STREAM/AQUIFER INTERACTIONS IN A SEMI-ARID EFFLUENT DEPENDENT RIVER: A CLOGGING CONCEPTUAL MODEL

by

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TABLE OF CONTENTS

ABSTRACT

Treated wastewater (effluent) has been used as a water source for aquifer recharge and sustaining perennial surface water flow. Artificial recharge basins allow effluent to seep into the ground relieving stressed aquifers. However, these basins frequently become clogged due to physical, chemical, and biological processes. Effluent is also used to replace baseflow for dry streambeds. However, little is known about the effect of effluent on stream-aquifer interactions. Effluent from the Nogales International Waste Water Treatment Plant sustains perennial flow in the Upper Santa Cruz River, Arizona. A series of monthly field campaigns were undertaken to understand the impact of effluent on the streambed at 16 different sites along a 30 km river reach. The field campaigns had two foci: physical transformations in the streambed and water source identification using chemical composition. Historic data sets including USGS stream gauging records, NIWTP outfall data, ADWR well transducer data and USGS well chemistry data were also analyzed to provide a larger context for the work. Results indicate that localized clogging forms in the Upper Santa Cruz River. The clogging layers perch the stream and shallow streambed causing a desaturation below the streambed. A clogging cycle is established in the context of a semi-arid hydrologic cycle: formation during dry and hot pre-monsoon months, and removal by a set of large flood flows (10+ m^3/sec) during the monsoon season. However, if the intensity of flooding during the semi-arid hydrologic cycle is lessened, the dependent riparian area can experience a die off.

INTRODUCTION

By their nature, arid and semiarid regions are water limited environments. Little precipitation, and high evaporation rates leave burgeoning populations dependent on groundwater for domestic, agricultural and industrial water needs (Llamas and Martinez-Santos, 2005). This reliance on groundwater aquifers has resulted in groundwater depletion and the desiccation of perennial rivers and riparian areas (Sophocleous, 2007).

Wastewater effluent increases as population increases. As such, it has been used to remedy both groundwater depletion and to support river restoration efforts (Brooks, 2006; Bouwer, 2002). To mitigate groundwater depletion, artificial recharge basins have been used to recharge effluent into aquifers. The range of artificial recharge methods and their associated problems have been detailed (Bouwer, 2002; Greskowiak et al., 2005). Effluent has also been used to supplement and replace baseflow in rivers (Brooks, 2006). However, there is an information gap regarding the impact that effluent-dependent rivers have on groundwater quantity and quality.

Artificial recharge basins are built to allow water to seep slowly into the ground, recharging the underlying aquifer. Artificial recharge basins often develop subsurface clogging, which limits aquifer recharge effectiveness. Clogging can develop as water moves through the surface and subsurface soil layers, decreasing pore size due to physical (particles settling out of the water), chemical (materials precipitating or gas becoming entrapped) or biological (algae or a biofilm forming) processes (Bouwer, 2002). Reduced pore sizes result in reduced infiltration rates and can lead to the development of an unsaturated zone in the subsurface beneath a ponded recharge basin (Bouwer, 2002; Greskowiak et al., 2005). Clogging is often remedied through a physical manipulation of the recharge basin; drying and scraping of the surface allows the flow of water through the soil to increase again for a period of time (Greskowiak et al., 2005).

Effluent dependent streams are defined as being “water bodies [that have] instream flows [that] are entirely dependent on effluent discharges” (Brooks, 2006). These systems are increasingly common as population increases and climate variability and change leads to frequent low flow conditions that are supplemented with effluent for river and riparian area sustainability (Sophocleus, 2007; Stromberg, 2001; and Smith 2000). In a Discharger Survey compiled in 1998 by the Arid West Water Quality Research Project (AWWQRP), there were 78 wastewater discharge sites considered effluent dependent or effluent dominant watercourses throughout the arid or semiarid west (Smith, 2000). Approximately two-thirds of these discharge sites (52 of 78) are put to some sort of restoration or preservation use (including: wildlife protection, recreation, and marsh rehabilitation), (Smith, 2000). However, little is known about effluent impacts on the streambed, stream/groundwater interactions, or the dependent riparian corridor. Given the prevalence of clogging in recharge basins it is evident that similar processes may occur in streams. This study will focus on addressing these issues with the following questions:

In effluent dominated rivers, does clogging exist and does it reduce streambed hydraulic conductivity?

What impact does the development of a clogging layer have on streambed infiltration and how does this alter the connection of the stream to the ground water system?

What is the relative importance of effluent as a water source to the riparian aquifer and how is this altered by the development of a clogging layer?

How do periods of stable low-flow and scour during high-flow flood events control the formation and removal of a clogging layer?

The Upper Santa Cruz River, an effluent dependent system in south central Arizona, provides an excellent opportunity to study the effluent-aquifer relationship and these questions. Physical stream measurements (piezometers, seepage pans and soil cores), water samples of the stream and aquifer, and historic data sets can be used to understand the hydrology of effluent dependent systems and the ramifications for the associated riparian ecosystem.

STUDY AREA

The Santa Cruz and San Pedro Rivers both sustain a riparian environment that is rare in semiarid southern Arizona. This project focuses on a 32 km effluent dependent reach of the Santa Cruz River. A 1 km reach of the natural baseflow San Pedro River was used as a control reach.

Santa Cruz River

The Santa Cruz River originates in the Canelo Hills of the San Rafael Basin, Arizona (Towne, 2003) traveling south 14 km crossing into Mexico and traversing approximately 56 km in Mexico. The river reenters Arizona 8 kilometers east of Nogales. The river then flows north by northwest for 140 km (Murphy and Hedley, 1984). Most of the Santa Cruz River is ephemeral except for a 5 kilometer perennial reach near Lochiel, Arizona and the parts of the river fed by effluent (Towne, 2003).

Fourteen km north of the international border, the Nogales International Waste Water Treatment Plant (NIWTP) treats water from the international twin cities of Nogales, Arizona and Nogales, Sonora. The plant releases effluent into the Upper Santa Cruz River streambed at a nearly constant rate generating flow (Nelson and Erwin, 2001). The treatment plant outfall to the Santa Cruz county line (approximately 32 km North) bounds the study area (named the SC study area in this work).

Climate

The Upper Santa Cruz Basin has a semiarid climate with a mean annual temperature of . 20°C and mean annual precipitation of approximately 40 cm (Nelson and Erwin, 2001; NOAA: http://www.ncdc.noaa.gov/oa/ncdc.html). Precipitation is distributed bimodally with the majority of rain falling during a summer monsoon season (50%, July through September) and a lesser winter rainy season (20%, typically December through February) with the rest distributed through the year (Coes et al., 2002; NOAA). Monsoon storms are of short durations, with intense local rainfall, inducing flooding; whereas, winter rains tend to be long lasting, low intensity storms with little runoff (Scott, 1997).

Geology/Hydrogeology

The Santa Cruz River flows through a wide alluvial basin that is part of the Basin and Range Province. The study area is bounded by the Pajarito, Atascosa, Tumacacori and Cerro Colorado Mountains to the west and the Patagonia, San Cayetano, and Santa Rita Mountains to the east. The width of the alluvial valley ranges from 8 to 30 kilometers (Coes et al., 2002). Three geologic formations dominate this river basin: the Nogales Formation, Older Alluvium and Younger Alluvium.

The Nogales Formation overlays bedrock and is a conglomerate composed of volcanic clasts (dominant), limestone, granite, sandstone and claystone (Coes et al., 2002; Gettings and Houser, 1997). The Nogales Formation is the least water productive of the three formations. Estimates of the hydraulic conductivity for the Nogales Formation range from 0.05-0.9 meters/day with a specific yield of approximately 5% (Nelson, 2007).

Older Alluvium, also known as basin fill, is comprised of a loose conglomerate of gravel, sand, silt and clay. It overlays the Nogales Formation or bedrock and blankets the valley (Murphy and Hedley, 1984). The Older Alluvium varies in thickness from a few meters atop bedrock to 260 meters in the northern most section of the study area (Gettings and Houser, 1997). The hydraulic conductivity of the Older Alluvium varies depending on the section of the basin (highest values in the north, lowest values to the east of the middle SC study area) but a general range for the hydraulic conductivity of the Older Alluvium is 0.3- 15 meters/day with a specific yield of 10% (Nelson, 2007).

The surficial Younger Alluvium surrounds the Santa Cruz River and some of its tributaries. It ranges in width from 1 to 5 kilometers (Scott, 1997; Nelson, 2007). The alluvium consists of unconsolidated cobbles, gravel and sand and is the thinnest of the formations being only 25 to 35 meters deep. The narrow band of Younger Alluvium overlays a small portion of the Older Alluvium (Coes et al., 2002). Estimates of hydraulic conductivity for the Younger Alluvium also vary depending on location within the basin (highest values in the south, lower values to the north) but range from 30-180 meters/day with a specific yield of 18% (Nelson, 2007).

The alluvial water table converges with the stream alluvium at discrete reaches along the SC study area. This convergence is evidenced by hydrographs and water chemistry suggesting gaining reaches at 10-15 and 20-24 km from the NIWTP outfall. Nelson (2007) and Coes (et al., 2007) both suggested that the water table intersects the stream channel for much of the distance from the NIWTP outfall to Tubac (20 km from outfall).

Surface Hydrology

The Upper Santa Cruz River is predominantly ephemeral, fed by precipitation, runoff events and washes. Tributaries of the study area include: Nogales Wash (the sole perennial contributor to the Santa Cruz River, fed by natural springs and sewage), Sonoita Creek, Aqua Fria Canyon, Peck and Josephine Canyons (Coes et al., 2002; Nelson and Erwin, 2001; Murphy and Hedley, 1984). In addition to ephemeral and perennial washes, the Upper Santa Cruz River receives water at a near constant rate from the NIWTP.

The Upper Santa Cruz River has two USGS stream gauges within the SC study area (at 20 and 35 km from NIWTP outfall, USGS gage numbers 09481740, and 09481770, respectively) and two more gages that bookend the SC study area (upstream at Nogales and 50 km from NIWTP outfall, USGS gage numbers 09480500, and 09482000, respectively). These stream gages (USGS stream gage data available at http://waterdata.usgs.gov/az/nwis) and the daily effluent information from the NIWTP provide a record of surface water flows that can be used to assess gains and losses to a 50 km reach of the river over the last 10 years.

Treatment Plant

The Nogales International Wastewater Treatment Plant (NIWTP) treats, on average, 60,000 m^3 of wastewater per day. The first stage in the treatment process entails settling basins and screens to remove large debris. During the second stage, the influent is aerated in two complete mix lagoons, and following that eight partial mix lagoons. The influent is then filtered again, disinfected with chlorine, and released in the Santa Cruz River streambed (IBWC brochure, 2004).

There are several properties of the NIWTP process that produce an interesting set of initial conditions for the Upper Santa Cruz River. First, the aerated lagoon process has a five day retention time, muting the peaks and valleys of daily water use and emitting a relatively constant flow. Second, although the plant was updated in 1992 and can treat up to 65,000 m^3/ day, the effluent leaving the plant has a high turbidity and nutrient load, including toxic ammonia levels (Sprouse, 2005). Thus, the effluent entering the dry channel at a constant rate is high in nutrients creating intense algal and biological productivity in the stream.

San Pedro River

The headwaters of the San Pedro River begin at Cananea, Sonora (Leenhouts et al., 2005). The river then travels 320 kilometers north by northwest through Sonora and Arizona to its confluence with the Gila River at Winkelman, Arizona (Leenhouts et al., 2005). The San Pedro River has both perennial and ephemeral reaches throughout its course.

Twenty-five kilometers north of the international border, the Arizona Highway 90 bridge spans the San Pedro River (31°33.111N, 110°08.324W). The study area (referred to as SP study area) for this project extends from the bridge one kilometer southward. This perennial stretch of the San Pedro River is part of a conservation area, the San Pedro Riparian National Conservation Area (SPRNCA). SPRNCA is managed by the Bureau of Land Management with the goal of protecting the river, and riparian corridor (Leenhouts et al., 2005).

Climate

The Upper San Pedro River Basin has a climate similar to the Upper Santa Cruz River Basin. Temperatures can range between -12°C and 42°C at Sierra Vista (NOAA). Mean temperature for the year is 19°C while the mean temperature for May-September is 24°C (NOAA). Precipitation patterns are bimodal with an average rainfall of just under 40 cm, 56% falling during the summer monsoon season (July, August, September) and 17% falling during the winter storm season (December, January, February) (NOAA).

Geology

The San Pedro River Basin, like the Santa Cruz River Basin, is part of the Basin and Range province. The SP study area is bounded by Mule Mountains to the east and the Huachuca Mountains to the west (Leenhouts et al., 2005). There are three main formations in the San Pedro Basin: the Pantano Formation, Upper Basin Fill and Lower Basin Fill units. In addition, the terrace deposits that overlay the upper basin fill will be discussed (Coes and Pool, 2005).

The Pantano Formation is the oldest and thickest of the formations. It overlies the bedrock and can range up to 900 m thick (Coes and Pool, 2005). It consists of semiconsolidated and consolidated conglomerate dating to the Oligocene (Leenhouts et al., 2005).

The Upper and Lower Basin Fill units overly the Pantano Formation. The Upper unit is comprised of weakly cemented sand, silt, gravel and clay (Coes and Pool, 2005). The Lower unit is made of interbedded, partially cemented gravel, sand, silt and clay (Coes and Pool, 2005). The Lower unit ranges in thickness from 45 to 90 m while the Upper unit is less than 120 m thick.

The terrace deposits consist of clay, silt, sand, and gravel and can be loosely classified in two groups: older and younger. Younger terrace deposits are the stream alluvium for the

San Pedro River and its tributaries. Older deposits composed of predominantly clay and silt can become local confining units adjacent to the San Pedro River (Coes and Pool, 2005).

Hydrology

All three formations have locally important water bearing units. Although the Pantano Formation is consolidated, fracturing has made the formation productive (Leenhouts et al., 2005). The Upper and Lower Basin Fill units are the major productive formations (Coes and Pool, 2005). Saturated younger terrace deposits are another water bearing unit. However, the older terrace deposits are predominantly dry outside the flood plain (Coes and Pool, 2005).

The SP study area is a perennial river reach. It is fed by groundwater which can be less than 1 m to more then 150 m below ground surface in the basin fill aquifer (Coes and Pool, 2005). There is extensive published information about the geology and hydrology of the San Pedro River (Coes and Pool, 2005; Leenhouts et al.. 2005).

METHODOLOGY

The main objectives of this project are to verify the existence of clogging in an effluent-dependent river, and then explore the ramifications of the clogging layer. These objectives were pursued using several methodologies. Soil cores were used to confirm or deny clogging and to assess changes to the saturated hydraulic conductivity caused by clogging. Piezometers and seepage pans were used in conjunction to create hydraulic profiles that would demonstrate the effects of clogging on streambed processes. Chemistry data from the river, wells and storms, collected in this study, as well as a wealth of historic data, were used to understand clogging in the larger context of the aquifer and riparian system. Finally, all data was used to explore the effects of low flow and flood flow periods on clogging.

Site Selection

Santa Cruz River

Field work along the Santa Cruz River focused on four main sampling locations. These four reaches were approximately 3, 15, 24, and 31 kilometers downstream of the NIWTP outfall (Figure 1). To collect a robust sampling of streambed conditions at each sampling location, four sampling points were established, each separated by 50 meters, for a total of 16 field measurements along the Santa Cruz River.

Sites were chosen for both situation and access. The four reaches in addition to being differing lengths from the NIWTP outfall had distinct characteristics. The 3 km reach starts as a run leading into a riffle with a mix forest/rangeland riparian environment. The 15 km reach begins at the end of a meander and is a run to the end of the reach; the vegetation is a robust riparian forest. The 24 km reach starts as a run, the streambed then widens, deepens and the river becomes a slow moving pool, the vegetation along this reach is transitional from forest to grassland. Finally, the 31 km reach is much like the 24 km reach, run to pool, the vegetation at 31 km, however, is minimal with a few isolated trees.

Synoptic Runs, Precipitation Events

Synoptic runs, stream grab sampling campaigns performed in a single day, were undertaken to investigate stream processes between primary reaches in an attempt to characterize a greater portion of the river. The sites included the four primary reaches and three additional sites, approximately 10, 18, and 19 km from the NIWTP outfall. In addition, two abbreviated synoptic runs including sites upstream of NIWTP outfall were performed during storm events.

Wells

Fifteen wells were sampled along the Santa Cruz River, 11 were sampled both pre, and post-monsoon. The wells, like the primary reaches, were chosen for access and distinct characteristics (Figure 1). Three wells lay to the east of the Santa Cruz close to the Santa Rita Mountains, these were chosen for the information they might provide about Santa Rita and Sonoita Creek groundwater recharge. Two wells lay to the west, one near Sopori

Wash to the north, and one near Agua Fria Canyon to the south, both ephemeral channels provide inputs to the Santa Cruz so samples were taken to provide possible end members. Five wells are in the riparian corridor surrounding the river. These samples were taken to understand the impact of the effluent dominated river on the aquifer water source. Finally, five wells are located above the NIWTP outfall. These wells were sampled to understand the aquifer response to storm inputs without effluent.

San Pedro River

The San Pedro River served as a control for this study. It is one of the few perennial rivers in southern Arizona and has been studied extensively by others (Leenhouts et al., 2005; Coes and Pool, 2005). Thus, a more limited sampling and analysis was conducted on the San Pedro.

The San Pedro River field work focused on one kilometer of the river. Three field sampling points were located at the top of the reach (south); three were located at the bottom of the one kilometer reach (north). The distance between the clustered points is 100 meters. As with the Santa Cruz, points were chosen for access and river characteristics. The top of the reach points have the following characteristics: the bottom of a riffle, a shallow, wide sunny pool, a deep shady pool. The bottom of the reach points from south to north have these characteristics: narrow run, deep run on a bend, wide shallow run under a bridge.

Field Work

Monthly sampling of the four primary reaches on the Santa Cruz River and the 1 km reach on the San Pedro included the use of piezometers and seepage pans at each point. Stream gauging and water sampling were also performed at the top and bottom of the reaches. Soil cores were taken twice before and twice after the monsoon season at every point on the Santa Cruz and at four of six points on the San Pedro River. (see Table 1 and Figure 3 for sampling schedule).

Soil Cores

Soil cores were taken to qualitatively and quantitatively assess the presence of clogging and the effect of clogging on saturated hydraulic conductivity (K_{sat}). Soil cores were collected by manually pounding 5.08 cm inner diameter, 25 cm in length plastic PVC pipes (type 1 schedule 40) into the streambed. The cores were then capped at the top. Next, a shovel was used to excavate around the core, revealing the bottom of the core so it could be capped. Finally, the cores were extracted from the streambed using the shovel (pers. comm. Paul Brooks and Marcel Schaap). The cores were then stored in a cold room until analyzed.

Soil cores provided a qualitative means of confirming the presence of clogging. Upon preparation for lab, analysis cores were examined and qualitatively confirmed to be clogging if they exhibited two traits: black sediments below a lighter colored topsoil and a harsh odor. These traits were highlighted by Laurel Lacher in her literature review of clogging layers for her 1996 PhD dissertation. “This **black odoriferous layer** [emphasis mine] is anaerobic…and has come to be known as a ‘schmutzdecke,’ which translates roughly from German to ‘dirty layer’” (Lacher, 1996).

The soil cores were then analyzed using a constant head soil core tank method. A detailed description of the experiment preconditions and design was written by W.D. Reynolds in *Methods of Soil Analysis Part 4* (2002) information was also provided by Karletta Chief (Chief, 2007; and pers. comm. 2007).

Piezometers and Seepage Pans

Piezometer and seepage pan data were used to study stream-aquifer interactions. Piezometers were used to observe the deep shallow streambed gradient, whereas, seepage pans were used to calculate flux through the streambed. The flux and gradient data were paired to create hydraulic profiles of the streambed. These profiles permit an interpretation of the impact of clogging on the shallow and deep streambed.

Piezometers were installed and removed during each sampling campaign at every point in the SC and SP study areas. Screened drive point piezometers 15.24 cm in length (Solinst model 615 N) were attached to 1.5 m stainless steel pipes and driven into the streambed using a rail driver. At each point, piezometers were coupled, one driven deep and one shallow (see Figure 4 for sampling schematic), to provide depth related information about the streambed (Kalbus et al., 2006). The piezometers were given twenty minutes to four hours to equilibrate. After equilibration, three measurements were taken from the top of the steel pipe: depth to stream water, depth to streambed and depth to water inside the pipe (Kalbus et al., 2006). The measurements inside the pipe were taken using a simple sounder that was marked and measured after removal from the pipe. All measurements have an assumed ± 1 cm error.

A seepage pan is a simplified seepage meter (Lee, 1977; Landon et al., 2001; Murdoch and Kelly, 2002; Kalbus et al., 2006) that was used at every point in the SC and SP study areas. A bottomless metal cylinder with a small threaded hole was pushed into the streambed (Kalbus et al., 2006), assumed to be on average 10 cm into the shallow streambed. Secured to the hole is a pipe elbow connected to a plastic bag (Figure 3) containing a specific volume of water. During the experiment, water is allowed to flow freely through the seepage pan and into or out of the bag while time was monitored (Murdoch and Kelly, 2002). At the end of the experiment, the volume of water in the bag was measured, and the amount of time that passed was recorded. Seepage pan experiments were performed at least three times at each point during every field campaign. All measurements were assumed to have ± 10 ml error.

Piezometer measurements generated gradient information: the height difference between water inside the pipe and the stream being the head difference, and the length of pipe below the streambed surface to the middle of the piezometer being the length difference (Figure 3) (Kalbus et al., 2006). Seepage pan measurements provided a flow into or out of the shallow streambed, by measuring the cross sectional area of the seepage pan flux data was generated. The flux and gradient data were used to determine gaining or losing conditions for the respective depths of the equipment at each sampling point.

Stream Gauging

The manual measurement of streamflow was performed at the top and bottom of all reaches to quantify gains and losses in the reach. Stream gauging was performed using the mid section method (Herschy, 1995). The stream width was measured and then divided into at least ten segments. Depth reading and velocity measurements were taken from the middle of each segment. The depth and velocity were applied to the width of the segment. A MMI Model 2000 Flo-Mate portable water flow meter produced by Marsh-McBirney Inc. was attached to a top-setting wading rod and used to measure stream velocity using standard methods (Marsh-McBirney, 1990). Stream gauging data was then compiled with streamflow data from the USGS, effluent flow from NIWTP and NOAA climate data to create water balances.

Historic Data Analysis

Historic data for the Upper Santa Cruz River exists including: NIWTP effluent outflow (IBWC unpublished data 2008), USGS stream gages, USGS well chemistry data, NOAA air temperature data, and ADWR well transducer data (ADWR unpublished data 2008). The NIWTP effluent outflow data and USGS streamflow data were paired and used to calculate a water balance for the length of the SC study area. The water balance assesses changes to the control volume of instream water. Inputs and outputs include: streamflow into and out of a reach, evaporation from the river, and a residual net-gain/loss to river water. There are two reaches for each year: a 0-20 km reach and a 20-50 km reach. The water balance year ranges from the monsoon of one year to the pre-monsoon season of the next year; the seasons are monsoon (July-September), winter (October-March) and pre-monsoon (April-June). Based on the length of the historic record, conclusions can be drawn about the changes in infiltration in time and space due to clogging and the impact of those changes on the aquifer and riparian area.

A water balance was calculated on a monthly basis for the instream control volume. The daily inflow and outflow data, provided by the NIWTP and USGS, were summed for the month. The evaporation rate (mm/day) was calculated for a day in the middle of the month and then applied to the surface area of the reach over the entire month. That evaporation rate was then subtracted from the difference between the stream inflow and outflow to generate the net gain-loss term for the river reach. This net gain-loss term value combines several water fluxes involving water gained or lost to the stream: transpiration, infiltration and exfiltration from the aquifer.

The calculation of evaporation required several assumptions to be made. The main assumption was that transpiration was consolidated with net gain-loss. This assumption was needed due to a lack of reliable vegetation information. Evaporation rate was calculated using two different methods: the Penman potential evaporation equation for open water and Hargreaves equation based solely on monthly temperature data (Shuttleworth, 1993; Mohan, 1991). The Penman equation uses extensive data including a wind function (an equation incorporating measurement height and wind speed), and cloud cover which was not available from the NOAA met station 15 km from outfall. However, calculation is not dependent on knowing the wind function, as it is only a fraction of the wind function that is added to a set value, before it is further processed in the Penman equation. In addition, the Penman equation is specifically for open water bodies (Shuttleworth, 1993). The Hargreaves equation, which is used to calculate reference crop evaporation (Shuttleworth, 1993), is to be calculated using solely extreme monthly temperature data, which is the only data collected by NOAA. So, evaporation was calculated using both equations and Penman had a consistently higher evaporation rate. As this exercise is being conducted to evaluate changes in net gain-loss through time, the net gain-loss term should be conservative. Thus, the Penman evaporation values assuming cloudless days were selected. A final assumption is that the river travels north by northwest, yet the latitude of the NOAA meteorological station 15 km from outfall was assumed for the entire river. The evaporation rate per month oscillated from approximately 4 mm/day in January to 11 mm/day in June.

The evaporation rate was then applied to each reach's surface area. That value was calculated using stream width measurements gathered during stream gauging. The width of the river was measured eight times, at the top and bottom of every primary reach during each of the eight field trips. The widest field measurement was then applied to the length of the river preceding and proceeding the measuring point. For instance, at the bottom of the 15 km reach the maximum width was 12.8 m (measured September 2, 2007). That width was applied to half the river distance between 15.15 km and 15 km (the measurement before) and half the river distance between 15.15 km and 24.4km (the next measurement site). In this manner, two distinct water bodies, one for the 0-20 km reach and one for the 20-50 km reach, for evaporation calculations were created.

The 0-20 km and 20-50 km reach distinction was made for three reasons. First, these (20 and 50 km) are the USGS stream gauges with the longest historical record. Second, it was hypothesized that clogging grows longitudinally downstream. Thus, by separating the reaches, a comparison of the start of the effluent river (0-20km) to the end of the effluent river (20-50 km) can be made. Third, an understanding can be developed about specific reach response to runoff events.

Water Quality

Water samples were taken from the NIWTP outfall pipe, the Upper Santa Cruz River and riparian wells to clarify the impact of effluent on the aquifer. Monthly campaign samples were taken at the top and bottom of the four primary reaches on the Santa Cruz, the NIWTP outfall and at the top and bottom of the 1 km San Pedro reach. In addition to the monthly sampling campaigns, water chemistry samples were taken during two monsoon events and twice during synoptic runs before and after the monsoon season. Sampling during the first monsoon event was at the receding limb of the storm flow and samples were taken from the primary sites. The second monsoon event sampling took place during recession from the main flow event. However, a secondary storm created a second, smaller peak during which samples were collected (Figure 2: 2007-2008 Hydrograph). All stream water samples were gathered from the thalweg of the river. Sample bottles were rinsed three times with river water before sample collection and were filled and capped underwater.

Well samples were also collected pre and post monsoon. Well samples, in most instances, were pumped with the specific purpose of sampling. However, some samples were taken from pipes or overflow tanks connected to windmills or pumps. These samples were from wells that were inaccessible (sealed by pump or windmill) except for overflow outlets. One to three casing volumes were pumped and sample bottles rinsed three times before gathering a sample.

After collection, all samples were kept cool and transported to the University of Arizona where they were filtered using a .2 µm membrane MCE filter and stored at 4°C in the dark until analyzed.

Chemical Analysis

Anions (F, Cl, NO_2, Br, NO_3, and SO_4) were analyzed using a Dionex Ion Chromatograph located at the Department of Hydrology and Water Resources at the University of Arizona following standard methods (Dionex, 2004). Detection thresholds were approximately 0.05 ppm for all anions. Due to high nutrient concentrations (NO_3 range: 0.486 – 158.395 mg/l) the water samples were diluted before analysis. Undiluted samples were run to check the accuracy of the diluted concentrations. In addition, duplicates and/or checks were run every eight samples to maintain quality control. Results indicate an error margin of less then 5% for concentrations greater than 1 ppm and 10% for concentrations above the detection threshold but below 1 ppm.

Stable isotopes ratios ($\delta^{18}O$‰ and $\delta^{2}H$‰) were measured using a Finnigan Delta S gas source isotope ratio mass spectrometer located in the Stable Isotope Laboratory of the Department of Geosciences following standard methods (Craig, 1957; Gehre et al., 1996). The analytical precision for $\delta^{18}O$‰ is 0.1% and 0.9% for $\delta^{2}H$‰. All samples with outlier values were rerun to ensure initial measurement integrity.

Mixing Model

Anion data from the Upper Santa Cruz River and the Santa Cruz Basin wells were used to quantify groundwater sources using a geochemical mixing model. The assumptions of the model are that the Upper Santa Cruz River is a strictly losing system with three chemically distinct water inputs: the perennial NIWTP effluent, and two seasonal flows: Sonoita Creek event runoff and other tributary event runoff.

The mixing model is a set of 3 linear algebraic equations used to estimate the partitioning of the aquifer’s water sources based on the chemical components of a sample. The analyzed wells included well samples obtained for this specific project and data acquired by the USGS from other Upper Santa Cruz Basin wells (USGS water quality data is available at http://nwis.waterdata.usgs.gov/usa/nwis/qwdata USGS well identification numbers are listed in Appendix A). All samples used from the USGS well database were taken after 1972, the date at which the NIWTP moved to its current location.

Mass Balance

Chloride data from the Santa Cruz River was used to create a water and chloride mass balance. The mass balance uses chloride concentration and stream discharge values to estimate the amount of water lost through the channel, then taking that loss and applying it to flow difference to determine evaporative loss. The mass balance was performed for the river reach starting at the NIWTP outfall and ending at the USGS stream gage 20 km downstream using the following equations:

$$\frac{Q_0 C_0 - Q_{20} C_{20}}{C_{ave}} = Q_{LOSS}$$

$$Q_0 - Q_{20} - Q_{LOSS} = Q_{EVAP}$$

Q_0 is flow from the NIWTP outfall. C_0 is the average chloride concentration from the outfall (49.76 mg/l). This approach was necessary as samples were not taken every month from NIWTP outfall, and the approach was possible as chloride concentrations from NIWTP varied little over time (mean: 49.76 mg/l; range: 49.76 $\pm$ .665 mg/l). Q_{20} is the flow at the 20 km from outfall stream gage. C_{20} is the chloride concentration for the 20 km gage, however samples were not taken at the 20 km stream gage, they were taken at the 15 and 24 km reach, so those values were averaged to create a chloride concentration estimate at the 20 km stream gage. C_{ave} is the mean chloride concentration for the 0-20 km reach. Q_{LOSS} is channel loss. Once channel loss is determined it can be subtracted from the difference in flow to obtain Q_{EVAP}, which is the evaporative loss.

RESULTS

Soil Cores

Saturated hydraulic conductivities (K_{sat}) from field collected soil cores were used to estimate changes in streambed conditions between the pre and post monsoon period. In addition to providing K_{sat} data, soil cores also provided a qualitative means of confirming clogging based on visual and olfactory characteristics, 14 of the 64 Santa Cruz soil cores were considered clogged. There were no clogged cores from the San Pedro River. Pre monsoon clogged cores were compared to post monsoon cores, as the post-monsoon cores include unclogged Ksat data, measured on two separate occasions, for all sample sites.

The descriptive statistics for the cumulative clogged cores indicate that clogging reduced the saturated hydraulic conductivity of the streambed (Table 2). In addition, the pre-monsoon clogged cores were compared to the post-monsoon clogged cores using the Wilcoxon rank sum test (Milton and Arnold, 2003). Results indicate, to a 97.5% confidence level, that the clogged cores have a lower K_{sat} value then unclogged cores.

The K_{sat} values of the soil cores were also assessed in the context of primary reach (3, 15, 24, and 31 km), sampling time (pre and post monsoon) and clogged status (pre-monsoon not clogged and clogged) (Figure 4). All of the clogged cores behaved as expected, the pre-monsoon clogged cores have a lower median than the post-monsoon cores. This result is further confirmed by another Wilcoxon rank sum test (Milton and Arnold, 2003) comparing the K_{sat} values clogged cores to all post-monsoon cores, by reach. The K_{sat} values for clogged cores at the 3 and 24 km reaches were significantly lower (alpha =0.025) than the post-monsoon cores. This result is indicative of the effect of the clogging layer on streambed hydraulic properties, especially for the 24 km reach, which had the most clogged cores (Table 3).

The K_{sat} values for clogged cores and post monsoon cores are not statically different at 15 and 31 km reaches . This result may be due to local conditions. The 31 km reach has only one clogged core (Table 3), creating too small a sample to test. This result might be because the distance from the NIWTP outfall lessens the effects of effluent. As for the 15 km reach, there are references (Scott 1997) to a gaining reach between 10 and 15 kilometers from the outfall. The upward pressure of water entering the system may hinder the production of a clogging layer.

There are two main facts to take from the soil core data. Soil cores qualitatively confirmed to have clogging were shown upon analysis to have lower mean and median K_{sat} values. These cores all occurred in the pre-monsoon period on the Santa Cruz River.

Streambed Hydraulic Profiles

Piezometer and seepage pan data were paired to create streambed profiles for the length of the river for each sampling trip (see appendix for all profiles). These profiles lend themselves to a discussion of the impact of clogging on the streambed and the impact of the stream on clogging (Figure 5).

Conditions in the shallow (0-10cm) streambed are considered gaining if water flowed into the stream from the ground (resulting in an increase in the volume of water in the seepage pan plastic bag). The shallow streambed was labeled losing if water flowed out of the stream into the ground (a decrease in the volume of water in the plastic bag), and hydrostatic if there was no water exchange (a less than 10 ml increase or decrease in the volume of water in the plastic bag). The deep streambed was measured using piezometers. The deep streambed is labeled gaining if water inside the piezometer has a higher total head (as measured by distance from the top of pipe attached to the piezometer) than the river water. It is labeled losing if water inside the piezometer has a lower total head than the river water. It is labeled unsaturated if there was no water in the piezometer, and hydrostatic if there was a less than 1 cm difference between the two head measurements.

February 2007 and June 2007:

The 3 kilometer reach showed gaining conditions in the shallow streambed despite losing or unsaturated conditions below. At 15.05 km from the NIWTP outfall there was an unsaturated layer with gaining conditions above. The 24 km reach was predominantly losing with the exception of the point 24.4 km from the outfall in February. Finally, the 31 km reach had mainly losing conditions and another unsaturated level 31.35 km from the outfall in February. In June both the 24km and 31km reach were dominated by hydrostatic conditions in the shallow streambed. There was no longer an unsaturated layer at 31.35 km in June, perhaps due to piezometer placement.

September 2007 and February 2008:

After the monsoon season (Figure 2: 2007-2008 Hydrograph) the dominant characteristic of the river during September was a restoration of losing conditions. At 3.05 km from the outfall, the shallow streambed was gaining while losing conditions prevail below and throughout the reach. Similarly, points 15.1, 24.45, and 31.3 km from NIWTP outfall had a similar gaining shallow streambed, deeper losing condition. As for February, there was a continuation of the overall losing trend with hydrostatic conditions dominating in the shallow streambed at the 31 km reach.

There are three pieces of evidence that can be drawn from this series of profiles. Before the monsoon period, there was a divergence between the conditions in the shallow and deep streambed. Pre-monsoon there were unsaturated areas underlying a full stream and a shallow streambed with gaining conditions (occurs three times in February 2007 and June 2007). After the monsoons, the shallow and deep streambed were in concurrence and there were no longer any unsaturated areas. Implying that large flows altered the streambed in some fashion.

Stream Gauging: Water Balance

Stream gauging data collected in the field was enhanced by NIWTP effluent data, USGS stream gage data, and NOAA temperature data to create an in stream water balance for all field excursions (see appendix for figure). Four water balances are presented (Figure 6).

The February 2007 water balance depicts water being conveyed downstream with some losses to infiltration (approximately half the water is lost over 31 kilometers). Evaporation averages a scant 4 mm/day in February. There were three gaining reaches 3.15-15 km, 20-24.4 km and 24.55-31.25 km.

The June 2007 water balance portrays a similar yet more intense version of February 2007. The river was consumed in 35 km. This condition was due in part to high transpiration, which as discussed in methods is assumed to be part of the infiltration term, evaporation averages 10 mm/day. During June there was only one gaining reach 20-24.4 km from the outfall.

The post-monsoon (September 2, 2007) water balance is distinct in that water was not lost throughout the river. The first 15 kilometers was dominated by a gaining reach. This phenomenon could be due to the monsoon storms that filled the aquifer, raised the groundwater level and contributed water to streamflow. However, net losses increased at the 15.15 km reach and the 24.55 km reach, with minimal losses in between. At the end of the 31.4 km reach only a fraction of flow remained.

The February 2008 water balance is unlike the February 2007 water balance. The first 15 km are in a roughly neutral state with no significant water being lost or gained. Then, on the 15.15-20 km reach approximately 30% of the instream flow was lost. Over the next 11 km (20-31.25 km), there was another rough neutral mass balance with only minor gains and losses to the system.

The stream gauging water balances raise questions. The river was gaining in some reaches, especially after monsoon events, suggesting a full aquifer able to add water inputs to the stream. February 2007 experienced only moderate losses to infiltration, and there is gaining. While, February 2008 exhibited a rough equilibrium with major losses occurring only during the 15.15-20 km reach. Thus, it would seem the February 2008 system was roughly hydrostatic, while the February 2007 system was losing.

Historic Data

Streamflow

Ten years of flow data was analyzed for the Santa Cruz River to understand the processes and conditions of the river over time. The hydrographs for the years 2004 and 2005 are explored in this section (Figure 7). Seasons are referred to in the following manner winter (January, February, March, October, November, December), pre-monsoon (April, May, June), and monsoon (July, August, September).

Early winter of 2004 had flow from NIWTP and at 20 km from the outfall that were similar. There was little infiltration occurring during those 20 km. Flow from 20 km to 35 km shows some losses, as there is approximately an order of magnitude difference between the two flows. As 2004 enters the pre-monsoon time period, storm events did not alter the baseflow conditions. During the pre-monsoon time, high evaporation removes water from the river, leaving it dry at 35 km, as shown in figure 8 as no flow from late May-July 2004. During the 2004 monsoon season, big storm events do not exceed 10 m^3/sec. In the time immediately following the monsoon season, flow at 35km decreased at first, but, then flow rate slowly increased. At the end of 2004, flow from the NIWTP, at 20 km, and 35 km were identical, implying few channel losses along the 35 km stretch of river.

Early winter 2005 showed a continuation of the late 2004 flow regime. Flow from the NIWTP at 20 and 35 km were the same showing no channel losses. In late winter of 2005 there was a new development, sustained daily flow at 50 km from the NIWTP outfall. During the pre-monsoon period, the sustained flow at 50 km stopped. However, there was still sustained flow at 35 km, indicating there was a lessening of the evaporation or transpiration effect that desiccated the river at 35 km in 2004. After a late start, the 2005 monsoon period produced flows exceeding 10 m^3/sec. After the monsoon season, flow from the NIWTP was consistent. However, there was an order of magnitude difference between the flow from NIWTP and at 20 km, and flow at 35 km and 50 km ceased. Thus, channel losses had increased dramatically.

Water Balance

The water balances for the 2004-2005, 2005-2006 and 2006-2007 (Figure 8) water years (as defined above) can extend this analysis. First, monsoon flow between the three years was different. The average monsoon flow on the 20-50 km reach for 2004 is less than half the monsoon flow for either 2005 or 2006. Second, the winter and pre-monsoon seasons following that low flow monsoon (2004-2005 graph) have water flowing out of the 20-50 km reach as streamflow in contrast to 2005-2006 and 2006-2007 when all water leaves the stream as infiltration or evaporation. Third, in 2004-2005, the inflow and outflow from the river in the 0-20 km reach during the winter closely matched implying little water was lost to infiltration during that time as compared to 05-06 and 06-07. The hydrograph and water balance are important in that it can be concluded decreased monsoon flow (2004) means longitudinally extended river flow the following year (winter and pre-monsoon season).

Transducers

Pressure transducers located at three wells within a 20 km radius of the NIWTP outfall monitor water elevation daily. That data was collected by ADWR for the calendar years

2004-2006 and compared to streamflow at 20 km from NIWTP outfall to illuminate the stream's impact on the aquifer (Figure 9).

The upstream well is located approximately 15 km upstream of the NIWTP outfall, within 200 m of the dry Santa Cruz River channel. The adjacent well is .5 km northeast of the NIWTP outfall. The downstream well is near the 20 km USGS stream gage and located within the confines a golf course. All three wells are thought to be in the alluvial aquifer.

Aquifer response is affected by patterns in the storm flow as seen in upstream and adjacent wells. In 2004, there were only two events exceeding 10 m^3/sec (Table 4), the events were separated by several months and all three wells had a muted response to subsequent moderate flow events. In 2005, there were several moderate flow events (Figures 7 and 9) before the monsoon season, but there was no aquifer impact until large flow events exceeding 10 m^3/sec occurred. In 2006, there were moderate events in the winter/ pre-monsoon time period with no aquifer response. But, similar to 2005, once there were a series of large flows exceeding 10 m^3/sec the aquifer responds. In 2006, there was more precipitation, lower cumulative stream flow, and fewer flows exceeding 10 m^3/sec (Table 4). The increased recharge, shown as aquifer response in Figure 10, and decreased cumulative streamflow (Table 4), indicates increased catchment recharge reducing overland flow to the stream, despite higher precipitation.

This effect of stormflow pattern while still present at the downstream well, was more muted. Thus, despite storm and flow events or lack of events, the aquifer there remained in rough stasis with only slight responses ($\pm$1 m) to large flow events.

There are two conclusions that can be drawn from the transducer data. First, the alluvial aquifer was impacted by streamflow: there was a response in aquifer levels during large flow events. Second, aquifer response was affected by patterns in storms. It appears that a set of large flows, (more than 2) exceeding 10 m^3/sec, and occurring within weeks of each other, are needed to prime the river for aquifer recharge, as occurred in 2005 and 2006. Then once primed, the aquifer responds to large and moderate flow events.

Water Chemistry

Water samples collected from the Santa Cruz River and nearby wells were analyzed for a range of anions and stable isotopes. Of all the concentration combinations, only sulfate and chloride had a linear relationship that appeared conservative and useful. This pairing showed three distinct water inputs that could be used in a mixing model to determine the dominant water sources for different segments of the aquifer (Figure 10a). The chloride data was also paired with flow data to create a mass balance of chloride over the first 20 km of the river. This pairing clarifies the partitioning of water losses from the stream over time.

Mixing Model

The mixing model has several initial assumptions: losing system, perennial NIWTP effluent flow (called Santa Cruz for this section), and seasonal flow from two sources: Sonoita Creek event runoff (called Sonoita Creek for this section) and event runoff from other tributaries (called tributary flow for this section). The tributary and Sonoita Creek flow occur during the monsoon season. During heavy flooding events, both surface water systems run and carry enough water to minimize the impact of effluent on stream chemical composition.

All end members were sampled numerous times and were collapsed into a single composite value to be used in the mixing model (Figure 10a). The Santa Cruz water, which was dominated by effluent, is one end member with a high (45+ mg/l) concentration of chloride and a similar concentration of sulfate. This composite includes outfall water, Nogales Wash water and non-event Santa Cruz River water. Nogales Wash water was not considered separately, as downstream of the NIWTP outfall, Nogales Wash water is part of the stream itself. Sonoita Creek water has a high sulfate concentration paired with a small chloride concentration. Samples were not taken from Sonoita Creek for this project but existing data was used (Gu, 2008). Sulfate and chloride concentrations for the event runoff samples were taken upstream of the NIWTP outfall during a monsoon storm. These samples have a low chloride, and low sulfate signature that provides the third end member (Figure 10a).

A water sample was defined water source dominant if that well was comprised of 50% or more of that source and was considered mixed if there was a less than 10% difference between constituent water sources. In addition, riparian wells were classified as those wells downstream of the NIWTP outfall within 1 km of the streambed all other wells were considered non-riparian wells.

Non-Riparian Wells

Applying the mixing model to non-riparian wells, shows that (Figure 10b and 11) wells in the Nogales Wash riparian corridor are a mixture of tributary flow and the Santa Cruz (ranging from 40-50% influence by each source). Wells to the west were dominated (90-95%) by tributary flow. The immediate water source of the aquifer is unknown as well samples from and immediately adjacent to the mountains (further to the west) show similar low chloride, low sulfate signatures (Murphy and Hedley, 1984). So water could be arriving to these wells as mountain front recharge or be recharged by tributary flow.

Wells upstream of the NIWTP outfall show a mixture of sources. Over half (6 of 11) of the upstream wells have tributary flow as a dominant input (52-80%). As these upstream wells (Figures 10b and 11) are along the dry Santa Cruz channel that sustains flow only during runoff events, it is reasonable the wells carry a tributary flow signature. One well measured twice, once before and once after the monsoon season, was Santa Cruz flow dominant. Two wells upstream of the Santa Cruz, Sonoita Creek confluence are dominated by Sonoita Creek water.

East wells are influenced by Sonoita Creek and tributary flow. Two wells are dominated by Sonoita Creek. The other well lies in the Santa Rita Mountains, the aquifer there seemingly fed by a mixture of surface runoff, tributary flow and mountain front recharge.

The analysis of the source waters for non-riparian wells leads to a discussion of stream flow paths and their temporal variability. Sonoita Creek and tributary flow both add to the system only during large storm events. During these events, the river downstream of the NIWTP outfall is a mixture of tributary and Sonoita Creek flow (Figure 10a). As the storm water recedes, the river downstream of the NIWTP outfall becomes a mixture of Santa Cruz, Sonoita Creek and tributary flow.

Santa Cruz River

The Santa Cruz River water also exhibited temporal variability. The constituent concentrations for the NIWTP outfall stayed constant over time (Cl range: 49.06-50.33 (mg/l), SO_4 range: 58.00-66.52 (mg/l)); however, the river water did not. The stream follows an enriched evaporation trend through time that was not dependent on the NIWTP outfall alone. Post monsoon samples, taken in September and October 2007 track close to the outfall concentrations. At this point the entire ecosystem was reset by large event flows. There are some indications of additional water inputs downstream from the NIWTP outfall. The most noticeable example stems from the September 5, 2007 sampling trip, chloride concentration decreased from 49-43 (mg/l) and sulfate stayed roughly the same between the 3-15 km reach.

February 2007 and February 2008 sample results exhibit similar trends. The March and April samples extend further above the mean outfall value. The pre-monsoon samples taken during June and July have the highest concentrations of chloride and sulfate.

This pattern of enriched evaporation has two possible explanations. First, during September, immediately following the monsoon runoff events, parts of the aquifer were fully recharged creating gaining areas in the stream (3-15 km reach). Throughout the rest of the year, evaporation and transpiration rates were variable, increasing with increasing temperature, creating the evaporation trend discussed above. Second, bank storage could explain the pattern. Large runoff events add water to stream flow, and some of that streamflow was stored adjacent to the river. During subsequent months, Santa Cruz River water flowed downstream but also intermingled with bank storage. That bank storage water had higher concentrations of chloride and sulfate as the water has been subjected to evaporation and transpiration. Thus, NIWTP concentrations remained the same while the stream concentrations increase in a semi step manner throughout the year and throughout the river. This process ends with a new monsoon season, as the large event runoff pushes out the existing bank storage, replacing it with new event runoff. However, it is impossible to test these theories as samples from the outfall were only taken from September 2007-February 2008 due to access issues.

Riparian Wells

Riparian wells 10-20 km from the NIWTP outfall were dominated (50-70%) by Santa Cruz water (Figure 10c). Excepting one sample taken in the middle of the monsoon, which shows a heavy Sonoita Creek influence, and wells to the west of the river. Western wells much like the non-riparian wells were dominated (94%) by tributary flow (Figure 11). Several pieces of data indicate the water source for these wells originates as mountain front recharge. First, like the other west wells, the aquifer is near mountains that have similar water signatures (Murphy and Hedley, 1984). Second, the USGS (Coes et al. 2002) performed a tritium test in one of these wells and found tritium to be below their detection standard (2.5 pCi/L), indicating the water was recharged before 1953. Third, the sample wells all lay west of the river at the end of what is thought to be a gaining reach (Scott 1997). Thus, it seems possible these wells, which lie within 1 km of the Santa Cruz River, received no water from the river.

Further downstream, the dominance of effluent as a source water weakens (Figure 11). The riparian wells 20-31 km from the NIWTP show a mixture of water sources with effluent dominant in 3 of 6 samples. There are, however, two outlier samples taken from the same well pre and post monsoon.

North of 31 km is a transition area for the aquifer. This phenomenon is exhibited near the end of the 20-31 km section, this well was effluent dominant (55%) before the monsoon.

After the monsoon a sample was taken again and the well was mixed (26% Sonoita, 36% Santa Cruz, 37% tributary) (Figure 10c). Sonoita Creek flow dominates riparian wells 31-35 km from the NIWTP outfall. This result is likely because the water in the aquifer originates as storm event or groundwater flow.

There are general conclusions that can be drawn from the mixing model. The immediate riparian aquifer is dependent (50-70%) on effluent within 30 km of the NIWTP outfall. Wells to the west, receive groundwater from mountain front recharge. Wells downstream of 31 km are reliant on monsoon event flow for recharge, including both tributary flow and Sonoita Creek flow. The monsoon does impact the system as the composition of some wells changes during the monsoon season from effluent dependent to mixed. Finally, the immediate riparian aquifer shows a dependence on the Santa Cruz River stream flow, whether in the form of effluent or event runoff.

Mass Balance

The mass balance results (Figure 12) confirm the results of the field stream gauging water balances: the river becomes more losing throughout the pre-monsoon time period. The ability to calculate a water balance in 2 different ways, one based on evaporation equations and the other based on the differences in chloride concentration as seen over time (Figures 6 and 12) strengthens initial conclusions. Additionally, by using two methods weaknesses are exposed in each method. For instance, mass balance calculations show the evaporation losses more clearly than the field stream gauging water balance.

The NIWTP flow remains roughly constant throughout the year, while flow at the 20 km USGS stream gage steadily decreases due to increasing channel loss and evaporative demand (as much as 22% of losses in June). In addition, while evaporative losses increase as the temperature increases cumulative loss and channel loss also increase indicating increased losses from the stream to the subsurface.

DISCUSSION

In effluent dominated rivers, does clogging exist and does it reduce streambed hydraulic conductivity?

The soil cores present both qualitative confirmation of the presence of a clogging layer and quantitative confirmation that it reduces K_{sat}. Of the 80 soil cores taken from the Upper Santa Cruz and Upper San Pedro Rivers, 14 pre-monsoon Santa Cruz River sediment samples were visually found to be clogged (Table 2). Those cores were then analyzed and clogged cores were found to have a statistically significant lower K_{sat} to a 97.5% confidence.

What impact does the development of a clogging layer have on streambed infiltration and how does this alter the connection of the stream to the ground water system?

A clogging layer reduces the hydraulic conductivity of the streambed sediments, slowing the transmission of water from the stream to the underlying aquifer (Greskowiak 2005; Bouwer 2002; Baveye et al 1998; and Berestov 1998). This process can be seen in the 2004, 2005 hydrographs, (Figure 7), as less water was infiltrated the magnitude of differences between flow at 20 and 35 km from NIWTP outfall were reduced. The disruption of stream-aquifer interactions has implications for the shallow streambed and hyporheic zone. By examining the soil profiles (Figure 5) two implications are established: localized gaining in the shallow streambed (6-10 cm) and disconnection between the stream and aquifer resulting in unsaturated conditions ranging from 20-60 cm below the streambed surface.

As a clogging layer develops in an artificial recharge basin, infiltration of water into the aquifer slows, resulting in ponded water on top of the basin. In a river, the ponding of water is not possible as water is moving both infiltrating the streambed and downstream. The water in the river has a higher hydraulic head then groundwater forcing water to be lost from the stream and move into the aquifer. In addition, a geologic gradient over the course of the river causes water to move downstream. After the formation of a clogging layer, the transmission of water through the streambed into the aquifer slows. However, the river water continues to move downstream. Thus, the stream and shallow streambed become perched creating localized gaining conditions. This phenomenon can be seen in the February 2007 and June 2007 soil profiles at 3 and 15 km, which all showed gaining in the top 10 cm despite losing or unsaturated conditions below. After the clogging layer is removed by large flows, the system becomes reconnected as seen by soil profiles September 2007 and February 2008 at 3 and 15 km. This observation is further confirmed by Lacher, when citing work by Esposito (1993), states "…a perched water table exists above the black anaerobic layer…"(Lacher 1996).

Unsaturated layers are reported under artificial recharge systems (Bouwer 2002; Greskowiak 2005), perennial streams subjected to pumping (Fox and Dunnford 2003; Su et al. 2006), and effluent dominated streams (Berestov 1998). For all of these scenarios, desaturation starts in the same manner, a band of comparatively low hydraulic conductivity material (a clogging layer or a clay lens) reduces the rate of infiltration. As the rate of infiltration decreases it “becomes less than the hydraulic conductivity of the soil below the clogging layer [or clay lens], this soil becomes unsaturated…”(Bouwer 2002). This condition is possible on the Santa Cruz River as the water table fluctuates primarily because of event runoff inputs and pumping. Thus, the river acts as a long artificial recharge basin, with infiltrated water mounding until less water infiltrates and unsaturated conditions develop at the deep streambed (seen in profile February 15.05, 31.35 and June 3.15, 15.05).

During the selection of reach size for the stream water balance, 0-20 km and 20-50 km reaches were chosen based on an initial hypothesis that clogging begins adjacent to the effluent source and moves downstream. This hypothesis is neither confirmed nor refuted as it seems the small-scale effects of clogging were localized and site specific during the time period of our study. Two examples are provided to demonstrate the complexity and ambivalent nature of the data set over the course of the river. Evidence that would support the initial hypothesis is that the 3 and 15 km reaches during February 2007 and June 2007 have a perched shallow streambed, and losing or unsaturated deep streambed conditions. Indicating the clogging layer is interconnected and grows downstream. Evidence to the contrary can be seen in analyzing the 24 and 31 km data set. Soil cores from the 24 km reach have the highest percentage of clogged cores, yet there was no perching of the shallow streambed or unsaturated areas. Hydraulic profiles of the 31 km reach show unsaturated areas in February 2007, despite having the fewest clogged cores in the pre-monsoon time period. It is hard to draw conclusions about the river as a whole in 2007 when the small-scale effects of clogging were variable and dependent on local conditions, thus, larger time scale data is necessary.

What is the relative importance of effluent as a water source to the riparian aquifer and how is this altered by the development of a clogging layer?

The riparian aquifer is dependent on the Upper Santa Cruz River for recharged water as shown by the mixing model analysis and transducer data results. Riparian wells near the outfall (0-25 km downstream from NIWTP outfall) show a reliance on effluent, especially in the midst of the dry winter and pre-monsoon season. In addition, all riparian wells (0-35 km downstream from NIWTP outfall) exhibit an alluvial aquifer dependent on Santa Cruz River stream inputs both perennial (effluent) and seasonal (event runoff).

The riparian aquifer dependence does not appear to be disrupted by a clogging layer in 2007. This conclusion is proven by the pre-monsoon 2007 mass balance (Figure 12). The mass balance shows an increase in overall losses, evaporative losses, and channel losses throughout 2007. This indicates that even though there are local indicators of clogging (soil cores, and hydraulic profiles) a cohesive, blanket clogging layer has not formed halting all transmission of water from the stream to the aquifer.

The minimal impact of the clogging layer on the aquifer seems to be based on an annual clogging cycle, evidenced by a lack of clogged cores and unsaturated areas after the monsoon storms. However, if the clogging layer continues to grow there are ramifications for the aquifer and riparian area. This phenomenon is exhibited in an unexplained tree die off in late winter/ pre-monsoon 2005.

In the spring of 2005 hundreds of cottonwood, willow, hackberry, elderberry and mesquite trees died along the Upper Santa Cruz River (Davis 2005). The tree deaths occurred throughout the first 15 km of the study area. Speculations as to causes included root rot, drought, insects and groundwater pumping. However, the cause might have been the clogging layer.

The hydrographs and water balances for 2004-2006 illuminate an altered riparian water balance in 2004-2005 that affected the river, aquifer and riparian area (Figures 7 and 8). In 2004 there was a temporally dispersed low flow monsoon season. The following winter and pre-monsoon season, flow was sustained 50 km downstream of NIWTP outfall, despite there being no additional river inputs. Also, during the pre-monsoon period, there was sustained flow at 35 km from the outfall an area that historically goes dry in the pre-monsoon period, due to evaporation and transpiration. It was during this winter and pre-monsoon period that the trees died at the 0-20 km reach. After the 2005 monsoon, there is no longer flow at 35 and 50 km from NIWTP outfall. This occurs despite the fact that a series of large temporally condensed flows added water to the aquifer (Figure 7).

There is not a comprehensive river field data set, or chemical data set from the riparian aquifer for this time period so it is impossible to draw definite conclusions. However, implications can be drawn from the hydrograph evidence. A low flow monsoon cycle, followed the next year by an extended streamflow with minimal channel losses, indicate that the clogging layer was not removed, leaving the stream and shallow streambed perched and the riparian aquifer separated from the river and therefore, unsaturated. This process could have resulted in the trees that normally tap into the deep streambed and aquifer area without water, leading to the tree die off.

How do periods of stable low-flow and scour during high-flow flood events control the formation and removal of a clogging layer?

The Upper Santa Cruz River receives runoff from tributaries during the monsoon season (see Site Description for more details) and to a lesser extent during winter rains. Throughout the rest of the year, the major water input is effluent from NIWTP. All of the accumulated data suggest a yearly cycle for the clogging layer that is dependent on the interannual variability of precipitation in semiarid systems. The data has been used to build a conceptual model (Figure 13) based in part on Greskowiak's et al. (2005) clogging cycle for artificial recharge basins.

The clogging layer begins as a thin layer of detritus material (stage 2 of conceptual model) that has been filtered out of the water by streambed sediment (Rinck-Pfeiffer et al., 2000). It is only over time the layer and subsequent biological activity increase the clogged layer thickness (Rinck-Pfeiffer et al., 2000; Battin and Sengschmitt, 1999). Biological activity increases rapidly with temperature (Baveye et al., 1998), creating clogged layers that can range from 9.5 to 20 cm thick by the pre-monsoon period as shown by the soil cores (14 clogged cores: 85% were 15 cm or thicker). Lacher (1996) notes that Schumann and Gaylean (1991) "…speculated that increased biological activity on the surface, 'caused by nutrient-rich sewage effluent and increasing ambient air temperatures', was responsible for decreasing streambed infiltration capacity over time…" Thus, as long as the streambed is not disturbed during this cycle, a clogging layer can develop from a thin detritus layer to 20 cm thick.

Soil core evidence suggests that by early June a clogging layer has developed in at least parts of the stream. However, examining the hydraulic profiles (Figure 5) shows the beginnings of a clogging layer in February 2007. During February the perching of the shallow streambed has taken place at the 3 and 15 km reach, meaning the clogging layer has formed since water infiltration into the aquifer has slowed (conceptual model stage 3). Thus, from February to June 2007, a period of minimal water inputs, the clogging layer continues to develop.

The September 2nd soil profiles reveal a different pattern. The shallow streambed and stream aquifer interface are reconnected hydrologically. Additionally, the soil cores reveal that all clogged cores come from the pre-monsoon time period. There are no clogged cores after the monsoon.

The hydrograph 20 km from the NIWTP outfall (Figure 2), shows a series of large flows in July and August. Monsoon storms, with their resultant large turbulent flows act like the drying and physical manipulation conducted in artificial recharge basins (stage 4 of conceptual model), removing the clogging layer through the process of scour. Lacher cites L.G. Wilson (1975) observing “stormflow …scoured out the black, anaerobic clogging layer in the channel” (Lacher, 1996). Scour literature for a southwest ephemeral wash (Walnut Gulch, a tributary of the San Pedro River) indicates that runoff events creating large flows (11 m^3/sec) that crest the banks of the river, can result in scouring depths of 15 to 50 cm (Powell et al., 2006). Additional literature for a perennial river in Canada also cites a bank cresting event as scouring to a mean depth of 20.3 cm (Haschenburger, 2006). However, it seems based on transducer data (Figure 9), and the riparian discussion above, that it takes more than one 10 m^3/sec (bank cresting?) flow event to scour out the clogging layer. It takes a set of time condensed large turbulent flows to remove a fully developed layer, the type of flows that usually occur during a semi-arid monsoon season.

After the monsoon period the clogging cycle begins again (stage 1) as it is a lack of storms throughout the year that allow the clogging layer to accumulate. In November, December, and February 2007-2008 there were a series of winter storms that created moderate flow increases along the Santa Cruz River (Figure 2: 2007-2008 Hydrograph). The February 2008 soil profiles shows losing or hydrostatic conditions and the February

2008 stream gauging water balance implies a generally hydrostatic system. It appears that a clogging layer had not formed as there was no perching of the shallow streambed or desaturation of the stream aquifer interface and the aquifer and river are in a rough neutral state. Thus, the moderate flow storms of November, December and February may have had enough turbulent power to destroy the shallow and thin clogging layer. However, as time from the last storm and temperature increase the clogging layer will thicken until it takes a series of large flows to be removed (stage 3).

The 2007 chloride mass balance and the 2005 tree deaths reinforce this conceptual model. In the bounds of a water year with time condensed large turbulent flows, as in 2007, localized clogging affects the streambed with only limited effects on the aquifer and riparian area (early and late stage 3). However, in years with only moderate flows or widely interspersed large flows, as in 2004, the localized clogging transforms into an interconnected layer that can halt the infiltration process (extended stage 3).

This model has implications for other effluent dependent streams and riparian areas in semiarid and arid regions. Clogging layers can develop in effluent dominant systems creating perched streams and shallow streambeds leading to an unsaturated deep streambed. Over the course of a year this seems to affect only the streambed. However, without a scouring of the streambed by floods to check clogging growth, the layer can spread and interconnect desiccating dependent riparian areas. This problem becomes especially troublesome as climate variability and change have unknown ramifications on the hydrologic cycle of the semi-arid southwest.

CONCLUSIONS

In water limited environments, population increases have lead to increased water demand that has stressed aquifers and perennial streams. As water tables drop perennial streams and riparian corridors go dry causing changes in ecosystems and water resources creating an untenable situation. Treated waste water effluent has been seen as a management option for both aquifer and river problems. The use of effluent however, carries its own set of management problems.

As shown in this study clogging occurs in effluent dependent river systems. Clogging has an effect on the streambed by perching the stream and shallow streambed thereby, allowing desaturation of the deep streambed. This phenomenon can have implications for the dependent aquifer and riparian corridor. The larger semi-arid hydrologic cycle serves as a control on the clogging as it is flows exceeding 10 m^3/sec, that destroy the clogging in the Santa Cruz, and a lack of floods that allow the clogging layer to flourish. The possible impacts of clogging on the aquifer and riparian corridor need to be considered when considering the use of effluent for river restoration projects.

FURTHER RESEARCH

There are aspects of the clogging layer and process that have yet to be fully understood. Remaining issues include the actual growth cycle of the clogging layer, and the degree to which the NIWTP process, which produces constant flow and poor quality effluent, is important to the formation of a clogging layer.

To address the specifics of the clogging cycle, more physical streambed measurements need to be made. Soil cores provided a yes/no approach to clogging presence, soil cores could continue to be taken over a longer time frame to confirm the presence of a nascent clogging layer. Sectioned soil cores that could confirm clogging for a few centimeters of streambed would answer questions relating to the growth of the clogging layer. In addition mini piezometers, sectioned piezometers or piezometers that are driven into the streambed and monitored over time with a pressure transducer could reduce field variability and clarify the effect of the clogging layer on the stream micro system.

The importance of this effluent system, constant flow, high nutrients could be addressed by replicating this study under different circumstances. Such a study will soon be possible on the Santa Cruz River itself, as the NIWTP transitions from the current aeration lagoon system to one that has an eight hour processing time and better processing, creating a pulse effluent flood system with low nutrient loads that might have a different impact on the Santa Cruz River and its related aquifers.

APPENDICES

Appendix A: Figures

Figure List

Figure 1: The Santa Cruz Study Area: Primary Reaches, USGS stream gages, project wells and natural vegetation

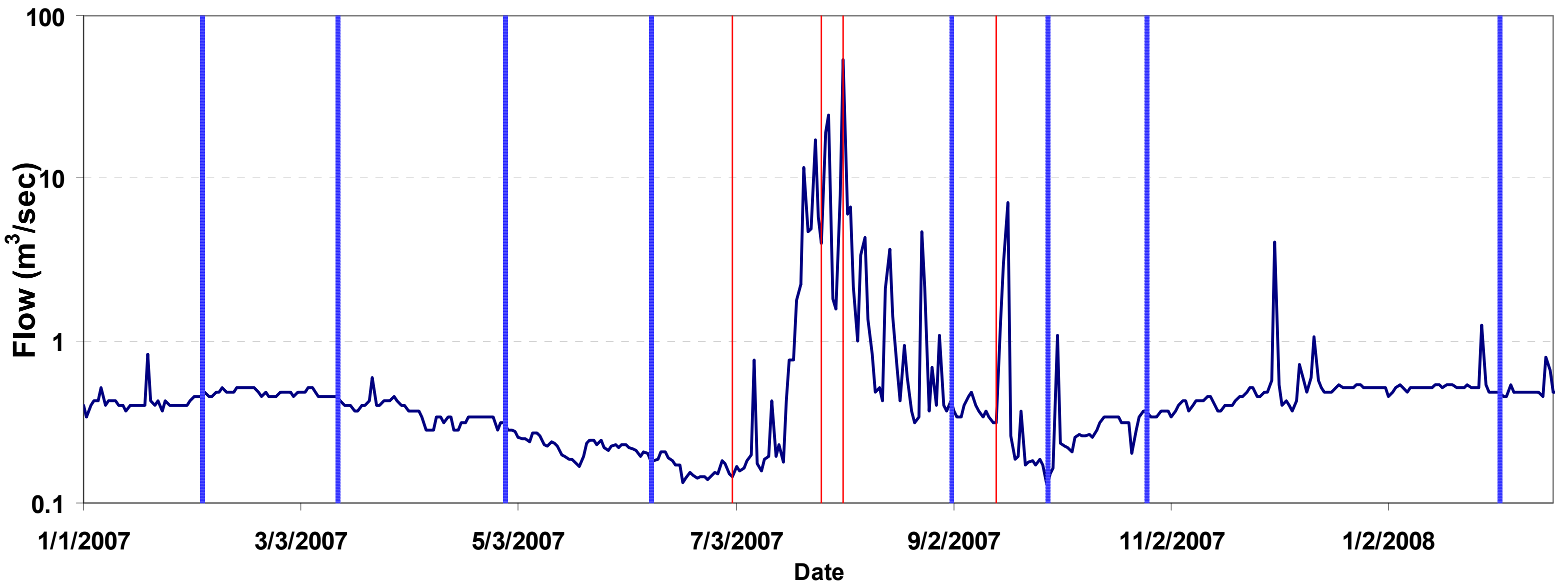

Figure 2: Streamflow at 20 km from NIWTP outfall 2007-2008, USGS stream gage 09481740. Blue vertical lines indicate day of field investigations. Red vertical line indicates days only water chemistry samples were taken for either synoptic run or monsoon event.

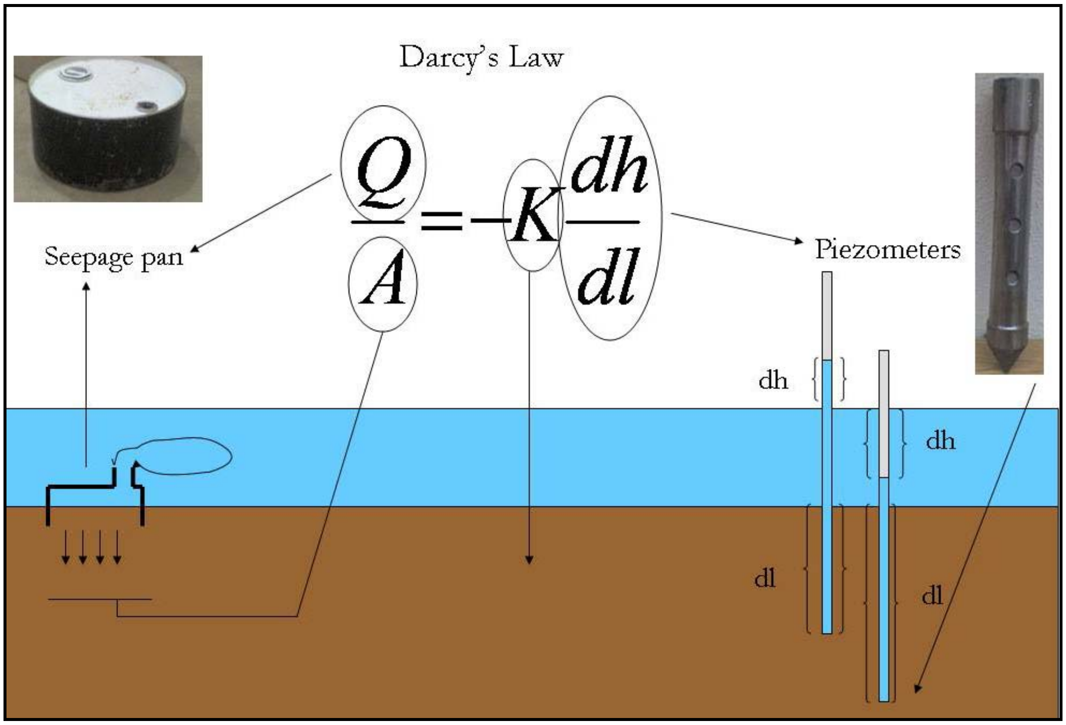

Figure 3: Piezometers and seepage pans schematic. The inset images are pictures of the actual equipment. Piezometers are used to measure gradient in the streambed. Seepage pans are used to measure the flow of water into or out of the stream.

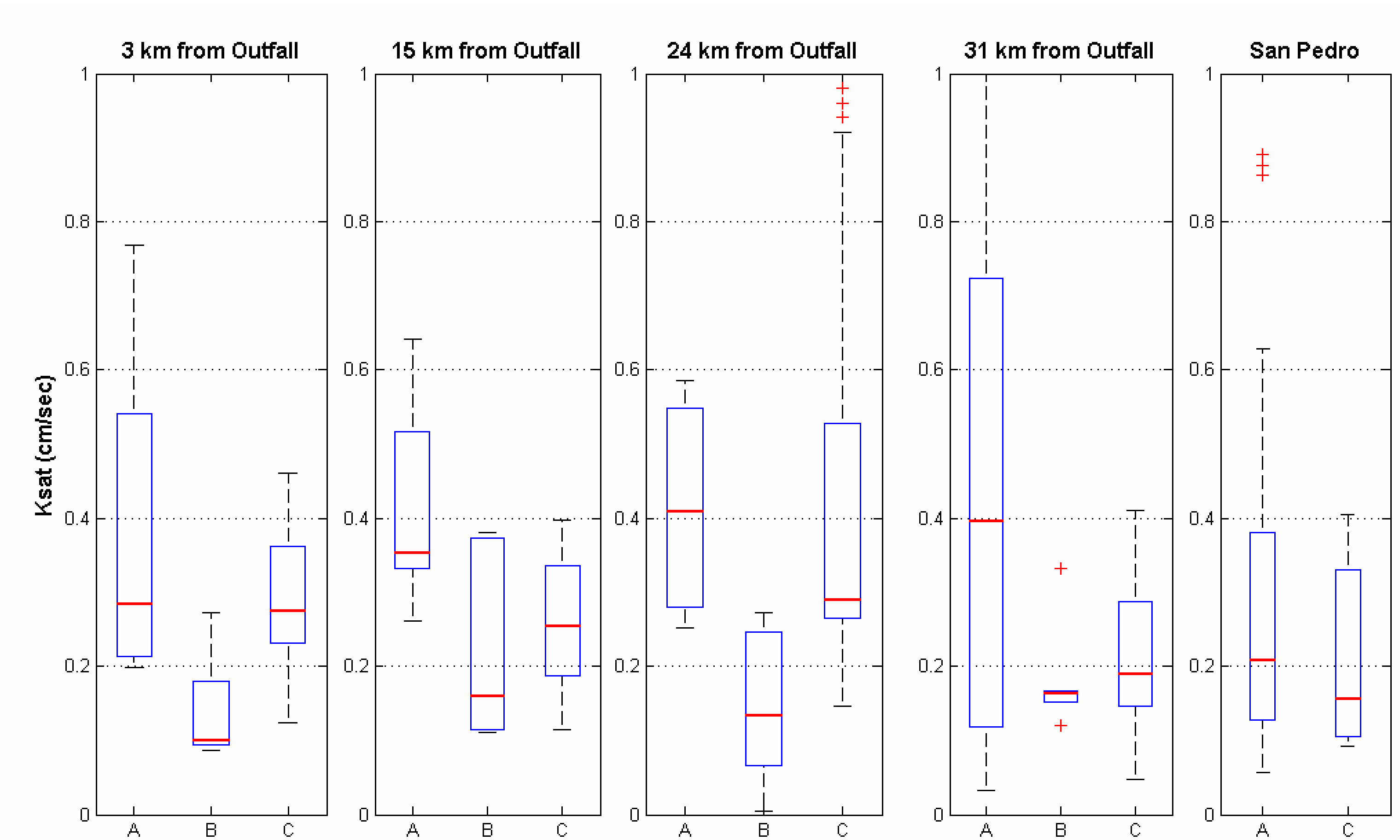

Figure 4: Ksat values based on soil core data for the Santa Cruz and San Pedro Rivers grouped into A. pre-monsoon not clogged, B. pre-monsoon clogged, and C. post monsoon for each of the primary reaches. The red line indicates the median value for the sample set, the line at the top of the box is the 75th percentile; the line at the bottom of the box is the 25th percentile. The outliers are those values 1.5 times more than the inter quartile range. Sample size for pre-monsoon clogged and unclogged cores fluctuates depending on the number of clogged cores per reach, refer to table 3 for number of clogged cores per reach.

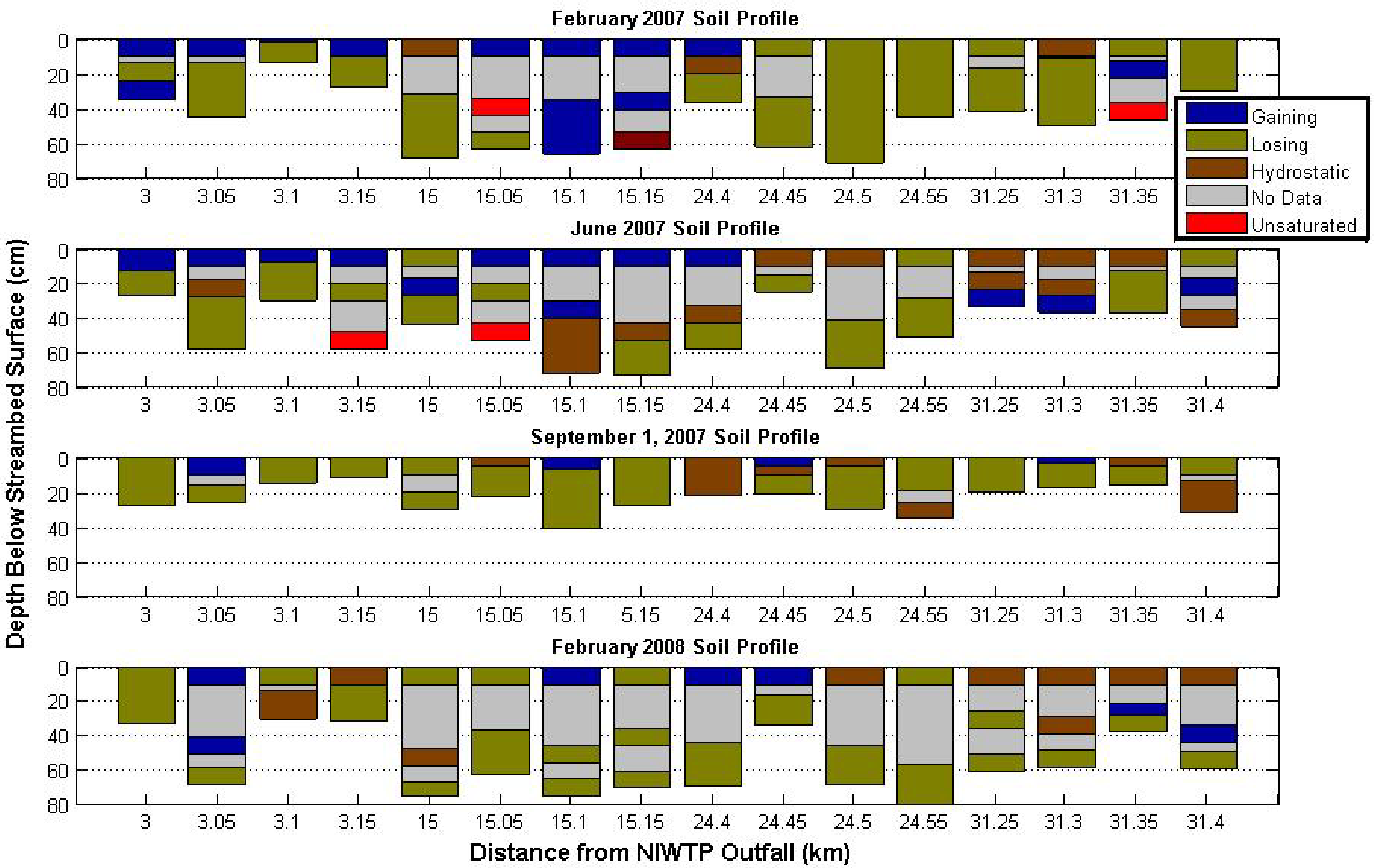

Figure 5: Hydraulic Profile for the Santa Cruz River, constructed using seepage pan and piezometer data.

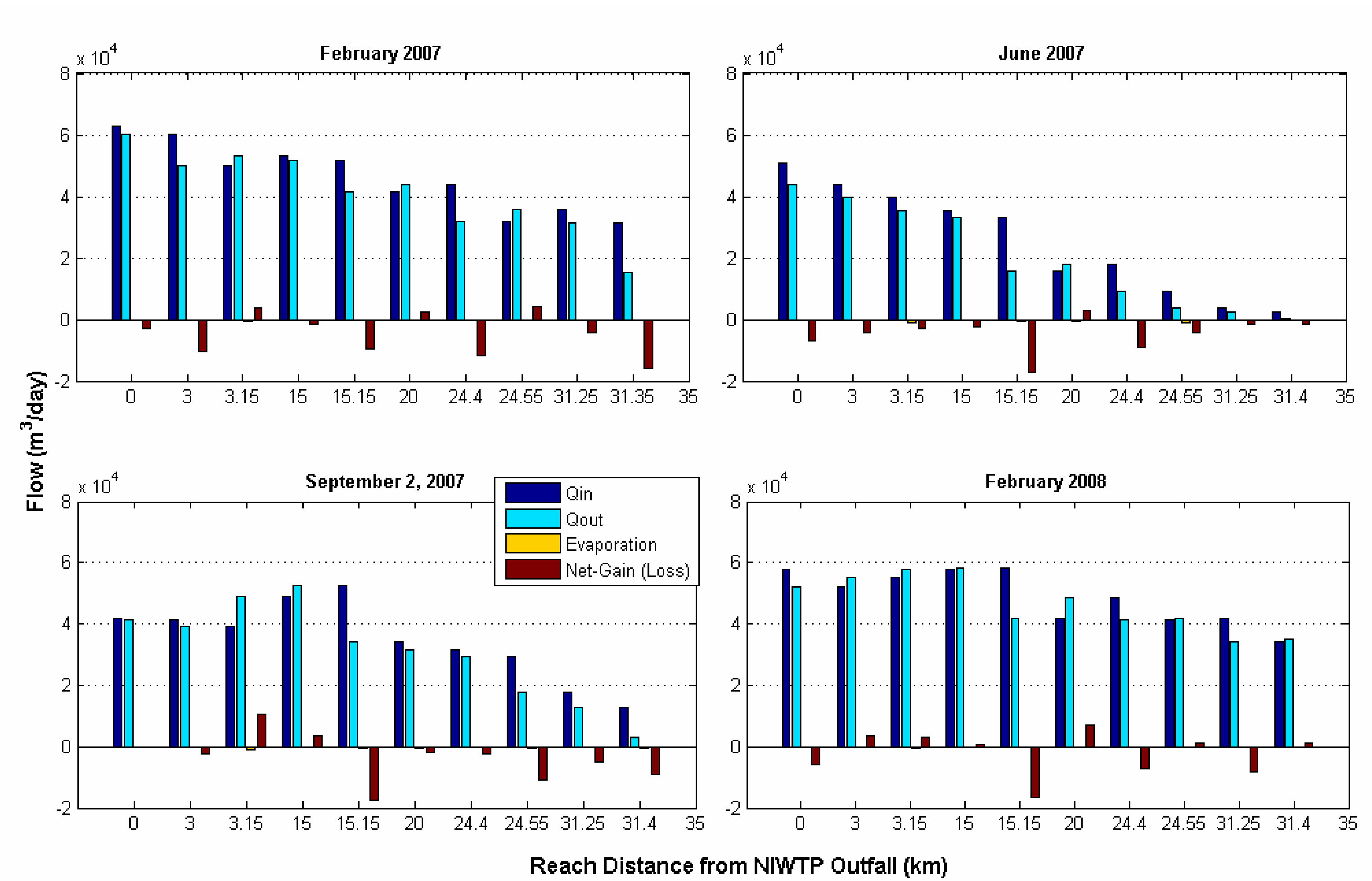

Figure 6: Stream water balance of Santa Cruz River for given dates based on field stream measurements, data from USGS, NIWTP and NOAA. Notice the x-axis is the start of the reach in km distance from NIWTP outfall. The end of the given reach is the next number, for instance the reaches are 0-3km, 3-3.15km etc.

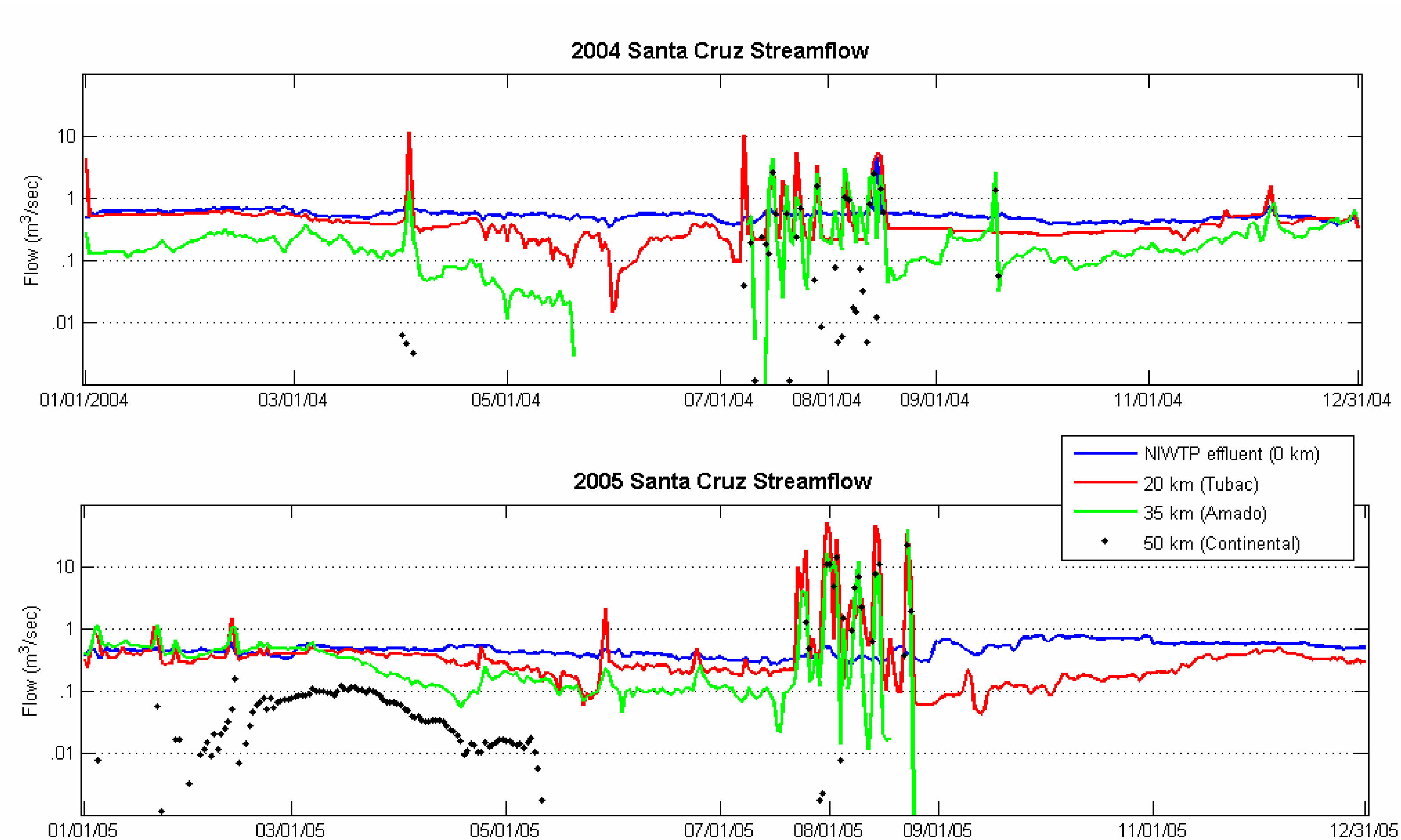

Figure 7: 2004-2005 Santa Cruz River Hydrograph measurement points include the outfall, 20, 35, and 50 km from NIWTP outfall.

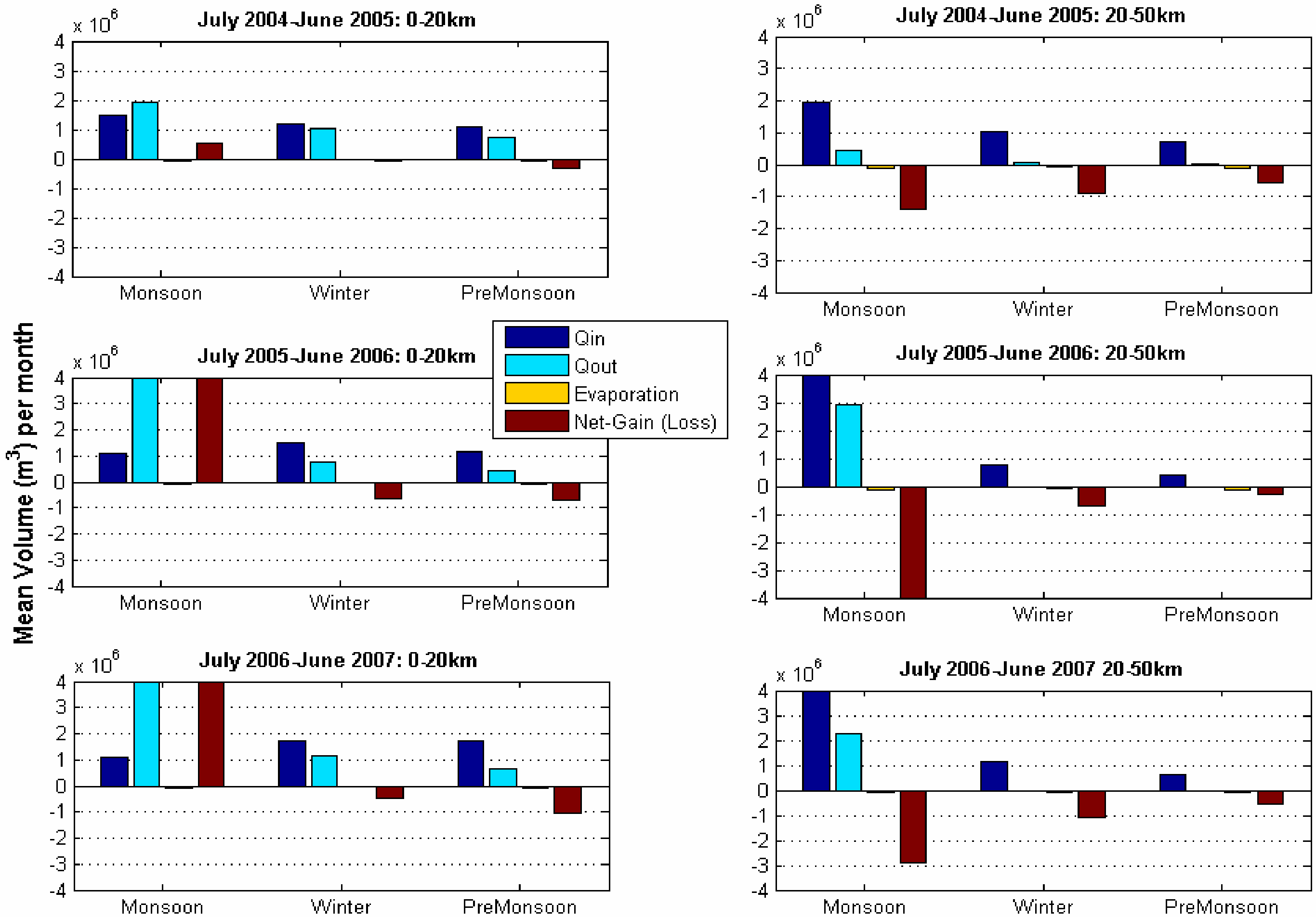

Figure 8: Water balance for July 2004- June 2007 Santa Cruz River. The monthly average of monsoon flow at the 20-50km reach for 2005-2006, and 2006-2007 is larger then the y-axis scale. However that scale is necessary to show differences between the three years during the winter/ pre-monsoon season on the 20-50km reach.

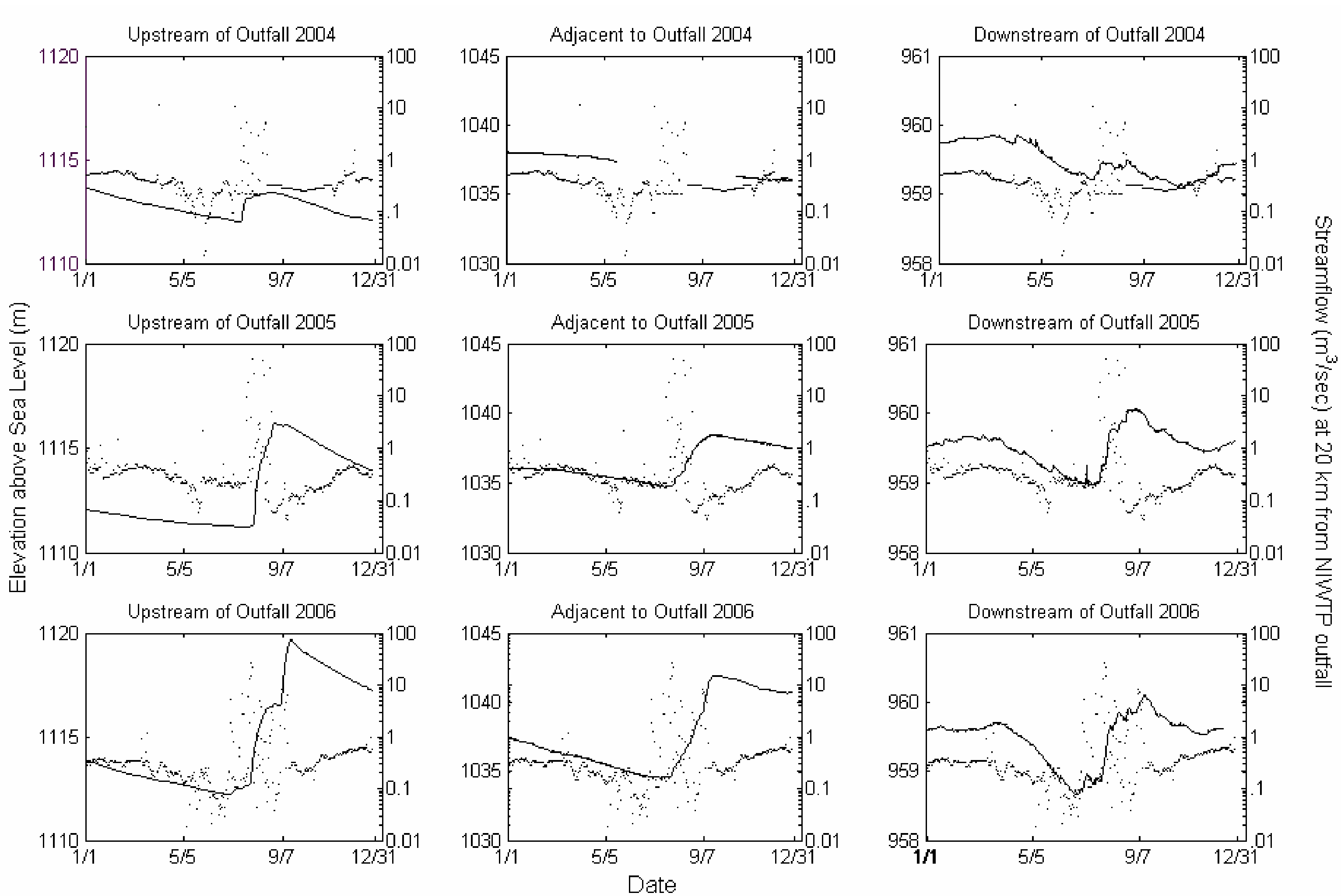

Figure 9: Pressure transducer data for 3 wells along the Santa Cruz River. The right y axis and dots show streamflow at 20 km from NIWTP outfall. The left axis and solid lines line represent the water elevation above sea level as measured by a pressure transducer.

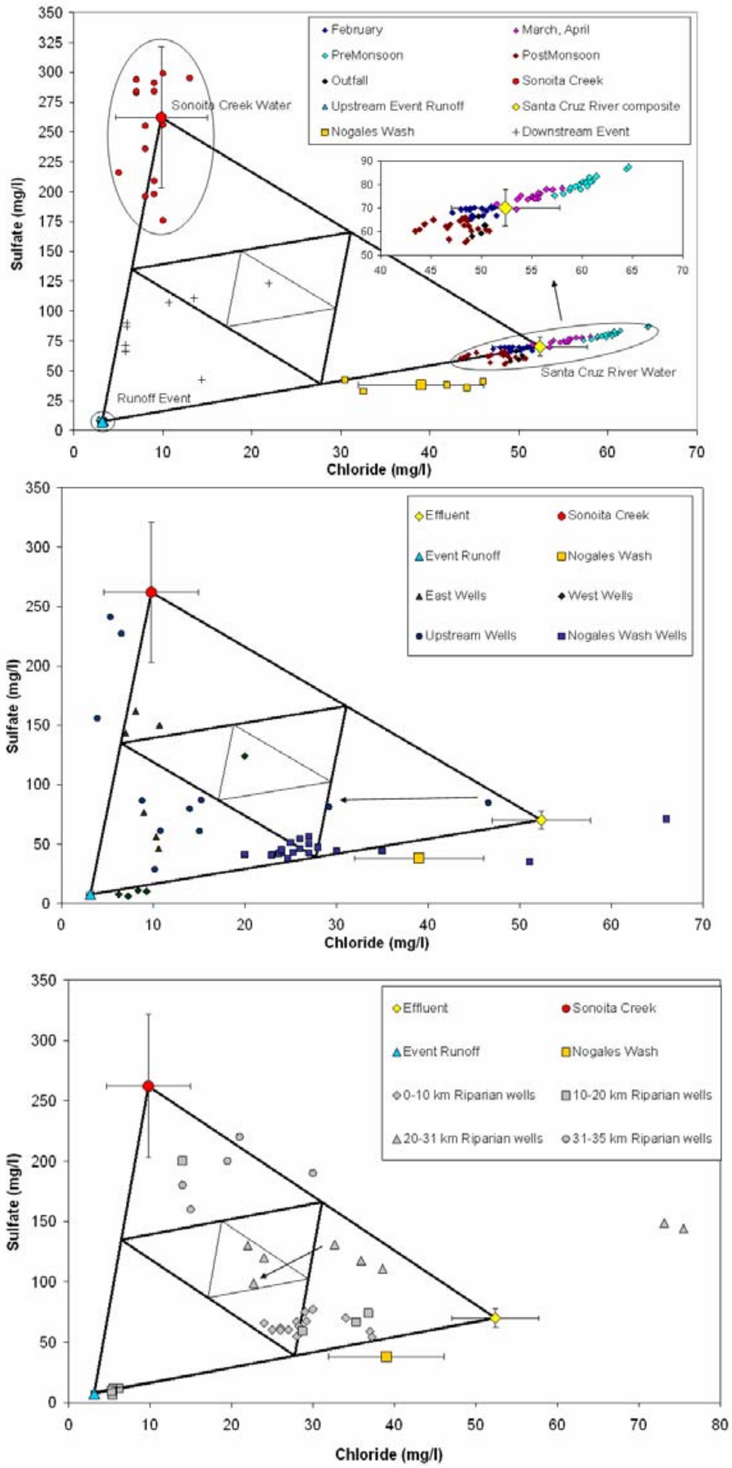

Figure 10 a, b and c: Mixing end members and results: Large triangle represents the bounds of the mixing model, medium black triangle portrays the partitioning of the samples by dominant water source, small black triangle portrays samples that are considered thoroughly mixed between sources. 10a. Mixing model end members. 10b. Mixing model results for non-riparian wells. 10c. Mixing model results for riparian wells.

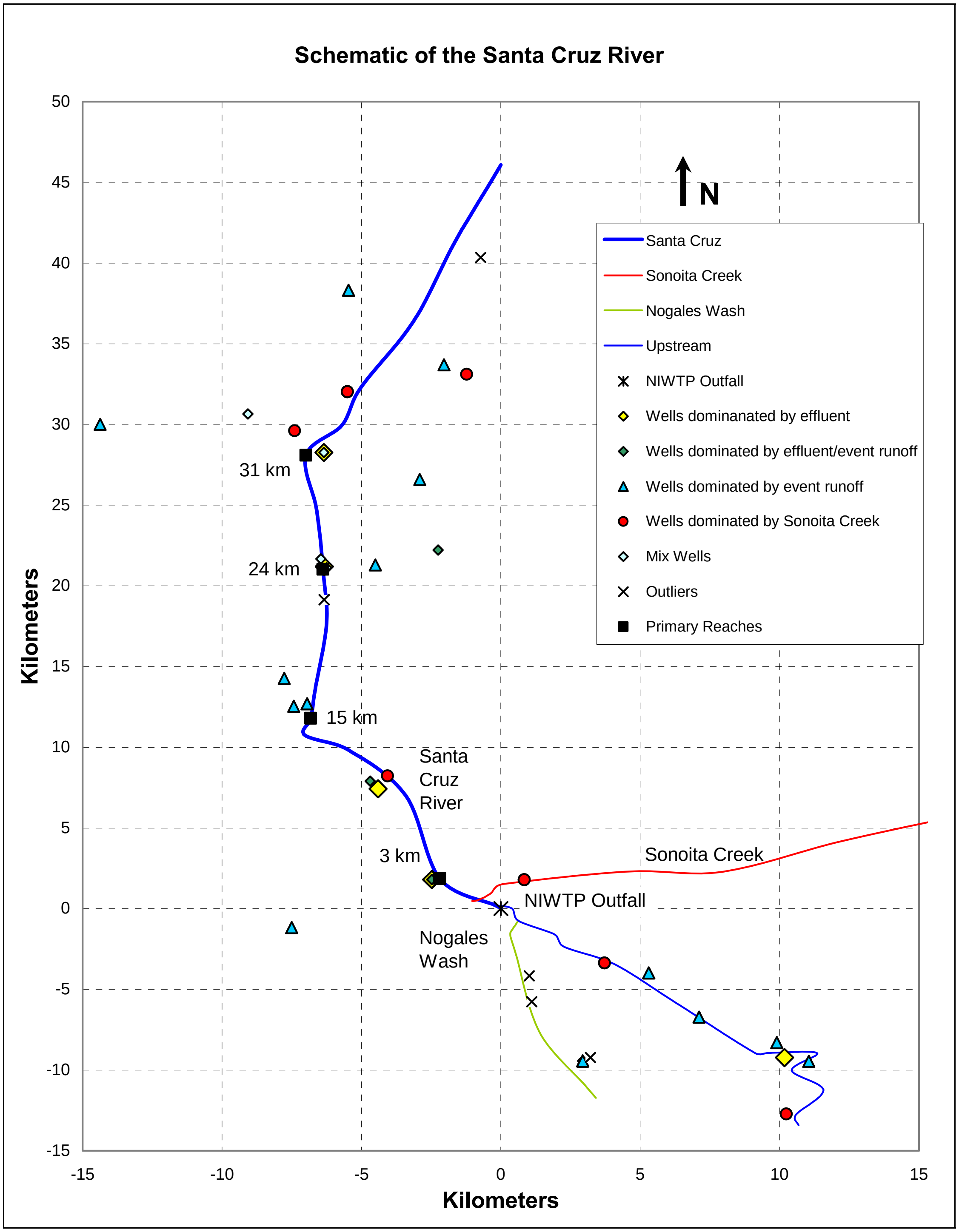

Figure 11: Schematic of the Santa Cruz River and major tributaries. Colored mark for well is related to source water dependence. Black rectangles on Santa Cruz River indicate field work locations. Outlier wells on the map are those whose chloride/ sulfate concentrations place them outside the bounds of the mixing model, as defined by the triangle in Figure 10.

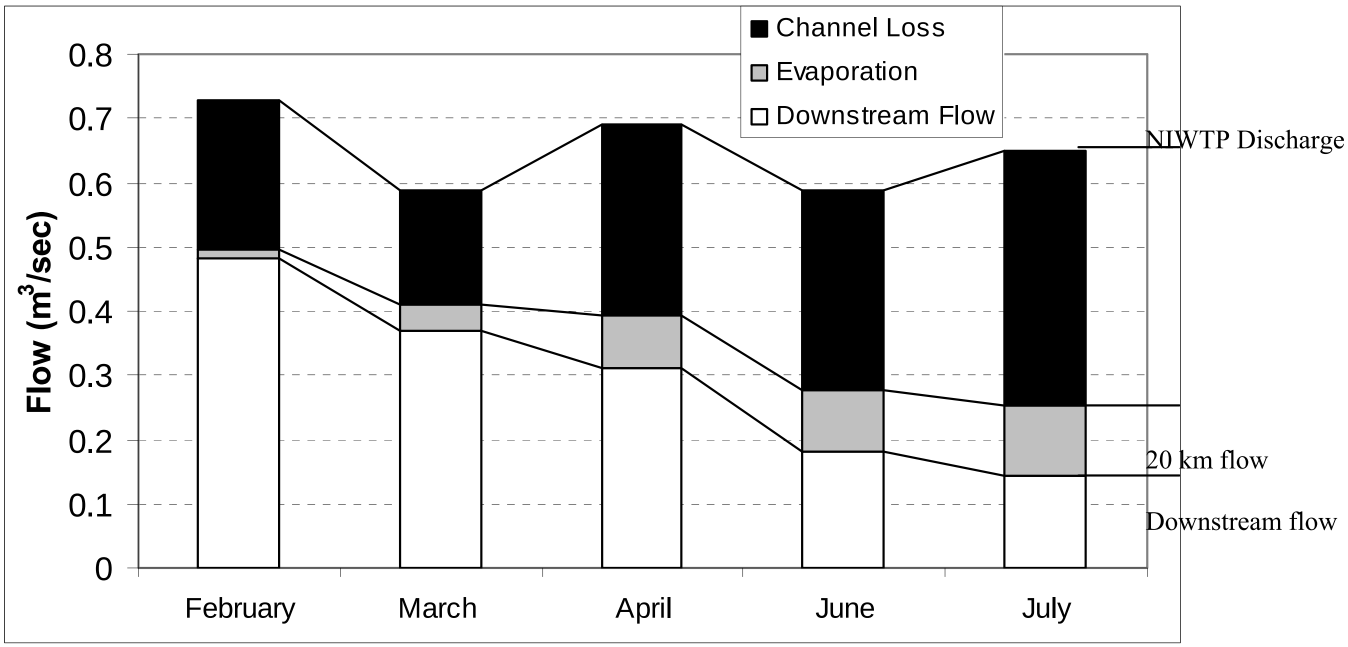

Figure 12: Results of the mass flux for the 0-20 km reach of the Santa Cruz River. Top line indicates flow from the NIWTP outfall. Bottom line is flow at 20 km UGS stream gage with remaining water flowing downstream. Mass flux calculated for 1 day in month.

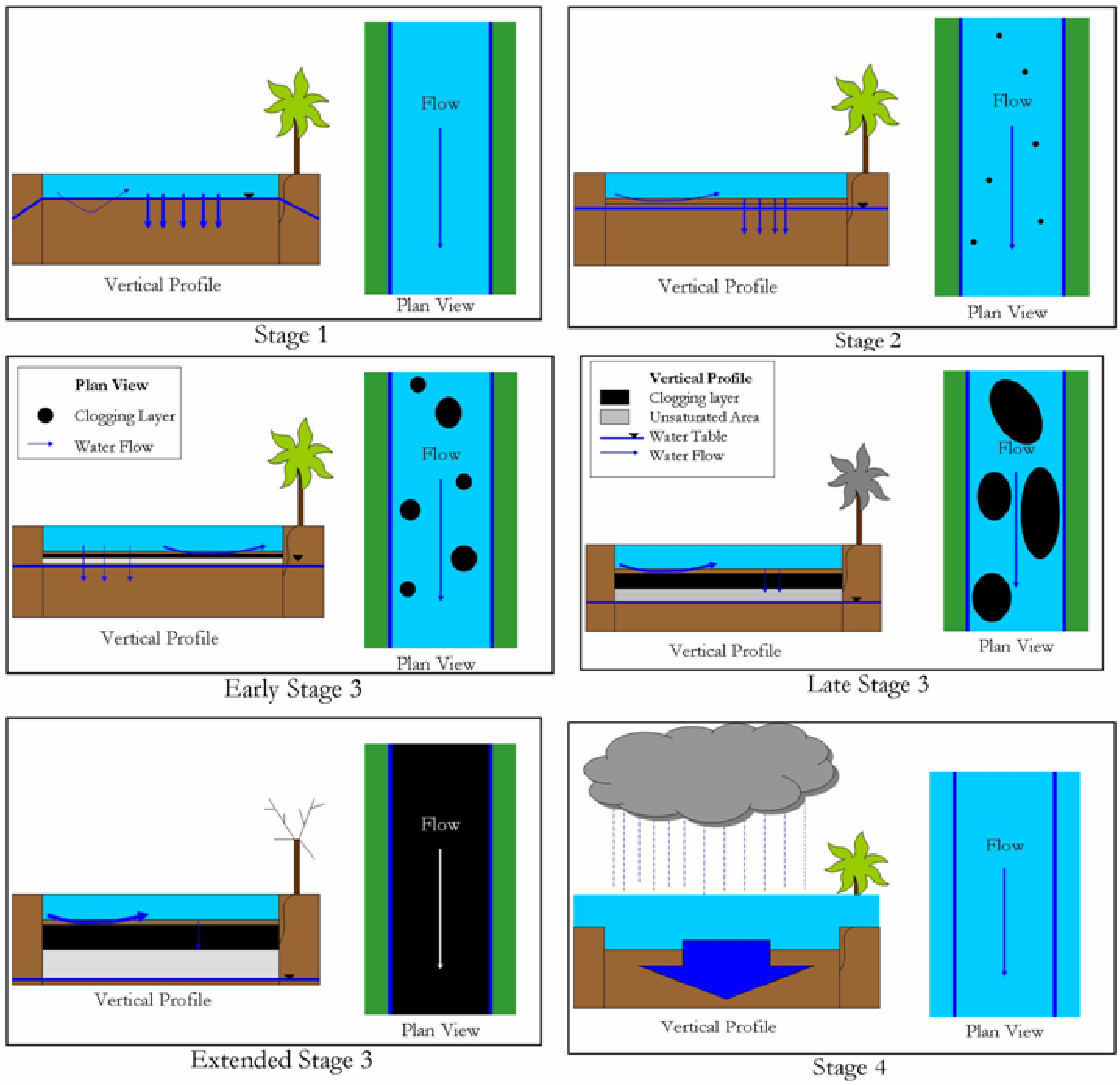

Figure 13: Conceptual model of clogging cycle. Stage 1, immediately post monsoon the river system is reset, there is no clogging. Although, the water table implies a losing reach, gaining or hydrostatic conditions are possible. Stage 2, a thin layer of detritus material forms in the streambed (vertical profile) in discrete locations based on geomorphology and other localized conditions (plan view). Early stage 3, usually late winter/early pre-monsoon, the clogging layer grows due to increasing biological activity, infiltration through the clogging layer slows, the streambed becomes perched and an unsaturated layer develops (vertical profile) in specific areas (plan view). Late stage 3, areas of clogging are growing and becoming interconnected (plan view), as the clogging layer grows, water table drops and vegetation begins to be effected (vertical profile). In a typical semi-arid hydrologic cycle stage 4 occurs, in that large storms come, eradicate the clogging layer and reset the system. However, in a year with only moderate flow events or events spaced widely in time, extended stage 3 occurs, an interconnected clogging layer blankets the streambed (plan view) isolating the stream from the aquifer as a result an unsaturated layer and the clogging layer grows in thickness and there is a vegetation die off (vertical profile).

Appendix B: Tables

Table List

Table 1: Sampling schedule

	Piezometers and Seepage Pans	Stream Gauging and Water Sampling	Soil Cores	Synoptic Run	Precipitation Event Sampling	Well Sampling
Santa Cruz River						
February 1-5, 2007	X	X				
March 12-13, 18, 2007	X	X				
April 29, 2007	X	X				
June 9,10, 2007	X	X	X			
June 20,21 2007						X
July 2, 2007			X	X		
July 27, 2007					X	
August 2, 2007					X	
September 1,5, 2007	X	X	X			
September 14, 2007				X		
September 27, 2007						X
September 28,29, 2007	X	X	X			
October 26, 27, 2007	X	X				
February 6, 2007	X	X				
San Pedro River						
November 25, 2006	X	X				
March 14, 2007	X	X				
April 28, 2007	X	X				
June 8, 2007	X	X	X			
July 2, 2007			X			
August 31, 2007	X	X	X			
October 27, 2007	X	X	X			

Table 2: Soil Cores: descriptive statistics

# of Cores	Type	Mean Ksat (cm/sec)	Median Ksat (cm/sec)
18	Santa Cruz Pre-monsoon (not clogged)	0.428 $\pm$ .288	0.347
14	Santa Cruz Pre-monsoon (clogged)	0.159 $\pm$ .099	0.136
32	Santa Cruz Post-monsoon cores	0.290 $\pm$ .159	0.263

Table 3: Number of clogged cores per primary reach of Santa Cruz River

	3 km	15 km	24 km	31 km
Pre Monsoon (June and July)	4	3	6	1
Post Monsoon (September 2nd and 27th)	0	0	0	0

Table 4: Flow thresholds on Santa Cruz River, Number of times per year flow reached given threshold at the USGS stream gauge 20 km downstream of NIWTP outfall. Also, cumulative streamflow at 20 km from NIWTP outfall and precipitation as measured by NOAA at Tumacacori.

Flow Range	**2004**	**2005**	**2006**
1-5 m^3/sec	10	12	19
5-10 m^3/sec	2	2	7
10-15 m^3/sec	2	0	1
15 m^3/sec +	0	7	3
Cumulative Streamflow (m^3*10^6)	**16.08**	**31.56**	**23.21**
Precipitation (cm)	**27.305**	**33.096**	**47.244**

Appendix C: Santa Cruz Data

This appendix will serve as a resource for all Upper Santa Cruz data collected during the course of the project. Please see Appendix B for San Pedro data. Both appendices will follow the same path as the main text: a discussion of soil cores, then piezometers and seepage pans, stream gauging and field water balances, all water samples and chemical compositions and finally, historic data including flow data from the NIWTP.

Soil Cores

Table 5: Saturated hydraulic conductivity Ksat (cm/sec) for soil cores from the 3 km reach. Numbers in italics represent clogged cores.

	6/9/2007	7/2/2007	9/2/2007	9/28/2007
3 km	0.219	*0.272*	0.462	0.132
	0.219	*0.255*	0.447	0.128
	0.219	*0.264*	0.447	0.124
	0.226	*0.259*	0.447	0.128
	0.240	*0.264*	0.454	0.124
	0.231	*0.251*	0.432	0.128
3.05 km	*0.100*	*0.086*	0.233	0.377
	0.100	*0.090*	0.274	0.362
	0.096	*0.092*	0.243	0.377
	0.102	*0.092*	0.259	0.362
	0.096	*0.086*	0.243	0.362
	0.100	*0.089*	0.259	0.362
3.1 km	*0.106*	0.209	0.249	0.361
	0.100	0.198	0.249	0.345
	0.107	0.198	0.249	0.337
	0.101	0.198	0.227	0.314
	0.103	0.198	0.238	0.329
	0.101	0.198		0.314
3.15 km	0.342	0.740	0.233	0.292
	0.342	0.740	0.237	0.281
	0.335	0.767	0.233	0.292
	0.342	0.767	0.233	0.281
	0.327	0.767	0.223	0.281
	0.335	0.767	0.233	0.269

Table 6: Ksat values for soil cores from the 15 and 24 km reaches of the Santa Cruz River. Numbers in italics represent clogged cores.

Distance	6/9/2007	7/2/2007	9/2/2007	9/28/2007	Distance	6/9/2007	7/2/2007	9/2/2007	9/28/2007
15 km	0.363	0.612	0.283	0.197	**24.4 km**	0.586301	*0.273004*	0.592058	0.264946
	0.326	0.581	0.262	0.188		0.567389	*0.261135*	0.657842	0.264946
	0.335	0.596	0.272	0.192		0.548476	*0.267069*	0.647057	0.255133
	0.344	0.642	0.262	0.188		0.548476	*0.267069*	0.657842	0.248591
	0.353	0.612	0.262	0.184		0.529563	*0.267069*	0.657842	0.235507
	0.344		0.251	0.188		0.529563	*0.261135*	0.690734	0.274759
									0.268217
									0.264946
15.05 km	*0.115*	0.480	0.294	0.121	**24.45 km**	0.286161	*0.065263*	0.290204	0.156566
	0.115	0.508	0.294	0.121		0.286161	*0.062155*	0.279651	0.153371
	0.111	0.518	0.255	0.121		0.286161	*0.067128*	0.274375	0.150176
	0.111	0.536	0.255	0.121		0.275155	*0.065263*	0.269098	0.153371
	0.111	0.518	0.255	0.114		0.275155	*0.065263*	0.263822	0.146981
	0.115	0.518	0.334	0.129		0.253143	*0.065263*	0.263822	0.150176
				0.114					
15.1 km	0.342	0.277	0.374	0.254	**24.5 km**	*0.170813*	*0.246311*	0.97991	0.34555
	0.358	0.262	0.372	0.254		*0.169034*	*0.257507*	0.940714	0.373873
	0.350	0.306	0.398	0.254		*0.170146*	*0.251909*		0.348382
	0.350	0.269	0.382	0.242		*0.16681*	*0.240713*	0.921115	0.356879
	0.350	0.277	0.382	0.266		*0.173482*	*0.246311*	0.960312	0.373873
	0.358	0.277	0.382	0.254		*0.170146*	*0.246311*	0.901517	0.356879
15.15km	*0.163*	*0.379*	0.348	0.180	**24.55km**	*0.00673*	*0.08959*	0.52071	0.31247
	0.156	*0.362*	0.356	0.180		*0.00673*	*0.08586*	0.54196	0.28781
	0.169	*0.380*	0.372	0.204		*0.00553*	*0.08959*	0.49945	0.29603
	0.156	*0.373*	0.381	0.180		*0.00725*	*0.09706*	0.52071	0.28781
	0.160	*0.380*	0.389	0.192		*0.00570*	*0.09519*	0.53133	0.28781
	0.152	*0.373*	0.381	0.180		*0.00622*	*0.09892*	0.51008	0.27958

Table 7: Ksat (cm/sec) values from soil core analysis for the 31 km from NIWTP outfall reach of the Upper Santa Cruz River. Numbers in italics represent clogged cores.

Distance	6/9/2007	7/2/2007	9/2/2007	9/28/2007
31.25 km	0.664786	0.376512	0.108519	0.196987
	0.684338	0.395527	0.10634	0.192967
	0.694114	0.41074	0.103865	0.192967
	0.733219	0.376512	0.119691	0.188947
	0.742996	0.365102	0.125077	0.188061
	0.772324	0.365102	0.130014	0.192967
31.3 km	0.340042	1.047449	0.37095	0.171532
	0.333502	1.142671	0.358158	0.15928
	0.333502	1.301375	0.37095	0.15928
	0.333502	1.237894	0.358158	0.147028
	0.333502	1.364857	0.37095	0.15928
	0.340042	1.333116	0.383741	0.147028
		1.333116		
		1.301375		
31.35 km	*0.120302*	0.506538	0.07355	0.187485
	0.165821	0.506538	0.071712	0.177069
	0.331643	0.506538	0.069873	0.197901
	0.160944	0.506538	0.069137	0.177069
	0.165821	0.506538	0.071099	0.177069
	0.15119	0.506538	0.066195	0.177069
31.4 km	0.045046	0.033002	0.399968	0.192727
	0.043593	0.032216	0.410493	0.218424
	0.043593	0.035359	0.410493	0.192727
	0.046499	0.03418	0.394705	0.205576
	0.043593	0.033002	0.410493	0.192727
	0.043593		0.394705	0.205576

Piezometers and Seepage Pans

The information gathered through the paired use of piezometers and seepage pans has been put to use different then originally expected. Piezometers were going to be used to gather gradient information in the deep streambed, and seepage pans were to be used to gather flux information in the shallow streambed. These numbers were to be assimilated to arrive at a saturated hydraulic conductivity value (Ksat) using Darcy's Law. Because of conditions in the Upper Santa Cruz River this was not feasible. Instead the flux and gradient data was paired to create hydraulic profiles of the streambed.

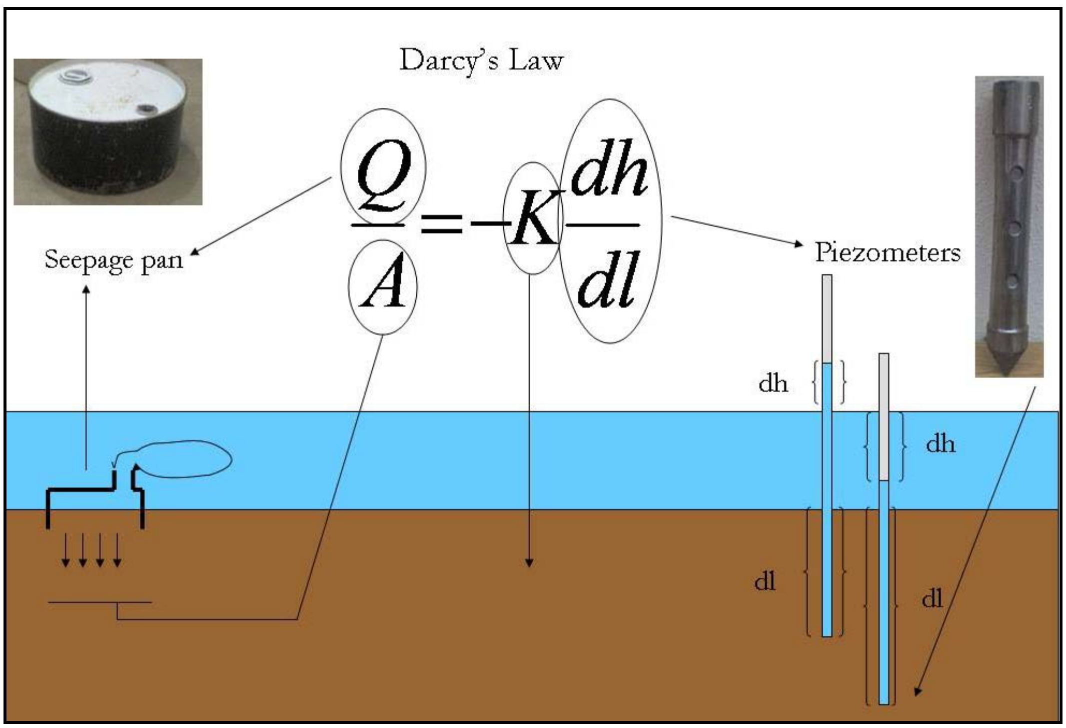

Figure 14: Seepage pans and piezometers being used in a stream to gather information to solve Darcy's Law for saturated hydraulic conductivity (Ksat) of streambed.

Table 8: Flux (cm/sec) values for the 3 km reach of the Santa Cruz River. Negative numbers indicate downward flux.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
3 km	0.002357383	0.004883	-0.00067	0.001684	-0.0032	-0.00253	-0.00067	-0.00354
	0.000336769	0.002526	-0.00034	0.005893	-0.00354	0.004546	-0.00926	-0.0032
	-0.000841923	0.005893	0	0.001515	-0.00438	-0.00168	-0.00977	-0.0032
	0.000336769	0.00623	-0.00034	0.01145	-0.00556	0.009261	-0.0096	
	0.000505154	0.009261		0.01044	-0.00286	0		
		0.006399		0.00943				
3.05 km	0.006061843	0.002021	0.001179	0.005725	0.012629	0.001515	-0.00152	0.001684
	0.006061843	0.002021	0.000289	0.00421	0.002598	0.002887	-0.00014	0.001684
	0.006735381	0.002021	0.002021	0.004546	0.007914	-0.00118	-0.00152	0
	0.010103071		0.001179	0.003873	0.002357	0.007914	-0.00135	0
	0.016838452				0.006399	0.000842		0.001179
	0.012123685							
	0.006061843							
3.1 km	0.00185223	0.000337	0.001347	0.010608	-0.00505	0	0.000337	-0.00084
	0.005051536	0.000337	0	0.013471	-0.00505	0.004715	-0.00135	-0.00118
	0.005893458	0.000168	0.000674	0.012797	-0.00337	0.004715	-0.00051	0
	0.003704459	0.000842	0.000674	0.009766	-0.00433	0.002598	-0.00058	0.001684
	0.002862537	0	0.000674	0.010608		0		0
		0.001852	0.001347					
		0.003368	0.000674					
3.15 km	0.000505154	0.000505	0.004715	0.009598	-0.00337	0.003199	-0.00623	0.000842
	0.001178692	0	0.004715	0.008588	-0.00606	0.003704	-0.00185	-0.00067
	0.000673538	0.000842	0.005388	0.011282	-0.00606	0.007072	-0.00724	0.001515
	0.000673538	0.000168		0.007914	-0.00589	0.011787	-0.00707	-0.00185
	0.001347076	0.000168		0.006735	-0.00387	0.00943	-0.01078	0.000168

Table 9: Flux (cm/sec) for the 15 km reach of the Santa Cruz River. Negative numbers indicate downward flux.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
15 km	0.000337	0	-0.00067	-0.00303	-0.00387	-0.00135	0.003199	-0.00253
	0.000168	0.000674	-0.00101	-0.00202	-0.00219	-0.00118	0.00421	-0.00202
	0.000337	0	-0.00017	-0.00152	-0.00168	-0.00202	0.005725	-0.00202
	0.000674	0.000337	-0.00051	-0.00084	-0.00135	-0.00051	0.003199	-0.00118
	0.000168	0.000842		-0.00219	-0.00202			
		0.000505						
15.05 km	0.007409	0.000337	-0.00067	0.00421	0	0.001684	0.000337	-0.00034
	0.006062	-0.00051	-0.00034	0.004378	0.001179	0.000842	0	-0.00058
	0.003368	-0.00067	-0.00034	0.004378	-0.00034	-0.00084	0.000674	-0.00101
	0.007409	-0.00034	-0.00101		0	-0.00152	0.000337	-0.00084
	0.005388	-0.00034	-0.00017			-0.00168		
15.1 km	0.001347	0.00101	0.000337	0.002526	0.000842	0.007914	-0.00152	0.000505
	0.001347	-0.00034	0.000674	0.000842	0.000505	0.010103	-0.00219	-0.00034
	0.001347	0.001347	0.000674	0.001684	0.000505	0.005893	-0.00152	0.000674
		0.000674		0.001684	0	0.006399	-0.00087	0.000842
		0.002021						
		0.001347						
15.15 km	0.015155	0.001347	0.000674	0.003873	-0.00354	-0.00017	-0.00152	-0.00101
	0.01768	0.001347	0.000842	0.002694	-0.00253	0.000842	-0.00101	-0.00219
	0.016838	0.002526	0.000842	0.002526	-0.00269	0.000842	-0.00087	-0.00173
		0.00101		0.002189	-0.00337	0.000505	-0.00101	-0.00168
		0.00101						

Table 10: Flux (cm/sec) for the 24 km reach of the Santa Cruz River. Negative numbers indicate downward flux.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
24.4 km	0.009261	-0.00242	-0.00101	0.001179	-0.00034	0.005557	0.001515	0.004041
	0.009261	0.001347	-0.00051	0.001684	-0.00101	0.003873	0.001179	0.008419
	0.00943	-0.00135	-0.00051	0.003199	-0.00017	0.006351	0.00101	0.006567
		-0.00067		0.002694	-0.00017	0.005773	0.000168	0.01044
		0.000842		0.001684	-0.00017			0.006062
		0.000505						0.011282
		0.000842						
24.45 km	-0.00135	0.001852	-0.00067	0.000505	0.001515	0.000674	0.000168	0.005557
	-0.00135	0.003536	0.000337	0	0.00101	-0.00168	0.000337	-0.00072
	-0.00202	0.003873	0.001684	0	0.001347	0.000674	0.000433	0.005893
	-0.00202	0.002526	-0.00067	0.001684	0.000337	0.000674		-0.00034
	-0.00202	0.00421	-0.00067	-0.00051				0.001684
				0				
24.5 km	-0.00135	-0.00135	-0.00337	0	0	0.002526	0	-0.00034
	-0.00168	-0.00236	-0.00034	0	0.000674	0.002526	0.00101	0.000168
	-0.00152	-0.00231	-0.00084	0	0	0.002694	0.000337	0.000168
		-0.00135	-0.00118		0.000168		0	
			-0.00084					
24.55 km	-0.00842	-0.00017	-0.00253	-0.00842	-0.00589	-0.00859	-0.00269	-0.00168
	-0.01515	-0.00101	-0.00337	-0.01094	-0.00488	-0.01263	-0.00387	-0.00253
	-0.01482	-0.00051	-0.00067	-0.01515	-0.00354	-0.01111	-0.00505	-0.00303
	-0.02694	-0.00051	-0.00253	-0.00926	-0.0032	-0.01448		-0.00202
	-0.02778	-0.00051	-0.00034					

Table 11: Flux (cm/sec) for the 31 km reach of the Santa Cruz River. Negative values indicate downward flux. Table continued on next page.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
31.25 km	-0.00017	-0.00051	0.002021	-0.00067	-0.00455	0.001684	-0.00067	0.002863
	-0.00022	0.000168	0.001347	-0.00017	-0.00286	0.002357	-0.00017	0.005052
	-0.00168	0.000674	0.001347	-0.00051	-0.00556	0.000842	-0.00084	0.014649
	-0.00067	0.000842		-0.00034	-0.00185	0.00101	-0.00072	0.007649
	-0.00168	0.000505			-0.00185			
	-0.00354	0.000337						
	-0.00253	0.001515						
	-0.00253	0.001515						
		0.000505						
		-0.00084						
		0.001347						
31.3 km	-0.00084	0.000674	-0.00034	0.000168	0.000505	-0.00253	0.000505	0
	-0.00034	-0.00202	-0.00051	0.000168	0.000505	-0.00253	0.00101	0
	-0.00034	0.001347	-0.00034	0.000337	0.000505	-0.00118	0.000505	0
	-0.00017	0.001347	0.000505			-0.00219	0.000674	
	0	0.000674						
	0	-0.00135						
		-0.00135						
		-0.00067						
31.35 km	-0.00084	-0.00017	-0.00337	0	0	0	-0.00173	0.00101
	-0.00084	-0.00034	-0.00168	0	0.000337	-0.00034	-0.00219	0.003031
	0	-0.00034	-0.00337	-9.2E-05	0.000306	0.000153	-0.0026	0.002602
	-0.00017	-0.00034	-0.00404				-0.00354	0.002189
		0.000168	-0.00286					
		-0.00051	-0.00303					
			-0.00185					

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
31.4 km	-0.01515	-0.00404	-0.00354	-0.00135	-0.00135	-0.00017	0	0.001852
	-0.01027	-0.00539	-0.0037	-0.0013	-0.00072	0.000722	0.000144	0.00101
	-0.00926	-0.00943	-0.00337	-0.00118	-0.00017	0.000674	0	0.001347
	-0.00522	-0.00674			-0.00101	0.000674		
	-0.01347	-0.00455			-0.00101			
	-0.01347							
	-0.0101							
	-0.0128							

Table 12: Gradient (dh/dl) measured using piezometers at the 3 and 15 km reaches on the Santa Cruz River. Negative number indicates a losing gradient. Table continued on following page.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
3 km	0.036231884	-0.07282	-0.25862	-0.06607	-0.07205	-0.09728	-0.09728	-0.02778
	-0.050505051	-0.10638	-0.12077	0.655	-0.07634	-0.13913	-0.13913	-0.07692
	0.256410256	0	-1.4	-1.15038	-0.05882	0.259259	0.259259	0.1
3.05 km	-0.84452975	0.06424	-0.01348	-0.55723	-0.26814	-0.02385	-0.02385	-0.46006
	-0.08361204	0.230548	0	0.011696	-0.14286	-0.05208	-0.05208	0.019749
	-1.869369369	-0.41667	-0.03876	-1.16149	-0.35079	0.043478	0.043478	-2.04142
3.1 km	-0.13559322	-0.24809	-0.06061	-0.57104	-0.09434	0.009174	0.009174	-0.0109
	-0.181818182	-0.18939	-0.07619	-0.1308	1.428571	0.05283	0.05283	-0.03051
	0.5	-0.30769	0	0	-3.53846	-0.17742	-0.17742	0.069444
3.15 km	-0.524934383	-1.29487	-0.03205	Unsaturated	-0.19231	-0.88428	-0.88428	-0.05191
	-0.178571429	Unsaturated	-0.02381	-0.67227	0.339506	-1.13569	-1.13569	-0.18077
	-0.891891892		-0.06667		-4.5	-0.16807	-0.16807	0.264151
15 km	-0.45332	-0.29755	-0.13975	-0.58727	-0.05764	-1.1637	-0.03795	-0.01731
	-0.04193	-0.52859	-0.06977	0.033742	-0.22293	-0.70539	-0.07182	0.011111
	-1.20229	0.414286	-0.28037	-1.84472	0.078947	-3.925	0.036364	-0.11732
15.05 km	-0.45052	-0.83072	0	Unsaturated	-0.43417	-0.00791	0	-0.57826
	Unsaturated	-0.07481	-0.05907	-0.97167	-0.16484	-1.08974	-0.09409	-0.06154
		-4.74194	0.1	-1.90826	-0.71429	3.079268	0.233333	-2.15882
15.1 km	0.034435	-0.47049	0	0.008883	-0.24896	-0.03655	-0.00797	-0.15144
	0.150391	-0.40254	0	0.032538	-0.16129	-0.00845	-0.16741	-0.03105
	-0.24299	-0.67742	0	-0.02446	-0.32075	-0.21739	0.391061	-0.54545

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
15.15 km	-0.00733	-0.59609	-0.02708	-0.03275	-0.11364	0.082781	-0.0677	-0.02677
	0.567452	0.2746	-0.03457	0.010169	-0.17327	0.011442	-0.30635	-0.05273
	-1.25581	-3.64	0	-0.15686	-0.03333	0.269461	1.75	0.029787

Table 13: Gradient (dh/dl) measured using piezometers at the 24 km reach of the Santa Cruz River. Negative numbers indicate losing gradient.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
24.4 km	-0.37412	-0.08621	-0.04691	-0.49069	0.017422	0.040984	-0.299	-0.02774
	0.015504	-0.16349	No Data	0	0.030864	0.042194	-0.08108	-0.03172
	-0.97605	0.046948	No Data	-2.125	0	0.036765	-0.64655	-0.01266
24.45 km	-0.02312	0.092166	-0.01153	0.013986	-0.07092	-1.27778	-0.06466	-0.03194
	-0.02869	0.034014	0.007782	-0.0918	0.02994	0.175097	-0.16244	-0.04403
	-0.0098	0.214286	-0.06667	0.274194	-0.21739	5.050847	0.485714	0.011236
24.5 km	-0.47938	-0.00909	-0.03597	-0.01571	-0.11364	0.157549	-0.02901	-0.02162
	-1.01972	-0.04198	-0.04032	-0.02622	-0.06757	0.011312	-0.0948	-0.02299
	-0.02375	0.653846	0	0.015625	-0.19231	4.466667	0.084211	-0.01527
24.55 km	-1.30906	-0.47619	-1.23501	-0.37461	0.012136	-0.01199	-0.06641	-0.05998
	-1.74046	-1.58046	-2.18468	-0.48691	-0.09921	-0.02033	-0.04077	-0.06713
	-0.84959	2.894737	-0.15385	-0.02128	0.1875	0.011429	-0.16364	-0.03465

Table 14: Gradient (dh/dl) for 31 fm reach of the Santa Cruz River. Negative numbers indicate a losing gradient.

	February 2007	March 2007	April 2007	June 2007	September 2, 2007	September 27, 2007	October 2007	February 2008
31.25 km	-0.47764	-0.52641	-0.07246	0.062563	-0.0566	0.013441	-0.03264	-0.06525
	-0.06024	-0.15086	-0.08721	-0.01011	-0.12295	-0.08711	-0.09127	-0.03912
	-1.34375	-0.77183	0	0.310345	0	0.352941	0.141176	-0.108
31.3 km	-0.51825	-0.05038	-0.02653	0.059102	-0.23207	-0.01619	-0.0782	-0.01899
	-0.09191	0.026882	-0.0722	-0.0117	-0.08021	0.023585	-0.02801	0.022124
	-0.93841	-1.2	0.1	0.358025	-0.8	-0.25714	-0.35385	-0.12222
31.35 km	0.890411	-0.75342	-0.52198	-0.04545	-0.08219	-0.01205	-0.08614	-0.05882
	Unsaturated	Unsaturated	0.070423	-0.06186	-0.08511	0.036458	-0.04739	0.400545
			-2.625	-0.00787	-0.07692	-0.07857	-0.23214	-2.96552
31.4 km	-0.78652	-5.04673	-1.51934	-0.002	0	-0.00638	-0.65147	-0.02512
	-0.64426	Unsaturated	-1.7236	0.131902	0	0.018727	-0.42132	0.12326
	-0.22222		0.125	-0.25287	0	-0.03941	-1.06364	-0.58209

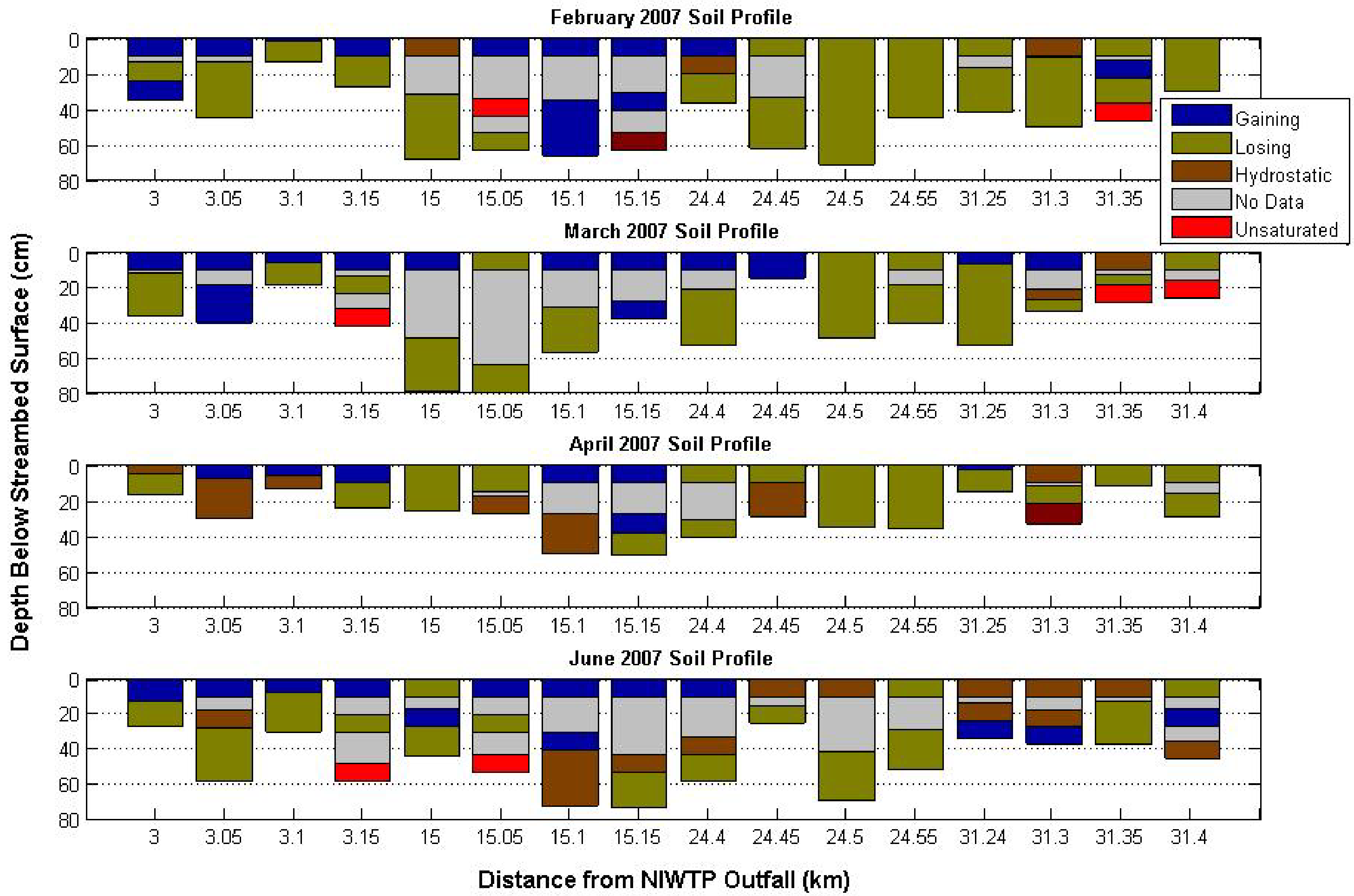

Figure 15: Hydraulic profiles for February-June 2007.

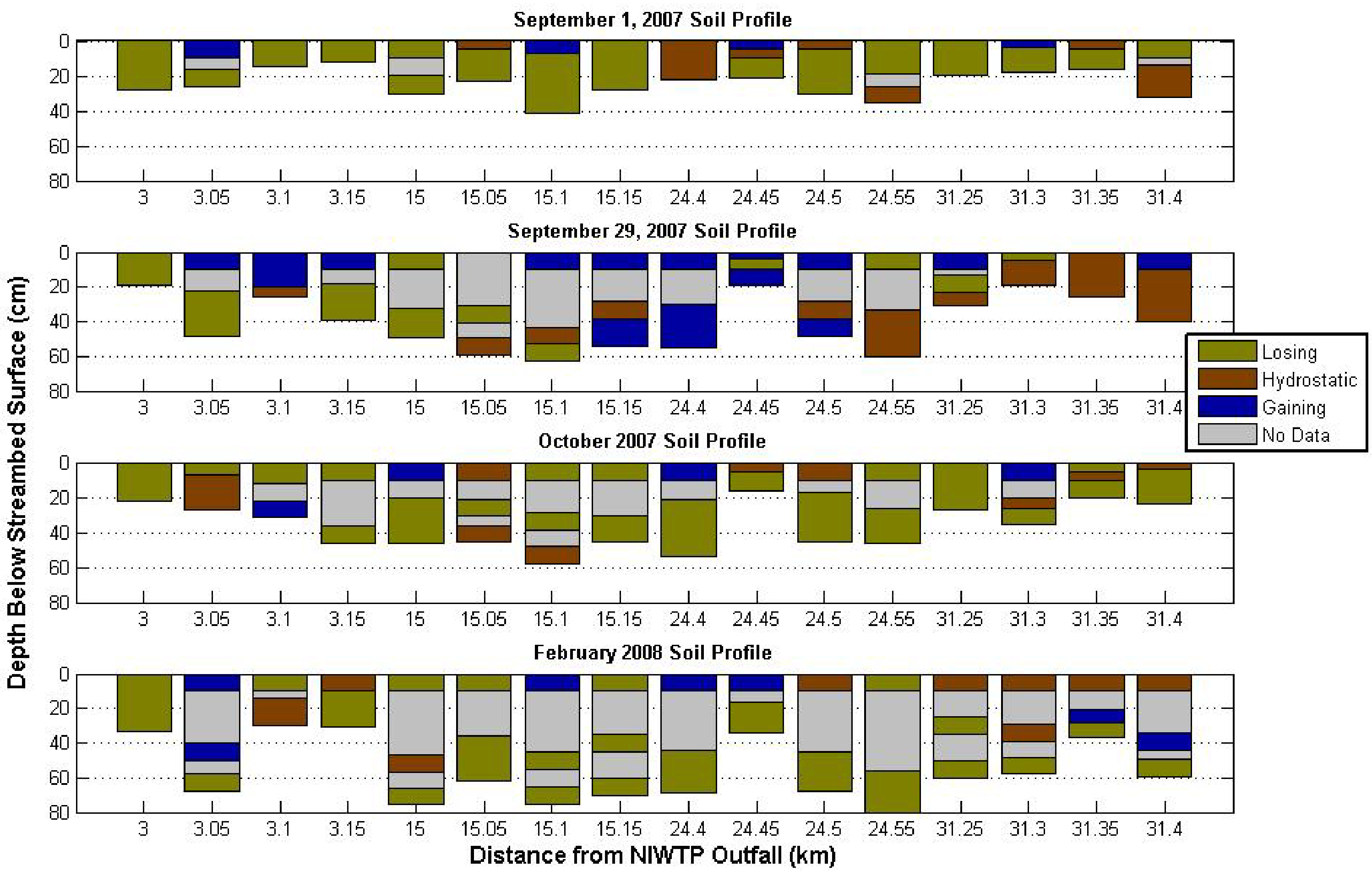

Figure 16: Hydraulic profiles for September 2007-February 2008. Notice no unsaturated conditions.

Measurements pertaining to the field work water balance for 2007-2008.

Table 15: Santa Cruz fieldwork stream flow (m^3/sec) by date and distance from NIWTP Outfall (km)

Distance	2/4/2007	3/18/2007	4/29/2007	6/9/2007	9/5/2007	9/29/2007	10/27/2007	2/6/2008
3	0.70	0.61	0.53	0.51	0.48	0.58	0.62	0.60
3.15	0.58	0.59	0.46	0.46	0.45	0.57	0.53	0.64
15	0.61	0.56	0.48	0.41	0.57	0.54	0.42	0.67
15.15	0.60	0.59	0.48	0.39	0.61	0.36	0.42	0.68
24.4	0.51	0.48	0.32	0.21	0.37	0.29	0.38	0.56
24.55	0.37	0.35	0.29	0.10	0.34	0.22	0.20	0.48
31.25	0.41	0.31	0.20	0.05	0.21	0.08	0.19	0.49
31.4	0.36	0.32	0.14	0.03	0.15	0.05	0.19	0.39

Table 16: Estimated evaporation rate (mm/day), using two different methods. The Penman calculation for evaporation from water bodies was used for the water balance.

Date	2/4/2007	3/18/2007	4/29/2007	6/9/2007	9/5/2007	9/29/2007	10/27/2007	2/6/2008
Penman Equation (mm/day)	4.285	7.355	8.904	10.056	8.724	7.589	6.105	3.868
Hargreaves Equation (mm/day)	2.580	5.511	6.798	8.430	6.319	4.917	4.514	2.004

Table 17: Calculated area per reach used in field work water balances for calculation of total evaporation from river.

Reach	0-3 km	3-3.15 km	3.15-15 km	15-15.15 km	15.15-20 km	20-24.4 km	24.4-24.55 km	24.55-31.25 km	31.25-31.4 km	31.4-35 km
Area (m^2)	27432	1371.6	124007.9	1821.18	62087.76	56327.04	1920.24	89855.04	42245.28	176022

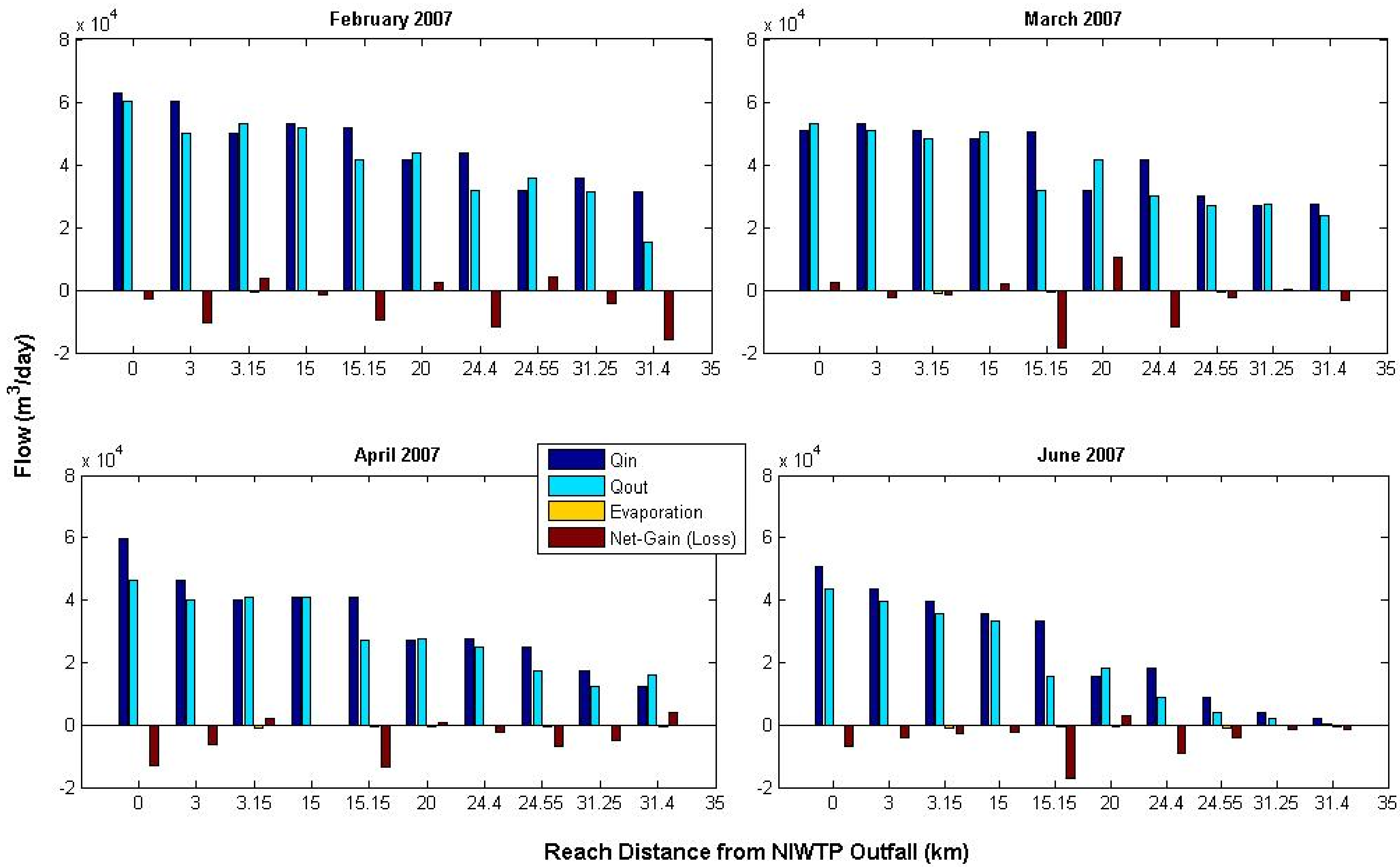

Figure 17: Field work water balance February-June 2007.

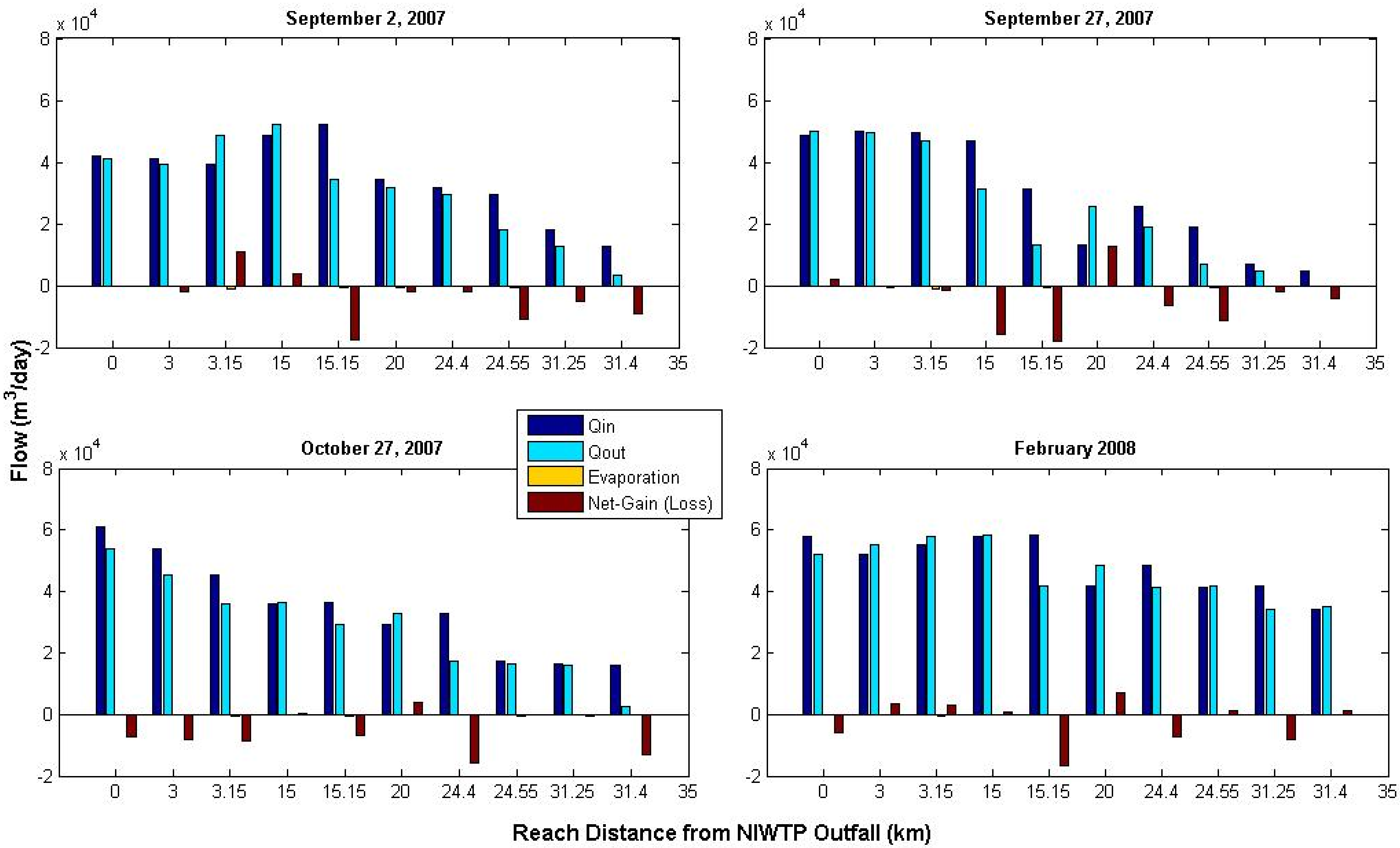

Figure 18: Fieldwork water balance September 2007-February 2008.

Water Quality

Table 18: Water Chemistry data for the Santa Cruz River, February-April 2007, all concentrations in mg/l.

Site Distance	Date	Alkalinity	Lab pH	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
3 km	2/4/2007	65.582	6.191	0.612	50.164	1.794	0.073	120.860	66.849	-6.919	-50.566
3.15 km	2/4/2007	241.695	7.226	0.656	51.483	0.127	0.066	4.985	66.779	-6.835	-49.761
15 km	2/4/2007	95.521	6.589	0.578	50.955	0.021	0.131	135.765	70.411	-6.941	-50.401
15.15 km	2/4/2007	92.506	6.407	0.626	50.050	1.365	0.085	107.597	69.702	-7.031	-51.553
24.4 km	2/4/2007	111.189	6.774	0.540	50.990	0.022	0.095	121.340	69.762	-6.600	-49.358
24.55 km	2/4/2007	113.284	6.757	0.547	49.087	0.355	0.075	115.578	66.848	-6.790	-50.370
31.25 km	2/4/2007	111.359	6.899	0.598	51.249	0.017	0.095	122.561	70.285	-6.854	-49.699
31.4 km	2/4/2007	110.783	6.893	0.553	50.471	0.015	0.064	118.009	68.795	-6.616	-49.957
3 km	3/18/2007	70.347	7.646	0.667	55.063	0.112	0.095	158.395	74.916	-6.852	-51.062
3.15 km	3/18/2007	69.801	7.044	0.660	53.454	0.021	0.096	142.239	69.481	-7.062	-52.173
15 km	3/18/2007	93.464	7.672	0.650	51.511	0.076	0.101	133.239	71.617	-6.962	-50.411
15.15 km	3/18/2007	99.036	7.288	0.636	53.896	0.044	0.096	139.715	75.134	-6.860	-50.194
24.4 km	3/18/2007	126.247	7.455	0.666	55.463	0.116	0.104	125.552	74.760	-6.759	-50.205
24.55 km	3/18/2007	127.260	7.645	0.611	55.183	0.055	0.103	122.694	74.229	-6.634	-49.296
31.25 km	3/18/2007	124.744	7.398	0.660	54.625	0.000	0.081	119.556	73.720	-6.476	-49.182
31.4 km	3/18/2007	117.769	7.468	0.695	52.686	0.043	0.112	114.785	69.915	-6.151	-48.387
3 km	4/29/2007	106.372	6.881	0.714	58.025	2.297	0.095	69.574	78.488	-6.953	-51.134
3.15 km	4/29/2007	123.077	7.040	0.652	55.626	0.642	0.094	55.216	74.030	-6.944	-51.227
15 km	4/29/2007	104.034	6.906	0.830	55.828	1.556	0.081	62.610	76.274	-6.647	-50.732
15.15 km	4/29/2007	174.826	7.196	0.721	56.433	0.483	0.079	7.183	77.986	-6.719	-50.897
24.4 km	4/29/2007	117.955	6.888	0.739	57.067	0.922	0.078	93.273	77.807	-6.718	-50.711
24.55 km	4/29/2007	111.885	6.828	0.664	53.570	1.968	0.064	102.826	73.643	-6.650	-50.577
31.25 km	4/29/2007	120.453	7.057	0.642	55.626	0.064	0.080	110.007	76.525	-6.388	-48.305
31.4 km	4/29/2007	193.734	6.916	0.665	55.334	0.148	0.112	0.116	73.988	-6.376	-48.543

Table 19: Water chemistry information for Santa Cruz River. June, July and two monsoon events. All concentrations in mg/l.

Distance	Date	Alkalinity	Lab pH	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
3 km	6/9/2007	175.526	6.982	0.627	57.268	0.091	0.102	17.390	75.251	-6.799	-50.061
3.15 km	6/9/2007	89.960	6.471	0.648	59.836	3.409	0.117	8.163	77.937	-6.735	-49.896
15 km	6/9/2007	151.083	6.879	0.661	60.085	1.991	0.103	24.682	80.973	-6.608	-49.452
15.15 km	6/9/2007	165.252	6.950	0.656	59.690	2.889	0.104	19.667	79.861	-6.561	-49.834
24.4 km	6/9/2007	158.610	7.053	0.684	60.409	4.461	0.124	34.665	81.159	-6.439	-48.997
24.55 km	6/9/2007	120.025	6.882	0.676	60.397	4.293	0.102	35.284	80.558	-6.457	-49.090
31.25 km	6/9/2007	137.203	7.313	0.666	64.429	5.989	0.137	58.320	86.577	-5.530	-45.454
31.4 km	6/9/2007	142.430	7.263	0.710	64.621	6.254	0.130	58.006	87.419	-5.470	-45.103
3 km	7/2/2007	255.144	7.453	0.706	60.519	15.438	0.120	4.636	79.158	-6.761	-50.205
3.15 km	7/2/2007	266.823	7.703	0.673	58.138	4.561	0.098	7.124	76.116	-6.875	-50.200
11 km	7/2/2007	253.934	7.882	0.680	58.769	0.014	0.107	18.409	77.534	-6.472	-49.224
15 km	7/2/2007	249.349	7.905	0.671	58.842	4.039	0.113	15.858	78.637	-6.416	-48.707
15.15 km	7/2/2007	248.038	7.728	0.711	61.058	0.086	0.119	26.772	81.366	-6.476	-48.976
18.35 km	7/2/2007	242.973	7.818	0.690	59.322	0.794	0.109	24.372	79.145	-6.304	-48.641
19 km	7/2/2007	246.781	7.848	0.706	60.816	0.127	0.120	25.913	81.211	-6.276	-48.341
24.4 km	7/2/2007	213.275	7.752	0.676	61.430	4.354	0.118	35.606	83.489	-6.252	-48.418
24.55 km	7/2/2007	204.425	7.681	0.676	60.730	1.788	0.107	41.053	83.074	-6.224	-48.418
31.45 km	7/27/2007	82.973	7.860	0.262	14.346	2.326	0.041	16.486	42.369	-8.173	-58.062
24.6 km	7/27/2007	106.482	7.877	0.289	10.673	1.443	0.047	9.790	106.853	-6.898	-51.533
11 km	7/27/2007	126.260	7.936	0.319	13.515	2.613	0.052	6.907	110.545	-6.875	-52.762
3 km	7/27/2007	-	-	0.443	21.888	1.944	0.062	2.136	123.115	-6.761	-49.612
3 km	8/2/2007	89.455	7.974	0.292	5.787	0.178	0.028	3.781	66.140	-7.905	-54.756
11 km	8/2/2007	87.970	7.967	0.293	5.789	0.687	0.032	4.204	71.124	-7.644	-54.064
24.6 km	8/2/2007	92.924	7.961	0.303	5.909	0.679	0.034	5.409	89.890	-7.536	-54.271
31.45 km	8/2/2007	87.960	7.914	0.281	5.919	0.561	0.035	5.020	86.962	-7.506	-53.971
Upstream	8/2/2007	69.311	7.651	0.362	3.547	0.012	0.014	2.558	6.423	-8.564	-58.134
Upstream	8/2/2007	71.297	7.722	0.361	3.146	0.016	0.013	2.481	6.374	-8.632	-58.093
Upstream	8/2/2007	76.281	7.941	0.309	2.773	0.035	0.017	2.592	9.785	-8.503	-57.349

Table 20: Water chemistry for the Santa Cruz River, September results, all concentrations in mg/l

Site Distance	Date	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
Nogales Wash	9/5/2007	0.323	41.910	7.108	0.138	0.650	38.166	-6.907	-50.874
Outfall	9/5/2007	0.465	50.330	4.763	0.057	0.595	62.671	-6.730	-50.306
3 km	9/5/2007	0.480	49.650	4.650	0.071	4.816	61.164	-6.702	-49.118
3.15 km	9/5/2007	0.466	49.003	5.145	0.082	4.395	60.257	-6.606	-49.635
15 km	9/5/2007	0.408	43.407	1.205	0.054	21.863	60.189	-6.699	-49.727
15.15 km	9/5/2007	0.421	43.822	0.488	0.069	22.040	60.895	-6.629	-49.975
24.40 km	9/5/2007	0.418	44.264	4.098	0.067	26.858	63.069	-6.489	-49.345
24.55 km	9/5/2007	0.401	44.368	4.292	0.077	27.313	63.223	-6.520	-49.335
31.25 km	9/5/2007	0.398	45.220	3.100	0.059	32.850	65.163	-6.301	-48.302
31.40 km	9/5/2007	0.406	45.222	3.006	0.066	32.913	64.997	-6.121	-47.785
Nogales Wash	9/14/2007	0.406	45.979	6.496	0.059	0.945	41.082	-6.813	-49.896
Outfall	9/14/2007	0.514	49.969	6.795	0.062	1.070	59.278	-6.992	-50.754
3 km	9/14/2007	0.544	50.802	4.230	0.067	5.700	60.215	-6.947	-51.198
3.15 km	9/14/2007	0.544	50.462	4.730	0.066	5.047	60.644	-6.984	-50.392
11km	9/14/2007	0.490	46.764	4.346	0.082	14.732	56.657	-6.813	-50.754
15 km	9/14/2007	0.459	46.594	1.574	0.065	20.386	61.693	-6.722	-49.690
15.15 km	9/14/2007	0.468	46.597	1.740	0.072	20.856	61.900	-6.711	-50.630
18.35 km	9/14/2007	0.471	46.470	1.967	0.074	25.589	62.056	-6.808	-50.299
24.6 km	9/14/2007	0.332	46.895	3.662	0.071	-	63.212	-6.696	-50.175
31.45 km	9/14/2007	0.421	48.036	6.154	0.084	39.798	65.409	-6.194	-47.964
Nogales Wash	9/29/2007	0.330	44.165	0.361	0.092	0.486	35.771	-6.863	-48.813
Outfall	9/29/2007	0.527	49.064	4.561	0.090	0.539	58.000	-6.973	-49.278
3 km	9/29/2007	0.582	48.588	3.540	0.066	3.237	56.281	-6.947	-48.999
3.15 km	9/29/2007	0.574	48.410	3.580	0.086	3.397	55.565	-6.837	-48.927
15 km	9/29/2007	0.471	48.748	1.280	0.076	16.995	62.245	-6.681	-48.534
15.15 km	9/29/2007	0.471	48.268	1.306	0.082	17.272	62.633	-6.743	-48.917
24.40 km	9/29/2007	0.453	48.556	2.814	0.067	28.678	64.700	-6.596	-47.842
24.55 km	9/29/2007	0.455	47.869	2.911	0.077	28.517	64.576	-6.415	-47.749
31.25 km	9/29/2007	0.437	48.422	2.761	0.082	36.024	65.778	-6.192	-46.840
31.4 km	9/29/2007	0.450	48.374	2.640	0.076	-	65.887	-6.027	-46.375

Table 21: Water chemistry results for the Santa Cruz River. All concentration in mg/l.

Site Distance	Date	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
Nogales Wash	10/27/2007	0.496	32.514	0.019	0.122	16.331	32.829	-6.733	-49.157
Outfall	10/27/2007	0.571	23.300	0.259	0.034	42.669	28.110	-6.951	-51.000
3 km	10/27/2007	0.609	53.807	0.291	0.005	85.423	65.872	-6.880	-50.179
3.15 km	10/27/2007	0.610	53.814	0.222	0.004	88.252	65.611	-6.867	-50.541
15 km	10/27/2007	0.586	51.647	0.009	0.001	93.259	69.351	-6.722	-49.704
15.15 km	10/27/2007	0.580	52.424	0.025	0.004	90.393	70.063	-6.138	-47.163
24.4 km	10/27/2007	0.342	27.105	0.015	0.042	43.076	36.318	-6.547	-49.136
24.55 km	10/27/2007	0.366	19.699	0.435	0.034	29.784	25.766	-6.031	-48.909
31.25 km	10/27/2007	0.599	53.163	0.007	0.029	78.711	70.432	-6.483	-48.785
31.4 km	10/27/2007	0.471	15.753	0.017	0.011	23.486	20.191	-6.196	-47.711
Nogales Wash	2/6/2008	0.342	30.459	0.312	0.097	16.442	42.292	-6.888	-50.572
Outfall	2/6/2008	0.522	49.697	4.665	0.100	1.225	66.521	-7.228	-52.028
3 km	2/6/2008	0.561	49.097	3.439	0.086	1.088	65.974	-7.139	-52.018
3.15 km	2/6/2008	0.550	48.889	2.935	0.096	0.898	65.421	-7.028	-51.987
15 km	2/6/2008	0.552	47.956	0.306	0.094	13.696	69.379	-7.073	-51.450
15.15 km	2/6/2008	0.537	47.098	1.980	0.095	14.026	67.937	-6.987	-51.791
24.4 km	2/6/2008	0.554	48.446	0.866	0.106	17.402	69.552	-6.938	-51.657
24.55 km	2/6/2008	0.579	49.296	0.681	0.107	21.150	70.129	-6.990	-52.152
31.25 km	2/6/2008	0.523	48.922	0.376	0.078	25.218	69.658	-6.881	-51.161
31.4 km	2/6/2008	0.544	48.784	0.731	0.105	21.342	69.430	-6.932	-51.553

Table 22: Water chemistry results for wells in the Santa Cruz Basin. All concentrations are in mg/l.

USGS ID	Date	ALK	Lab pH	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
314214111025601	6/20/2007	241.474	7.423	0.495	32.649	0.001	0.111	12.187	130.909	-7.165	-50.680
313735111023701	6/20/2007	362.078	7.809	0.380	73.115	-	0.270	0.181	148.597	-6.524	-48.000
313120111005801	6/20/2007	186.981	7.624	0.345	36.809	-	0.104	35.751	73.723	-7.199	-51.976
313845111023101	6/20/2007			0.399	35.908	0.012	0.034	4.341	117.305	-7.155	-51.744
312633111023301	6/20/2007	93.362	7.025	0.176	7.285	-	0.498	0.662	5.803	-6.543	-49.115
312823110573501	6/20/2007	167.539	7.809	0.428	8.087	0.003	0.063	0.461	161.930	-5.962	-46.883
313408111025601	6/20/2007	98.524	7.878	0.972	5.452	0.002	0.050	2.246	11.488	-7.082	-52.224
312230110503301	6/21/2007	184.481	7.849	0.355	8.802	0.002	0.072	7.566	86.455	-7.021	-52.017
312240110511001	6/21/2007	281.410	8.148	0.195	46.568	-	0.115	0.523	84.644	-6.647	-48.815
312523110542801	6/21/2007	183.255	8.054	0.406	15.064	-	0.087	16.576	60.897	-7.139	-51.151
312545110552801	6/21/2007	151.786	7.417	0.353	5.332	-	0.034	9.336	241.270	-7.458	-50.758
313851110012303	6/20/2007	117.039	7.649	0.382	8.989	-	0.055	2.459	76.706	-7.428	-52.529
314157111003701	6/20/2007	174.225	8.101	0.291	10.333	0.017	0.086	2.851	56.112	-7.646	-54.440
312048110504901	6/21/2007	156.691	7.756	0.395	6.535	0.002	0.059	0.035	227.212	-6.731	-49.879
314214111025601	9/27/2007			0.457	22.719	0.013	0.010	10.807	98.733	-7.337	-53.739
313735111023701	9/27/2007			0.293	75.427	0.162	0.068	0.454	143.933	-6.891	-50.795
313120111005801	9/27/2007			0.282	35.323	0.006	-	22.085	66.597	-7.305	-50.755
313845111023101	9/27/2007			0.412	38.554	0.008	0.024	5.418	110.823	-7.057	-52.293
312633111023301	9/27/2007			0.159	6.259	0.002	0.049	0.123	7.466	-5.062	-43.331
312823110573501	9/27/2007			0.344	7.017	0.000	0.038	2.456	143.337	-6.127	-45.911
313408111025601	9/27/2007			0.746	5.285	0.000	0.034	1.980	9.700	-7.715	-53.142
312230110503301	9/27/2007			0.374	10.163	0.004	0.013	6.457	28.682	-7.296	-50.259
312240110511001	9/27/2007			0.195	29.198	0.004	0.051	0.195	81.323	-6.897	-48.762
312523110542801	9/27/2007			0.370	15.251	0.001	0.019	15.160	86.992	-7.342	-51.138
312545110552801	9/27/2007			0.515	3.909	0.042	0.017	4.876	155.803	-6.968	-47.904
314321111075001	10/13/2007			0.411	8.353	0.068	0.055	3.215	10.765	-7.296	-52.439

Measurements used in calculation of historic water balance

Table 23: NIWTP cumulative discharge per month, all values in m^3*10^4

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
January	136.57	144.52	162.33	160.84	137.53	178.82	170.43	147.73	160.05	117.54	138.00	179.49
February	133.04	124.11	160.99	132.91	160.68	165.81	154.01	131.41	165.13	98.64	134.82	174.80
March	130.98	134.57	172.03	140.36	167.33	192.47	167.30	171.97	142.02	129.04	145.52	171.63
April	115.11	116.93	161.54	120.30	143.03	179.50	154.77	122.62	148.76	124.55	124.54	188.44
May	105.56	114.32	147.46	120.15	128.54	131.34	150.37	126.23	131.81	106.16	119.91	166.92
June	99.44	105.14	146.69	94.58	140.76	169.19	130.30	124.15	136.00	95.90	102.32	161.97
July	111.58	107.97	130.39	99.00	157.88	169.20	141.64	139.76	132.51	87.25	90.85	158.71
August	111.87	126.89	149.15	147.23	162.65	182.51	168.19	139.57	149.20	97.07	128.71	171.99
September	110.90	125.25	145.01	165.78	165.09	185.76	152.33	142.92	127.76	145.05	113.76	140.00
October	123.70	140.41	139.46	182.61	206.15	189.28	151.20	128.76	106.18	187.90	164.07	
November	124.13	120.64	133.29	166.26	225.00	169.99	149.77	134.96	115.24	147.11	166.65	
December	138.49	145.49	142.52	112.53	182.18	172.03	156.17	145.26	127.25	143.09	160.41	

Table 24: Calculated water surface area for the calculation of evaporation losses.

Reach	**0-20km**	**20-50 km**
Area (m^2)	216720.4	367901.2

Table 25: Evaporation rate (mm/day) calculated using the Penman equation. This rate was used for the water balance.

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
January	4.83	4.57	4.63	5.17	5.11	4.52	4.91	5.02	4.57	4.70	4.83	4.83
February	5.63	5.46	5.29	5.83	5.91	5.69	6.06	5.84	5.75	5.19	5.84	5.68
March	7.26	7.54	6.98	7.15	7.04	7.16	7.17	7.00	7.58	7.00	6.83	6.83
April	9.19	8.59	8.56	8.71	9.27	8.90	8.92	8.57	8.74	8.83	8.84	8.75
May	10.61	10.35	9.64	9.88	10.60	10.21	10.45	10.29	9.98	10.68	10.13	10.05
June	10.93	10.65	10.95	10.73	10.72	10.86	11.02	10.85	10.80	11.00	10.84	10.78
July	10.57	10.93	10.75	10.74	10.68	10.74	10.63	10.80	10.50	10.81	10.63	10.80
August	9.81	9.80	9.73	9.74	9.81	9.90	9.91	10.11	9.81	9.68	9.45	9.80
September	8.30	8.45	8.45	8.51	8.76	8.63	8.69	8.63	8.76	8.65	8.27	8.57
October	7.31	7.23	7.16	7.18	7.15	7.00	6.82	7.22	6.97	7.00	7.11	7.11
November	5.37	5.52	5.26	5.69	4.78	5.86	5.86	5.13	5.26	5.28	5.28	5.28
December	4.70	4.12	4.43	4.82	4.37	4.49	4.31	4.72	4.62	4.56	4.50	4.50

Table 26: Evaporation rate (mm/day) calculated using Hargreaves equation.

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
January	3.31	3.05	3.10	3.62	3.54	2.99	3.34	3.52	3.05	3.19	3.28	3.28
February	4.09	3.89	3.68	4.30	4.41	4.16	4.51	4.33	4.20	3.53	4.32	4.13
March	5.84	6.23	5.48	5.70	5.53	5.70	5.64	5.49	6.28	5.49	5.28	5.28
April	8.24	7.29	7.28	7.51	8.37	7.79	7.81	7.29	7.42	7.68	7.67	7.55
May	10.35	9.84	8.56	9.00	10.34	9.58	10.04	9.74	9.16	10.49	9.36	9.27
June	10.74	10.10	10.81	10.35	10.06	10.61	10.97	10.52	10.50	10.90	10.47	10.33
July	9.51	10.91	10.16	10.06	10.02	10.00	9.81	10.29	9.83	10.43	9.81	10.24
August	8.86	8.44	8.44	8.39	8.90	9.01	9.18	9.39	9.00	8.22	7.74	8.32
September	6.88	7.15	7.33	7.29	7.94	7.61	7.75	7.56	7.98	7.72	6.91	7.48
October	6.11	5.94	5.97	6.04	6.00	5.75	5.47	6.06	5.72	5.75	5.87	5.87
November	3.86	4.05	3.76	4.16	3.24	4.28	4.28	3.60	3.64	3.66	3.66	3.66
December	3.12	2.61	2.89	3.27	2.87	2.97	2.80	3.09	3.08	3.03	2.94	2.94

Historic Data

Table 27: List of id numbers for all historic data including: NOAA, USGS stream gages, USGS chemistry data for wells, and USGS id for ADWR transducer wells

Agency	ID Number	Purpose/Use
USGS	09480500	Stream gage near Nogales, AZ
USGS	09481740	Stream gage at Tubac, AZ (20 km from NIWTP outfall)
USGS	09481770	Stream gage near Amado, AZ (35 km from NIWTP outfall)
USGS	09482000	Stream gage at Continental, AZ (50 km from Outfall)
USGS	314524110593801	Well water chemistry data used with mixing model
USGS	314535111001601	Well water chemistry data used with mixing model
USGS	314446111022801	Well water chemistry data used with mixing model
USGS	314356111044101	Well water chemistry data used with mixing model
USGS	314313111034101	Well water chemistry data used with mixing model
USGS	314800111023601	Well water chemistry data used with mixing model
USGS	313845111023101	Well water chemistry data used with mixing model
USGS	313858111023901	Well water chemistry data used with mixing model
USGS	314913110583401	Well water chemistry data used with mixing model
USGS	312026110373801	Well water chemistry data used with mixing model
USGS	312538110351601	Well water chemistry data used with mixing model
USGS	312223110554201	Well water chemistry data used with mixing model
USGS	312422110570801	Well water chemistry data used with mixing model
USGS	312512110571701	Well water chemistry data used with mixing model
USGS	313150111005801	Well water chemistry data used with mixing model
USGS	313133111011001	Well water chemistry data used with mixing model
USGS	312818110594501	Well water chemistry data used with mixing model
USGS	314644110490501	Well water chemistry data used with mixing model
USGS	315109110482301	Well water chemistry data used with mixing model
USGS	313456111032001	Well water chemistry data used with mixing model
USGS	313404111030701	Well water chemistry data used with mixing model
USGS	312301110512301	Well water chemistry data used with mixing model
USGS	312350110531701	Well water chemistry data used with mixing model
USGS	**312230110503301**	Well has pressure transducer operated by ADWR
USGS	**312740110581301**	Well has pressure transducer operated by ADWR
USGS	**313735111023701**	Well has pressure transducer operated by ADWR
NOAA	028865: Tumacacori National Monument	ID for cooperative weather station, used to gather temperature data for evaporation calculation

Table 28: Santa Cruz River ID table. Chemistry label ID's (Lable id's), Alternate id (name or id for different sample time), thesis id (as sample is referred to in this thesis)

Label ID	ALT ID	Longitude	Latitude	Thesis ID
SC 1-1	Rio Rico 1	110°59.548W	31°28.175N	3 km
SC 1-2	Rio Rico 2	110°59.561W	31°28.196N	3.05 km
SC 1-3	Rio Rico 3	110°59.578W	31°28.224N	3.1 km
SC 1-4	Rio Rico 4	110°59.597W	31°28.243N	3.15 km
SC 2-0	Palo Parado			11 km
SC 3-1	Santa Gertrudis 1	111°02.786W	31°33.631N	15 km
SC 3-2	Santa Gertrudis 2	111°02.783W	31°33.653N	15.05 km
SC 3-3	Santa Gertrudis 3	111°02.770W	31°33.679N	15.1 km
SC 3-4	Santa Gertrudis 4	111°02.759W	31°33.702N	15.15 km
SC 4-1	Chavez Siding 1	111°02.784W	31°38.628N	24.4 km
SC 4-2	Chavez Siding 2	111°02.811W	31°38.655N	24.45 km
SC 4-3	Chavez Siding 3	111°02.828W	31°38.678N	24.5 km
SC 4-4	Chavez Siding 4	111°02.839W	31°38.705N	24.55 km
SC 5-1	Amado 1	111°03.281W	31°42.357N	31.25 km
SC 5-2	Amado 2	111°03.299W	31°42.379N	31.3 km
SC 5-3	Amado 3	111°03.312W	31°42.404N	31.35 km
SC 5-4	Amado 4	111°03.322W	31°42.426N	31.4 km
SC07020701	Old Bailey Crossing	111°02.933W	31°35.310N	18.35 km
SC07020702		111°02.928W	31°35.693N	19 km
SC08020701	Upstream	110°56.110W	31°26.042N	
SC08020702	Upstream	110°50.574W	31°22.443N	
SC08020703	Upstream	110°52.730W	31°23.950N	
SC06200701	SC09270701	111°02.824W	31°42.515N	314214111025601
SC06200702		111°00.643W	31°41.915N	314157111003701
SC06200703	SC09270702	111°02.600W	31°38.774N	313845111023101
SC06200704		111°01.411W	31°38.856N	313851110012303
SC06200705	SC09270703	111°02.640W	31°37.594N	313735111023701
SC06200706	SC09270704	111°02.975W	31°34.144N	313408111025601
SC06200707	SC09270705	111°01.016W	31°31.345N	313120111005801
SC06200708	SC09270706	111°02.616W	31°26.530N	312633111023301
SC06200709	SC09270707	110°57.596W	31°28.416N	312823110573301
SC06210701		110°51.002W	31°20.703N	312048110504901
SC06210702	SC09270711	110°50.637W	31°22.508N	312230110503301
SC06210703	SC09270710	110°51.213W	31°22.676N	312240110511001
SC06210704	SC09270709	110°54.514W	31°25.458N	312523110542801
SC06210705	SC09270708	110°55.482W	31°25.727N	312545110552801
SC101307		111°08.007W	31°43.321N	314321111075001

Appendix D: San Pedro Data

This appendix will serve as a resource for all Upper San Pedro data collected during the course of the project. Please see Appendix A for Santa Cruz data. This appendix will follow the same path as the main text: map of study area, soil core data, then piezometers and seepage pans, stream gauging, and finally, water quality samples. A note on site labels, they are measured as the distance from the most upstream (southern) point. For instance the point under the bridge is the point farthest upstream, and is labeled .9 km. The labels are (0km, .1 km, .2 km, .7 km, .8 km, and .9 km)

Site Map

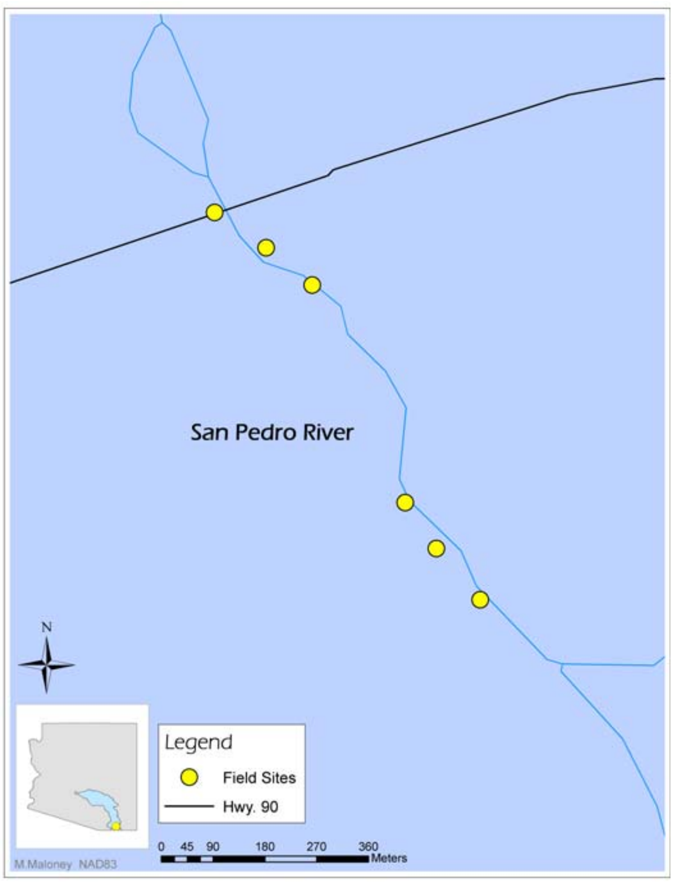

Figure 19: Map of San Pedro River showing field sites

Soil Cores

Table 29: Ksat values (cm/sec) for soil cores removed from the San Pedro River

Distance	6/8/2007	7/2/2007	8/31/2007	10/27/2007
.1km	0.1071	0.0587	0.3397	0.1612
	0.1071	0.0619	0.3397	0.1504
	0.1015	0.0587	0.1698	0.1397
	0.1128	0.0587	0.3523	0.1397
	0.1043	0.0576	0.3523	0.1504
	0.1043	0.0652	0.3523	0.1504
			0.3649	
.2 km	0.4718	0.8910	0.2220	0.1047
	0.4893	0.8769	0.1414	0.1047
	0.5242	0.8769	0.4046	0.1047
	0.5592	0.8628	0.2023	0.1047
	0.4893	0.8628	0.2171	0.0982
	0.6291	0.8769	0.2220	0.1113
	0.6088			0.0982
.7 km	0.1254	0.1958	0.2176	0.1000
	0.1304	0.1907	0.2176	0.1000
	0.1304	0.1907	0.2176	0.0923
	0.1304	0.1958	0.2219	0.1004
	0.1304	0.1958	0.2132	0.0994
	0.1254	0.1958	0.2176	0.1076
		0.1907		
.9 km	0.2632	0.2084	0.3446	0.1135
	0.2732	0.1310	0.3297	0.1059
	0.2682	0.4048	0.3371	0.1180
	0.2732	0.1965	0.3371	0.0999
	0.2682	0.2084	0.3371	0.1044
	0.2781	0.2084	0.3371	0.0999
	0.3552			
	0.3552			
	0.3441			
	0.3552			
	0.3441			
	0.3552			

Piezometers and Seepage Pans

Table 30: Flux (cm/sec) measurements for the upstream part of the San Pedro River reach, negative numbers indicate downward flux.

Sites	November 2006	March 2007	April 2007	June 2007	August 2007	October 2007
0 km	-0.002188999	0.001347076	0.004041228	0.00235738	0.005893458	0.001347076
	-0.000841923	0.000673538	0.003872844	0.00319931	0.004883151	0.001683845
	-0.001515461	0.000673538	0.004041228	0.00235738	0.007408919	0.001298966
		0.000673538		0.00303092	0.004714767	0.001178692
				0.00235738		
.1 km	-0.001178692	-0.000505154	-0.000336769	-0.00033677	0.000673538	-0.000841923
	-0.001178692	-0.000673538	0.000168385	0.00016838	0.000841923	-0.00336769
	-0.000841923	-0.000505154	-0.000168385	0	0.000673538	-0.000841923
	-0.001515461		-0.000336769	0		-0.001683845
						-0.001683845
.2 km	-0.000673538	0.000168385		-0.00033677	0.000673538	0.000336769
	-0.000673538	-0.000168385		-0.00050515	0.002020614	0.000168385
	-0.00185223	0		-0.00016838	0.001683845	0.000168385
	-0.000673538				0.002188999	0.000168385

Table 31: Flux (cm/sec) for the downstream part of the San Pedro River reach, negative number indicates downward flux.

Site	November 2006	March 2007	April 2007	June 2007	August 2007	October 2007
.7km	0.000505154	0.00185223	0.001178692	0.001515461	0.00336769	0.001178692
	0.000336769	0.00336769	0.001515461	0.002020614	0.005556689	0.001515461
	0.00336769	0.005556689	0.001683845	0.001683845	0.004041228	0.001683845
	0.00336769	0.002525768	0.002525768	0.001010307	0.00858761	0.000841923
	-0.000673538		0.002188999	0.001178692	0.004714767	
	0.001010307					
	0.002357383					
	0.002357383					
	-0.001010307					
.8 km	-0.002020614	0.002525768	-0.000336769	0.000673538	-0.002525768	0.002694152
	0.009934687	0.002525768	0.000505154	0.001178692	-0.002862537	0.00336769
	0.004883151	0.000505154	0.001683845	0.001347076	-0.003704459	0.003030921
	0.004377998	0.003030921	0.001683845	0.001515461	-0.002188999	0.003030921
	0.003704459		0.001683845	0.001010307		
.9 km	N/A	0.003030921	0.000505154	0.000673538	-0.002020614	0.002188999
	N/A	0.001010307	0.000505154	0	-0.001347076	0.002694152
	N/A	0.001178692	0.000785794	0.001347076	-0.001178692	0.001683845
		0.001010307		0.002188999	-0.000841923	0.002020614
				0.001010307		

Table 32: Hydraulic gradient (dh/dl) for the San Pedro River, negative number indicates losing gradient.

Site	November 2006	March 2007	April 2007	June 2007	August 2007	October 2007
0 km	0.11821975	0.022522523	-0.025735294	-0.14886731	0.049180328	-0.616858238
	-0.133027523	0	-0.047120419	0.83410138	0.414746544	-0.409610984
	0.505300353	0.111111111	0.024691358	-2.4673913	-2.888888889	-1.682352941
.1 km	0.010062893	0.030911901	0.027675277	-0.31067961	-0.024793388	-1.005042017
	-0.004395604	0	0.103305785	-0.35315985	-0.082417582	-1.094262295
	0.029411765	0.129032258	-0.603448276	-0.23076923	0.15	-0.598130841
.2 km	-1.191986644	0	N/A	-0.10179641	-0.064655172	0.018975332
	0.009367681	-0.136054422	N/A	-0.10218978	-0.150943396	-0.007281553
	-4.174418605	1	N/A	-0.1	0.85	0.113043478
.7km	-0.677943166	-0.746606335	0.024024718	0.00549451	-0.097701149	0
	-0.753488372	-0.160818713	0.038324678	0.00833333	0.222929936	-0.426160338
	-0.159574468	-2.75	-0.048780488	0	-3.058823529	0.497536946
.8km	-0.355294118	0.045317221	0.007699925	0.02048417	-0.054852321	0.017006803
	0.0273794	0.024271845	0.06489209	0.03267974	-0.057377049	0
	-3.891566265	0.08	-0.272727273	0.004329	-0.052173913	0.051546392
.9km	N/A	-0.027675277	-0.02372856	-0.23372781	0.063694268	0.014802632
	N/A	0	0.016897848	-0.01242236	0.394366197	-0.006410256
	N/A	-0.05	-0.346153846	-0.43502825	-3.066666667	0.085714286

Field Stream Gauging data

Table 33: Stream flow (m3/sec) for the top and bottom of the 1 km San Pedro River reach.

Site	3/14/2007	4/28/2007	6/8/2007	8/31/2007	10/27/2007
0 km	0.1862	0.0787	-0.0034	0.1966	0.0124
.9 km	0.2556	0.0869	-0.0246	0.1960	0.0124

Water Quality

Table 34: Water quality data for the San Pedro River.

Site	Date	ALK	Lab pH	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulfate	δ18O ‰	δD ‰
0 km	3/14/2007	263.264	8.260	0.448	12.801	0.063	0.140	0.042	59.868	-6.9	-51
.9 km	3/14/2007	255.923	8.329	0.445	11.910	0.001	0.141	0.071	58.205	-7.0	-52
0 km	6/8/2007	246.540	8.086	0.568	10.441	0.026	0.117	0.209	39.998	-7.4	-53
.9 km	6/8/2007	220.709	8.137	0.548	7.788	0.016	0.085	0.672	25.816	-7.8	-57
0 km	7/2/2007	231.418	8.087	0.469	7.615	0.113	0.073	0.300	20.377	-7.8	-53
.9 km	7/2/2007	213.284	8.145	0.456	6.305	0.020	0.061	1.044	17.111	-8.3	-59
0 km	8/31/2007			0.291	9.326	0.003	0.096	0.115	50.513	-6.9	-49
.9 km	8/31/2007			0.291	9.432	0.028	0.092	0.174	47.595	-7.0	-51
0 km	10/27/2007			0.273	4.470	0.004	0.048	0.089	20.462	-7.6	-54
.9 km	10/27/2007			0.468	9.088	0.003	0.098	1.045	36.380	-8.0	-57

Table 35: San Pedro site ID's. Label id (chem sample label), Longitude, Latitude and id for this thesis.

Label ID	Longitude	Latitude	Thesis ID
SP 1-37	110°08.076W	31°32.749N	0 km
SP 1-33	110°08.117W	31°32.797N	.1 km
SP 1-29	110°08.146W	31°32.840N	.2 km
SP 1-9	110°08.233W	31°33.043N	.7 km
SP 1-5	110°08.276W	31°33.078N	.8 km
SP 1-1	110°08.324W	31°33.111N	.9 km

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