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CLOGGING OF AN EFFLUENT DOMINATED SEMIARID RIVER: A CONCEPTUAL MODEL OF STREAM-AQUIFER INTERACTIONS[1]

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ABSTRACT: Water managers in arid and semiarid regions increasingly view treated wastewater (effluent) as an important water resource. Artificial recharge basins allow effluent to seep into the ground relieving stressed aquifers, however these basins frequently clog due to physical, chemical, and biological processes. Likewise effluent is increasingly used to maintain perennial base flow for dry streambeds, however, little is known about the impact of effluent on streambed hydraulic conductivity and stream-aquifer interactions. We address this issue by investigating: if a clogging layer forms, how the formation of a clogging layer alters stream-aquifer connections, and what hydrologic factors control the formation and removal of clogging layers. We focused on the Upper Santa Cruz River, Arizona where effluent from the Nogales International Waste Water Treatment Plant sustains perennial flow. Monthly sampling, along a 30 km river reach, was done with two foci: physical streambed transformations and water source identification using chemical composition. Historical dataset were included to provide a larger context for the work. Results show that localized clogging occurs in the Upper Santa Cruz River. The clogging layers perch the stream and shallow streambed causing desaturation below the streambed. With these results, a conceptual model of clogging is established in the context of a semiarid hydrologic cycle: formation during the hot premonsoon months when flow is nearly constant and removal by large flood flows (>10 m^3/s) during the monsoon season. However, if the intensity of flooding during the semiarid hydrologic cycle is lessened, the dependent riparian area can experience a die off. This conceptual model leads us to the conclusion that effluent dominated riparian systems are inherently unstable due to the clogging process. Further understanding of this process could lead to improved ecosystem restoration and management.

(KEY TERMS: effluent; stream-ground-water interaction; semiarid; clogging.)

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INTRODUCTION

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

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population increases. As such, it has been used to remedy both ground-water depletion and to support river restoration efforts (Bouwer, 2002; Brooks *et al.*, 2006).

To mitigate ground-water depletion, artificial recharge basins have been used to recharge effluent into aquifers. Artificial recharge basins often develop subsurface clogging, which limits aquifer recharge effectiveness. Clogging develops as water moves through the surface and subsurface soil layers, decreasing pore size due to physical (particle settling), chemical (precipitating or gas entrapment), or biological (algae or a biofilm formation) processes (Bouwer, 2002). Reduced pore sizes decrease hydraulic conductivity resulting 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). The full range of artificial recharge methods and their associated problems are detailed elsewhere (Bouwer, 2002; Greskowiak *et al.*, 2005).

Effluent is used to supplement and replace base flow resulting in effluent dominated streams defined as "water bodies [that have] instream flows [that] are entirely dependent on effluent discharges" (Brooks *et al.*, 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 (Smith, 2000; Stromberg, 2001; Sophocleous, 2007). A 1998 survey throughout the Western United States found 78 sites considered effluent dominated watercourses (Smith, 2000). Approximately two-thirds of these discharge sites were used for riparian restoration or preservation activities including wildlife protection, recreation, and marsh rehabilitation (Smith, 2000).

There is an information gap regarding the impact of effluent on streambed hydraulic conductivity, stream-aquifer interactions, riparian ground water sources and quality, and the dependent riparian ecosystem. Given the prevalence of clogging in recharge basins, it is evident that similar processes may occur in streams. This study will address these issues by answering the following questions:

(1) In effluent dominated rivers, does clogging exist and does it reduce streambed hydraulic conductivity?
(2) 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?
(3) 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?
(4) How do periods of stable low-flow and scour during high-flow flood events control the formation and removal of a clogging layer?

STUDY AREA

The Upper Santa Cruz River, an effluent dominated system in south central Arizona, provides an excellent opportunity to study the effluent-aquifer relationship. The Santa Cruz River originates in the San Rafael Basin, Arizona (Towne, 2003). It travels south and then west through Mexico for 70 km before reentering Arizona 8 km east of Nogales. The Nogales International Wastewater 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 14 km north of the international border (shown as outfall in Figure 1) at a nearly constant rate generating a stable downstream base flow (Nelson and Erwin, 2001). The international border to a USGS stream gage 50 km north of the NIWTP form the bounds the study area (Figure 1).

The Upper Santa Cruz Basin has a semiarid climate with a mean annual temperature of 20°C and mean annual precipitation of ~40 cm [Nelson and Erwin, 2001; National Oceanic and Atmospheric Administration (NOAA): http://www.ncdc.noaa.gov/oa/ncdc.html]. Seasons are referred to in the following manner here and throughout this paper: winter (October, November, December, January, February, and March), premonsoon (April, May, and June), and monsoon (July, August, and September). Precipitation is distributed bimodally with the majority of rain falling during the summer monsoon season (50%, July through September) and a lesser winter rainy season (20%, from December through February) with the rest distributed through the year (Coes *et al.*, 2002; NOAA http://www.ncdc.noaa.gov/oa/ncdc.html). Monsoon storms are of short duration, with intense local rainfall, inducing flooding, whereas winter rains tend to be long lasting, low intensity storms with little runoff (Hirschboeck, 1988).

The Santa Cruz River flows through an alluvial basin surrounded by mountains, a hydrogeologic setting characteristic of the Basin and Range Geologic Province. The study area is bounded by the Pajarito, Atascosa, Tumacacori, and Cerro Colorado Mountains

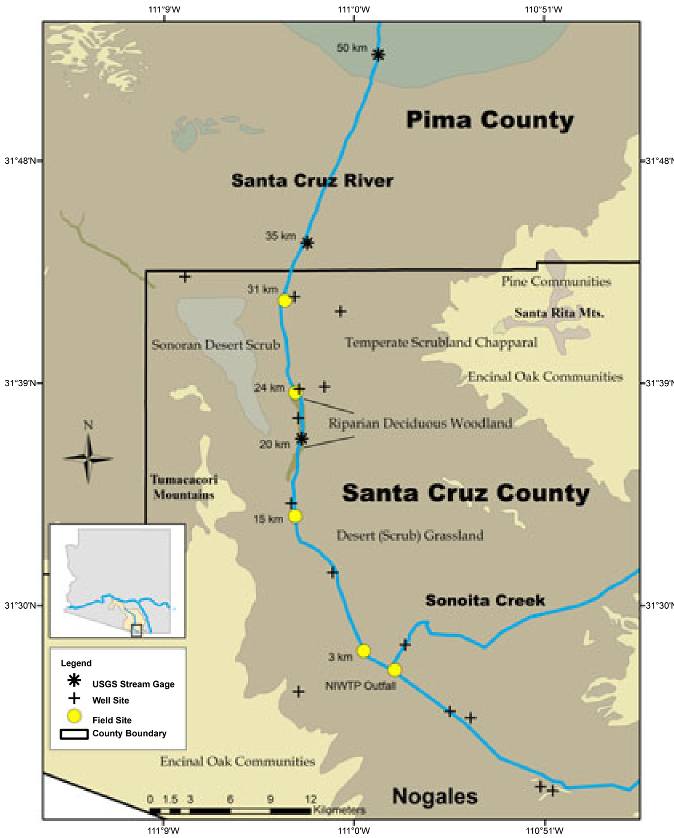

FIGURE 1. The Santa Cruz Study Area: Field Sites, USGS Stream Gages, Project Wells, and Natural Vegetation.

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 km (Coes *et al.*, 2002). Three geologic formations dominate this river basin: the Nogales Formation (hydraulic conductivity: 0.05-0.9 m/day; specific yield: 5%), Older Alluvium (0.3-15 m/day; 10%), and Younger Alluvium (30-180 m/day; 18%) (Nelson, 2007). The alluvial water table converges to the surface at local bedrock highs in the study area (Coes *et al.*, 2002 and Nelson, 2007).

The Upper Santa Cruz River is predominantly ephemeral, fed by precipitation, runoff events, and tributary washes. Tributaries within the study area include: Nogales Wash (the sole perennial contributor to the Santa Cruz River, fed by natural springs and raw sewage), Sonoita Creek, Aqua Fria, Peck, and Josephine Canyons (Murphy and Hedley, 1984; Nelson and Erwin, 2001; Coes *et al.*, 2002). The Upper Santa Cruz River has two USGS streamflow-gaging stations within the study area [at 20 and 35 km from NIWTP outfall (shown as outfall in Figure 1), Gage #09481740 and 09481770, respectively] and two more gages that bookend the study area (upstream at Nogales and 50 km from NIWTP outfall, Gage #09480500 and 09482000, respectively). USGS streamflow records (available at http://waterdata.usgs.gov/az/nwis) and the daily effluent information from the NIWTP provide a record of surface-water flows over the last 10 years.

The NIWTP treats, on average, 60,000 m^3 of wastewater per day (IBWC, 2004). NIWTP uses a modified aerated lagoon treatment process with a five-day retention time, muting the peaks and valleys of daily wastewater production. Effluent leaving the plant has a high nutrient load, including toxic ammonia levels (Sprouse, 2005). Thus, effluent enters the dry channel at a nearly constant rate and is high in nutrients creating intense algal and biological productivity in the stream (Coes *et al.*, 2002).

METHODOLOGY

Site Selection

Field work along the Santa Cruz River focused on four locations. Sites were chosen for access and distance downstream of the NIWTP. These four reaches were ~3, 15, 24, and 31 km downstream of the NIWTP outfall (Figure 1). To collect a representative sampling of streambed conditions at each location, four sampling points were established, each separated by 50 meters, for a total of 16 field measurement sites along the Santa Cruz River.

Monthly sampling of the four primary reaches on the Santa Cruz River included the use of piezometers and seepage pans at each point. Stream gaging and water sampling were also performed monthly at the top and bottom of the reaches. Soil cores were taken twice before and twice after the monsoon season at each sample point.

Soil Cores

Soil cores were taken to qualitatively and quantitatively assess the presence of a clogging layer 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 and a shovel used to excavate to the bottom so it could be capped and extracted from the streambed (Paul Brooks and Marcel Schaap, Professors, University of Arizona, 2007, personal communication). 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 Lacher (1996) in her literature review of clogging layers: “This black odoriferous layer is anaerobic…and has come to be known as a ‘schmutzdecke,’ which translates roughly from German to ‘dirty layer’.” The K_{sat} of the soil cores was determined using a constant head soil core tank method (Reynolds and Elrick, 2002; Chief, 2007; Karletta Chief, Research Soil Physicist, Desert Research Institute, 2007, personal communication).

Piezometers and Seepage Pans

Piezometer and seepage pan data were used to study stream-aquifer interactions. Piezometers were used to observe 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. Seepage pan data were only utilized to indicate gaining or losing. Piezometers elevation head was similarly used to determine gaining or losing condition when compared with the observed hydraulic head of water at the stream surface. 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 each sample point. 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 to provide depth related information about the streambed (Kalbus *et al.*, 2006). The piezometers were given 20 min to 4 h to equilibrate. After equilibration, three measurements, relative to the top of the steel pipe, were taken: depth to stream water, depth to streambed, and depth to water table inside the pipe (Kalbus *et al.*, 2006). Measurements inside the pipe were taken using a depth 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, 2003; Kalbus *et al.*, 2006). A bottomless metal cylinder with a small threaded hole was pushed ~10 cm into the streambed (Kalbus *et al.*, 2006). Secured to the hole was a pipe elbow connected to a plastic bag containing a measured volume of water. During the experiment, water flowed freely through the seepage pan into or out of the bag while time was monitored (Murdoch and Kelly, 2003). 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 screened interval of the piezometer being the length difference (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 were generated. The flux and gradient data can then be used to determine gaining or losing conditions for the respective depths of the equipment at each sampling point.

Stream Gaging

Streamflow data for the Upper Santa Cruz River includes: NIWTP effluent outflow (IBWC, unpublished data written communication 2008), and four USGS stream gages. In addition, manual measurement of streamflow was performed using the mid section method (Herschy, 1995) at the top and bottom of the four study reaches to quantify gains and losses. A Marsh-McBirney Incorporated Model 2000 Flo-Mate portable water flow meter was attached to a top-setting wading rod and used to measure stream velocity using standard methods (Marsh-McBirney, 1990). Streamflow measurements were then compiled with USGS streamflow-gaging stations, effluent flow from NIWTP, and NOAA climate data to create a water balance for each reach on the day of the stream gaging. Inputs and outputs of the water balance include: streamflow into and out of a reach, evaporation from the river, and a residual net-gain/loss to river water. This net-gain-loss term combines several water fluxes including: near-stream riparian transpiration, infiltration and exfiltration from the aquifer.

The evaporation rate was estimated using the Penman potential evaporation equation for open water (Mohan, 1992; Shuttleworth, 1993). 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 the 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 (Shuttleworth, 1993). Additionally, a cloudless day was assumed for all calculations. The evaporation rate oscillated from ~4 in January to 11 mm/day in June. The evaporation rate was calculated for the day of streamflow measurements and then applied to the surface area of a river reach. That surface area was calculated using stream width measurements gathered during the stream gaging. As there were two width measurements (at top and bottom) for each reach, the mean width was applied to the length of the reach.

Surface-Water Sampling

Water samples were taken from the NIWTP outfall, the Upper Santa Cruz River, and riparian wells to clarify the impact of effluent on the aquifer. Monthly samples were taken at the top and bottom of the four primary reaches on the Santa Cruz, and from the NIWTP outfall. In addition, synoptic surface-water sampling, stream grab sampling campaigns performed in a single day, were undertaken during two monsoon events and before and after the monsoon season (Figure 2). Sites included the four primary reaches and three additional sites, ~10, 18, and 19 km from the NIWTP outfall. All surface-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.

Ground-Water Sampling

Ten wells were sampled along the Santa Cruz riparian corridor, nine were sampled both premonsoon and postmonsoon. Wells within 1 km of the streambed were considered riparian wells. These wells, like the primary reaches, were chosen for access and hydrogeologic situation (Figure 1). Five wells, called riparian wells, located close to the river downstream of the NIWTP outfall were sampled to understand the impact of effluent on aquifer water source. Five wells upstream of the NIWTP outfall were sampled to understand the aquifer response to storm inputs without effluent. Well samples, in most instances, were pumped with the specific purpose of sampling. A few wells that were inaccessible (sealed by pump or windmill) were sampled from pipes or overflow tanks. One to three casing volumes were pumped and sample bottles rinsed three times before gathering a sample. In addition to the wells we were able to directly sample we utilized data from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/nwis) as detailed further in the mixing model section below.

Chemical Analysis

After collection, all water samples were kept cool and transported to the University of Arizona where they were filtered using a 0.2 μm membrane mixed cellulose ester (MCE) filter and stored at 4°C in the dark until analyzed.

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 Corporation, 2004). Detection thresholds were ~0.05 mg/l for all anions. Due to high nutrient concentrations (NO_3 ranged as high as 158 mg/l) many samples were diluted before analysis. Duplicates and/or checks were run every eight samples to maintain quality control. Results indicate an error margin of less than 5% for concentrations greater than 1 mg/l and upwards of 10% for concentrations above the detection threshold but below 1 mg/l.

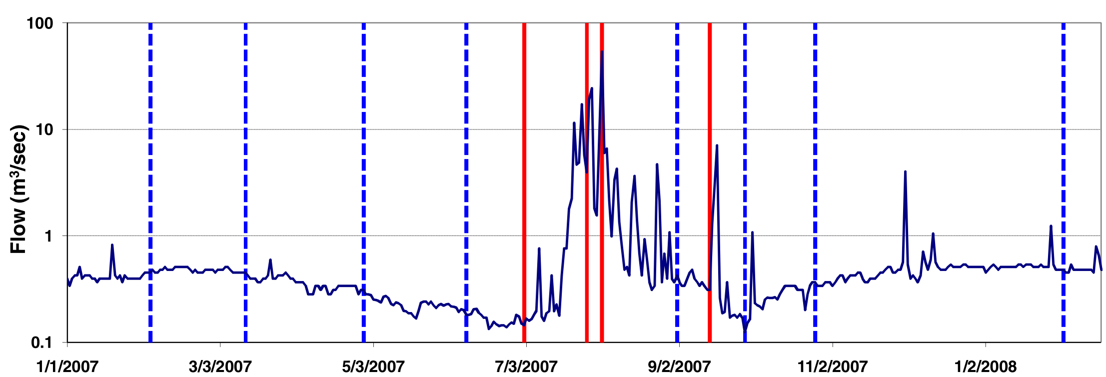

FIGURE 2. Streamflow at 20 km From NIWTP Outfall 2007-2008, USGS Stream Gage 09481740. Vertical dashed lines indicate day of field investigations. Vertical solid line indicates days only water chemistry samples were taken for either synoptic run or monsoon event.

Mixing Model

Anion data from the Upper Santa Cruz River and the Santa Cruz wells were used to quantify groundwater sources using a geochemical mixing model. The mixing model is a set of three linear algebraic equations used to estimate the partitioning of the aquifer's water sources based on the chemical components of a sample. The assumptions of the model are that the Upper Santa Cruz River is a strictly losing system with three chemically distinct water inputs: NIWTP effluent, tributary runoff during flood events, and Sonoita Creek flood runoff. Note that Sonoita Creek is distinct because local geology imparts a high sulfate concentration to this water (Gu *et al.*, 2008). The analyzed wells included well samples obtained for this study and data acquired by the USGS from other Upper Santa Cruz Basin wells (USGS water quality data are available at http://nwis.waterdata.usgs.gov/usa/nwis/qwdata). All samples used from the USGS well database were taken after 1972, the date the NIWTP moved to its current location.

RESULTS

Physical Hydrology

Soil Cores. Soil cores provided a qualitative means of confirming clogging; based on visual and olfactory characteristics, 14 of the 64 soil cores were considered clogged. All clogged cores were sampled during the premonsoon period (Table 1). Statistics for the clogged cores indicate that clogging reduced the saturated hydraulic conductivity of the streambed (Table 2). In addition, comparison of the premonsoon clogged cores and postmonsoon cores using the Wilcoxon rank sum test (Milton and Arnold, 2003) indicate that the clogged cores have a lower K_{sat} value than unclogged cores (significant at an $\alpha = 0.025$) (Figure 3). Thus, soil cores qualitatively confirmed to have clogging all occurred in the premonsoon period and were shown upon analysis to have lower mean and median K_{sat} values than premonsoon and postmonsoon unclogged samples (Table 2).

TABLE 1. Number of Clogged Cores Per Primary Reach of Santa Cruz River.

	3 km	15 km	24 km	31 km
Premonsoon (June and July)	4	3	6	1
Postmonsoon (September 2nd and 27th)	0	0	0	0

TABLE 2. Soil Cores: Descriptive Statistics.

Number of Cores	Type	Mean K_{sat} (cm/s)	Median K_{sat} (cm/s)
18	Santa Cruz premonsoon (not clogged)	0.428 ± 0.288	0.347
14	Santa Cruz premonsoon (clogged)	0.159 ± 0.099	0.136
32	Santa Cruz postmonsoon cores	0.290 ± 0.159	0.263

Streambed Hydraulic Profiles. Piezometer and seepage pan data were paired to create hydraulic profiles for the length of the river at each sampling time (Figure 4). During February and June 2007, prior to the monsoon season, the 3 km reach and the 15.05 km point showed gaining conditions in the shallow streambed despite losing or unsaturated conditions below. 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 area 31.35 km from the outfall in February. In June both the 24 km and 31 km 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.

After the monsoon season (Figure 2), the dominant characteristic of the river during September was a return to overall losing conditions. Exceptions to this occurred at 3.05, 15.1, 24.45, and 31.3 km from the NIWTP outfall, the shallow streambed was gaining while losing conditions prevailed in the deeper streambed. In February 2008, there was a continuation of the overall losing trend with hydrostatic conditions dominating in the shallow streambed at the 31 km reach.

The hydraulic profiles indicate temporal trends in streamwater – aquifer exchange across the streambed. Premonsoon 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 monsoon, the surface, ~20 cm and ~60 cm shallow and deep streambed had similar ground-water heads and generally indicated the expected losing condition and there were no longer any unsaturated areas.

Stream Gaging and Water Balance. Stream gaging data collected in the field was enhanced by NIWTP effluent data, USGS stream gage data, and NOAA temperature data to create an instream water balance during each sampling campaign (Figure 5). The February 2007 water balance depicts minor losses due to evaporation (531 m^3/day over the

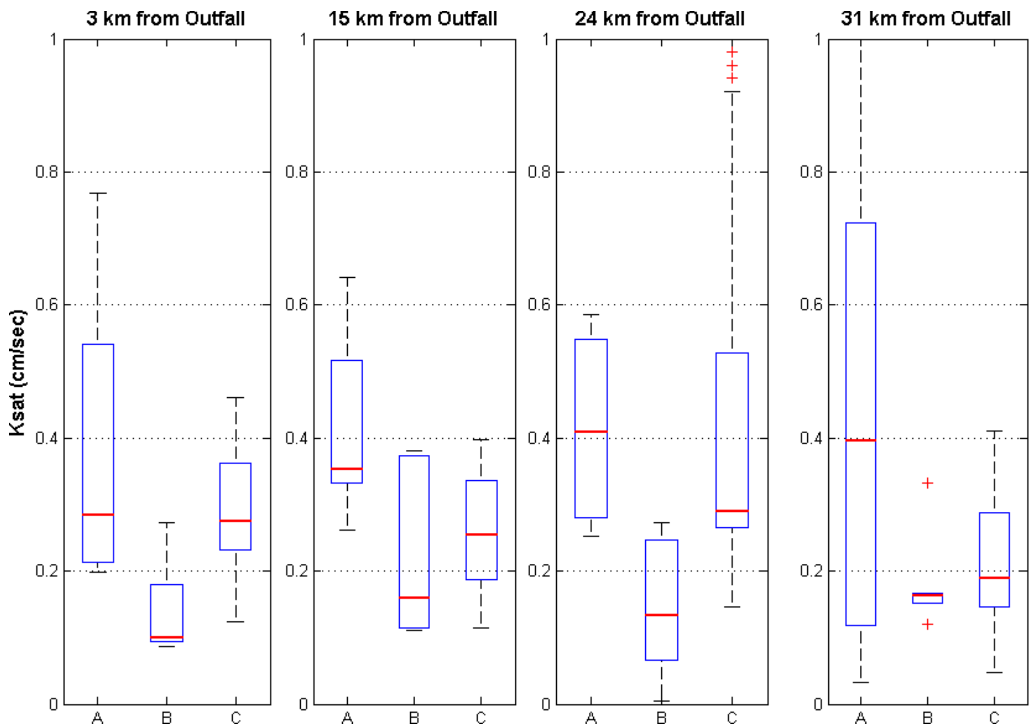

FIGURE 3. Saturated Hydraulic Conductivity (K_{sat}) Values Based on Soil Core Data for the Santa Cruz River Grouped into (A) Premonsoon Not Clogged, (B) Premonsoon Clogged, and (C) Postmonsoon for Each of the Primary Reaches. The red line indicates the median value for the sample set, the line at the 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 premonsoon clogged and unclogged cores fluctuates depending on the number of clogged cores per reach, refer to Table 2 for number of clogged cores per reach.

longest reach) and significant losses due to infiltration (approximately two-thirds of instream water is lost over 35 km). There were three gaining reaches 3.15-15 km, 20-24.4 km, and 24.55-31.25 km. The June 2007 water balance is similar to February 2007 but with more substantive losses due to evaporation (1,246 m^3/day over the longest reach) the river disappears prior to reaching 35 km downstream. During June there was only one gaining reach 20-24.4 km from the outfall.

The postmonsoon (September 2, 2007) water balance is distinct in that water was not lost throughout the river. The first 15 km were gaining. This phenomenon could be due to the monsoon storms that filled the aquifer, raised the ground-water 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 35 km reach only a small fraction of flow remained.

Finally, the February 2008 water balance shows the first 15 km in a roughly neutral state with no significant water being lost or gained. Then, on the 15.15-20 km reach ~30% of 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. Unlike the February 2007 water balance, which showed a loss of two-thirds of streamflow, the February 2008 water balance showed a system that lost less than half of instream flows over 35 km.

Historic Streamflow. Santa Cruz River streamflow data for the years 2004 and 2005 were explored in detail using log scale hydrographs (Figure 6). In early winter of 2004 flow from NIWTP and at 20 km from the outfall were similar indicating minimal infiltration was occurring. Flow from 20 to 35 km included losses, as there is approximately an order of magnitude difference between the two flows. As 2004 enters the premonsoon time period, high rates of evapotranspiration remove water from the river, leaving it dry at 35 km from late May to July 2004. During the 2004 monsoon season, runoff events do not exceed 10 m^3/s. In the time following the monsoon season, flow at 35 km decreased slightly at first, but then slowly increased. At the end of 2004, flow from the NIWTP, at 20 km, and 35 km were identical, implying little channel losses along the 35 km stretch of river.

Early winter 2005 saw the continuation of the late 2004 flow regime with nearly constant flows from the NIWTP and at 20 and 35 km. By February of 2005

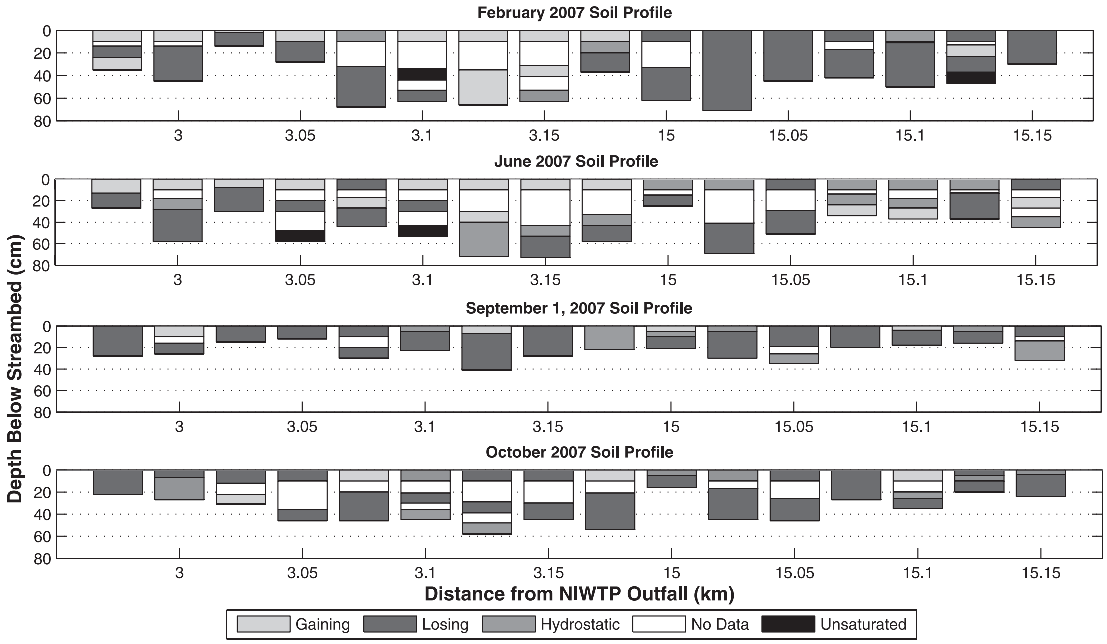

FIGURE 4. Hydraulic Profile for the Santa Cruz River, Constructed Using Seepage Pan and Piezometer Data. Each profile should be understood as follows – the top color band was determined using the seepage pan, the next band down with a shallow piezometer, and the bottom band of color was determined with the deep piezometer. Due to differences in piezometer placement, measurement depths differ between surveys. In general, note that the premonsoon period (February and June 2007) streambed is gaining; however, deeper conditions are losing or even unsaturated indicating a disconnection between stream and aquifer. In contrast following the monsoon season most all profiles are losing indicating a reconnection between aquifer and stream.

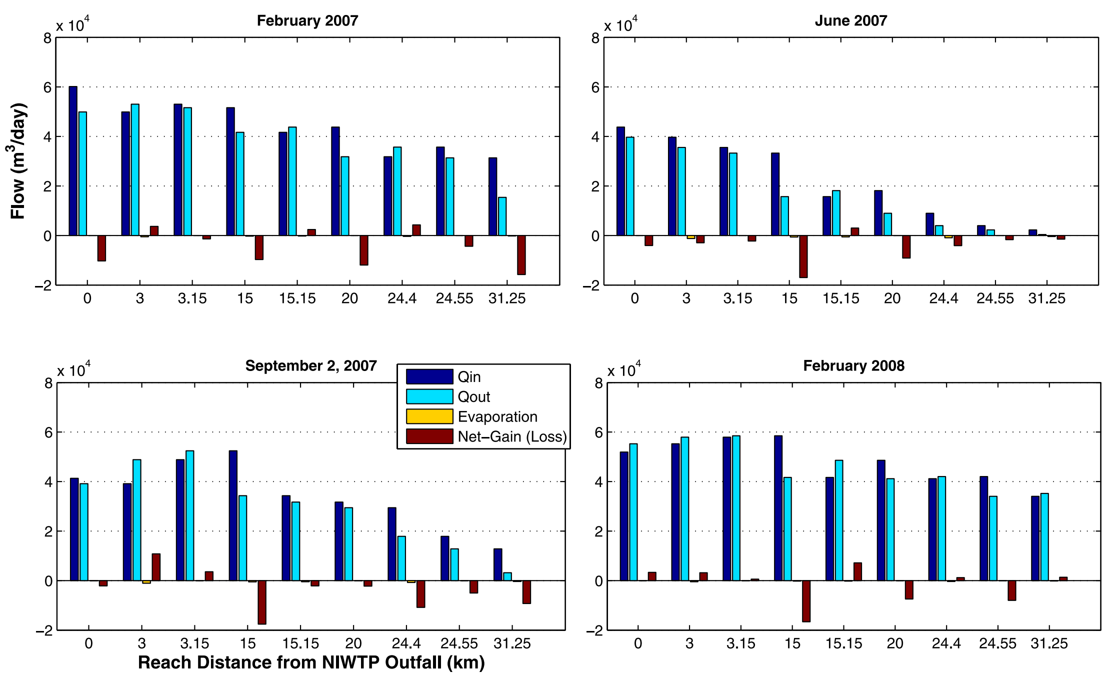

FIGURE 5. Stream Water Balance of Santa Cruz River for Given Dates Based on Field Stream Measurements, Data From USGS, NIWTP, and NOAA. Note the x-axis is the start of the reach in km distance from NIWTP outfall. The end of the given reach is the next number, for instance the reaches are 0-3, 3-3.15 km, etc.

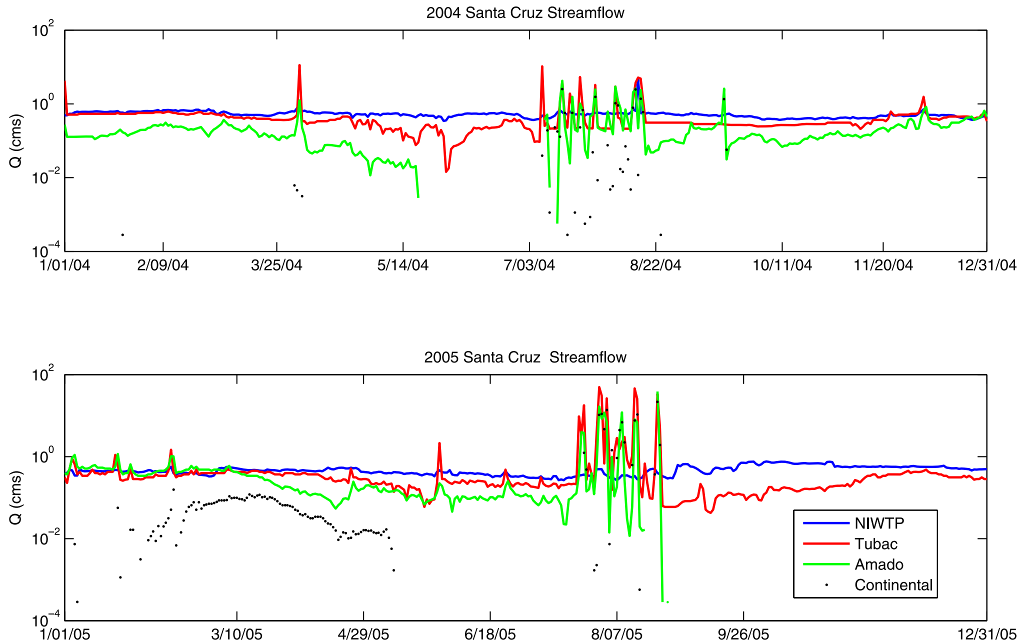

FIGURE 6. 2004-2005 Santa Cruz River Hydrograph Measurement Points Include the Outfall, 20, 35, and 50 km From NIWTP Outfall. In general, note that the 2004 monsoon season produced no events above 10 m^3/s, whereas 2005 had several. Following the 2004 monsoon season significant surface flow continued downstream, even reaching 50 km downstream in early 2005. Following the 2005 monsoon season flow ceased 35 km downstream, see text for further discussion.

there was a new development, sustained daily flow at 50 km from the NIWTP outfall. During the premonsoon period, the flow at 50 km stopped. At 35 km however, unlike 2004, there was still sustained flow at 35 km, indicating there was a lessening of the stream water losses that normally desiccate the premonsoon river at 35 km. The 2005 monsoon season, which started in mid-July, saw several events exceeding 10 m^3/s (Table 3). Postmonsoon the flow from the NIWTP remained consistent, however there was an order of magnitude difference between the flow from NIWTP and at 20 km, and flow at 35 km ceased. Thus, channel losses had increased dramatically following the 2005 summer flood season. This analysis demonstrates that decreased monsoon flow (2004) meant longitudinally extended river flow the following year (winter and premonsoon season 2005) indicating less net stream water infiltration.

Water Chemistry

End Member Waters. Sulfate and chloride concentrations were useful in identifying three distinct water inputs and were used to create a mixing model to estimate water sources for the aquifer and river throughout the year (Figure 7A). All end member waters were sampled numerous times and were averaged into a single composite value to be used in the mixing model (Figure 7A). Effluent is the first end member. As Santa Cruz river water is dominated by NIWTP effluent (with a minor input of geochemically similar water from Nogales Wash) an average of these value provides a good estimate. The effluent end member is characterized by high concentrations of chloride (45+ mg/l) and sulfate (60+ mg/l). The second end member is tributary runoff during monsoon floods, including runoff from the upstream portion of the Upper Santa Cruz. This end member is based on samples taken upstream of the NIWTP outfall during a monsoon storm and is characterized by both low chloride and sulfate concentrations (Figure 7A). Finally, runoff from Sonoita Creek is recognized as geochemically distinct due to high (250+ mg/l) sulfate

TABLE 3. Flow Thresholds on Santa Cruz River, Number of Days Per Year Flow Reached Given Threshold at the USGS Stream Gage (#09481740) 20 km Downstream of NIWTP Outfall.

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

Note: Cumulative streamflow at 20 km from NIWTP outfall and precipitation as measured by NOAA at Tumacacori.

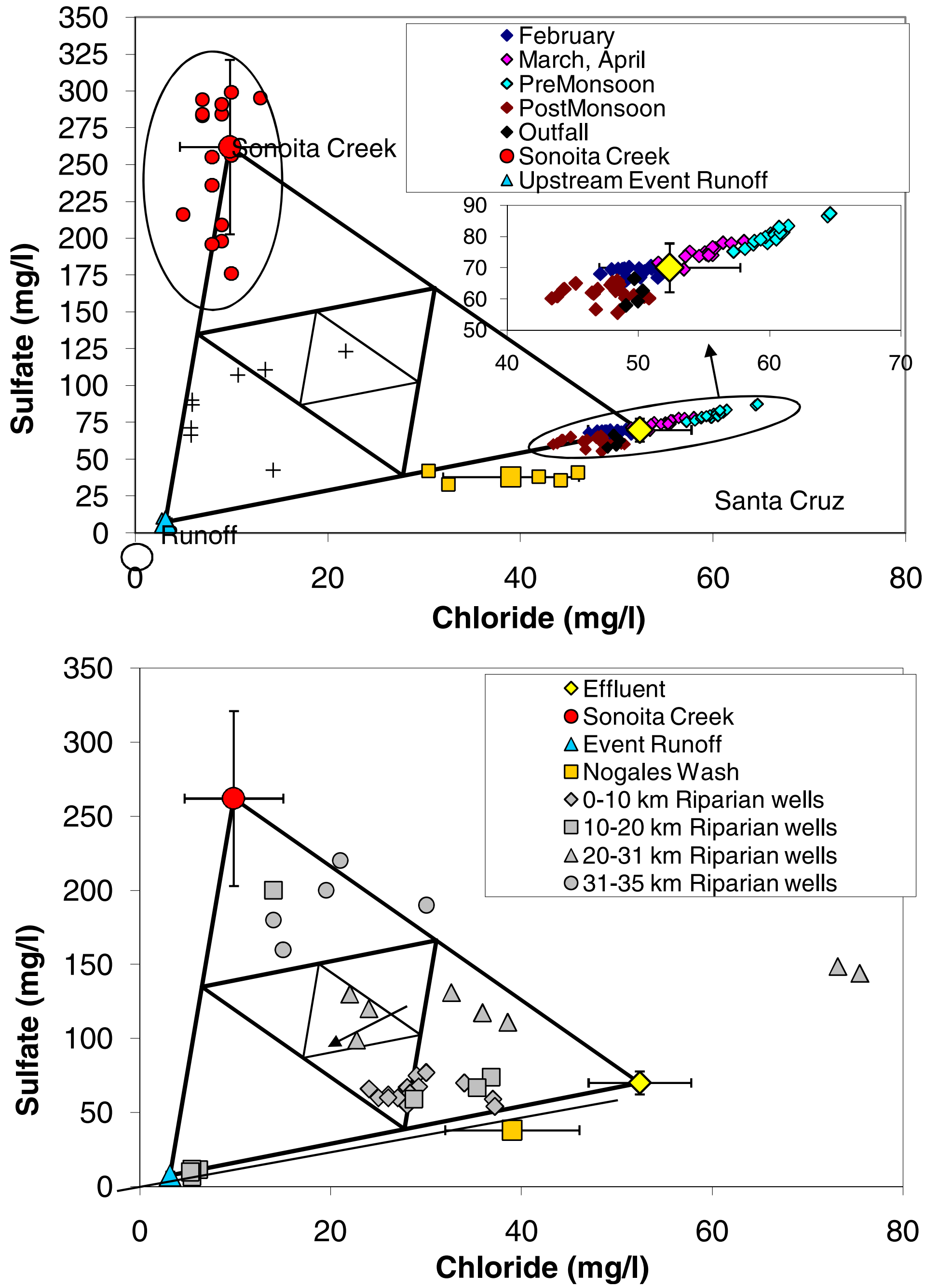

FIGURE 7. Mixing End Members and Results. Large triangle represents the bounds of the mixing model, medium black triangle portrays the partitioning of the samples by dominant water source, and small black triangle portrays samples that are considered thoroughly mixed between sources. (A) Top panel shows samples used to characterize end member water. (B) Bottom panel shows the results for riparian wells.

concentration paired with a low chloride concentration (10 mg/l). Samples were not taken from Sonoita Creek for this project but existing data were used (Gu *et al.*, 2008). A well-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.

Santa Cruz River. During large runoff events Sonoita Creek and other tributary runoff flow contribute to the downstream flow. As a result the river

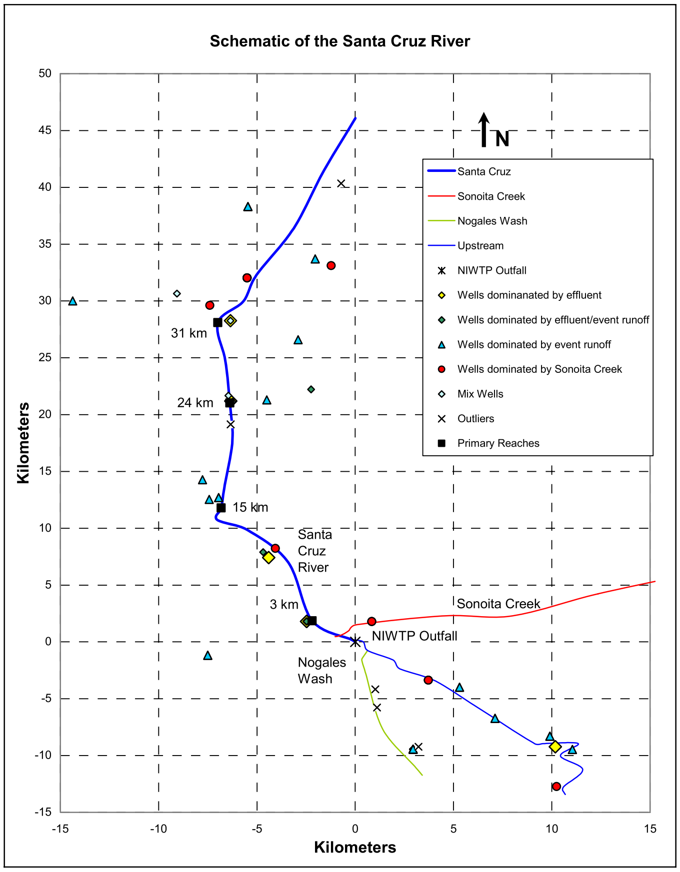

FIGURE 8. Schematic of the Santa Cruz River and Major Tributaries. Colored mark for well is related to source water dependence. Black rectangles on Santa Cruz River indicate field-work locations. Outlier wells on the map are those whose chloride/sulfate concentrations place them outside the bounds of the mixing model, as defined by the triangle in Figure 7.

downstream of the NIWTP outfall is a mixture of tributary and Sonoita Creek flow (Figure 7A). As the stormwater recedes, the river downstream of the NIWTP outfall becomes a mixture of Santa Cruz, Sonoita Creek, and tributary event flow.

During periods of base flow the Santa Cruz River exhibits some temporal variability (Figure 7A inset box). The constituent concentrations for the NIWTP outfall stayed constant over time (Cl range: 49.1-50.3 (mg/l), SO_4 range: 58.0-66.5 (mg/l)); however, river water did not. The stream follows an enriched evaporation trend through time that was not dependent on the NIWTP outfall alone.

Riparian Wells. Riparian wells 10-20 km from the NIWTP outfall were dominated (50-70%) by effluent (Figure 7B), excepting one sample taken in the middle of the monsoon, which shows a significant Sonoita Creek influence. Western riparian wells were dominated (94%) by tributary flow (Figure 8). The USGS (Coes *et al.*, 2002) analyzed water from one of these wells and found tritium to be below their detection standard (2.5 pCi/l), indicating the water was recharged before 1953. Thus, this part of the aquifer seems to have received no water from the river. Farther downstream, the dominance of effluent as a source water weakens (Figure 8). The riparian wells 20-31 km from the NIWTP show a mixture of water sources with effluent dominant in 3 of 6 samples. 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 ground-water flow (Figure 7B).

In summary, the results of the mixing model indicate that the riparian aquifer is dependent (50-70%) on effluent within 30 km of the NIWTP outfall. Riparian wells downstream of 31 km show increasing dominance of monsoon event flow for recharge, including both tributary flow and Sonoita Creek flow. Taken together these results demonstrate that the immediate riparian aquifer is dependent on the Santa Cruz River streamflow, whether in the form of effluent or event runoff.

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 64 cores collected, 14 premonsoon samples were visually confirmed as clogged. 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 (Baveye *et al.*, 1998; Berestov *et al.*, 1998; Bouwer, 2002; and Greskowiak *et al.*, 2005). The disruption of stream-aquifer interactions has implications for the shallow streambed and hyporheic zone. By examining the hydraulic profiles (Figure 4) 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 cm to 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 in the basin. In a losing river, ponding is not possible as water that does not infiltrate moves down gradient by continuing downstream. After the formation of a clogging layer, the transmission of water through the streambed into the aquifer slows. However, water continues to move downstream. As, as our data show, the clogging does not occur at the sediment surface some streambed sediments remain in connection with the stream. The gradient in these sediments can be alternating losing and gaining dependant on stream hydraulic conditions (Dent and Henry, 1999). This phenomenon can be seen in the February 2007 and June 2007 soil profiles at 3 km and 15 km, which all showed gaining in the top 10 cm despite losing or unsaturated conditions below. 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). 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.

Unsaturated layers are reported under artificial recharge systems (Bouwer, 2002; Greskowiak *et al.*, 2005), perennial streams subjected to pumping (Fox and Durnford, 2003; Su *et al.*, 2007), and effluent dominated streams (Berestov *et al.*, 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 clogging develops, infiltration slows, and unsaturated conditions develop below the streambed (seen in profile February 15.05, 31.35 and June 3.15, 15.05, Figure 4).

While the development of a clogging layer and its small-scale effects are clear, the impacts were localized and site specific. The 3 and 15 km reaches during February 2007 and June 2007 have a perched shallow streambed, and losing or unsaturated deep streambed conditions. This condition indicates the clogging layer is interconnected and grows downstream. However soil cores from the 24 km reach have the highest percentage of clogged cores (Table 2), 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 premonsoon (Table 2). 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.

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. Riparian wells near the outfall (0-25 km downstream from NIWTP outfall) show a reliance on effluent. In addition, all riparian wells (0-35 km downstream from NIWTP outfall) exhibit an alluvial aquifer dependent on perennial (effluent) and seasonal (event runoff) Santa Cruz River stream inputs.

The riparian aquifer dependence does not appear to be disrupted by the development of a clogging layer in 2007. As shown by the 2007 stream gaging water balance, which indicates an increase in overall losses, evaporative losses, and channel losses throughout the premonsoon period. This result 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. As discussed above, the hydrographs for 2004-2005 illustrate an altered riparian water balance that affected the river, aquifer, and riparian area (Figure 6) that are consistent with a cohesive, blanket clogging layer. It was during this winter and premonsoon period that unexplained tree mortality occurred throughout the first 15 km of the study area. This mortality affected hundreds of cottonwood, willow, hackberry, elderberry, and mesquite trees along the Upper Santa Cruz River (Davis, 2005). Speculations as to causes included root rot, drought, insects, and ground-water pumping, however the results of this study indicate that the cause might have been the clogging layer.

An alternative speculative cause of the tree die off has been developed as an outcome of the current study. There is not a comprehensive physical or chemical data set from the riparian aquifer for this time period so it is impossible to draw definite conclusions about the importance of effluent as a water source during this period. The hydrograph evidence however implies that a low-flow monsoon cycle, followed the next year by 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 this water source being left dry resulting in mortality.

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 and to a lesser extent during winter rains. Throughout the rest of the year, the major water input is effluent from the NIWTP. All of the accumulated data suggest a yearly cycle for the clogging layer that is dependent on the interannual variability of precipitation and runoff in semiarid systems. The data has been used to build a conceptual model (Figure 9) based in part on

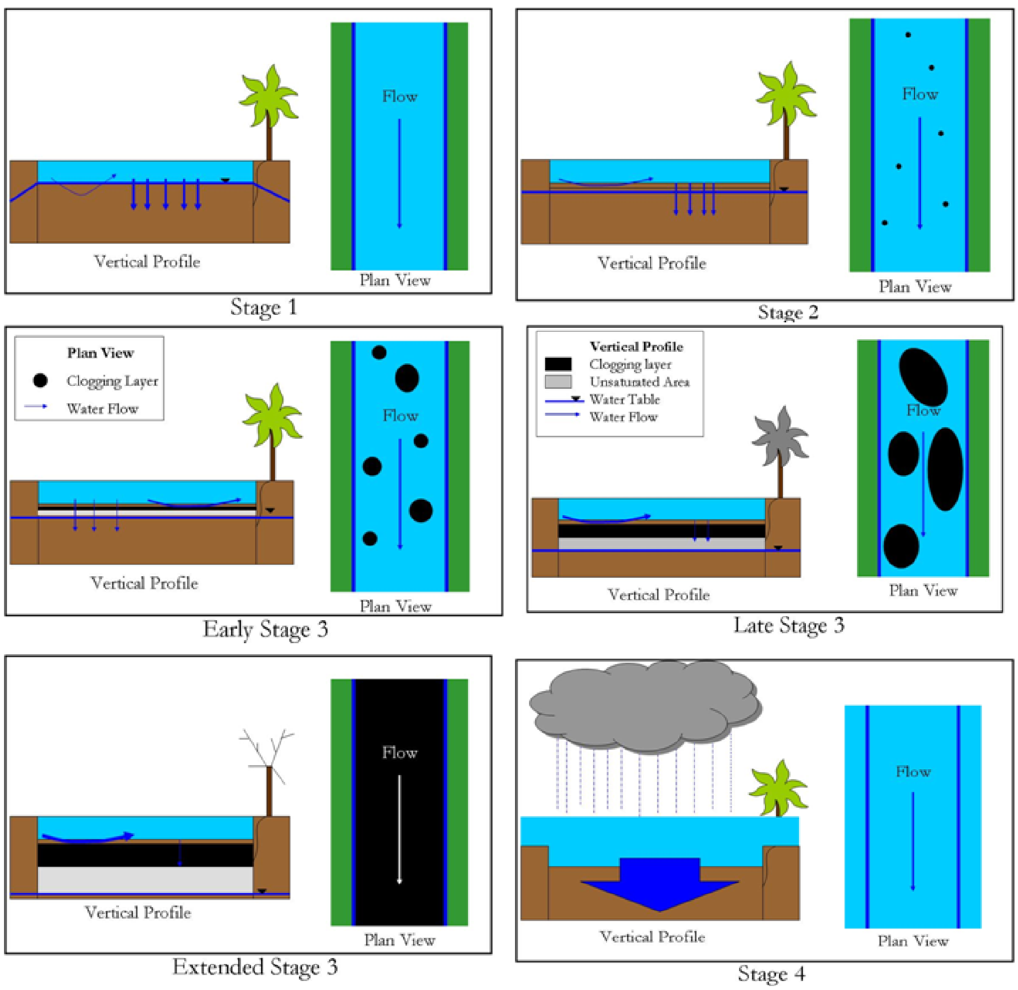

FIGURE 9. Conceptual Model of Clogging Cycle. Stage 1, immediately postmonsoon the river system is reset, there is no clogging. Although, the water table implies a losing reach, gaining or hydrostatic conditions are locally possible. Stage 2, a thin layer of detritus material forms in the streambed (vertical profile) in discrete locations based on geomorphology and other localized conditions (plan view). Early Stage 3, usually late winter/early premonsoon, 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 semiarid hydrologic cycle Stage 4 follows where large runoff events 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).

Greskowiak *et al.* (2005) clogging cycle for artificial recharge basins.

Stage 1 represents a streambed with no clogging layer present. 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). Over time, subsequent biological activity increases the clogged layer thickness (Battin and Sengscmitt, 1999; Rinck-Pfeiffer *et al.*, 2000). 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 premonsoon period as shown by the soil cores (14 clogged cores: 85% were 15 cm or thicker). Lacher (1996) notes that Schumann and Galyean (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 4) 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 as water infiltration into the aquifer has slowed (conceptual model Stage 3). Thus, from February to June 2007, a period with minimal runoff events and constant effluent input, the clogging layer continues to develop. In contrast the September hydraulic profiles reveal a different pattern. The shallow streambed and stream-aquifer interface were reconnected hydrologically and there were no clogged cores.

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 *et al.* (1975) observing "storm flow…scoured out the black, anaerobic clogging layer in the channel" (Lacher, 1996). Scour literature for Walnut Gulch, a nearby ephemeral wash, indicates that runoff events creating large flows (11 m^3/s) that crest the banks of a river, can result in scouring depths of 15-50 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). In a 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).

After the monsoon period, if the clogging layer has been scoured out, the clogging cycle begins again (Stage 1). In general, the lack of runoff events throughout the rest of the year 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). The February 2008 soil profiles show losing or hydrostatic conditions and the February 2008 stream gaging 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).

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 unsaturated conditions beneath the 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 semiarid Southwest.

CONCLUSIONS

In water-limited environments, population increases have led to increased water demand stressing aquifers and perennial streams. As water tables drop perennial streams and riparian corridors go dry causing changes in ecosystems and water resources. Treated wastewater effluent has been seen as a management option to address 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 natural hydrologic cycle in the Southwest serves as a control on the clogging as flows exceeding 10 m^3/s, associated with summer Monsoon events, destroy the clogging in the Santa Cruz. If however there is a lack of floods the clogging layer will persist with possible impacts on the aquifer and riparian corridor. These issues need to be considered when contemplating the use of effluent for river restoration projects.

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 a constant flow of poor quality effluent, is important to the formation of a clogging layer. To address the specifics of the clogging cycle, more physical streambed measurements are needed, including piezometers that are driven into the streambed and monitored over time with pressure transducers to thoroughly quantify temporal and spatial ground-water variability. The importance of this effluent system with constant flow and 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 8-h processing time and greater nutrient, turbidity and dissolved organic matter removed, 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.

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