Date	Discharge at Crook gage (cms)	Cross section 1	Cross section 2	Cross section 3	Cross section 4
10/7/2010	1.99	4.28	3.79	3.43	Failed QA/QC
10/14/2010	3.09	6.03	5.21	5.05	4.82
10/28/2010	1.24	2.48	2.11	2.89	2.95
11/4/2010	0.89	2.24	Not measured	2.19	2.47
11/18/2010	6.03	Not measured	10.76	Not measured	Failed QA/QC
9/7/2011	5.04	8.97	Not measured	7.01	7.59
9/28/2011	1.79	5.56	6.68	6.55	6.99

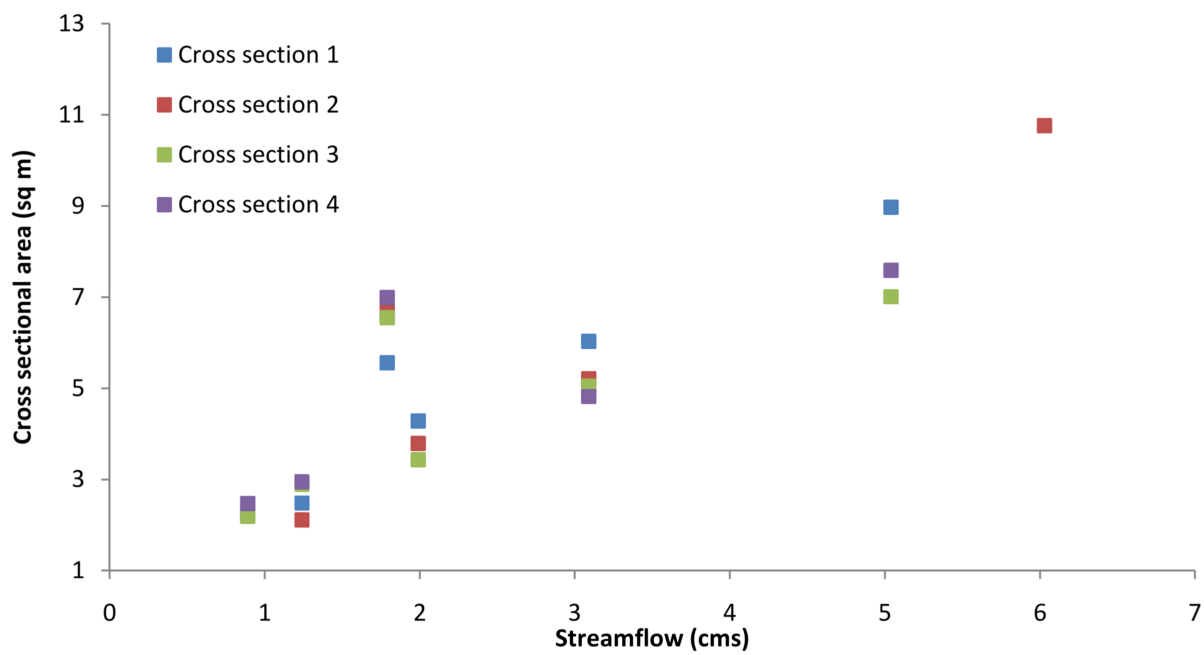

Figure 8: Streamflow (cms) versus cross sectional area (m^2) for cross sections 1-4.

The cross sectional profile of cross section 4 did not change significantly over the 5 sampling dates (Figure 8). Profiles on Oct 14^{th}, Oct 28^{th}, and Nov 4^{th} showed braiding (2 separate channels). The large flows of Nov 18^{th} submerged the river bed, with no indication of significant sediment movement.

Cross sectional area increased with an increase in discharge (Table 7 and Figure 8). Figure 8 shows a linear relationship between discharge and area. However, from the cross sectional profiles, an increase in discharge resulted in an increase in stream depth with no lateral expansion.

Groundwater flow

Pressure transducers (PT) measure the total head. The changes in potentiometric surface measured by the PTs at all cross sections reflected changes in the river stage, meaning that a change in river stage produced a subsequent change in water table elevations (Figures 9-14). Additionally, the potentiometric surface at all piezometers was usually higher than the river stage, suggesting the groundwater flowed toward the river. The exception was the PT in the deep piezometer at cross section 3 (Figure 11), which was placed too deep in the water to record water elevation changes until Sept 1^{st}, 2011.

Cross section 2 contained data loggers in the shallow and medium depth piezometers (Figure 9). The two piezometers displayed similar water levels until July 14^{th} where the shallow piezometer began to record higher levels than the medium depth piezometer. Both the medium and shallow piezometers were unvented until June 22^{nd} (operator error). Water table elevations in the shallow piezometer increased and decreased at a rapid rate beginning on from November 9^{th}, 2011 through Jan 19^{th}, 2012.

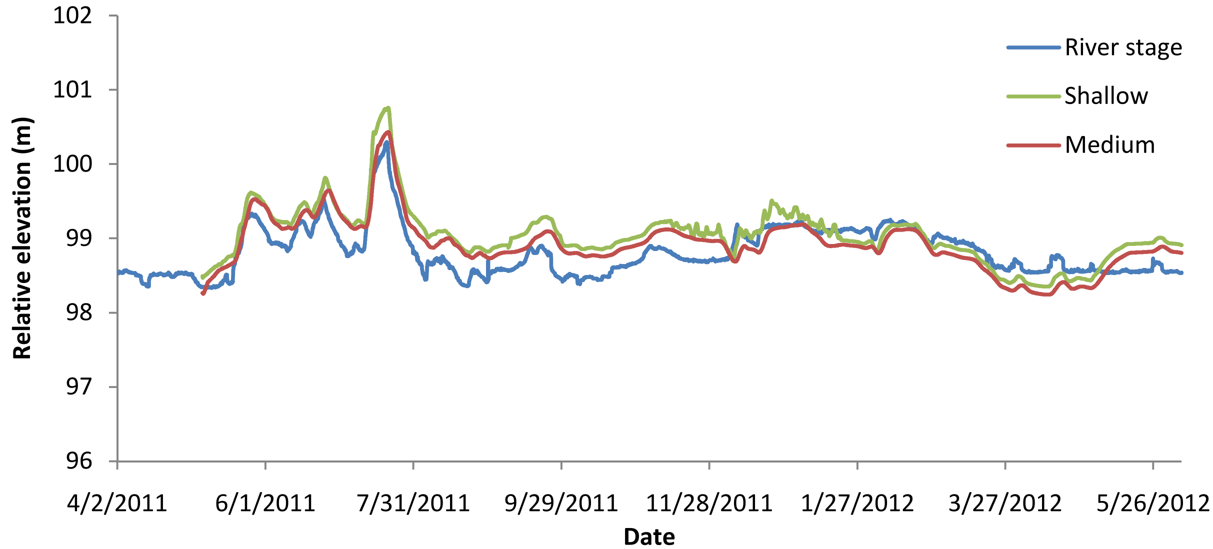

Figure 9: Pressure transducer data from shallow and medium depth piezometers for cross section 2 (3-day moving average). Water table elevations were compared to the surface elevation and the discharge values of the South Platte River. Measurements were taken on an hourly basis from May 3rd, 2011 to June 6th, 2012.

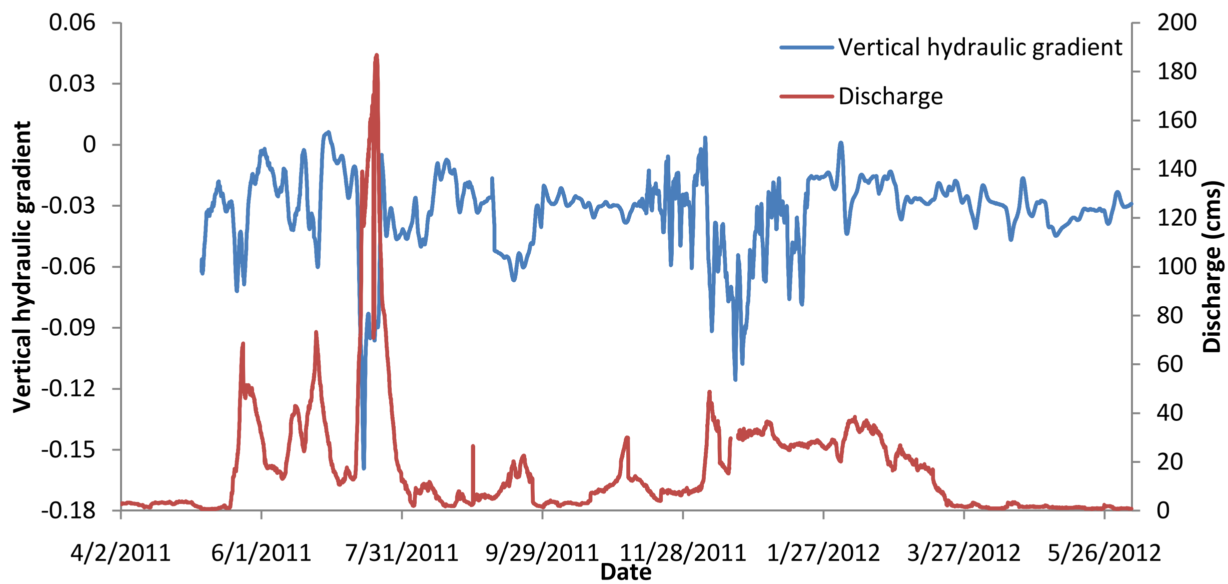

Figure 10: Vertical hydraulic gradient between the shallow and medium piezometers (screen depths at 4.67 and 8.03 m, respectively) from May 3rd, 2011 to June 6th, 2012 at cross section 2. The daily average discharge in the South Platte River is also shown.

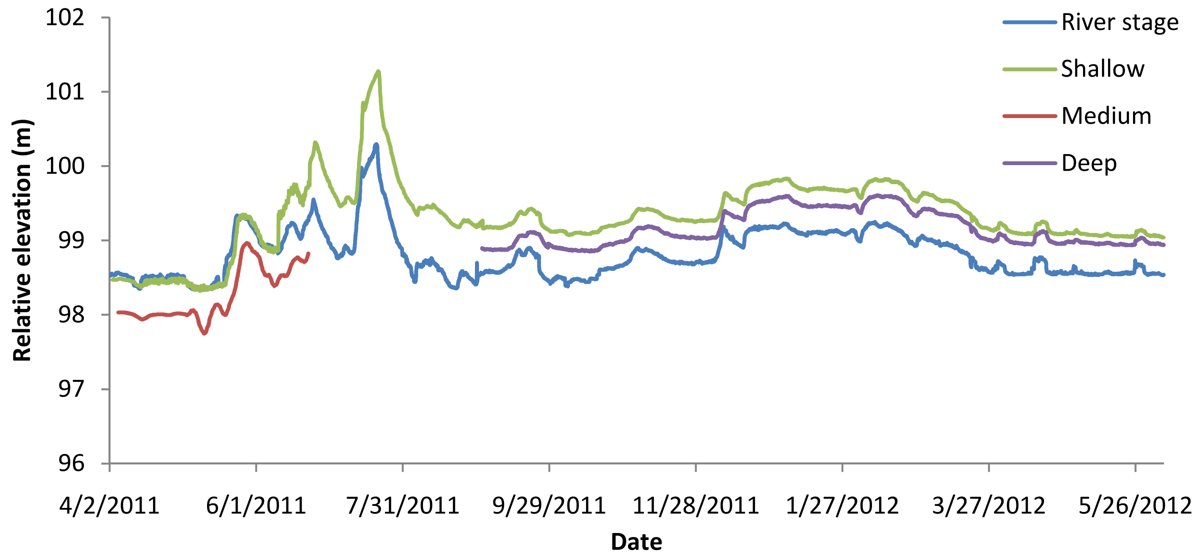

Figure 11: Pressure transducer data from shallow, medium, and deep piezometers for cross section 3. Water table elevations were compared to the surface elevation values of the South Platte River. Measurements from the medium piezometer were taken on an hourly basis from May 3rd to June 22nd, 2011, and from April 2nd, 2011 to June 6th, 2012 for the shallow and deep piezometers.

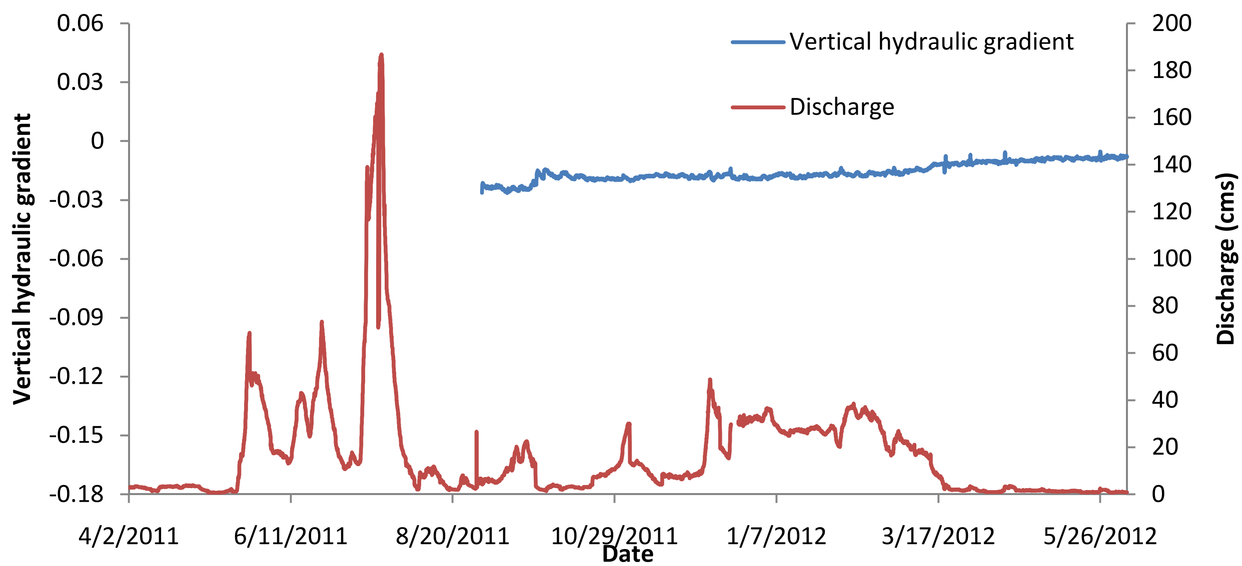

Figure 12: Vertical hydraulic gradient between the deep and shallow piezometers (screen depths at 5.36 and 18.07 m, respectively) from September 1st, 2011 to June 6th, 2012 at cross section 3. The daily average discharge in the South Platte River is also shown.

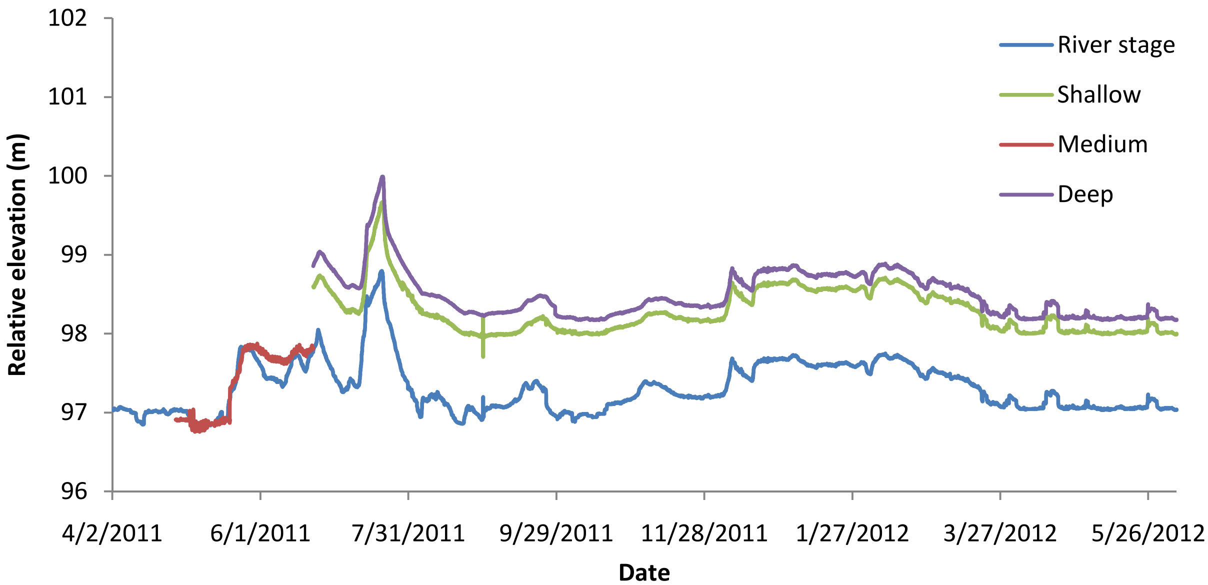

Figure 13: Pressure transducer data from shallow, medium, and deep piezometers for cross section 4. Water table elevations were compared to the surface elevations of the South Platte River. Measurements from the medium piezometer were taken on an hourly basis from April 27th to June 22nd, 2011, and from June 22nd, 2011 to June 6th, 2012 for the shallow and deep piezometers. Data were corrected from Nov 28th, 2010 through June 6th, 2012.

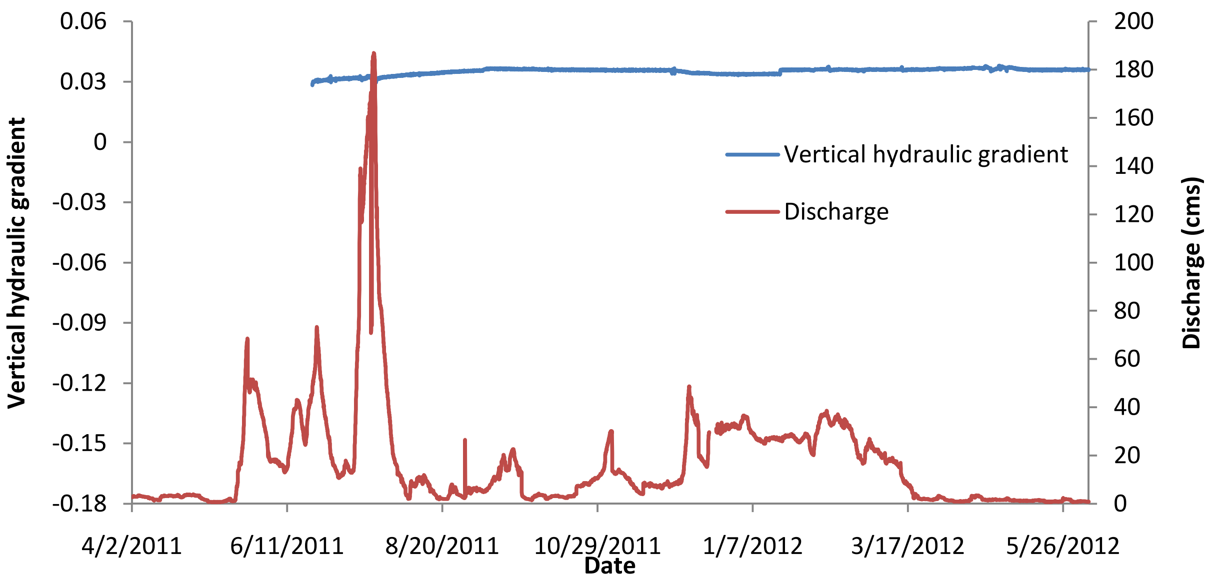

Figure 14: Vertical hydraulic gradient between the deep and shallow piezometers from June 22nd, 2010 to June 6th, 2012 (screen depths at 4.60 and 14.55 m, respectively) at cross section 4. The daily average discharge in the South Platte River is also shown.

The vertical hydraulic gradient data for cross section 2 showed a slight negative gradient on average, suggesting downwelling (Figure 10). The gradient values were positive during low flows from June 27th – June 30th, 2011, and again on December 7th, 2011. The hydraulic gradient was inversely proportional to the daily discharge of the South Platte River, meaning that an increase in daily average discharge in the South Platte River caused a decrease in the vertical hydraulic gradient.

The shallow piezometer in cross section 3 had consistently higher head values than the medium and deep piezometers (Figure 11). The PT in the deep piezometer was initially placed too deep in the water to record water table elevation changes. Data from this piezometer were unusable until Sept 1st when the transducer was reset. The PT from the medium well was removed on June 22nd to replace a stolen transducer in cross section 4.

The vertical hydraulic gradient between the shallow and deep piezometers for cross section 3 was negative from Sept 1st to June 6th (Figure 12). This suggests the downward movement of groundwater. The vertical hydraulic gradient initially responded to changes in discharge in the South Platte River. From Sept 1st through Oct 20th, an increase in discharge produced a decrease in gradient, or a stronger negative gradient. However, after Oct 20th the gradient did not respond to changes in discharge. For example, the streamflow peaks on Nov 4th and Dec 9th did not produce a decrease in vertical hydraulic gradient.

Data logging of cross section 4 began with PTs in the medium and deep piezometers. However, the PT from the deep piezometer was stolen before the data were downloaded. Data from the medium piezometer showed daily fluctuation because the vent cap was inadvertently left on the PT (Figure 13). After the cap was removed, data showed less noise. Beginning on May 28th, the water level in the piezometer was higher than the river stage. It is unclear if this was the result of the recharge water or the vent cap error. The shallow and deep PTs were launched on June 22nd 2011.

The vertical hydraulic gradient for cross section 4 data showed consistently positive values, suggesting upward movement of water (Figure 14). The gradient increased in response to a decrease in discharge from the South Platte River. However, gradient data from cross section 4 is less responsive to changes in discharge than cross sections 2 and 3 (Figures 10 and 12).

Water table elevation

Water table elevations were measured in the matrix of piezometers over the course of the tracer study. Pumping ceased on May 4th, and the recharge pond was dry by May 5th 2011. Depth to water measurements were taken from a total of 14 piezometers. Sampling was split into three categories based on distance from the recharge pond. The upper eolian sand piezometers, located adjacent to the recharge pond, were comprised of T13s, T13d, T17d, T18d, and T19. The middle alluvium piezometers, located between the recharge pond and the South Platte River, included T5, T7, T8, T9, and T12. The lower alluvium piezometers, located adjacent to the South Platte River, were comprised of cross sections 1 through 4 (XS 1-4).

Depth to water measurements of the upper eolian sand piezometers, located adjacent to the recharge pond (Figure 2), began on May 3rd 2011. Figure 15 shows a pulse of groundwater moving through the system in early May. Five of the six piezometers (T13s, T16, T17d, T18d, and T19) showed the highest water table elevations on May 5, two days after the dye was released into the recharge pond (Figure 15). The water table of each of the 5 piezometers increased by approximately 0.3 m. Piezometer 13d showed the highest water table elevation on

May 3rd. Piezometers T17d and T18d showed a secondary peak in water table elevation on May 16th. After May 19th, the water table elevations in all wells remained constant.

Water table elevation measurements of middle alluvium piezometers, T15, T5, T7, T8, and T12, located between the recharge pond and the South Platte River (Figure 2), began on May 19th. The measured potentiometric surfaces were relatively constant across all measuring dates, with the exception of T15 (Figure 16). T15 showed a decrease from 1131.39 m on May 19th to 1126.66 m on May 26th. The initial potentiometric surfaces of T5, T7, T8, and T12 measured on May 19th did not change significantly over the remaining measuring dates.

Measurements of the lower alluvium piezometers, XS2, XS3, and XS4, located adjacent to the South Platte River, began on May 3rd (with the exception of XS1 which began on June 9th). The water table elevations of cross sections 2 and 4 increased by approximately 2 m on June 17th (Figure 17). Cross sections 1 and 3 did not change more than 1 m over the course of the sampling period.

Potentiometric surface maps were developed from water table elevation measurements (Figures 18 and 19). Groundwater flows downgradient and perpendicular to the head contour lines. The potentiometric surface maps suggest that water followed a northeasterly return path, perpendicular to the river. Additionally, the maps suggest that groundwater likely returned to cross sections 2, 3, and 4 through multiple flowpaths. Figures 18 and 19 compare total head values between May 3rd and July 15th.

Comparing the changes in total head across the Tamarack State Wildlife Area between May 3rd and July 15th suggests a pulse of groundwater from the recharge pond moved toward the river (Figures 18 and 19). Total head at the upper piezometers near the recharge pond decreased

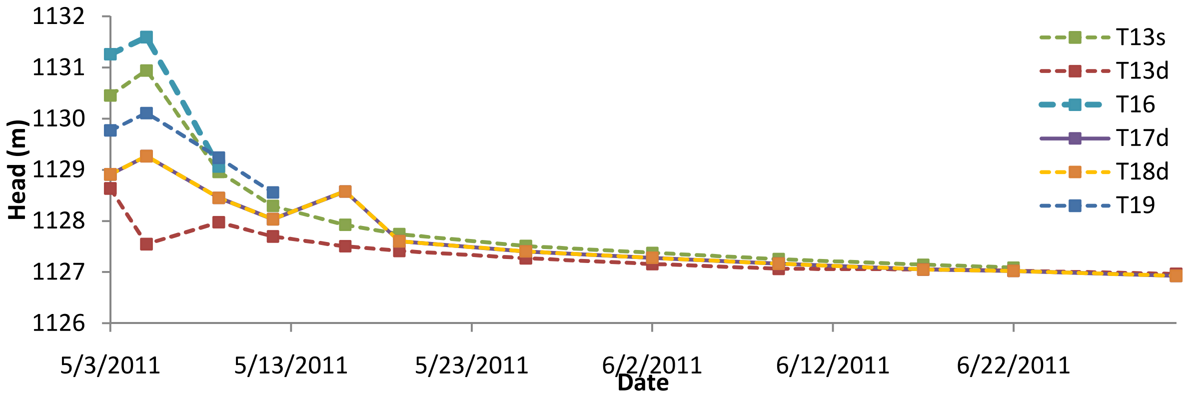

Figure 15: Total head values measured from the upper eolian sand piezometers from May 3rd – July 1st 2011. Pumping to the recharge pond ceased on May 4th, after which there is a pulse of groundwater moving through the piezometers.

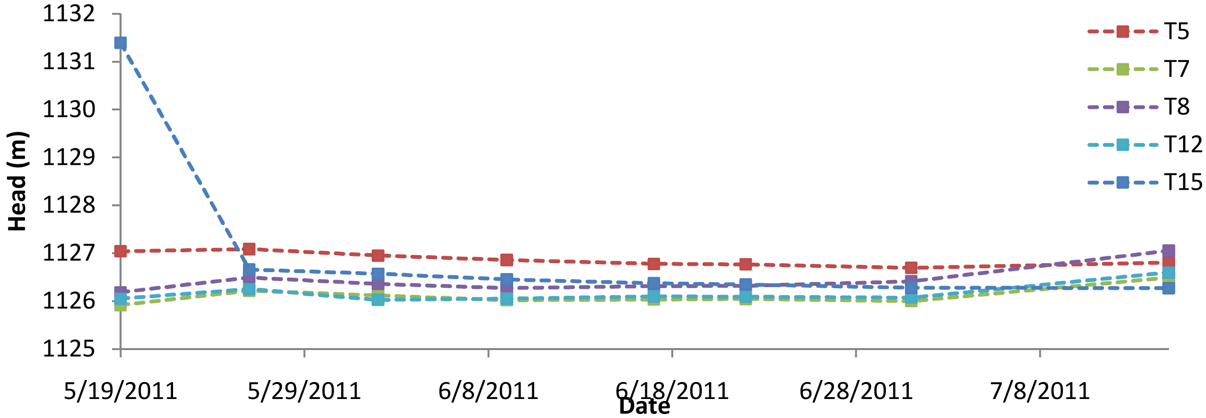

Figure 16: Total head values of the middle alluvium piezometers from May 19th- July 15th 2011. T15 seems to display the tail of the groundwater pulse flow, while the other piezometers do not show any pulse flows.

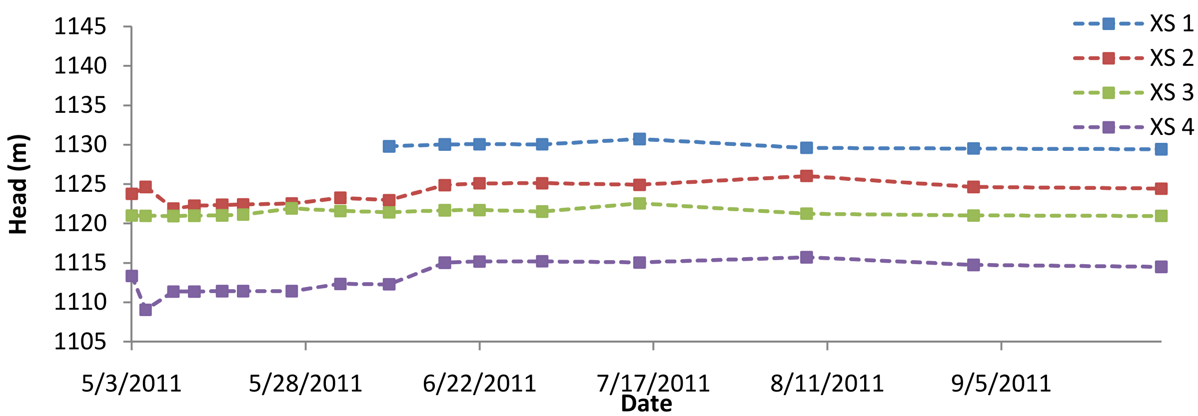

Figure 17: Total head values of the lower alluvium piezometers from May 3rd - Sept 28th 2011. Cross sections 2 and 4 increased by 2 m on June 17th. Cross sections 1 and 3 did not change by more than 1 m over the course of the sampling period.

2-4 m over the course of the sampling period. While there was no change in total head at cross section 2, cross section 3 showed an increase of 1 m, and cross section 4 showed an increase of 2 m over the course of the sampling period. However, changes in water table elevation in the lower piezometers were likely a response to changes in river stage.

Water table elevations in the upper eolian sand piezometers show an immediate pulse of groundwater moving through the system, as elevations decrease between 2-4 m after the pumps were shut off. The middle and lower alluvium piezometers do not show a significant decrease in water table elevations, suggesting that either these piezometers were sampled at an inappropriate timeframe, or that the groundwater mound dissipated by the time it reached these areas.

Groundwater tracer study

Approximately 9 kg (20 lbs) of fluorescein dye were released into the recharge pond on May 3rd, 2011 after the pumps to the recharge pond had been turned off. However, the pumps ran again from April 27th - May 4th, 2011 to fill the minnow ponds. As a result, the subsurface conditions at the time of the tracer study may not represent true pumping conditions.

A total of 13 piezometers were sampled for fluorescein. Sampling was split into three categories based on their distance from the recharge pond. The upper eolian sand piezometers, located adjacent to the recharge pond, were comprised of T13s, T13d, T17d, T18d, and T19. The middle alluvium piezometers, located between the recharge pond and the South Platte River, included T5, T7, T9, and T12. The lower alluvium piezometers, located adjacent to the South Platte River, were comprised of cross sections 1 through 4 (XS 1-4).

Sampling of the upper eolian piezometers began 2 days after the dye was released on May 5th. Fluorescein was detected in all five piezometers sampled (Table 8). Values ranged

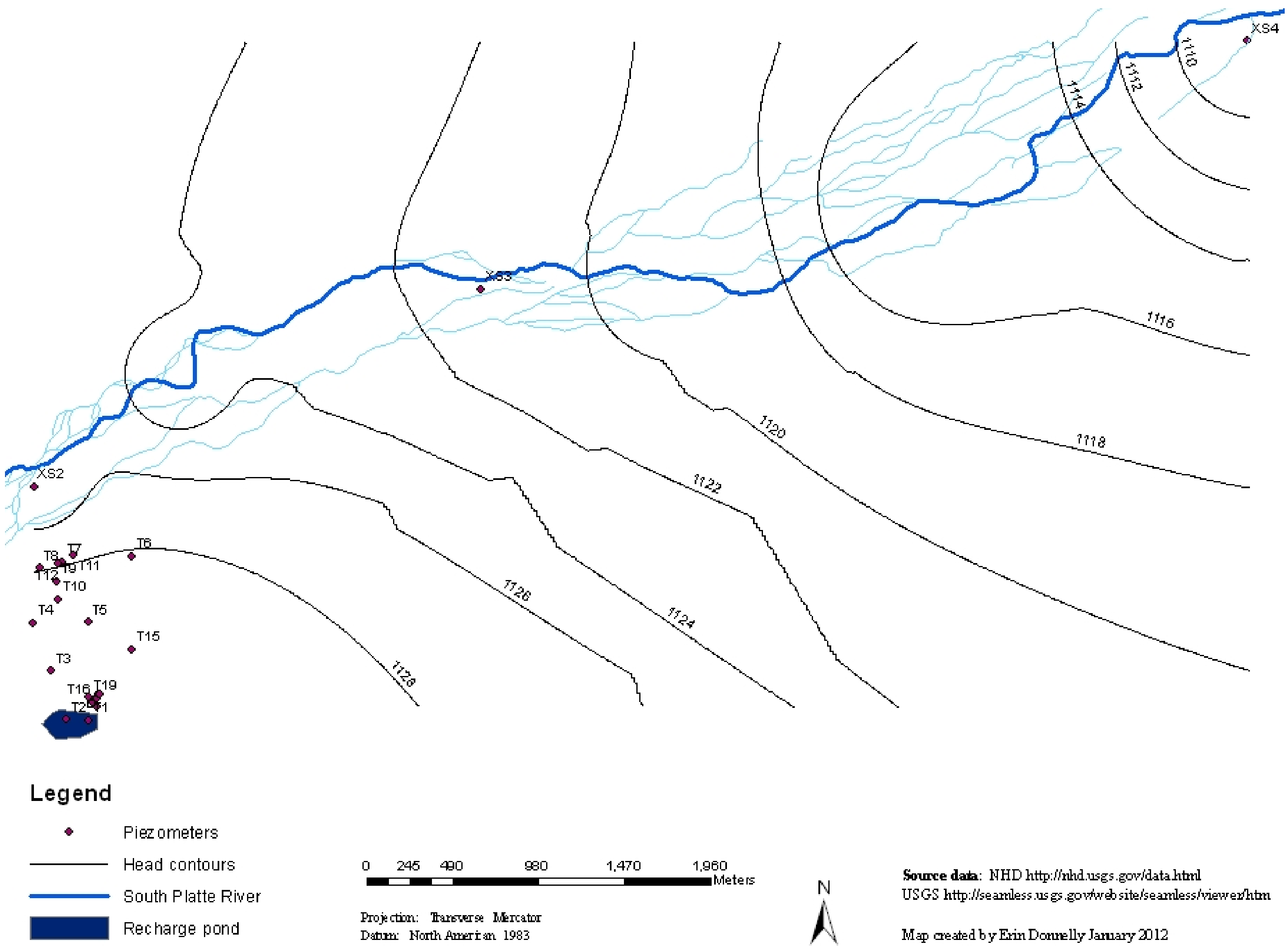

Figure 18: Potentiometric surface (meters) measured on Tamarack State Wildlife Area on May 3rd, 2011. Contour lines were created using the Inverse Distance weighting function in ArcGIS.

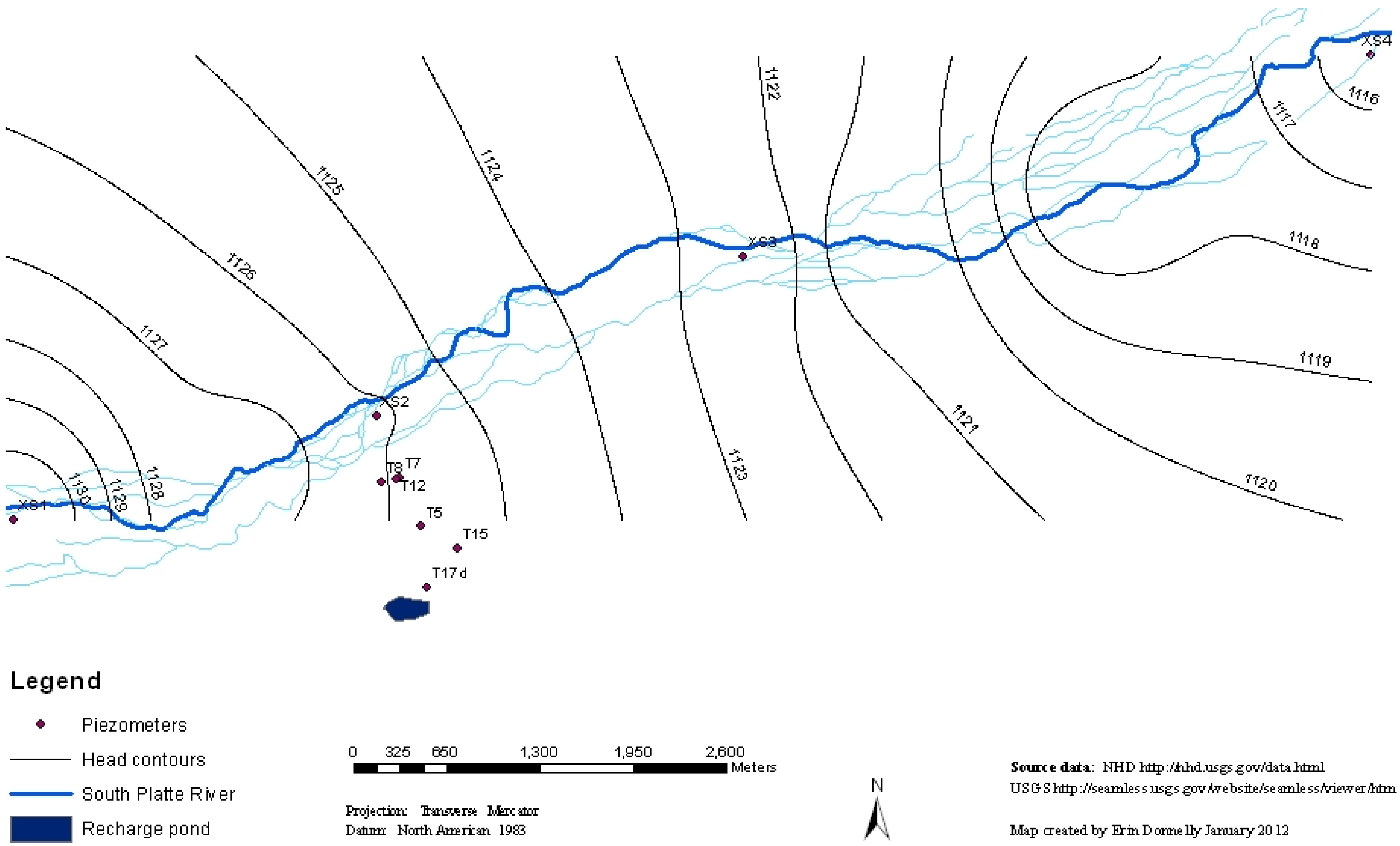

Figure 19: Potentiometric surface (meters) measured on Tamarack State Wildlife Area on July 15th 2011. Contour lines were created using the Inverse Distance weighting function in ArcGIS.

Table 8: Fluorescein concentrations from groundwater sampled from 11 piezometers (ppb).

Date	T19	T13D	T13S	T17D	T18D	T5	T12	XS 1	XS 2	XS 3	XS 4
5/5/2011	0.120	0.167	0.644	0.639	0.489						
5/9/2011	0.041	0.026	0.129	0.050	0.489						
5/12/2011	0.057	0.049	0.025	0.310	0.009						
5/16/2011		0.031	0.046	0.068	0.033						
5/19/2011		0.048		0.02	0.044	0.494	0.151				
5/26/2011		0.031		0.044	0.024	N/A	0.162				
6/2/2011		0.034		N/A	N/A	N/A	0.29				
6/9/2011		0.032		0.017	0.012	N/A	N/A	0	0	0	0.031
6/17/2011		0.031		0.012		N/A	N/A	0	0.009	0	0.01
6/22/2011		0.036		0.014		N/A	0.008	0	N/A	0	0
7/1/2011		0		0		N/A	0.007	0	0	0.006	0
7/15/2011		0		0		0.031	0	0	0.021	0.006	0.04
7/28/2011		0.035		0		0	N/A	0	0	0	0
8/8/2011		0.035						0	0	0	0

Table 9: Fluorescein concentrations from carbon packets sampled from 8 piezometers (ppb).

Date	T17d	T18d	T5	T12	XS 1	XS 2	XS 3	XS 4
5/26/2011	0.255	0.208	1.02	2.09				
6/2/2011	0.310	0.42	1.26	4.31				
6/9/2011	0.376	0	2.94	0.884				
6/17/2011	0.271	0.244	1.24	0	0.157	0.325	0.350	1.04

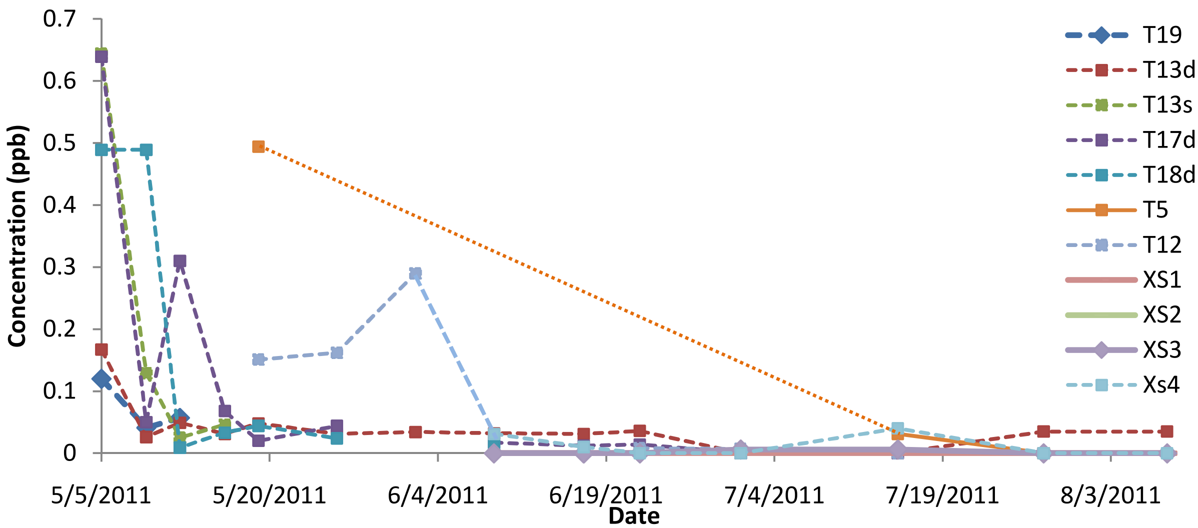

Figure 20: Fluorescein tracer results from water samples taken from a total of 11 piezometers. T19, T13d, T13s, T17d, and T18d are part of the upper eolian sand piezometers; T5 and T12 are part of the middle alluvium piezometers; cross sections (XS) 1-4 are part of the lower alluvium piezometers. Arrival time for the breakthrough curves in T13s, T17d, T18d, T5, and T12 were used to estimate hydraulic conductivity and Darcian flux rates. The remaining piezometers did not produce adequate breakthrough curves to use in the analysis.

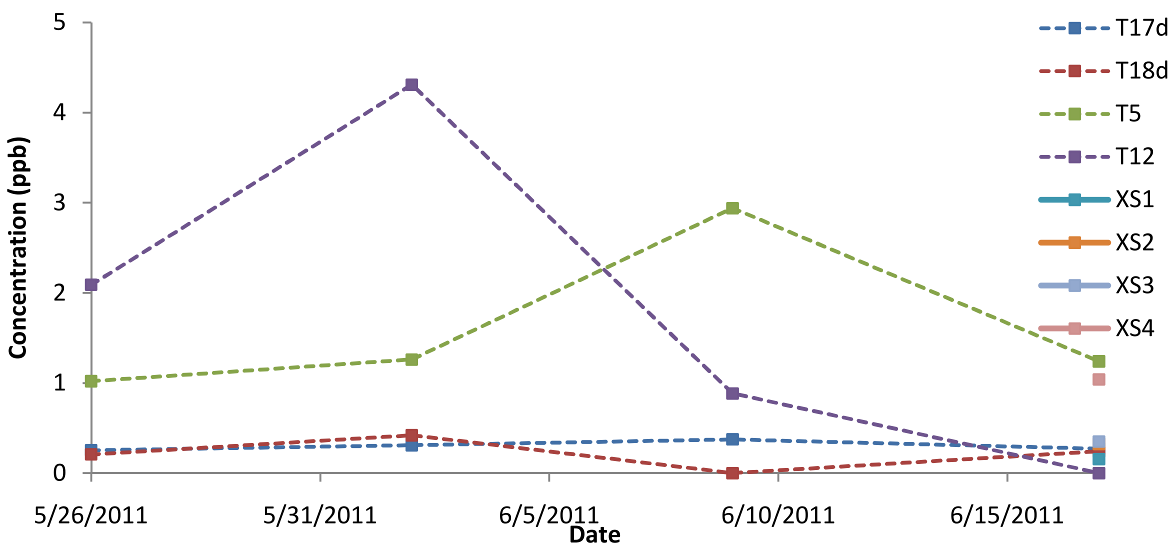

Figure 21: Fluorescein tracer results from carbon samples placed in a total of 8 piezometers. Carbon packets were analyzed from May 26th through June 22nd, 2011.

from 0.120 ppb to 0.644 ppb (Figure 20). Samples taken four days later on May 9th showed dye concentrations in T19, T13d, T13d, and T17d decreased to 0.41, 0.026, 0.129, 0.050, and 0.489 ppb, respectively. This suggests that the fluorescein peak in these piezometers occurred before May 9th. Fluorescein concentration in T18d did not change between May 5th and May 9th. May 12th data showed that no major changes in fluorescein concentrations occured in the upper eolian piezometers with the exception of T17d, which increased from 0.05 to 0.31 ppb. By May 16th, piezometer 19 was dry and T17d decreased to 0.068 ppb. After May 16th, concentrations in the upper eolian piezometers did not exceed 0.04 ppb.

On May 19th (16 day after dye release), T5 and T12 were added to the sampling protocol (Table 8). Both piezometers showed the presence of the dye, with T5 measuring 0.494 ppb and T12 measuring 0.151 ppb. Water samples collected from T5 between May 19th and July 15th contained too much sediment from the borehole to analyze. The water sample from July 15th was 0.031 ppb. Because there were 6 missing measuring dates for T5, it was difficult to determine peak time.

T12 showed a slight increase in fluorescein concentration on May 26th from 0.151 to 0.162 ppb. T12 did not yield a usable sample on June 9th or June 17th due to sediment contamination, so like T5, it was difficult to tell when the peak concentration occurred.

On June 9th (40 days after release) the lower alluvium piezometers at cross sections 1, 2, 3, and 4 were sampled. The piezometers were sampled a total of 7 times over the course of 2 months. No dye was ever detected at cross section 1. The water sample taken from the piezometers at cross section 2 showed 0.009 ppb on June 17th, followed by no dye on June 22nd or July 1st. On July 15th 0.021 ppb was detected at cross section 2. No dye was found on July 28th or August 8th. Cross section 3 showed 0.006 ppb of dye on July 1st and July 15th. Cross section 4 began with an initial value of 0.031 ppb, which decreased to 0.01ppb on June 17th and finally decreased to 0 on June 22nd. However, a value of 0.04 was measured on July 15th, which decreased to 0 for the remaining 2 sampling dates.

Carbon

Carbon packets were used in conjunction with water samples to determine the time of peak dye concentration. They continuously adsorb and accumulate dye and allow for greater detection limits than water samples. Carbon packets were placed in T17d and T18d of the upper piezometers, T5 and T12 of the middle piezometers, and cross sections 1-4 (Table 9). The first packets were placed in T17d, T18d, T5, and T12 on May 19th 2011. These samples were collected and analyzed on May 26th. The results from the carbon packet analysis for piezometers T17d and T18d showed that the dye concentrations were relatively low over the sampling period (Figure 21). Piezometer T17d ranged from 0.255 to 0.376 ppb. Piezometer T18d ranged from 0 to 0.42 ppb. These consistently low results showed a similar pattern to the water sample results. The exception is June 9th, when the carbon packet did not detect any dye while the water sample showed a concentration of 0.012 ppb.

Piezometer T5 showed the largest dye accumulation between June 2nd and June 9th when the measured concentration increased from 1.26 to 2.95 ppb. The concentration decreased to 1.24 ppb by June 17th. The water sample results showed the highest concentration on May 19th, so it is likely that the carbon packets were placed too late to catch the breakthrough curve. However, the carbon packets seemed to catch a secondary fluorescein pulse moving through around June 9th. The water samples showed a low dye reading on June 9th, so the secondary curve most likely occurred prior to June 9th.

Piezometer T12, which is 377 m further north from the recharge pond than T5, showed the largest dye accumulation between May 26th and June 2nd when the concentration increased from 2.09 to 4.31 ppb. By June 9th the concentration decreased to 0.884 ppb, then finally to 0 ppb by June 17th. Water sample results for T12 measured the largest concentration on May 26th. However, the sample collected from June 2nd was damaged and could not be used in the analysis. It is possible that the breakthrough curve occurred between May 26th and June 2nd.

The use of carbon packets was discontinued after the first round of analysis. While past studies showed carbon packet dye concentrations to be 400 times greater than the concentration of water samples (Aley 2002), results from this study measured concentrations at only 10 times the concentrations of the water samples, which made the numbers difficult to interpret. However, the results from the carbon analysis were used to better determine the time of the breakthrough curve of the water samples.

Hydraulic conductivity and Darcy flux

Data from the fluorescein tracer study were used to estimate the average linear velocity, Darcy flux (q), and hydraulic conductivity (K) of the substrate under the Tamarack State Wildlife Area (Table 10). Hydraulic conductivity was estimated using Darcy's Law. Complete equations are described in Materials and Methods. Only 5 of the 11 piezometers displayed full breakthrough curves needed to estimate hydraulic conductivity (Figure 20). The fluorescein concentrations in the other piezometers appeared to be on the falling limb of the breakthrough curve, and therefore were not used in the analysis.

Table 10: Estimates of horizontal hydraulic conductivities at 5 piezometer locations based on fluorescein tracer data and measured water table elevations. Pond elevation is 1139 m.

Piezometer ID	Distance (m)	Elevation (m)	Peak arrival time (days)	Average linear velocity (m/d)	Geology	Effective porosity (Fox 2004)	Darcy flux (q) (m/d)	Range of K_h (m/d)
T13s	189.57	1141.18	2	94.8	Eolian sand	0.2	19.0	300.0-322.7
T17d	206.18	1142.07	2	103.1	Eolian sand	0.2	20.6	348.7-462.5
T18d	238.17	1142.930	4	59.5	Eolian sand	0.2	11.9	235.0-291.5
T5	568.3	1131.6	16	35.5	Alluvium	0.3	10.7	362.5-374.3
T12	891.4	1127.83	25	35.7	Alluvium	0.3	10.7	311.1-325.4
Minimum				23.6			7.1	235.0
Maximum				103.1			20.6	462.5
Average				65.7			14.6	330.7

Table 11: Estimated return times for each cross section using the average Darcy flux from Table 10.

Cross section	Distance from recharge pond (m)	Average return time (days)
XS1	2773	190.3
XS2	1343	92.1
XS3	3410	234.1
XS4	7776	533.7

The average linear velocity was 65.7 m/d, the average Darcy flux was 14.6 m/d, and the average hydraulic conductivity was 330.7 m/d (Table 10). The estimated range of hydraulic conductivity was larger in eolian sand than the alluvium (235.0 – 462.5 m/d compared to 311.1 – 374.3 m/d). A larger range indicates a larger difference in total head between measuring dates. The eolian sand also larger estimated values of Darcy flux with a range of 11.9 – 20.6 m/d compared to 10.7 m/d in the alluvium. The average linear velocity was also larger in the eolian sand with values ranging from 59.5 to 103.1 compared to 35.7 m/d in the alluvium.

The average Darcy flux (q) of 14.6 m/d was used to estimate the arrival time (Table 11). The average return time to cross section 1 was 190 days, 92 days to cross section 2, 234 days to cross section 3, and 534 days to cross section 4.

Groundwater contribution to streamflow

The vertical hydraulic gradient is a major determinant of the vertical flow and ultimately the groundwater contribution to streamflow. The vertical gradient was determined by placing a PVC pipe in the streambed and comparing the groundwater head to surface water head. The gradient was measured in the streambed in part to clarify the results from the vertical hydraulic gradient data from the nested piezometers, as well as gain information about the surface/groundwater interaction in the streambed.

The vertical hydraulic gradient was measured on September 7th and 28th, 2011 and March 30th, 2012. There was a positive vertical gradient for all cross sections on both dates in September (Table 12). Cross section 3 increased from 0.06 on Sept 7th to 0.08 on Sept 28th. Cross section 1 had a vertical hydraulic gradient of 0.06 on Sept 7th, which decreased to 0.01 on

Table 12: Groundwater contribution to daily flows in the South Platte River on September 7th and September 28th, 2011 and March 30th, 2012. Groundwater volume was calculated from vertical hydraulic gradient measurements made in the streambed at 4 cross sections. This was used in Darcy's equation using a vertical hydraulic conductivity of 33.3 m/d (Paschke 2011), and multiplied by the reach length to find the total groundwater contribution**.**

	September 7th 2011			**September 28th 2011**				**March 30th 2012**			
	XS1	**XS3**	**XS4**	**XS1**	**XS2**	**XS3**	**XS4**	**XS1**	**XS2**	**XS3**	**XS4**
Surface head (m)	0.41	0.40	0.40	0.34	0.27	0.12	0.13	0.36	0.21	0.30	0.27
Groundwater head (m)	0.44	0.42	0.42	0.35	0.30	0.16	0.15	0.36	0.25	0.19	0.26
Vertical gradient	0.06	0.06	0.04	0.01	0.06	0.08	0.04	0.00	0.08	-0.22	-0.02
Width (m)	25.3	22.6	27.7	24.7	33.3	43.3	28.0	17.5	17.7	23.3	17.3
Q (m^2/day) vertical flow	47.2	42.1	36.9	8.2	66.5	115.4	37.3	0.0	47.2	-170.7	-11.5
Reach length (m)	2625	3694	4599	2625	2707	3694	4599	2625	2707	3694	4599
South Platte discharge (m+/day)	492471	423706	413657	262820	311662	280005	341548	183168	183168	183168	183168
GW contribution (m^3/day)	123841	155402	169859	21590	180126	426096	171513	0	127657	-630533	-52985
% of surface water	25	37	41	8	58	152	50	0	70	0	0

Table 13: Variance of groundwater contribution to streamflow (m^3).

	XS1	**XS2**	**XS3**	**XS4**
Variance of Q	428232	441609	602624	727424

Sept 28th. Cross section 4 remained constant at 0.06 and 0.04, respectively, on both measuring dates.

Data from March 30th showed a positive vertical gradient of 0.08 for cross section 2 only (Table 8). Cross sections 3 and 4 had negative vertical gradients at -0.22 and -0.02, respectively. Cross section 1 measured a vertical gradient of 0, or no vertical flow.

The vertical hydraulic gradient was used in Darcy's equation to determine the vertical flow at each cross section. The mean horizontal hydraulic conductivity of 331 m/d calculated from the tracer study was divided by the anisotropy ratio of 9.9 (Paschke 2011) to determine the vertical hydraulic conductivity of 33 m/d (Equation 19). This value was used in all calculations. Therefore, vertical discharge values followed a similar pattern to the vertical gradient results (Table 12).

The vertical flow values were multiplied by the distance between cross sections to determine the groundwater volume over the reach length. The volumes on Sept 7th range from 123,841 to 169,859 m^3/d. By Sept 28th, the groundwater contribution in cross section 1 decreased to from 123,841 to 21,590 m^3/d. The volume in cross sections 3 and 4 increased from 155,402 to 426,096 m^3/d and 169,859 to 171,513 m^3/d, respectively. On March 30th, only cross section 2 showed a positive vertical gradient. The total groundwater contribution to surface water flows at cross section 2 was 127,657 m^3/d.

Daily volume of water in the South Platte River decreased by 144,000 m^3 from Sept 7th to Sept 28th. Discharge measurements were not taken on March 30th, so the daily average of 183,170 m^3/d measured from the Division of Water Resources at the Crook bridge was used (Colorado Division of Water Resources 2012). The groundwater contribution was divided by the water volume to determine the percent of streamflow that was groundwater. This amount ranged from less than 0 to 152% over all measuring dates. The percentage of groundwater in the surface water at cross section 1 decreased from 25 to 8% between Sept 7th to Sept 28th. Cross sections 3 and 4 increased from 37-152% and 41-50%, respectively. Cross sections 1, 3, and 4 decreased to less than 0% by March 30th 2012, while cross section 2 increased to 70%.

On both dates in September, the percentage of groundwater that contributed to streamflow in the lower cross sections was higher than cross section 1. Cross section 2 was not measured on Sept 7th. On Sept 28th the groundwater contribution from cross section 2 was 58%. By March 30th 2012, there was no indication that groundwater contributed to surface water flow at the lower cross sections.

Groundwater contribution to streamflow values varied by cross section and by date. The variances associated with the estimates of groundwater contribution to streamflow in the South Platte River for cross sections 1-4 were 428232, 441609, 602624, and 727424 m^3, respectively. These values are much larger than the estimates of groundwater contribution to surface water flows.

DISCUSSION

Streamflow

The original research plan called for discharge measurements at 4 cross sections during and after the target period (April-September). Discharge values measured between April and September would be compared to discharge values measured after the target period to determine stream augmentation. However, the 2011 streamflow was often unusually high and precluded in-stream discharge measurements due to safety considerations (Figure 5).

Estimates of groundwater travel time from the fluorescein tracer study suggest that recharge water arrived at the lower cross sections after the projected time. The return time for cross section 3 was 8 months. The return time for cross section 4 was greater than 1 year. All discharge measurement dates were assumed to be within the recharge window for analysis purposes.

A Student's t test of the six discharge measuring dates showed that there was not a significant increase in streamflow in the cross sections downstream of the recharge pond compared to the upstream cross sections. The exception was on Oct 28th 2010, where discharge in the downstream cross sections was significantly greater than discharge in the upstream cross sections (p-value < 0.05).

Error is inherent in stream discharge measurements. Sources of error can be random (such as uncertainties in cross sectional area, uncertainties in mean velocity, uncertainties in computation procedures), or systematic (such as calibration errors or improper use of equipment) (Sauer and Meyer 1992). There is also error associated with discharge measurements in sandbed streams. Sand bed streams have a high sediment transport capacity that can mobilize the streambed and alter the fluid properties of water (Sauer and Meyer 1992). One study of alluvial streams in Arizona found that the error associated with individual discharge measurements for an alluvial stream was 5% for flows less than 11 cms (400 cfs), and 7% for flows greater than 11 cms (Burkham and Dowdy 1970).

The average percent difference between the recorded discharge value at the Colorado Division of Water Resources (CDWR) and the measured discharge with FlowTracker® for cross sections 1-4 ranged from 2.4-27.0% for the 6 measuring dates. The CDWR gage is located at cross section 1, so if stream augmentation occurred, cross sections 3 and 4 would show a positive percent difference when compared to the data from the CDWR gage. However, regarding the CDWR gauging station as the "true" discharge is problematic, as the gage has an estimated error of 5-8% (Personal communication, 2012, CDWR). Additionally, a past study found large discrepancies in USGS 15-min rating curve discharge in timing and magnitude of discharge of gauges in close proximity to one another in sand bed rivers in New Mexico (Isaacson and Coonrod 2011). This raised concerns about the accuracy of sand-bed channel gauging, mainly because sand bed channels are subject to scour and fill. With a highly mobile channel, the ideal gauging site characteristics outlined by the USGS are difficult to meet, including a straight stream channel for 100 m upstream and downstream of the gauge, the presence of a pool upstream of the control at low stages, and no braiding (Rantz 1982).

Regardless of measuring error and sample size, it is unlikely that any water returning to the river from the recharge pond was measureable. The South Platte River Compact mandates that Colorado deliver 10,000 acre-feet to the Nebraska border between April and September, of which 3,000 acre-ft was delivered (Table 2). The South Platte River yielded 548,641 acre-ft during the 2011 water year (Colorado Division of Water Resource 2012). The total water volume between April and September was 273,663 acre-ft (Figure 6). This means that the volume of 3,000 acre-ft is approximately 1% of the total flow in the South Platte over the course of 5 months. This creates a difficult environment in which to measure the effects of managed groundwater recharge on surface water volumes. The error associated with individual discharge measurements for sand bed streams is 5-7%, which means that any measurement of augmentation can be contributed to error.

Stream depth

An increase in stream discharge generally led to an increase in cross sectional area. Channel surveys showed that all four cross sections were relatively incised, as indicated by the high bank angles. For this reason, all cross sections showed an increase in depth with higher discharge rates, and no lateral expansion. This is significant because native species of the area prefer shallow sandy habitat. One study performed in the Central Platte River Basin developed habitat suitability curves for 3 native species also found in the Lower South Platte River. These include the sand shiner (*Notropis stramineus*), red shiner (*Notropis lutrensis*), and plains killifish (*Fundulus zebrinus*). In the study, these species preferred habitats with sandy substrate and depths between 0.01 and 0.02 m (Conklin and others 1996). Based on the cross sectional data collected in this study, an increase in streamflow will not lead to an increase in usable habitat in the channel. An increase in discharge may actually decrease the amount of available habitat due to channel incision. However, an increase in discharge may also increase the availability of backwater habitats, which was not addressed in this study.

Groundwater flow

Nested piezometers were used to determine the vertical hydraulic gradient at the four cross sections. The vertical hydraulic gradient is positive under discharging conditions and negative under recharging conditions (Baxter and others 2003). If the Tamarack experiment delivered water to the river at the target place and time, the piezometers would show a positive vertical hydraulic gradient for the cross sections downstream of the recharge pond (cross sections 3 and 4) during April-September, with a noticeable drop in gradient after the target period. However vertical hydraulic gradient data suggests downwelling occurred at cross sections 2 and 3, and upwelling occurred only at cross section 4 (Baxter and others 2003). None of the cross sections showed a clear pulse of groundwater moving through the system.

Cross section 2 showed a downward gradient from April 2011 to June 2012. The gradient was highly responsive to changes in streamflow, meaning that an increase in streamflow caused a decrease in vertical hydraulic gradient. However, this contradicts the data from the groundwater contribution to streamflow. In-stream measurements of vertical hydraulic gradient at cross section 2 on Sept 7th and 28th 2011 showed a positive gradient, suggesting a gaining stream, but the nested piezometers showed a negative gradient for the same time period. This may reflect measurement error in total station equipment while determining the relative elevations of the nested piezometers.

Vertical hydraulic gradient data for cross section 3 was only calculated from September 1st, 2011 to June 6th, 2012 due to the theft of a pressure transducer and the unusable data from another. Cross section 3 had a downward gradient for all measurement dates with an observable increase in gradient at the end of September. After September, the gradient is less responsive to changes in streamflow. Like cross section 2, this is also contrary to data from in-stream measurements of vertical hydraulic conductivity.

Cross section 4 exhibited an upward gradient over the course of the sampling period (June 22nd 2011– June 6th 2012). This suggests that stream augmentation occurred during this time. The augmentation may be the result of water from the recharge pond, or the result of nearby irrigation.

The vertical hydraulic gradient of cross section 4 did not respond to changes in streamflow. This may be because the nested piezometers of cross section 4 are located at a farther distance from the South Platte River than the other cross sections, which may be less representative of the physical processes occurring between the surface and groundwater. One study found that groundwater heads in piezometers located further from the surface water showed less seasonal variation than river stage (Benner and others 2008).

Discrepancies exist between vertical hydraulic gradient calculated from the nested piezometers and the in-stream measurements of vertical hydraulic gradient for cross sections 2 and 3. The nested piezometer data from cross sections 2 and 3 suggest a losing stream, while the in-stream measurements suggest a gaining stream. Past studies have found vented pressure transducers to have a measuring error of 0.01 m (Sorensen and Butcher 2011), so the source is probably human error in the field. The Lower South Platte River is a gaining stream during the growing season due to irrigation return flows (Strange and others 1999), which is consistent with the in-stream measurements of vertical hydraulic gradient. This suggests that the discrepancy may stem from measurements of the relative elevations of the nested piezometers or that the flow field is more complex.

Several of the pressure transducers showed highly fluctuating values, which made it difficult to determine the true height of the water column. Cross sections 2, 3, and 4 showed initial fluctuation. This is because the vent caps were left on the pressure transducers, which interfered with the readings. The exception was the shallow piezometer of cross section 2, which began to fluctuate on November 9th through the rest of the sampling period. These fluctuations followed a 24 hour cycle, with the peak occurring at approximately 8 pm and the low occurring at 2pm. This pattern is typically associated with a plugged or covered vent tube. With a fixed amount of trapped air in the vent tube, temperature rises during the day and air expands in the vent tube. Conversely, temperature drops during the night and the air condenses (Personal communication, 2012, Stan Capps of In-Situ Inc.).

Groundwater direction may change seasonally with the hydrograph. For example, there is often a downward gradient with a falling limb of the hydrograph and upward gradient during a rising limb (Benner and others 2008). The shift in groundwater direction affects chemical and biological processes in the transitional area between the surface and groundwater ecosystems known as the hyporheic zone. Groundwater discharge to a gaining reach has been shown to limit the size of this area (Hucks Sawyer and others 2009). So while the Tamarack Project was designed to increase habitat for native aquatic species, it may alter important biological interchanges that occur in the hyporheic zone.

Water table elevation

Water table elevations were measured in the matrix of piezometers over the course of the tracer study. Pumping ceased on May 4th and the recharge pond was dry by May 5th, 2011. Water table elevations were used to develop potentiometric surface of the Tamarack site. While these maps agree with the stream depletion factor maps (water returned to the river toward cross section 2), they also suggest that groundwater returned to the river through other flowpaths (toward cross sections 3 and 4).

Water table elevations taken in the field showed a groundwater mound of 2 m moving through the upper eolian piezometers shortly after the pumps were shut off. However, the mound dispersed by the time it reached the middle and lower alluvium wells. There was an increase in water table at the lower alluvium wells between May 3rd and July 15th. However, data of groundwater elevation from the nested piezometers in the lower alluvium show that groundwater levels were very responsive to changes in streamflow (Figures 9, 11, and 13), so the increase in water table is most likely the result of an increase in discharge from the South Platte River.

Groundwater tracer study

Groundwater models of the Tamarack site are based on the assumption of a homogenous aquifer, which can limit the understanding of stream-aquifer interactions (Heeren 2010).

A fluorescein tracer study was used to estimate hydraulic conductivity and volumetric flow rate of groundwater at the Tamarack site. The average hydraulic conductivity was 331 m/d, which was used to calculate groundwater contribution to streamflow. The average Darcy flux was 14.6 m/d, which was used to calculate groundwater return times for multiple flow paths identified from the potentiometric surface maps. Estimates of hydraulic conductivity and Darcy flux were based on the breakthrough curves of fluorescein. Breakthrough curves are characterized by tracer first arrival time, peak time, center of tracer mass, and tailing

(McDermott and others 2008). These characteristics all reveal different things about groundwater behavior.

The first arrival time indicates the quickest flow time from the recharge pond to the well (Gamlin and Clark 2001). This can determine the degree of heterogeneity within the aquifer. The hydraulic gradient is the major driver of groundwater flow. Solute moved by this type of movement is referred to as advection (Sterret 2007). However, solute movement can also be influenced by other factors, such as hydrodynamic dispersion. Hydrodynamic dispersion, which includes mechanical mixing or dispersivity and molecular diffusion, can lead to a larger solute spread than would occur through advection alone (Fetter 2001).

Mechanical mixing is the result of velocity differences within the pore structure of the substrate. This may include size and arrangement of grains, as well as the degree of tortuosity of pore channels (Sterret 2007). Molecular diffusion, or chemical dispersion, is when solute moves from an area of high concentration to an area of low concentration. However, the effects of molecular diffusion are greatest in areas with low hydraulic conductivities and low hydraulic gradients. Tamarack is an area of high hydraulic conductivities as estimated by field measurements of 331 m/d (Table 10). Therefore molecular diffusion is not considered a strong determinant of solute spread.

If the processes of diffusion or dispersion were absent, the fluorescein dye would move through the soil column as a sharp front, referred to as piston flow. However, the resultant breakthrough curves from the tracer study do not reflect piston flow (Figure 20), which suggests a certain degree of heterogeneity in the aquifer. Many of the piezometers were not sampled in an appropriate timeline to capture the entire breakthrough curve. For example, the upper eolian sand piezometers that were sampled 2 days after the release only captured the tail end of the breakthrough curve. However it is difficult to determine if this is the actual groundwater travel time or the result of hydrodynamic dispersion. Furthermore, a small amount of dye was found in the carbon packet of cross section 1, even though the flow lines suggest that there was not a significant amount of water traveling in the northwestern direction.

The quick travel times and atypical distribution of the fluorescein tracer may also be the result of preferential flow paths. Previous research suggests the presence of a paleochannel running parallel to the South Platte River (Poceta 2005). In gravel alluvial systems, preferential flow paths (PFPs) can act as divergence zones in high flow events, allowing stream water to quickly enter the groundwater system, and as convergence zones or source in low flow events (Heeren 2010).

The peak arrival time used to estimate the average linear velocity is a measure of the average velocity of groundwater. The average linear velocity was used to estimate hydraulic conductivity and the Darcian flux at different locations throughout the Tamarack State Wildlife Area. Actual groundwater velocities are greater than the Darcian flux indicates because flow only occurs through the actual pore space and not through the entire cross section of the porous medium.

Some of the piezometers exhibit tailing. For example, piezometer 13d measured 0.03 ppb for many of the sampling dates. The water table elevation measurements support this assumption. Piezometers 13s, 13d, 17d, and 18d all showed a gradual decline in water table elevation after May 19th. This could have been the result of groundwater flowing through slower, deeper flow paths (Clark and others 2005).

It was difficult to determine which concentration values to consider zero. The initial background level taken from the South Platte River near cross section 1 measured a background concentration of 0.005 ppb while the surface water at the end of the study area near cross section 4 did not display any background concentrations. It is possible that some of the tailing could actually be background concentrations from other anthropogenic activities. For example, many brands of car antifreeze utilize fluorescein to detect leaks (McStay and Gordon 2007).

Some of the piezometers had multiple breakthrough curves. Piezometers T5 and T12 both showed a slight increase in dye on July 15th, while piezometer T13d showed an increase in dye on July 28th. Water table elevation data for T12 and T13d also showed a slight increase on these respective dates. T5 did not show an increase in potentiometric surface on July 15th. Multiple breakthrough curves may be indicative of multiple groundwater pathways leading to the piezometers (McDermott and others 2008).

While horizontal hydraulic conductivities are generally an order of magnitude greater than vertical hydraulic conductivity, vertical hydraulic conductivity may play a role in groundwater movement at Tamarack. One study found a strong correlation between travel times and vertical depths and no correlation between travel time and horizontal distance. Depth may be the most important factor influencing travel time because the deeper the piezometer perforation is, the more likely it is for the screen to be situated below layers with low hydraulic conductivity (McDermott and others 2008).

Many potential sources of error exist in the estimates of hydraulic conductivity. Initially the distance value used in the Darcy equation was measured between the recharge pond and the respective piezometers. However this greatly increased the hydraulic gradient of the piezometers that were located further away. This is because the estimate of hydraulic conductivity is a function of velocity, porosity, head, and distance traveled. With larger distance values, the resultant hydraulic conductivity value is small. This distance was adjusted in the analysis so that the distance of T5 was measured from 18d to T5, and the distance used for T12 was the measured distance between T5 and T12.

Estimates of groundwater travel time were better resolved for the upper piezometers due to the frequency of sampling dates as well as the density of piezometers. The piezometers were sampled 2 days after the dye was released, then again 6 days after the release. For T13d and T17d, the peak arrival time may have happened on day 1, or between days 3-5. So there was a potential misestimation of 3 days. For piezometer 18d, the peak arrival time may have occurred on day 3 or 5. The potential misestimation is only 1 day.

For the lower piezometers T5 and T12 the potential for error was much greater due to their distances away from the pond as well as the sampling frequency. T5 and T12 had shallower screen depths than the eolian sand piezometers, which often produced sediment-laden water samples. T5 only produced 2 sediment-free samples, on May 19th and July 15th. The value on May 19th was used as the date of the breakthrough curve. Water sample analysis for T12 suggests that the peak arrival time occurred on June 2nd. However, T12 did not produce a useable water sample on June 9th.

Results from the carbon packet analysis were difficult to evaluate. While the manufacturer states that carbon packets should register approximately 400 times the concentration of the water samples (Aley 2002), the datum from this study show values that were an order of magnitude lower, or 10 times the concentration of the water samples. While the values from the carbon packet analysis were difficult to evaluate, the results were nevertheless used to determine peak arrival time. Similar to the water sample analysis, carbon packet analysis for T12 suggests the peak arrival time occurred on June 2nd. However, because the carbon packets are an accumulation of dye, the peak occurred sometime between May 26th and June 2nd.

Carbon packet analysis of T5 differs from the water sample analysis. T5 shows the highest fluorescein concentration on June 9th, after the peak concentration of T12 (located further away) on June 2nd and to a lesser value. However, the water sample analysis shows the largest concentration occurred on May 19th. This suggests that the increase in fluorescein indicated by the carbon packet analysis on June 9th may be a secondary peak, and that the true breakthrough curve of T5 may have occurred near May 19th.

Groundwater contribution to streamflow

The groundwater contribution to streamflow in the South Platte River was greater in the downstream cross sections than the control cross sections for September 7th and 28th 2010. This suggests that augmentation may have occurred at cross sections 3 and 4. Measurements from the March 30th, 2012 sample suggest that the river is losing at the downstream cross sections (Table 12).

The recharge pond was designed to have the groundwater return to the river in 70-90 days. The results from this research agree with the estimate for cross section 2, which is the cross section perpendicular to the recharge pond. However, while some of the water appeared to move in a direction perpendicular to the river, there were also flowpaths moving in a northeastern direction. The estimated return rate at cross section 3 was approximately 234 days, or 8 months, while the return rate for cross section 4 was 534 days, or 18 months. This suggests that recharge returned to the river between the months of August and January for cross section 3 and possibly greater than a year later for cross section 4.

Results from the groundwater contribution study support this assumption. The groundwater volume in cross section 3 increases from 155,402 to 426,096 m^3/day between Sept

7th and Sept 28th. If recharge were occurring during the target time frame, there would be less groundwater volume at the end of September than the beginning.

Results suggest that groundwater contributed to streamflow at cross section 1 in September. However, it was difficult to determine the origin of this groundwater. There was not strong evidence from the water table contour maps that a significant amount of recharge is moving northwest in the direction of cross section 1. However, the carbon packet collected on June 17th from cross section 1 picked up trace amounts of fluorescein (Table 9), suggesting sample contamination, or that some recharge water moved toward cross section 1.

Estimates of groundwater contribution to streamflow from this analysis were large, sometimes exceeding the daily streamflow in the South Platte River. If these values were true, there should have been a measureable increase in streamflow in the downstream cross sections. The calculations of groundwater contribution to streamflow included several variables, which created many potential sources of error. The variance in groundwater contribution to streamflow was determined for each cross section. For cross sections 1-4 the values were 428232, 441609, 602624, and 727424 m^3, respectively. These values are larger than the estimates of groundwater contribution, which calls into question the utility of this method. Based on the equation for variance, the distance from the recharge pond was the largest determinant of groundwater contribution due to the sheer size of the numbers. Changes in the vertical hydraulic gradient made no difference in variance values.

Despite the high variance values, this analysis proved useful in determining the vertical hydraulic gradient of the streambed. The vertical gradient can be used to determine if the South Platte River is gaining during the target time window (April-September), and if the downstream cross sections are gaining more than the upstream cross sections. However, further studies are needed to determine a more accurate vertical hydraulic conductivity in the streambed. With a more representative vertical hydraulic conductivity, better estimates can be made about the groundwater contribution to streamflow.

CONCLUSIONS

Groundwater movement at the Tamarack State Wildlife Area is complex. Discharge and water table elevation data from this study suggest that the Tamarack Project did not produce a measureable increase in streamflow in the South Platte River between April and September of 2011. The groundwater tracer study and in-stream vertical hydraulic gradient data suggest that groundwater nevertheless contributed to streamflow, but the water returned to the river outside of the target time window.

Discharge measurements were taken at 4 cross sections on the South Platte River to determine if there was an increase in streamflow due to conjunctive use. There was not a significant increase in streamflow in the cross sections downstream of the recharge pond compared to upstream cross sections. The average flow of the upstream cross sections was 2.64 cms compared to 2.66 cms downstream.

The channel was surveyed over varying discharge rates to determine changes in depth and area. The cross-sectional profiles showed that all cross sections were somewhat incised as exhibited by high bank angles. Due to the channel shape and heavily vegetated banks, an increase in river discharge resulted in an increase in stream depth and no change to stream width.

Water table elevations were measured between May 3rd and September 28th 2011 with a matrix of piezometers in the Tamarack State Wildlife Area. These data were used to develop potentiometric surface maps of the area. Water pumping occurred between December 1st 2010 and May 4th 2011 into a pond with a volume of 2 acre-ft. Shortly after the pumps were shut off, water table elevations decreased 2-4 m in the deep eolian sand piezometers near the recharge pond (T13s, T13d, T17d and T18d) between May 3rd and July 15th 2011. The shallow piezometers (T16, T17s, T18s and T19) were dry by late May. Water table elevations in the middle alluvium piezometers (T5, T7, T11, and T12) increased between 0.5 and 1 m between May 19th and July 15th. Of the lower alluvium piezometers (cross sections 2-4) cross section 2 increased by 2.5 m, cross section 3 increased 1.5 m and cross section 4 increased 2 m between May 3rd and July 15th 2011. These data suggest a groundwater mound of approximately 2 m moved away from the recharge pond toward the lower alluvium piezometers. However, the increase in water table elevation in the lower alluvium piezometers is most likely a response to higher streamflows in the South Platte River.

Because groundwater flows downgradient, the potentiometric surface maps were used to identify the potential groundwater return flowpaths. The maps showed that groundwater returned to the river through multiple flowpaths toward cross sections 2, 3, and 4. This differs from the SDF model that was used to develop the Tamarack Project, which suggests that water moves toward the river using the shortest distance path. The potentiometric maps also suggest that cross section 2 is probably not upgradient of the recharge pond, as heads are greater at cross section 2 than the recharge pond.

The vertical hydraulic gradient was measured between April 2011 and June 2012 with nested piezometers at cross sections 2, 3, and 4 to determine groundwater flow direction. Cross section 2 had a noisy data set, but the moving average showed negative values ranging from approximately -0.02 to -0.08, suggesting a downward movement of groundwater. Cross section 3 also showed a downward gradient with negative values ranging from -0.01 to -0.03. Cross section 4 had a positive gradient, with values ranging from 0.02 to 0.03 suggesting upward movement of groundwater.

Fluorescein dye was used to estimate groundwater travel times and hydraulic conductivity. Five piezometers (T13s, T17d, T18d, T5 and T12) showed breakthrough curves of fluorescein concentration. Piezometers T13s, T17d, and T18d are located in the eolian sand near the recharge pond, while T5 and T12 are located in the alluvium. The peak arrival times from these curves were used to estimate average linear velocity, Darcy flux, and hydraulic conductivity. The average linear velocity was 65.7 m/d, the average Darcy flux was 14.6 (m/d), and the average hydraulic conductivity was 330.7 m/d.

The average hydraulic conductivity was used to estimate groundwater travel time. Groundwater return time for cross section 2, located 1340 m directly north of the recharge pond, was 92 days and matches the SDF return time estimate. However, the return time for cross section 3, located 3400 m in a northeast direction, was 234 days, or 8 months. The return time estimate for cross section 4, located 7776 m in the northeastern direction, was 534 days, or 18 months. These results suggest that groundwater returning to the river through alternate flowpaths (toward cross sections 3 and 4) arrived at the river outside of the target time window.

Measuring the vertical flow in the stream channel showed that groundwater contributes a large amount to streamflow during the fall. On Sept 7th 2011 this amount ranged from 123,841-169,859 m^3/d for cross sections 1-4, which comprised 25-41% of the daily streamflow. On September 28th 2011, the groundwater contribution ranged from 21,590-426,096 m^3/d, which comprised 8-152% of the daily streamflow. The downstream cross sections showed a higher contribution of groundwater during September, which suggests the augmentation is the result of recharge water. In-stream measurements on March 30th 2012 showed that only cross section 2 was gaining, or receiving, groundwater. Cross section 2 had a groundwater contribution of 127,657 m^3/d, which was 70% of the daily streamflow. Cross section 1 showed no vertical movement, while cross sections 3 and 4 were losing surface water to the aquifer. This suggests that the South Platte River is a gaining stream during the fall and a losing stream during the winter and early spring.

Measurements of discharge and water table elevations suggesting that Tamarack Project did not produce a measureable increase in streamflow in the South Platte River are not indicative of project functionality. The annual volume of water pumped into the recharge pond was 1% of the annual streamflow volume of the South Platte River. The error associated with individual discharge measurements for sand bed streams is 5-7%, meaning any measurement of augmentation can be attributed to error. While the volume of return flows did not produce measureable results in the river, data from the tracer study and in-stream vertical hydraulic gradient data suggest a gaining stream. The source of this return water may be from the recharge pond or from upstream irrigation return flows. This warrants further study into the source of the return flows, as well as more rigorous field studies into quantity of water returning to the river.

RECOMMENDATIONS

This study showed that groundwater contributed to streamflow in the South Platte River. However, the volume of water from the recharge pond was not large enough to produce a measureable augmentation in streamflow. As a result, the source of the return flows cannot be directly attributed to the Tamarack Project. A more rigorous quantification of groundwater return flows from the recharge pond versus irrigation return flows would provide further insight into the effectiveness of the Tamarack Project. This could also provide a template for measuring the effectiveness of small-scale augmentation projects across the state.

Measuring the vertical hydraulic gradient in the streambed proved a successful technique in quantifying vertical hydraulic gradient at 4 cross sections at the Tamarack State Wildlife Area. Increasing the number of these measurements would give more informative results about the effect of groundwater on streamflow over the course of the pumping season. These measurements, which are not limited by streamflow, could be made throughout the spring and summer. Future studies into the vertical hydraulic conductivity of the streambed would provide more accurate estimates of groundwater contribution to streamflow.

Improved subsurface imagery would aid in the overall understanding aquifer heterogeneity at the Tamarack site, and ultimately gain a better understanding of groundwater movement. Expanding on earlier geophysics work, the paleo-channel could be better identified through additional resistivity studies.

This research also showed that return water travels in a northeastern direction. Installing additional piezometers in the return flow paths in the alluvium east of the existing piezometers would supply additional information about return flows.

While this study suggests that the recharge pond did not increase habitat for desired native fish species, further studies could be conducted into backwater habitats along the downstream cross sections. This would determine if pumping increases refuge and/or spawning habitat for native species between April and September.

This research suggests that the recharge water is not reaching the South Platte River during the target time window. If water managers wish to have greater control of the recharge site, perhaps an aquifer storage and recovery model would be more appropriate. Ideally, this would entail lining a pond and covering with alluvium to minimize evaporation. The stored water could be released into the river at the appropriate time and in the desired amount.

Finally, in the 14 years that the Tamarack Recharge Project has been operating, the annual pumping volume has not exceeded 3,500 acre-feet, which is 6,500 below compact requirements. For the project to have a significant impact on downstream wildlife habitat, the project should operate at full capacity.

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APPENDIX

Table 14: Discharge measurement output table using Sontek® equipment for cross section 1 on October 7th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	10:57	13.78	0	0	0	0	0	0	0
1	10:57	14.23	0.061	0.6	0.024	0.3629	0.033	0.0118	0.4
2	11:00	14.84	0.159	0.6	0.063	0.5413	0.097	0.0523	1.9
3	11:02	15.45	0.213	0.6	0.085	0.6268	0.13	0.0815	3
4	11:04	16.06	0.259	0.6	0.104	0.7561	0.158	0.1194	4.4
5	11:07	16.67	0.29	0.6	0.116	0.6902	0.177	0.1218	4.5
6	11:09	17.28	0.457	0.6	0.183	0.7301	0.279	0.2035	7.5
7	11:10	17.89	0.457	0.6	0.183	0.7799	0.279	0.2174	8
8	11:11	18.5	0.274	0.6	0.11	0.7495	0.167	0.1253	4.6
9	11:12	19.11	0.305	0.6	0.122	0.7409	0.186	0.1377	5
10	11:14	19.72	0.198	0.6	0.079	0.649	0.121	0.0784	2.9
11	11:16	20.33	0.168	0.6	0.067	0.6641	0.102	0.0679	2.5
12	11:17	20.94	0.201	0.6	0.08	0.7148	0.123	0.0877	3.2
13	11:19	21.55	0.168	0.6	0.067	0.7002	0.102	0.0715	2.6
14	11:20	22.16	0.146	0.6	0.059	0.609	0.089	0.0543	2
15	11:24	22.77	0.122	0.6	0.049	0.5269	0.074	0.0392	1.4
16	11:25	23.38	0.122	0.6	0.049	0.5917	0.074	0.044	1.6
17	11:26	23.99	0.152	0.6	0.061	0.6576	0.093	0.0611	2.2
18	11:28	24.6	0.146	0.6	0.059	0.7242	0.089	0.0646	2.4
19	11:29	25.21	0.152	0.6	0.061	0.707	0.093	0.0657	2.4
20	11:31	25.82	0.189	0.6	0.076	0.6694	0.115	0.0771	2.8
21	11:35	26.43	0.274	0.6	0.11	0.6939	0.167	0.116	4.3
22	11:36	27.04	0.305	0.6	0.122	0.6735	0.186	0.1251	4.6
23	11:38	27.65	0.36	0.6	0.144	0.5595	0.219	0.1227	4.5
24	11:40	28.26	0.396	0.6	0.158	0.5889	0.242	0.1422	5.2
25	11:41	28.86	0.427	0.6	0.171	0.6664	0.26	0.1733	6.4
26	11:45	29.47	0.36	0.6	0.144	0.7326	0.219	0.1606	5.9
27	11:47	30.08	0.305	0.6	0.122	0.4622	0.186	0.0859	3.1
28	11:48	30.69	0.366	0.6	0.146	0.0909	0.223	0.0203	0.7
29	11:48	31.3	0	0	0	0	0	0	0

Table 15: Discharge measurement output table using Sontek® equipment for cross section 2 on October 7th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	13:49	3.81	0	0	0	0	0	0	0
1	13:49	3.87	0.085	0.6	0.034	0.0975	0.029	0.0028	0.1
2	13:52	4.48	0.165	0.6	0.066	0.2511	0.1	0.0252	1.1
3	13:54	5.09	0.229	0.6	0.091	0.473	0.139	0.0659	3
4	13:56	5.7	0.229	0.6	0.091	0.5916	0.139	0.0824	3.7
5	13:58	6.31	0.244	0.6	0.098	0.6685	0.149	0.0994	4.5
6	13:59	6.92	0.238	0.6	0.095	0.623	0.145	0.0903	4.1
7	14:03	7.53	0.335	0.6	0.134	0.5304	0.204	0.1084	4.9
8	14:05	8.14	0.457	0.6	0.183	0.636	0.279	0.1773	8
9	14:08	8.75	0.488	0.6	0.195	0.648	0.297	0.1927	8.7
10	14:09	9.36	0.29	0.6	0.116	0.6961	0.177	0.1229	5.6
11	14:10	9.97	0.244	0.6	0.098	0.6644	0.149	0.0987	4.5
12	14:12	10.58	0.335	0.6	0.134	0.7547	0.204	0.1543	7
13	14:25	11.19	0.259	0.6	0.104	0.7213	0.158	0.1139	5.2
14	14:27	11.8	0.259	0.6	0.104	0.7303	0.158	0.1153	5.2
15	14:28	12.41	0.244	0.6	0.098	0.7189	0.149	0.1068	4.8
16	14:29	13.02	0.274	0.6	0.11	0.6762	0.167	0.1131	5.1
17	14:30	13.62	0.28	0.6	0.112	0.7372	0.171	0.126	5.7
18	14:32	14.23	0.274	0.6	0.11	0.65	0.167	0.1087	4.9
19	14:33	14.84	0.268	0.6	0.107	0.6577	0.163	0.1075	4.9
20	14:35	15.45	0.259	0.6	0.104	0.516	0.158	0.0815	3.7
21	14:36	16.06	0.268	0.6	0.107	0.5287	0.163	0.0864	3.9
22	14:38	16.67	0.122	0.6	0.049	0.2827	0.074	0.021	1
23	14:40	17.28	0.046	0.6	0.018	0.1317	0.028	0.0037	0.2
24	14:42	17.89	0.046	0.6	0.018	0.0692	0.055	0.0038	0.2
25	14:45	19.69	0.091	0.6	0.037	0.0085	0.164	0.0014	0.1
26	14:45	21.49	0	0	0	0	0	0	0

Table 16: Discharge measurement output table using Sontek® equipment for cross section 3 on October 7th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	15:43	2.59	0	0	0	0	0	0	0
1	15:43	3.05	0.274	0.6	0.11	0.1262	0.146	0.0185	0.9
2	15:46	3.66	0.131	0.6	0.052	0.1688	0.08	0.0135	0.7
3	15:47	4.27	0.061	0.6	0.024	0.3787	0.074	0.0282	1.4
4	15:49	6.1	0.091	0.6	0.037	0.5182	0.111	0.0577	2.9
5	15:50	6.71	0.107	0.6	0.043	0.5646	0.065	0.0367	1.8
6	15:52	7.32	0.107	0.6	0.043	0.5958	0.065	0.0388	1.9
7	15:53	7.92	0.122	0.6	0.049	0.577	0.074	0.0429	2.1
8	15:54	8.53	0.168	0.6	0.067	0.5677	0.102	0.058	2.9
9	15:56	9.14	0.198	0.6	0.079	0.6329	0.121	0.0764	3.8
10	15:57	9.75	0.183	0.6	0.073	0.6547	0.111	0.073	3.6
11	15:58	10.36	0.183	0.6	0.073	0.6911	0.111	0.0771	3.8
12	15:59	10.97	0.198	0.6	0.079	0.7271	0.121	0.0878	4.4
13	16:01	11.58	0.183	0.6	0.073	0.6756	0.111	0.0753	3.8
14	16:02	12.19	0.207	0.6	0.083	0.6382	0.126	0.0806	4
15	16:03	12.8	0.183	0.6	0.073	0.6505	0.111	0.0725	3.6
16	16:04	13.41	0.213	0.6	0.085	0.6825	0.13	0.0888	4.4
17	16:05	14.02	0.223	0.6	0.089	0.6904	0.136	0.0936	4.7
18	16:07	14.63	0.229	0.6	0.091	0.7172	0.139	0.0999	5
19	16:08	15.24	0.244	0.6	0.098	0.6444	0.149	0.0958	4.8
20	16:09	15.85	0.259	0.6	0.104	0.732	0.158	0.1156	5.8
21	16:10	16.46	0.244	0.6	0.098	0.6183	0.149	0.0919	4.6
22	16:12	17.07	0.238	0.6	0.095	0.6386	0.145	0.0925	4.6
23	16:13	17.68	0.213	0.6	0.085	0.6401	0.13	0.0833	4.1
24	16:14	18.29	0.189	0.6	0.076	0.6266	0.115	0.0722	3.6
25	16:15	18.9	0.152	0.6	0.061	0.6999	0.093	0.065	3.2
26	16:17	19.51	0.122	0.6	0.049	0.6026	0.074	0.0448	2.2
27	16:18	20.12	0.116	0.6	0.046	0.5876	0.071	0.0415	2.1
28	16:19	20.73	0.116	0.6	0.046	0.6093	0.071	0.043	2.1
29	16:20	21.34	0.107	0.6	0.043	0.5525	0.065	0.0359	1.8
30	16:22	21.95	0.082	0.6	0.033	0.5066	0.05	0.0254	1.3
31	16:23	22.56	0.076	0.6	0.03	0.499	0.046	0.0232	1.2
32	16:24	23.16	0.076	0.6	0.03	0.4367	0.046	0.0203	1
33	16:25	23.77	0.076	0.6	0.03	0.3243	0.046	0.0151	0.8
34	16:26	24.38	0.061	0.6	0.024	0.2854	0.037	0.0106	0.5
35	16:28	24.99	0.055	0.6	0.022	0.2919	0.043	0.0125	0.6
36	16:28	25.94	0	0	0	0	0	0	0

Table 17: Discharge measurement output table using Sontek® equipment for cross section 1 on October 14th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	13:40	2.68	0	0	0	0	0	0	0
1	13:40	3.05	0.122	0.6	0.049	0.0264	0.078	0.0021	0.1
2	13:42	3.96	0.22	0.6	0.088	0.1187	0.201	0.0238	0.8
3	13:43	4.88	0.244	0.6	0.098	0.5694	0.223	0.1269	4.3
4	13:44	5.79	0.213	0.6	0.085	0.5873	0.195	0.1146	3.8
5	13:45	6.71	0.213	0.6	0.085	0.5949	0.195	0.1161	3.9
6	13:46	7.62	0.183	0.6	0.073	0.6632	0.167	0.1109	3.7
7	13:48	8.53	0.159	0.6	0.063	0.6071	0.145	0.088	3
8	13:49	9.45	0.137	0.6	0.055	0.6397	0.125	0.0803	2.7
9	13:50	10.36	0.152	0.6	0.061	0.6422	0.139	0.0895	3
10	13:51	11.28	0.152	0.6	0.061	0.6358	0.139	0.0886	3
11	13:53	12.19	0.152	0.6	0.061	0.6319	0.139	0.0881	3
12	13:54	13.11	0.152	0.6	0.061	0.6232	0.139	0.0868	2.9
13	13:56	14.02	0.198	0.6	0.079	0.5581	0.181	0.1011	3.4
14	13:57	14.94	0.213	0.6	0.085	0.5707	0.195	0.1114	3.7
15	13:58	15.85	0.213	0.6	0.085	0.6426	0.195	0.1254	4.2
16	13:59	16.76	0.198	0.6	0.079	0.6572	0.181	0.119	4
17	14:00	17.68	0.244	0.6	0.098	0.5423	0.223	0.1209	4.1
18	14:02	18.59	0.244	0.6	0.098	0.6237	0.223	0.139	4.7
19	14:04	19.51	0.32	0.6	0.128	0.5777	0.293	0.169	5.7
20	14:05	20.42	0.274	0.6	0.11	0.4972	0.251	0.1247	4.2
21	14:07	21.34	0.396	0.6	0.158	0.5269	0.362	0.1909	6.4
22	14:08	22.25	0.427	0.6	0.171	0.4966	0.39	0.1938	6.5
23	14:10	23.16	0.61	0.6	0.244	0.4572	0.557	0.2549	8.6
24	14:13	24.08	0.762	0.2	0.61	0.3952	0.465	0.1614	5.4
24	14:16	24.08	0.762	0.8	0.152	0.2999			
25	14:27	24.38	0.762	0.2	0.61	0.4746	0.348	0.1227	4.1
25	14:23	24.38	0.762	0.8	0.152	0.2297			
26	14:30	24.99	0.402	0.6	0.161	0.1061	0.276	0.0293	1
27	14:30	25.76	0	0	0	0	0	0	0

Table 18: Discharge measurement output table using Sontek® equipment for cross section 2 on October 14th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	11:49	2.74	0	0	0	0	0	0	0
1	11:49	3.35	0.335	0.6	0.134	0.1605	0.255	0.041	1.4
2	11:51	4.27	0.152	0.6	0.061	0.2894	0.139	0.0403	1.3
3	11:52	5.18	0.061	0.6	0.024	0.3602	0.056	0.0201	0.7
4	11:54	6.1	0.137	0.6	0.055	0.5146	0.125	0.0646	2.2
5	11:55	7.01	0.168	0.6	0.067	0.5688	0.153	0.0872	2.9
6	11:56	7.92	0.229	0.6	0.091	0.5446	0.209	0.1138	3.8
7	11:57	8.84	0.229	0.6	0.091	0.6319	0.209	0.1321	4.4
8	11:59	9.75	0.274	0.6	0.11	0.6053	0.251	0.1518	5.1
9	12:01	10.67	0.274	0.6	0.11	0.5985	0.251	0.1501	5
10	12:02	11.58	0.29	0.6	0.116	0.6202	0.265	0.1642	5.5
11	12:03	12.5	0.29	0.6	0.116	0.6676	0.265	0.1768	5.9
12	12:04	13.41	0.305	0.6	0.122	0.6739	0.279	0.1878	6.3
13	12:05	14.33	0.457	0.6	0.183	0.6788	0.418	0.2838	9.5
14	12:06	15.24	0.305	0.6	0.122	0.6972	0.279	0.1943	6.5
15	12:08	16.15	0.335	0.6	0.134	0.6942	0.307	0.2128	7.1
16	12:10	17.07	0.32	0.6	0.128	0.6085	0.293	0.1781	5.9
17	12:11	17.98	0.244	0.6	0.098	0.6479	0.223	0.1444	4.8
18	12:12	18.9	0.213	0.6	0.085	0.6867	0.195	0.134	4.5
19	12:14	19.81	0.198	0.6	0.079	0.6224	0.181	0.1127	3.8
20	12:15	20.73	0.183	0.6	0.073	0.5957	0.167	0.0996	3.3
21	12:16	21.64	0.152	0.6	0.061	0.6108	0.139	0.0851	2.8
22	12:17	22.56	0.137	0.6	0.055	0.5388	0.125	0.0676	2.3
23	12:19	23.47	0.122	0.6	0.049	0.5489	0.111	0.0612	2
24	12:20	24.38	0.137	0.6	0.055	0.4082	0.125	0.0512	1.7
25	12:21	25.3	0.122	0.6	0.049	0.3162	0.111	0.0352	1.2
26	12:23	26.21	0.091	0.6	0.037	0.0478	0.077	0.0037	0.1
27	12:23	26.97	0	0	0	0	0	0	0

Table 19: Discharge measurement output table using Sontek® equipment for cross section 3 on October 14th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	10:00	4.24	0	0	0	0	0	0	0
1	10:00	4.36	0.031	0.6	0.012	0.1907	0.005	0.001	0
2	10:02	4.57	0.137	0.6	0.055	0.0089	0.077	0.0007	0
3	10:04	5.49	0.259	0.6	0.104	0.3766	0.237	0.0892	3
4	10:05	6.4	0.274	0.6	0.11	0.6667	0.251	0.1672	5.6
5	10:06	7.32	0.274	0.6	0.11	0.657	0.251	0.1648	5.6
6	10:09	8.23	0.381	0.6	0.152	0.814	0.348	0.2836	9.6
7	10:11	9.14	0.457	0.6	0.183	0.6734	0.418	0.2815	9.5
8	10:13	10.06	0.533	0.6	0.213	0.5845	0.488	0.2851	9.6
9	10:14	10.97	0.503	0.6	0.201	0.6512	0.46	0.2995	10.1
10	10:15	11.89	0.442	0.6	0.177	0.796	0.404	0.3217	10.9
11	10:16	12.8	0.442	0.6	0.177	0.8345	0.404	0.3373	11.4
12	10:17	13.72	0.402	0.6	0.161	0.6931	0.368	0.255	8.6
13	10:19	14.63	0.366	0.6	0.146	0.653	0.334	0.2184	7.4
14	10:20	15.54	0.274	0.6	0.11	0.5871	0.251	0.1473	5
15	10:21	16.46	0.198	0.6	0.079	0.3835	0.181	0.0695	2.3
16	10:25	17.37	0.168	0.6	0.067	0.2254	0.153	0.0345	1.2
17	10:27	18.29	0.213	0.6	0.085	0.0393	0.195	0.0077	0.3
18	10:28	19.2	0.213	0.6	0.085	0.0074	0.195	0.0014	0
19	10:30	20.12	0.037	0.6	0.015	-0.0094	0.032	-0.0003	0
20	10:30	20.97	0	0	0	0	0	0	0

Table 20: Discharge measurement output table using Sontek® equipment for cross section 4 on October 14th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	8:10	14.33	0	0	0	0	0	0	0
1	8:10	14.63	0.091	0.6	0.037	0.2538	0.056	0.0141	0.5
2	8:17	15.54	0.213	0.6	0.085	0.4469	0.195	0.0872	3
3	8:18	16.46	0.305	0.6	0.122	0.6145	0.279	0.1713	5.9
4	8:19	17.37	0.335	0.6	0.134	0.6173	0.307	0.1893	6.6
5	8:21	18.29	0.366	0.6	0.146	0.6692	0.334	0.2238	7.8
6	8:22	19.2	0.335	0.6	0.134	0.809	0.307	0.248	8.6
7	8:24	20.12	0.28	0.6	0.112	0.6871	0.256	0.1762	6.1
8	8:25	21.03	0.244	0.6	0.098	0.5897	0.223	0.1315	4.6
9	8:26	21.95	0.213	0.6	0.085	0.5858	0.195	0.1143	4
10	8:27	22.86	0.183	0.6	0.073	0.5769	0.167	0.0965	3.3
11	8:29	23.77	0.168	0.6	0.067	0.5051	0.153	0.0774	2.7
12	8:31	24.69	0.183	0.6	0.073	0.6259	0.167	0.1047	3.6
13	8:32	25.6	0.207	0.6	0.083	0.6285	0.19	0.1191	4.1
14	8:34	26.52	0.274	0.6	0.11	0.6803	0.251	0.1706	5.9
15	8:35	27.43	0.457	0.6	0.183	0.6458	0.418	0.27	9.4
16	8:37	28.35	0.402	0.6	0.161	0.5761	0.368	0.2119	7.4
17	8:38	29.26	0.427	0.6	0.171	0.697	0.39	0.272	9.4
18	8:40	30.18	0.335	0.6	0.134	0.6349	0.307	0.1947	6.8
19	8:45	31.09	0.335	0.6	0.134	0.0334	0.255	0.0085	0.3
20	8:45	31.7	0	0	0	0	0	0	0

Table 21: Discharge measurement output table using Sontek® equipment for cross section 1 on October 28th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	12:43	12.19	0	0	0	0	0	0	0
1	12:43	12.5	0	0.6	0	-0.0009	0	0	0
2	12:44	13.41	0.031	0.6	0.012	-0.0109	0.028	-0.0003	0
3	12:45	14.33	0.152	0.6	0.061	0.058	0.139	0.0081	1.2
4	12:50	15.24	0.122	0.6	0.049	0.0662	0.111	0.0074	1.1
5	12:51	16.15	0.122	0.6	0.049	0.2167	0.111	0.0242	3.4
6	12:52	17.07	0.146	0.6	0.059	0.1063	0.134	0.0142	2
7	12:53	17.98	0.146	0.6	0.059	0.31	0.134	0.0415	5.9
8	12:54	18.9	0.213	0.6	0.085	0.3589	0.195	0.07	10
9	12:55	19.81	0.198	0.6	0.079	0.4383	0.181	0.0794	11.3
10	12:56	20.73	0.244	0.6	0.098	0.4227	0.223	0.0942	13.5
11	12:57	21.64	0.259	0.6	0.104	0.4591	0.197	0.0906	12.9
12	12:59	22.25	0.274	0.6	0.11	0.4012	0.167	0.0671	9.6
13	12:59	22.86	0.244	0.6	0.098	0.4405	0.149	0.0655	9.3
14	13:00	23.47	0.259	0.6	0.104	0.385	0.197	0.076	10.9
15	13:02	24.38	0.229	0.6	0.091	0.3114	0.209	0.0651	9.3
16	13:03	25.3	0.268	0.6	0.107	-0.0127	0.204	-0.003	-0.4
17	13:05	25.91	0.268	0.6	0.107	0.0001	0.094	0	0
18	13:05	26	0	0	0	0	0	0	0

Table 22: Discharge measurement output table using Sontek® equipment for cross section 2 on October 28th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	11:20	2.53	0	0	0	0	0	0	0
1	11:21	2.83	0.183	0.6	0.073	0.0998	0.139	0.0139	1.8
2	11:23	4.05	0.076	0.6	0.03	0.3812	0.093	0.0354	4.7
3	11:24	5.27	0.091	0.6	0.037	0.3982	0.111	0.0444	5.8
4	11:25	6.49	0.122	0.6	0.049	0.464	0.149	0.069	9.1
5	11:26	7.71	0.116	0.6	0.046	0.4732	0.141	0.0668	8.8
6	11:27	8.93	0.137	0.6	0.055	0.3124	0.167	0.0523	6.9
7	11:29	10.15	0.091	0.6	0.037	0.3394	0.111	0.0378	5
8	11:31	11.37	0.091	0.6	0.037	0.2476	0.111	0.0276	3.6
9	11:32	12.59	0.095	0.6	0.038	0.4062	0.115	0.0468	6.2
10	11:34	13.81	0.091	0.6	0.037	0.3369	0.111	0.0375	4.9
11	11:37	15.03	0.183	0.6	0.073	0.5133	0.223	0.1145	15.1
12	11:38	16.25	0.152	0.6	0.061	0.4521	0.186	0.084	11.1
13	11:39	17.47	0.152	0.6	0.061	0.508	0.186	0.0944	12.4
14	11:41	18.68	0.122	0.6	0.049	0.2333	0.149	0.0347	4.6
15	11:44	19.9	0.061	0.6	0.024	0.0018	0.074	0.0001	0
16	11:45	21.12	0.031	0.6	0.012	-0.0011	0.037	0	0
17	11:45	22.34	0	0	0	0	0	0	0

Table 23: Discharge measurement output table using Sontek® equipment for cross section 3 on October 28th 2010 .

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	10:00	3.96	0	0	0	0	0	0	0
1	10:00	4.15	0.085	0.6	0.034	0.0693	0.047	0.0032	0.2
2	10:01	5.06	0.061	0.6	0.024	0.168	0.056	0.0094	0.7
3	10:04	5.97	0.076	0.6	0.03	-0.0179	0.081	-0.0015	-0.1
4	10:05	7.19	0.076	0.6	0.03	0.3559	0.081	0.0289	2.1
5	10:07	8.11	0.229	0.6	0.091	0.4098	0.209	0.0857	6.2
6	10:08	9.02	0.274	0.6	0.11	0.493	0.251	0.1237	9
7	10:10	9.94	0.335	0.6	0.134	0.607	0.307	0.1861	13.6
8	10:11	10.85	0.305	0.6	0.122	0.6144	0.279	0.1712	12.5
9	10:12	11.77	0.29	0.6	0.116	0.6389	0.265	0.1692	12.3
10	10:13	12.68	0.305	0.6	0.122	0.5892	0.279	0.1642	12
11	10:15	13.59	0.32	0.6	0.128	0.5271	0.293	0.1542	11.2
12	10:17	14.51	0.213	0.6	0.085	0.4926	0.195	0.0961	7
13	10:18	15.42	0.122	0.6	0.049	0.5652	0.111	0.063	4.6
14	10:19	16.34	0.122	0.6	0.049	0.4551	0.111	0.0507	3.7
15	10:20	17.25	0.091	0.6	0.037	0.1669	0.084	0.0139	1
16	10:22	18.17	0.085	0.6	0.034	0.3741	0.078	0.0292	2.1
17	10:23	19.08	0.091	0.6	0.037	0.2931	0.084	0.0245	1.8
18	10:25	19.99	0.091	0.6	0.037	0.0015	0.084	0.0001	0
19	10:25	20.91	0	0	0	0	0	0	0

Table 24: Discharge measurement output table using Sontek® equipment for cross section 4 on October 28th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	8:36	13.62	0	0	0	0	0	0	0
1	8:37	13.9	0.006	0.6	0.002	0.3028	0.005	0.0014	0.1
2	8:40	15.12	0.183	0.6	0.073	0.5538	0.223	0.1235	8.2
3	8:41	16.34	0.213	0.6	0.085	0.6363	0.26	0.1656	10.9
4	8:42	17.56	0.213	0.6	0.085	0.6329	0.26	0.1647	10.9
5	8:43	18.78	0.168	0.6	0.067	0.5652	0.204	0.1155	7.6
6	8:45	19.99	0.122	0.6	0.049	0.4849	0.149	0.0721	4.8
7	8:46	21.21	0.107	0.6	0.043	0.4737	0.13	0.0616	4.1
8	8:47	22.43	0.091	0.6	0.037	0.4562	0.111	0.0508	3.4
9	8:50	23.65	0.116	0.6	0.046	0.431	0.141	0.0609	4
10	8:51	24.87	0.134	0.6	0.054	0.4992	0.163	0.0816	5.4
11	8:52	26.09	0.152	0.6	0.061	0.6013	0.186	0.1117	7.4
12	8:54	27.31	0.207	0.6	0.083	0.5626	0.253	0.1422	9.4
13	8:56	28.53	0.305	0.6	0.122	0.6457	0.325	0.21	13.9
14	8:57	29.44	0.274	0.6	0.11	0.5454	0.251	0.1368	9
15	8:58	30.36	0.274	0.6	0.11	0.0897	0.184	0.0165	1.1
16	9:00	30.78	0.122	0.6	0.049	0	0.052	0	0
17	9:01	31.21	0.122	0.6	0.049	0.0002	0.052	0	0
18	9:01	31.64	0	0	0	0	0	0	0

Table 25: Discharge measurement output table using Sontek® equipment for cross section 1 on November 4th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	13:43	12.5	0	0	0	0	0	0	0
1	13:43	13.41	0.031	0.6	0.012	0.0384	0.028	0.0011	0.2
2	13:45	14.33	0.122	0.6	0.049	0.018	0.111	0.002	0.3
3	13:46	15.24	0.122	0.6	0.049	0.2224	0.111	0.0248	3.7
4	13:47	16.15	0.122	0.6	0.049	0.2713	0.111	0.0302	4.5
5	13:48	17.07	0.137	0.6	0.055	0.342	0.125	0.0429	6.4
6	13:49	17.98	0.152	0.6	0.061	0.4309	0.139	0.06	9
7	13:50	18.9	0.168	0.6	0.067	0.4584	0.153	0.0703	10.5
8	13:51	19.81	0.152	0.6	0.061	0.4912	0.139	0.0685	10.3
9	13:52	20.73	0.213	0.6	0.085	0.4625	0.195	0.0902	13.5
10	13:53	21.64	0.198	0.6	0.079	0.4332	0.181	0.0785	11.8
11	13:55	22.56	0.213	0.6	0.085	0.4469	0.195	0.0872	13.1
12	13:56	23.47	0.244	0.6	0.098	0.0397	0.223	0.0089	1.3
13	13:57	24.38	0.274	0.6	0.11	0.4067	0.251	0.102	15.3
14	13:58	25.3	0.274	0.6	0.11	0.0263	0.209	0.0055	0.8
15	14:00	25.91	0.152	0.6	0.061	-0.0679	0.07	-0.005	-0.7
16	14:00	26.21	0	0	0	0	0	0	0

Table 26: Discharge measurement output table using Sontek® equipment for cross section 3 on November 4th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	11:16	9.75	0	0	0	0	0	0	0
1	11:16	10.06	0.091	0.6	0.037	0.2973	0.056	0.0166	1.6
2	11:17	10.97	0.244	0.6	0.098	0.4134	0.223	0.0922	8.8
3	11:18	11.89	0.274	0.6	0.11	0.5435	0.251	0.1363	13
4	11:19	12.8	0.274	0.6	0.11	0.5508	0.251	0.1382	13.1
5	11:20	13.72	0.274	0.6	0.11	0.5929	0.251	0.1487	14.1
6	11:22	14.63	0.229	0.6	0.091	0.5977	0.209	0.1249	11.9
7	11:23	15.54	0.244	0.6	0.098	0.5382	0.223	0.12	11.4
8	11:24	16.46	0.244	0.6	0.098	0.5354	0.223	0.1194	11.3
9	11:25	17.37	0.152	0.6	0.061	0.4281	0.139	0.0597	5.7
10	11:26	18.29	0.107	0.6	0.043	0.4122	0.098	0.0402	3.8
11	11:27	19.2	0.122	0.6	0.049	0.1371	0.111	0.0153	1.5
12	11:29	20.12	0.076	0.6	0.03	0.3618	0.07	0.0252	2.4
13	11:30	21.03	0.031	0.6	0.012	0.3051	0.028	0.0085	0.8
14	11:31	21.95	0.031	0.6	0.012	0.2374	0.028	0.0066	0.6
15	11:32	22.86	0.031	0.6	0.012	-0.0007	0.028	0	0
16	11:32	23.77	0	0	0	0	0	0	0

Table 27: Discharge measurement output table using Sontek® equipment for cross section 4 on November 4th 2010.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	9:59	14.33	0	0	0	0	0	0	0
1	9:59	14.63	0.031	0.6	0.012	0.3147	0.023	0.0073	0.6
2	10:01	15.85	0.183	0.6	0.073	0.3673	0.223	0.0819	6.8
3	10:02	17.07	0.189	0.6	0.076	0.5719	0.23	0.1318	11
4	10:03	18.29	0.183	0.6	0.073	0.5279	0.223	0.1177	9.8
5	10:04	19.51	0.122	0.6	0.049	0.4992	0.149	0.0742	6.2
6	10:08	20.73	0.085	0.6	0.034	0.3274	0.104	0.034	2.8
7	10:09	21.95	0.061	0.6	0.024	0.351	0.074	0.0261	2.2
8	10:10	23.16	0.061	0.6	0.024	0.3509	0.074	0.0261	2.2
9	10:11	24.38	0.046	0.6	0.018	0.3583	0.056	0.02	1.7
10	10:12	25.6	0.061	0.6	0.024	0.4222	0.074	0.0314	2.6
11	10:16	26.82	0.116	0.6	0.046	0.4587	0.141	0.0648	5.4
12	10:18	28.04	0.198	0.6	0.079	0.4858	0.242	0.1173	9.8
13	10:20	29.26	0.366	0.6	0.146	0.6811	0.334	0.2278	19
14	10:21	29.87	0.305	0.6	0.122	0.6797	0.186	0.1263	10.5
15	10:22	30.48	0.335	0.6	0.134	0.5538	0.204	0.1132	9.5
16	10:23	31.09	0.213	0.6	0.085	-0.0217	0.13	-0.003	-0.2
17	10:23	31.7	0	0	0	0	0	0	0

Table 28: Discharge measurement output table using Sontek® equipment for cross section 2 on November 18th 2010 .

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	15:36	2.44	0	0	0	0	0	0	0
1	15:38	3.05	0.274	0.6	0.11	0.0571	0.209	0.0119	0.2
2	15:41	3.96	0.518	0.6	0.207	0.0688	0.474	0.0326	0.5
3	15:43	4.88	0.549	0.6	0.219	0.4692	0.502	0.2354	3.6
4	15:44	5.79	0.488	0.6	0.195	0.6823	0.446	0.3043	4.6
5	15:47	6.71	0.564	0.6	0.226	0.7375	0.516	0.3803	5.8
6	15:50	7.62	0.549	0.6	0.219	0.6713	0.585	0.3929	6
7	15:52	8.84	0.32	0.6	0.128	0.2858	0.39	0.1115	1.7
8	15:55	10.06	0.518	0.6	0.207	0.7392	0.632	0.467	7.1
9	15:56	11.28	0.472	0.6	0.189	0.7113	0.576	0.4097	6.2
10	16:01	12.5	0.518	0.6	0.207	0.6752	0.632	0.4266	6.5
11	16:03	13.72	0.549	0.6	0.219	0.7302	0.669	0.4884	7.4
12	16:04	14.94	0.472	0.6	0.189	0.6346	0.576	0.3655	5.6
13	16:05	16.15	0.503	0.6	0.201	0.7816	0.613	0.4792	7.3
14	16:08	17.37	0.412	0.6	0.165	0.836	0.502	0.4194	6.4
15	16:09	18.59	0.457	0.6	0.183	0.6727	0.557	0.375	5.7
16	16:11	19.81	0.396	0.6	0.158	0.762	0.483	0.3681	5.6
17	16:12	21.03	0.351	0.6	0.14	0.7782	0.427	0.3325	5.1
18	16:13	22.25	0.351	0.6	0.14	0.5857	0.427	0.2503	3.8
19	16:14	23.47	0.305	0.6	0.122	0.6306	0.372	0.2343	3.6
20	16:16	24.69	0.29	0.6	0.116	0.6036	0.353	0.2131	3.2
21	16:17	25.91	0.366	0.6	0.146	0.3638	0.446	0.1622	2.5
22	16:19	27.13	0.305	0.6	0.122	0.3197	0.372	0.1188	1.8
23	16:19	28.35	0	0	0	0	0	0	0

Table 29: Discharge measurement output table using Sontek® equipment for cross section 1 on September 7th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	13:16	2.74	0	0	0	0	0	0	0
1	13:16	4.57	0.183	0.6	0.073	0.3254	0.307	0.0998	1.8
2	13:17	6.1	0.259	0.6	0.104	0.6774	0.395	0.2675	4.7
3	13:19	7.62	0.335	0.6	0.134	0.7759	0.511	0.3965	7
4	13:21	9.14	0.372	0.6	0.149	0.7122	0.567	0.4037	7.1
5	13:22	10.67	0.366	0.6	0.146	0.7674	0.557	0.4278	7.5
6	13:24	12.19	0.412	0.6	0.165	0.634	0.627	0.3976	7
7	13:25	13.72	0.427	0.6	0.171	0.6256	0.65	0.4068	7.1
8	13:26	15.24	0.427	0.6	0.171	0.6884	0.65	0.4477	7.9
9	13:28	16.76	0.579	0.6	0.232	0.7152	0.883	0.6312	11.1
10	13:29	18.29	0.579	0.6	0.232	0.7281	0.883	0.6426	11.3
11	13:30	19.81	0.366	0.6	0.146	0.5955	0.557	0.332	5.8
12	13:31	21.34	0.274	0.6	0.11	0.6611	0.418	0.2764	4.8
13	13:32	22.86	0.351	0.6	0.14	0.5712	0.534	0.3051	5.4
14	13:34	24.38	0.427	0.6	0.171	0.5226	0.65	0.3398	6
15	13:36	25.91	0.396	0.6	0.158	0.545	0.604	0.3291	5.8
16	13:37	27.43	0.168	0.6	0.067	-0.0199	0.179	-0.0036	-0.1
17	13:37	28.04	0	0	0	0	0	0	0

Table 30: Discharge measurement output table using Sontek® equipment for cross section 3 on September 7th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	11:00	22.86	0	0	0	0	0	0	0
1	11:00	21.95	0.046	0.6	0.018	0.255	0.056	0.0142	0.3
2	11:02	20.42	0.152	0.6	0.061	0.547	0.232	0.127	2.6
3	11:04	18.9	0.29	0.6	0.116	0.7725	0.441	0.3409	7
4	11:05	17.37	0.32	0.6	0.128	0.8435	0.488	0.4114	8.4
5	11:06	15.85	0.396	0.6	0.158	0.8021	0.604	0.4843	9.9
6	11:08	14.33	0.351	0.6	0.14	0.9105	0.534	0.4864	9.9
7	11:10	12.8	0.381	0.6	0.152	0.6651	0.581	0.3862	7.9
8	11:12	11.28	0.442	0.6	0.177	0.7787	0.674	0.5245	10.7
9	11:13	9.75	0.518	0.6	0.207	0.769	0.79	0.6073	12.4
10	11:15	8.23	0.442	0.6	0.177	0.8107	0.674	0.5461	11.1
11	11:16	6.71	0.427	0.6	0.171	0.7708	0.65	0.5012	10.2
12	11:17	5.18	0.305	0.6	0.122	0.5829	0.465	0.2708	5.5
13	11:20	3.66	0.259	0.6	0.104	0.234	0.395	0.0924	1.9
14	11:22	2.13	0.229	0.6	0.091	0.3137	0.348	0.1093	2.2
15	11:25	0.61	0.183	0.6	0.073	0.0117	0.167	0.002	0
16	11:25	0.3	0	0	0	0	0	0	0

Table 31: Discharge measurement output table using Sontek® equipment for cross section 4 on September 7th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	9:48	2.13	0	0	0	0	0	0	0
1	9:49	2.44	0.168	0.6	0.067	0.147	0.153	0.0225	0.5
2	9:51	3.96	0.305	0.6	0.122	0.4441	0.465	0.2063	4.3
3	9:53	5.49	0.213	0.6	0.085	0.41	0.325	0.1333	2.8
4	9:54	7.01	0.177	0.6	0.071	0.478	0.269	0.1288	2.7
5	9:56	8.53	0.183	0.6	0.073	0.5262	0.279	0.1467	3.1
6	9:57	10.06	0.137	0.6	0.055	0.5142	0.209	0.1075	2.2
7	9:58	11.58	0.122	0.6	0.049	0.5445	0.186	0.1012	2.1
8	10:00	13.11	0.137	0.6	0.055	0.5645	0.209	0.118	2.5
9	10:01	14.63	0.213	0.6	0.085	0.6619	0.325	0.2153	4.5
10	10:02	16.15	0.213	0.6	0.085	0.7174	0.325	0.2333	4.9
11	10:04	17.68	0.284	0.6	0.113	0.6186	0.432	0.2673	5.6
12	10:05	19.2	0.32	0.6	0.128	0.6302	0.488	0.3073	6.4
13	10:07	20.73	0.381	0.6	0.152	0.8474	0.581	0.492	10.3
14	10:08	22.25	0.427	0.6	0.171	0.7236	0.65	0.4706	9.8
15	10:09	23.77	0.366	0.6	0.146	0.8012	0.557	0.4467	9.3
16	10:11	25.3	0.366	0.6	0.146	0.7334	0.557	0.4089	8.5
17	10:12	26.82	0.457	0.6	0.183	0.8131	0.697	0.5665	11.8
18	10:14	28.35	0.488	0.6	0.195	0.5787	0.669	0.3871	8.1
19	10:17	29.57	0.284	0.6	0.113	0.1315	0.216	0.0284	0.6
20	10:17	29.87	0	0	0	0	0	0	0

Table 32: Discharge measurement output table using Sontek® equipment for cross section 1 on September 28th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	13:37	3.66	0	0	0	0	0	0	0
1	13:37	5.49	0.122	0.6	0.049	0.0557	0.223	0.0124	0.4
2	13:39	7.32	0.177	0.6	0.071	0.4179	0.323	0.1351	4.4
3	13:40	9.14	0.344	0.6	0.138	0.566	0.63	0.3565	11.7
4	13:41	10.97	0.442	0.6	0.177	0.6051	0.808	0.4891	16.1
5	13:43	12.8	0.533	0.6	0.213	0.6523	0.975	0.6363	20.9
6	13:45	14.63	0.32	0.6	0.128	0.5996	0.536	0.3217	10.6
7	13:47	16.15	0.274	0.6	0.11	0.6566	0.418	0.2745	9
8	13:48	17.68	0.201	0.6	0.08	0.6229	0.307	0.191	6.3
9	13:49	19.2	0.152	0.6	0.061	0.5827	0.232	0.1353	4.4
10	13:51	20.73	0.152	0.6	0.061	0.5454	0.232	0.1267	4.2
11	13:59	22.25	0.137	0.6	0.055	0.1176	0.209	0.0246	0.8
12	14:02	23.77	0.04	0.6	0.016	0.3444	0.06	0.0208	0.7
13	14:03	25.3	0.122	0.6	0.049	0.4372	0.186	0.0812	2.7
14	14:04	26.82	0.274	0.6	0.11	0.5663	0.418	0.2367	7.8
15	14:04	28.35	0	0	0	0	0	0	0

Table 33: Discharge measurement output table using Sontek® equipment for cross section 2 on September 28th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	9:09	1.83	0	0	0	0	0	0	0
1	9:10	2.13	0.284	0.6	0.113	0.0358	0.173	0.0062	0.2
2	9:12	3.05	0.274	0.6	0.11	0.2232	0.251	0.056	1.6
3	9:16	3.96	0.366	0.6	0.146	0.5868	0.334	0.1963	5.4
4	9:18	4.88	0.488	0.6	0.195	0.6687	0.52	0.3479	9.6
5	9:21	6.1	0.472	0.6	0.189	0.5409	0.576	0.3115	8.6
6	9:23	7.32	0.274	0.6	0.11	0.5781	0.334	0.1933	5.4
7	9:25	8.53	0.229	0.6	0.091	0.6349	0.279	0.177	4.9
8	9:27	9.75	0.168	0.6	0.067	0.5189	0.204	0.106	2.9
9	9:30	10.97	0.244	0.6	0.098	0.6756	0.297	0.2008	5.6
10	9:31	12.19	0.198	0.6	0.079	0.6283	0.242	0.1517	4.2
11	9:34	13.41	0.168	0.6	0.067	0.5323	0.204	0.1088	3
12	9:36	14.63	0.122	0.6	0.049	0.5455	0.149	0.0811	2.2
13	9:39	15.85	0.335	0.6	0.134	0.5778	0.409	0.2362	6.5
14	9:40	17.07	0.457	0.6	0.183	0.7216	0.557	0.4022	11.2
15	9:42	18.29	0.351	0.6	0.14	0.7162	0.427	0.3061	8.5
16	9:44	19.51	0.213	0.6	0.085	0.5975	0.26	0.1555	4.3
17	9:45	20.73	0.213	0.6	0.085	0.6374	0.26	0.1658	4.6
18	9:47	21.95	0.168	0.6	0.067	0.5257	0.204	0.1074	3
19	9:48	23.16	0.122	0.6	0.049	0.4265	0.149	0.0634	1.8
20	9:50	24.38	0.091	0.6	0.037	0.1167	0.111	0.013	0.4
21	9:51	25.6	0.061	0.6	0.024	0.2754	0.074	0.0205	0.6
22	9:53	26.82	0.031	0.6	0.012	0.227	0.037	0.0084	0.2
23	9:56	28.04	0.031	0.6	0.012	0.0851	0.065	0.0055	0.2
24	9:59	31.09	0.031	0.6	0.012	0.2562	0.065	0.0167	0.5
25	10:01	32.31	0.152	0.6	0.061	0.4103	0.186	0.0762	2.1
26	10:02	33.53	0.152	0.6	0.061	0.4074	0.186	0.0757	2.1
27	10:03	34.75	0.152	0.6	0.061	0.1456	0.123	0.0179	0.5
28	10:03	35.14	0	0	0	0	0	0	0

Table 34: Discharge measurement output table using Sontek® equipment for cross section 3 on September 28th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	10:44	0.3	0	0	0	0	0	0	0
1	10:46	2.74	0.098	0.6	0.039	0.0247	0.208	0.0051	0.2
2	10:48	4.57	0.125	0.6	0.05	0.0018	0.229	0.0004	0
3	10:51	6.4	0.061	0.6	0.024	0.0003	0.112	0	0
4	10:54	8.23	0.031	0.6	0.012	0.0046	0.056	0.0003	0
5	10:55	10.06	0.061	0.6	0.024	0.1204	0.112	0.0134	0.4
6	10:58	11.89	0.134	0.6	0.054	0.2721	0.245	0.0667	2.1
7	10:59	13.72	0.152	0.6	0.061	0.3624	0.279	0.101	3.1
8	11:01	15.54	0.152	0.6	0.061	0.4449	0.279	0.124	3.8
9	11:02	17.37	0.116	0.6	0.046	0.5572	0.212	0.118	3.6
10	11:06	19.2	0.152	0.6	0.061	0.6569	0.279	0.1831	5.6
11	11:07	21.03	0.152	0.6	0.061	0.6025	0.279	0.1679	5.2
12	11:08	22.86	0.168	0.6	0.067	0.6096	0.307	0.1868	5.8
13	11:10	24.69	0.134	0.6	0.054	0.3271	0.245	0.0802	2.5
14	11:11	26.52	0.101	0.6	0.04	0.4493	0.184	0.0827	2.6
15	11:12	28.35	0.067	0.6	0.027	0.5123	0.123	0.0629	1.9
16	11:14	30.18	0.122	0.6	0.049	0.284	0.223	0.0633	2
17	11:15	32	0.198	0.6	0.079	0.4213	0.362	0.1526	4.7
18	11:18	33.83	0.427	0.6	0.171	0.8191	0.52	0.4261	13.1
19	11:19	34.44	0.457	0.6	0.183	0.8602	0.279	0.2397	7.4
20	11:21	35.05	0.305	0.6	0.122	0.8107	0.186	0.1506	4.6
21	11:23	35.66	0.518	0.6	0.207	0.6603	0.316	0.2086	6.4
22	11:24	36.27	0.366	0.6	0.146	0.6949	0.223	0.155	4.8
23	11:26	36.88	0.442	0.6	0.177	0.6633	0.269	0.1787	5.5
24	11:27	37.49	0.381	0.6	0.152	0.6193	0.232	0.1438	4.4
25	11:28	38.1	0.274	0.6	0.11	0.5565	0.293	0.1628	5
26	11:30	39.62	0.122	0.6	0.049	0.5434	0.186	0.101	3.1
27	11:31	41.15	0.122	0.6	0.049	0.1141	0.186	0.0212	0.7
28	11:33	42.67	0.107	0.6	0.043	0.343	0.13	0.0446	1.4
29	11:33	43.59	0	0	0	0	0	0	0

Table 35: Discharge measurement output table using Sontek® equipment for cross section 4 on September 28th 2011.

Station	Time	Location	Depth (m)	%Dep	MeasD	Velocity (m/s)	Area (m^2)	Flow Q (cms)	% Q
0	12:18	1.83	0	0	0	0	0	0	0
1	12:18	2.74	0.259	0.6	0.104	0.1806	0.316	0.0571	1.4
2	12:19	4.27	0.259	0.6	0.104	0.4294	0.395	0.1696	4.3
3	12:21	5.79	0.168	0.6	0.067	0.4608	0.255	0.1177	3
4	12:23	7.32	0.131	0.6	0.052	0.3968	0.2	0.0793	2
5	12:24	8.84	0.101	0.6	0.04	0.4007	0.153	0.0614	1.6
6	12:26	10.36	0.116	0.6	0.046	0.4627	0.176	0.0817	2.1
7	12:27	11.89	0.116	0.6	0.046	0.5069	0.176	0.0895	2.3
8	12:28	13.41	0.116	0.6	0.046	0.4745	0.176	0.0837	2.1
9	12:29	14.94	0.137	0.6	0.055	0.5716	0.209	0.1195	3
10	12:31	16.46	0.213	0.6	0.085	0.6608	0.325	0.2149	5.4
11	12:32	17.98	0.192	0.6	0.077	0.6393	0.293	0.1871	4.7
12	12:34	19.51	0.22	0.6	0.088	0.6312	0.335	0.2111	5.3
13	12:35	21.03	0.238	0.6	0.095	0.6583	0.362	0.2385	6
14	12:37	22.56	0.305	0.6	0.122	0.6149	0.372	0.2285	5.8
15	12:39	23.47	0.396	0.6	0.158	0.6033	0.362	0.2186	5.5
16	12:41	24.38	0.494	0.6	0.198	0.7431	0.452	0.3355	8.5
17	12:42	25.3	0.518	0.6	0.207	0.6748	0.474	0.3197	8.1
18	12:44	26.21	0.463	0.6	0.185	0.6832	0.424	0.2894	7.3
19	12:48	27.13	0.64	0.6	0.256	0.7281	0.585	0.4262	10.8
20	12:49	28.04	0.61	0.6	0.244	0.6671	0.557	0.3719	9.4
21	12:51	28.96	0.427	0.6	0.171	0.1342	0.39	0.0524	1.3
22	12:51	29.87	0	0	0	0	0	0	0

Table 36: Total station output for cross section 1 for October 7th, 14th, and November 4th.

Oct 7 2010		Oct 14 2010		Nov 4 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5000	100.026	5000	100.1057	5000	100.8377
5006.678	100.1148	5010.166	100.7921	5000.897	100.4741
5015.887	99.69154	5011.25	100.4337	5001.983	100.0521
5016.538	99.67914	5012.114	100.0146	5010.881	99.98805
5017.36	99.63574	5021.285	99.94369	5011.489	99.90212
5017.656	99.61817	5021.641	99.89761	5012.186	99.84635
5018.072	99.63475	5022.003	99.86059	5012.992	99.80445
5018.381	99.6457	5022.312	99.85357	5013.453	99.79422
5018.704	99.61835	5022.623	99.82286	5014.019	99.81874
5019.003	99.62049	5023.009	99.79298	5014.657	99.80366
5019.254	99.62206	5023.509	99.77037	5015.178	99.79923
5019.628	99.65845	5023.882	99.72422	5015.658	99.79923
5019.871	99.6573	5024.257	99.73112	5016.163	99.78123
5020.191	99.6507	5024.575	99.73617	5016.814	99.7747
5020.489	99.67052	5025.012	99.77116	5017.311	99.76717
5020.805	99.68648	5025.388	99.76521	5017.736	99.74774
5021.102	99.67754	5025.726	99.75412	5018.235	99.75548
5021.446	99.68612	5026.242	99.74878	5018.766	99.76398
5021.798	99.69528	5026.642	99.74445	5019.264	99.74885
5022.114	99.70384	5027.066	99.74218	5019.652	99.7109
5022.357	99.6942	5027.385	99.73971	5020.105	99.71306
5022.783	99.71005	5027.79	99.74714	5020.447	99.70245
5023.029	99.70666	5028.193	99.67869	5020.987	99.69998
5023.332	99.7188	5028.625	99.68467	5021.438	99.66089
5023.623	99.72856	5029.164	99.66496	5022.009	99.67811
5023.965	99.72453	5029.579	99.66166	5022.501	99.6616
5024.261	99.71761	5030.038	99.63331	5022.991	99.65149
5024.585	99.72677	5030.414	99.64363	5023.445	99.63437
5024.884	99.73096	5030.779	99.62821	5023.94	99.64041
5025.258	99.71073	5031.258	99.6251	5024.36	99.66048
5025.476	99.69971	5031.635	99.61647	5024.815	99.84612
5025.824	99.69381	5031.962	99.61407	5025.158	99.97111
5026.178	99.69741	5032.361	99.65818	5025.567	100.2921
5026.491	99.68296	5032.63	99.57573		
5026.752	99.69959	5032.871	99.63864		
5027.012	99.69779	5033.225	99.6283		
5027.296	99.68896	5033.655	99.63593		
5027.636	99.66266	5033.859	99.63525		

Oct 7 2010		**Oct 14 2010**	
Location	**Elevation**	**Location**	**Elevation**
5027.975	99.70427	5034.114	99.54531
5028.255	99.67337	5034.382	99.57682
5028.608	99.68161	5034.864	99.68344
5028.929	99.65624	5035.106	99.7661
5029.176	99.65993	5035.672	100.0387
5029.575	99.66887	5035.977	100.3516
5029.92	99.65779	5061.082	100.119
5030.173	99.63757		
5030.407	99.64107		
5030.71	99.65368		
5031.02	99.6541		
5031.346	99.64832		
5031.693	99.65457		
5031.939	99.64482		
5032.293	99.57875		
5032.564	99.62243		
5032.899	99.61335		
5033.245	99.60651		
5033.609	99.60083		
5033.887	99.63032		
5034.17	99.5761		
5034.513	99.57165		
5034.69	99.5738		
5035.215	99.56258		
5035.573	99.48729		
5036.165	99.41952		
5036.504	99.4405		
5036.87	99.40871		
5037.242	99.32877		
5037.565	99.21281		
5038.001	99.16143		
5038.341	99.23381		
5038.676	99.51613		
5039.053	99.67673		
5039.438	99.76769		
5039.824	100.2659		
5040.273	100.0241		

Table 37: Total station output for cross section 2 for October 7th and 14th and November 4th and 18th 2010.

October 7 2010		October 14 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5000	99.15013	5000	100.0739	5000	100.019	5000	99.95017
5000.624	98.86261	5004.022	100.035	5000.582	99.94634	5004.538	99.81895
5000.975	98.64272	5004.973	99.19363	5000.966	99.17985	5005.083	98.95847
5001.246	98.52445	5005.946	98.70724	5001.619	98.86586	5005.228	98.90682
5001.576	98.6126	5006.323	98.56969	5001.893	98.61762	5005.601	98.72908
5001.914	98.66564	5006.707	98.65638	5002.477	98.59458	5005.872	98.63727
5002.207	98.72155	5007	98.65872	5002.761	98.6032	5005.918	98.62378
5002.543	98.75158	5007.307	98.68922	5002.969	98.58077	5006.298	98.49283
5002.853	98.76485	5007.614	98.696	5003.263	98.55352	5006.576	98.48375
5003.098	98.78093	5008	98.68451	5003.604	98.60296	5006.896	98.48758
5003.449	98.76975	5008.27	98.69682	5003.932	98.629	5007.207	98.46936
5003.753	98.77854	5008.596	98.67388	5004.239	98.63609	5007.486	98.42288
5003.938	98.70828	5008.82	98.65122	5004.565	98.60436	5007.81	98.49641
5004.371	98.69637	5009.201	98.67692	5004.836	98.61685	5008.138	98.52037
5004.706	98.69841	5009.537	98.65075	5005.149	98.60784	5008.435	98.51505
5005.063	98.68034	5009.789	98.66571	5005.575	98.60302	5008.743	98.48896
5005.321	98.67354	5010.169	98.64559	5006.049	98.60293	5009.086	98.51568
5005.603	98.65876	5010.486	98.65518	5006.369	98.59845	5009.401	98.51502
5005.975	98.64662	5010.87	98.63324	5006.712	98.58574	5009.692	98.44322
5006.176	98.63278	5011.073	98.64521	5007.074	98.5884	5009.967	98.39728
5006.614	98.63274	5011.412	98.64921	5007.52	98.55997	5010.242	98.43685
5006.951	98.60176	5011.657	98.64218	5007.981	98.55096	5010.605	98.50089
5007.254	98.60164	5011.945	98.62339	5008.222	98.51747	5010.877	98.49938
5007.534	98.57713	5012.185	98.61659	5008.567	98.54995	5011.224	98.46649
5007.836	98.5835	5012.498	98.6128	5008.907	98.56652	5011.496	98.47422
5008.142	98.58521	5012.803	98.64534	5009.202	98.58394	5011.801	98.50639
5008.554	98.57764	5013.173	98.64261	5009.504	98.66709	5012.163	98.46227
5008.811	98.56407	5013.401	98.66425	5009.804	98.68168	5012.426	98.48903
5009.144	98.57425	5013.798	98.67083	5010.171	98.69859	5012.803	98.50772
5009.394	98.57121	5014.155	98.67032	5010.452	98.695	5013.026	98.52644
5009.702	98.55619	5014.417	98.68089	5010.789	98.72208	5013.33	98.51144
5009.904	98.56367	5014.775	98.66688	5011.056	98.70718	5013.628	98.52007
5010.328	98.54899	5015.045	98.67735	5011.413	98.70453	5013.967	98.53532
5010.627	98.57694	5015.44	98.68634	5011.657	98.7042	5014.272	98.55087
5010.956	98.55829	5015.725	98.68826	5011.996	98.71285	5014.565	98.5334
5011.211	98.55198	5016.161	98.66562	5012.212	98.7083	5014.877	98.50252
5011.516	98.5593	5016.5	98.63575	5012.637	98.69001	5015.231	98.53499

October 7 2010		October 14 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5011.889	98.54267	5016.78	98.64305	5012.861	98.68471	5015.565	98.55684
5012.186	98.5401	5017.176	98.63654	5013.16	98.67659	5015.785	98.57996
5012.708	98.54595	5017.539	98.65019	5013.531	98.64365	5016.062	98.56699
5013.009	98.56255	5018.015	98.60304	5013.799	98.6147	5016.384	98.5664
5013.345	98.57885	5018.31	98.60507	5014.157	98.60165	5016.686	98.58664
5013.663	98.56793	5018.793	98.5715	5014.42	98.57175	5017.006	98.59962
5014.015	98.56637	5019.042	98.5739	5014.663	98.57906	5017.313	98.5894
5014.358	98.55003	5019.417	98.56857	5015.044	98.5577	5017.614	98.60488
5014.635	98.53318	5019.725	98.55968	5015.332	98.56083	5017.937	98.60793
5014.953	98.53755	5019.99	98.57296	5015.642	98.5646	5018.271	98.62807
5015.271	98.56182	5020.339	98.58097	5015.97	98.55858	5018.523	98.58124
5015.545	98.58321	5020.661	98.55804	5016.314	98.5664	5018.852	98.55344
5015.893	98.5713	5020.914	98.5448	5016.645	98.5693	5019.164	98.54692
5016.217	98.55998	5021.241	98.5482	5017.001	98.56961	5019.474	98.54748
5016.512	98.58616	5021.605	98.54945	5017.354	98.56695	5019.806	98.56073
5016.725	98.6065	5021.846	98.56015	5017.678	98.57789	5020.065	98.55766
5017.011	98.62134	5022.123	98.56305	5018.038	98.61761	5020.396	98.54672
5017.291	98.66212	5022.419	98.58316	5018.552	98.62625	5020.731	98.54807
5017.689	98.6582	5022.767	98.58498	5019.022	98.64403	5020.978	98.56915
5017.993	98.66394	5023.137	98.60952	5019.391	98.65637	5021.349	98.566
5018.342	98.66354	5023.402	98.64179	5019.94	98.69387	5021.641	98.57651
5018.681	98.69425	5023.734	98.67217	5020.331	98.72465	5021.94	98.58721
5019.045	98.68237	5024.028	98.6978	5020.68	98.74601	5022.249	98.63571
5019.384	98.71372	5024.349	98.71868	5021.459	98.75146	5022.548	98.6237
5019.671	98.71543	5024.636	98.71527	5021.971	98.75055	5022.864	98.65346
5019.951	98.71011	5024.922	98.7048	5022.439	98.73973	5023.172	98.63584
5020.291	98.71568	5025.539	98.71255	5022.974	98.73448	5023.457	98.674
5020.628	98.74126	5026.141	98.72998	5023.421	98.76565	5023.781	98.65656
5020.915	98.72189	5026.975	98.71763	5023.769	98.73786	5024.091	98.63966
5021.22	98.73663	5027.374	98.70481	5024.32	98.73475	5024.368	98.64276
5021.58	98.73851	5027.751	98.75549	5024.809	98.73146	5024.726	98.62371
5021.874	98.75431	5028.205	98.77595	5025.414	98.70988	5025.015	98.64389
5022.168	98.74808	5028.587	98.75216	5025.96	98.84374	5025.279	98.70336
5022.516	98.75605	5029.575	98.6999	5026.548	98.83166	5025.616	98.72954
5022.714	98.75616	5029.646	98.66792	5027.267	99.22574	5025.975	98.72533
5023.17	98.73248	5030.242	98.83029	5056.869	100.0656	5026.252	98.696
5023.322	98.73306	5031.457	99.22587			5026.561	98.65767
5023.673	98.7493	5060.944	100.0817			5026.865	98.69543
5023.915	98.7618					5027.174	98.70523

October 7 2010		October 14 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5024.253	98.79655					5027.498	98.74822
5024.585	98.78					5027.786	98.73604
5024.876	98.83743					5028.115	98.70856
5025.317	98.83677					5028.428	98.66694
5025.812	98.82278					5028.734	98.66894
5026.373	99.11065					5029.038	98.70759
5055.475	99.99235					5029.312	98.6962
5056.156	100					5029.638	98.72439
5058.435						5029.933	98.68899
						5030.248	98.78295
						5030.536	98.78828
						5030.882	98.92456
						5031.105	99.03027
						5031.532	99.36252
						5031.797	99.52919
						5032.014	99.63515
						5032.39	99.77375

Table 38: Total station output for cross section 3 for October 7th, 14th, 28th, and November 4th 2010.

October 7 2010		October 14 2010		October 28 2010		November 4 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5000	99.92484	5000	99.91278	5000	100.0926	5000	99.88324
5002.19697	99.78519	5002.192	99.7735	5005.722	99.97833	5000.558	99.7149
5003.10502	99.49885	5002.967	99.53624	5007.867	99.84046	5001.27	99.51275
5003.461	99.39772	5003.38	99.4303	5008.948	99.46841	5001.968	99.42479
5003.73604	99.33906	5003.704	99.37816	5009.35	99.42584	5002.824	99.46741
5003.75323	99.33653	5004.024	99.33639	5009.6	99.44212	5003.679	99.55157
5004.07831	99.3143	5004.324	99.32016	5009.955	99.45007	5004.334	99.48851
5004.40351	99.28553	5004.637	99.30271	5010.587	99.42359	5004.858	99.33976
5004.70021	99.27908	5004.996	99.28549	5010.894	99.43521	5005.317	99.27185
5004.98612	99.27148	5005.232	99.29042	5011.193	99.43526	5005.826	99.25896
5005.28964	99.28335	5005.575	99.27947	5011.458	99.45065	5006.193	99.22737
5005.59526	99.27905	5005.925	99.31211	5011.831	99.4986	5006.573	99.21834
5005.89925	99.28501	5006.177	99.30826	5012.088	99.47457	5007.004	99.21625
5006.22444	99.27515	5006.476	99.2525	5012.431	99.42079	5007.453	99.22559
5006.48445	99.25902	5006.874	99.23027	5012.689	99.30732	5007.838	99.21894
5006.79065	99.2042	5007.133	99.20488	5013.001	99.26459	5008.23	99.22652
5007.13982	99.10819	5007.429	99.18621	5013.318	99.26149	5008.581	99.24438
5007.43714	99.06953	5007.728	99.17846	5013.627	99.26323	5009.013	99.24184
5007.75642	99.03503	5008.009	99.12759	5013.882	99.2788	5009.438	99.23276
5008.05818	99.00844	5008.339	99.05627	5014.284	99.2246	5009.876	99.2315
5008.33044	99.00988	5008.647	99.01707	5014.573	99.20998	5010.23	99.22944
5008.67423	99.00225	5009.013	99.06489	5014.905	99.21139	5010.61	99.23806
5008.9386	99.02853	5009.288	99.0887	5015.168	99.18174	5010.999	99.24335
5009.2552	99.05913	5009.617	99.10086	5015.456	99.20426	5011.463	99.28559
5009.6022	99.10581	5009.921	99.06874	5015.819	99.20806	5011.85	99.31043
5009.6347	99.10767	5010.263	99.10249	5016.101	99.22808	5012.34	99.37738
5009.91713	99.12497	5010.514	99.1093	5016.332	99.24263	5012.844	99.41015
5010.23011	99.14789	5010.851	99.1212	5016.698	99.2534	5013.317	99.41084
5010.55668	99.17676	5011.129	99.14243	5017.043	99.23703	5013.72	99.3916
5011.14098	99.18584	5011.463	99.13522	5017.339	99.23935	5014.135	99.39793
5011.5089	99.19948	5011.804	99.12215	5017.691	99.23143	5014.603	99.41582
5011.77693	99.20665	5011.994	99.14462	5018.267	99.20019	5015.224	99.41876
5012.07244	99.19332	5012.391	99.15472	5018.56	99.18828	5015.651	99.45075
5012.39175	99.18565	5012.68	99.1498	5018.868	99.21017	5016.127	99.43867
5012.70383	99.18267	5012.986	99.13882	5019.192	99.28003	5016.435	99.45269
5013.02386	99.1932	5013.334	99.17558	5019.512	99.28876	5016.83	99.44553
5013.30088	99.18953	5013.599	99.21227	5019.908	99.32462	5017.167	99.40571

October 7 2010		October 14 2010		October 28 2010		November 4 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5013.60565	99.18055	5013.943	99.23024	5020.065	99.39026	5017.632	99.48179
5013.93231	99.18527	5014.263	99.26537	5020.446	99.41129	5018.089	99.65943
5014.22372	99.18306	5014.538	99.30752	5020.674	99.42903	5043.741	100.1117
5014.53008	99.19731	5014.837	99.34273	5021.088	99.40946		
5014.86121	99.18013	5015.09	99.33459	5021.258	99.38915		
5015.14961	99.17452	5015.435	99.37594	5021.646	99.31592		
5015.46573	99.17972	5015.758	99.3964	5022	99.39196		
5015.75972	99.16572	5016.033	99.39333	5022.282	99.40963		
5016.04014	99.2559	5016.363	99.41816	5022.546	99.42431		
5016.37982	99.32766	5016.681	99.39723	5022.833	99.42723		
5016.68645	99.35738	5016.976	99.35111	5023.233	99.43868		
5016.97479	99.39507	5017.252	99.32386	5023.562	99.44806		
5017.28022	99.38092	5017.628	99.42695	5023.855	99.44347		
5017.59967	99.36662	5017.937	99.4749	5024.108	99.43993		
5017.87593	99.35829	5018.263	99.51736	5024.397	99.37383		
5018.21868	99.38331	5018.479	99.53426	5024.816	99.39983		
5018.53209	99.4033	5018.783	99.54637	5024.95	99.4712		
5018.86646	99.41413	5019.099	99.49776	5025.717	99.72539		
5019.15795	99.34887	5019.474	99.43355	5051.269	100.1069		
5019.60461	99.29375	5019.717	99.5273				
5044.6714	100.0849	5020.097	99.65919				
5044.72427	100.2483	5045.66	100.0144				

Table 39: Total station output for cross section 4 for October 7th, 14th, 28th, and November 4th and 18th 2010.

October 7 2010		October 14 2010		October 28 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5000	99.74809	5000	99.95871	5000	100.0967	5000	99.68198	5000	99.97133
5000.5022	99.48384	5002.61911	99.80804	5004.93064	99.69344	5000.6441	99.40092	5003.75905	100.0295
5001.2327	99.41789	5003.06387	99.63174	5005.27768	99.48918	5002.0452	99.52549	5005.17003	99.48822
5001.6753	99.45035	5003.41709	99.51549	5008.83133	99.49957	5003.912	99.50214	5005.64843	99.29721
5002.1478	99.51986	5003.75652	99.48666	5015.59151	99.55983	5006.0814	99.61466	5005.91821	99.24708
5002.697	99.54361	5004.05488	99.49374	5016.36634	99.3924	5009.4595	99.58247	5006.31484	99.25858
5003.2208	99.52265	5004.34414	99.53585	5016.72327	99.33586	5011.0239	99.48511	5006.56642	99.2229
5003.7244	99.51062	5004.6292	99.56777	5016.96736	99.29597	5011.512	99.34742	5006.9048	99.24928
5004.2043	99.53796	5004.98121	99.56904	5017.2947	99.26896	5012.0905	99.27544	5007.2134	99.2509
5004.6895	99.58505	5005.24694	99.58477	5017.66515	99.21992	5012.3822	99.24463	5007.50999	99.31841
5005.3124	99.62149	5005.58006	99.59294	5017.88459	99.19734	5012.6879	99.22098	5007.80291	99.35563
5005.7867	99.64101	5005.90771	99.58267	5018.24079	99.20013	5013.005	99.20795	5008.13202	99.37726
5006.2514	99.64378	5006.21626	99.57366	5018.60281	99.21812	5013.2508	99.17201	5008.39983	99.36065
5006.7855	99.65073	5006.47457	99.58544	5018.87886	99.20633	5013.6218	99.18814	5008.72717	99.37228
5007.2646	99.64634	5006.80244	99.5957	5019.41105	99.21255	5013.8397	99.18905	5009.05397	99.36403
5007.7911	99.66876	5007.15271	99.61283	5019.79758	99.22133	5014.2038	99.18925	5009.33756	99.35704
5008.2867	99.64356	5007.38949	99.66005	5020.11223	99.22593	5014.5476	99.18026	5009.63016	99.35455
5008.7509	99.62689	5007.74272	99.68681	5020.39665	99.21158	5014.8432	99.20743	5009.95751	99.36841
5009.2854	99.60165	5007.98747	99.68745	5020.78452	99.23338	5015.1837	99.19912	5010.25769	99.39583
5009.8001	99.58586	5008.35617	99.69436	5021.12223	99.24186	5015.4331	99.21019	5010.61676	99.39425
5010.3313	99.55985	5008.65124	99.69788	5021.43125	99.24882	5015.7666	99.22235	5010.92045	99.406
5010.8237	99.58688	5008.99176	99.70551	5021.76364	99.26938	5016.1191	99.21515	5011.23202	99.39791
5011.4598	99.5708	5009.28371	99.70677	5022.04141	99.2803	5016.6172	99.24744	5011.51921	99.42094
5011.9744	99.46299	5009.62743	99.70444	5022.29234	99.28021	5017.0024	99.27907	5011.82528	99.36502
5012.5263	99.39003	5009.96736	99.71454	5022.5819	99.29897	5017.2947	99.27907	5012.14405	99.39336
5012.9892	99.34347	5010.31296	99.70833	5022.90823	99.31538	5017.551	99.28256	5012.46156	99.3979

October 7 2010		October 14 2010		October 28 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**	**Elevation**
5013.5446	99.287	5010.58859	99.70535	5023.18411	99.31195	5017.8937	99.30477	5012.75877	99.40058
5014.1041	99.24621	5010.96844	99.69538	5023.50064	99.32744	5018.1808	99.31206	5013.09668	99.38787
5014.6133	99.21826	5011.18798	99.69332	5023.77628	99.32886	5018.4943	99.32503	5013.37459	99.39326
5015.1283	99.19181	5011.52107	99.68439	5024.14489	99.33264	5018.8371	99.33447	5013.69295	99.40981
5015.6479	99.18794	5011.85624	99.67601	5024.41603	99.34102	5019.1323	99.33964	5013.96553	99.40582
5016.1262	99.21005	5012.17691	99.66159	5024.76958	99.35788	5019.3843	99.33762	5014.28382	99.34541
5016.6126	99.23428	5012.47043	99.62754	5025.0063	99.34989	5019.715	99.33894	5014.62217	99.3053
5017.1907	99.24125	5012.73829	99.59401	5025.34878	99.34499	5020.0419	99.32688	5014.96301	99.32533
5017.6967	99.26984	5013.04554	99.63237	5025.74818	99.34185	5020.3636	99.31734	5015.27401	99.28652
5018.2588	99.29408	5013.38913	99.65174	5026.03809	99.34039	5020.9156	99.32111	5015.59497	99.28737
5018.7204	99.30505	5013.69297	99.65279	5026.28258	99.32136	5021.2583	99.32532	5015.86012	99.21776
5019.1808	99.32743	5013.95009	99.59922	5026.63495	99.31073	5021.5982	99.31678	5016.18442	99.19794
5019.6931	99.33621	5014.26108	99.56306	5026.85645	99.31744	5021.8709	99.31783	5016.55159	99.17004
5020.1954	99.3607	5014.58058	99.50631	5027.24862	99.3057	5022.2245	99.30971	5016.82966	99.16082
5020.7397	99.37599	5014.87584	99.4773	5027.53755	99.30267	5022.5215	99.26953	5017.13068	99.13657
5021.2649	99.37829	5015.20289	99.4318	5027.97592	99.27931	5022.832	99.2587	5017.41426	99.12565
5021.7381	99.37786	5015.51781	99.4	5028.21757	99.28221	5023.1634	99.27203	5017.7824	99.10359
5022.2403	99.38425	5015.79475	99.38148	5028.50789	99.25721	5023.5331	99.24427	5018.12928	99.06891
5022.7041	99.37141	5016.13086	99.32573	5028.80785	99.25117	5023.9122	99.246	5018.40095	99.09552
5023.2129	99.34664	5016.41922	99.31786	5029.11066	99.27891	5024.3282	99.23132	5018.74897	99.12007
5023.7806	99.31992	5016.74044	99.31004	5029.42241	99.24901	5024.7389	99.22427	5019.13107	99.13941
5024.1949	99.27813	5017.03864	99.29218	5029.76433	99.22069	5025.2099	99.13704	5019.39035	99.13333
5024.7177	99.24807	5017.35002	99.28041	5030.02985	99.20528	5025.5559	99.08617	5019.6771	99.09448
5025.2184	99.20304	5017.68814	99.26624	5030.29708	99.20222	5025.8587	99.05535	5020.01453	99.10022
5025.7111	99.14531	5017.98849	99.27146	5030.69271	99.17178	5026.2507	99.00029	5020.28769	99.11336
5026.2265	99.12883	5018.25743	99.2755	5030.97292	99.14509	5026.8206	98.97294	5020.63987	99.12003
5026.7489	99.14383	5018.61282	99.28081	5031.31703	99.13608	5027.1189	98.97138	5020.96202	99.13273
5027.2421	99.15376	5018.89688	99.29626	5031.66732	99.10606	5027.4181	98.92566	5021.21621	99.13663

October 7 2010		October 14 2010		October 28 2010		November 4 2010		November 18 2010	
Location	**Elevation**	**Location**	**Elevation**	**Location**	**Location**	**Elevation**	**Location**	**Elevation**	**Location**
5027.7262	99.14365	5019.21593	99.29883	5031.944	99.12508	5027.7283	98.94632	5021.59911	99.10575
5028.213	99.08006	5019.51365	99.33045	5032.24771	99.11622	5028.0706	99.03225	5021.88787	99.14383
5028.746	99.12909	5019.84872	99.33021	5032.54419	99.09926	5028.4369	99.31113	5022.21965	99.13061
5029.3179	99.47235	5020.17963	99.34039	5032.8769	99.1102	5028.9434	99.72326	5022.6023	99.14752
5029.7861	99.85596	5020.48362	99.34975	5033.14503	99.12052	5062.3237	100.1278	5022.84305	99.14995
5030.1791	100.2398	5020.74848	99.35536	5033.42003	99.15743			5023.18858	99.14743
5030.6638	100.5098	5021.03884	99.3647	5033.81574	99.32363			5023.4408	99.14453
5065.2066	100.0309	5021.39417	99.39339	5034.22504	99.63298			5023.74836	99.14569
5065.273	100.0168	5021.67966	99.40241	5067.42721	100.1104			5024.02686	99.13472
		5021.96368	99.40066					5024.36193	99.14456
		5022.26264	99.40986					5024.61132	99.12649
		5022.59278	99.40994					5024.98716	99.1301
		5022.96445	99.42227					5025.32575	99.13692
		5023.25821	99.41697					5025.53844	99.1311
		5023.57665	99.43228					5025.94239	99.09489
		5023.85	99.41384					5026.26415	99.11157
		5024.20607	99.43971					5026.49605	99.10842
		5024.54484	99.43051					5026.82665	99.10339
		5024.83507	99.43005					5027.12451	99.08946
		5025.13893	99.41728					5027.45011	99.07244
		5025.47423	99.40036					5027.77688	99.09576
		5025.70337	99.37933					5028.08314	99.06377
		5026.02112	99.34864					5028.38235	99.02268
		5026.32865	99.34552					5028.68351	98.98411
		5026.7413	99.31494					5028.97732	99.02044
		5027.03745	99.31731					5029.26053	98.98172
		5027.33378	99.27491					5029.61047	98.99344
		5027.59327	99.24275					5030.01623	98.91675

October 7 2010		October 14 2010		October 28 2010		November 4 2010		November 18 2010	
Location	Elevation	Location	Elevation	Location	Location	Elevation	Location	Elevation	Location
		5027.98154	99.20631					5030.30101	98.87926
		5028.24181	99.18534					5030.55346	98.87045
		5028.54196	99.167					5030.78996	98.83731
		5028.87499	99.15254					5031.30515	98.78956
		5029.11943	99.15796					5031.56775	98.77034
		5029.4894	99.13717					5031.90021	98.73067
		5029.83372	99.13748					5032.1949	98.74632
		5030.10384	99.13144					5032.5201	98.71572
		5030.42625	99.16153					5032.87724	98.61168
		5030.74512	99.19517					5033.13886	98.63998
		5031.1055	99.18794					5033.46291	98.67746
		5031.39944	99.28277					5033.82454	98.73896
		5031.81798	99.54486					5034.1194	98.83449
		5032.17861	99.77451					5034.38857	99.06862
		5065.59733	100.2303					5034.61896	99.43916
								5034.92492	99.55582
								5035.33497	99.75202
								5035.82053	100.2619