Surface Flow, Sediment Transport and Water Quality Connections in the Lower Santa Cruz River, Arizona

Thomas Meixner, Associate Professor of Hydrology and Water Resources, University of Arizona

Eylon Shamir, Research Hydrologist, Hydrologic Research Center, San Diego

Jennifer Duan, Assistant Professor of Civil Engineering, University of Arizona

Report Prepared for U.S. EPA Region IX

October 2009
Executive Summary

The nature of hydrologic connections and their impact on water quality conditions in rivers is of ecological, hydrologic and biogeochemical importance. In this report, the nature of hydrologic connections and water quality impacts between the Upper Santa Cruz River basin, the Lower Santa Cruz River, and the Gila River are investigated. First a discussion of the important processes active in arid and semi-arid rivers is provided, emphasizing the nature of sediment and particulate transport and the opportunity for the channel network to provide an ecosystem service in the way of contaminant and nutrient removal. Following this, an analysis is conducted of the historical nature of hydrologic connections within the Lower Santa Cruz River system. The result of this analysis shows that existing infrastructure and actions of decision-making organizations recognize that the Upper and Lower Santa Cruz rivers are hydrologically connected. Next the nature of this hydrologic connection between the USGS gages at Cortaro and Laveen is analyzed through specific events, hydrologic response, and statistically. This analysis shows that large flows at Cortaro take approximately two days to propagate through the Santa Cruz River channel to Laveen. The statistical analysis shows that large flows at Cortaro lead to the largest flows observed during the period of record at Laveen and that these hydrologic connections of import occur approximately on an annual to bi-annual basis. An analysis of sediment budgets for the Gila River demonstrates that approximately 13 percent of the sediment observed in the Gila River originates from the Lower Santa Cruz. This 13 percent of the sediment is dependent upon flows with a return interval of 1-2 years or longer. These flows are most dependent on hydrologic connections between the Upper and Lower Santa Cruz as shown in the statistical analysis. Additionally the episodic nature of these flows means that these floods are the ones most likely to contain significant organic carbon and suspended sediment loads. As a result, these episodic connections are the conditions most likely to transport significant quantities of nutrients and organic contaminants that are associated with suspended sediments. Finally, the multi-step nature of the hydrologic and water quality connection in the Lower Santa Cruz is described and advice is offered on how studies in other arid and semi-arid river systems can be conducted.
(This page left intentionally blank.)
# Contents

Executive Summary ........................................................................................................................................... 1

Figures .......................................................................................................................................................... 5

Tables ........................................................................................................................................................... 7

1 Introduction .................................................................................................................................................. 9

2 Study Site and History .................................................................................................................................. 11

2.1 Site Description ........................................................................................................................................ 11

2.2 Historical Information Regarding Connectedness of Upper and Lower Santa Cruz River ............ 13

3 Hydrology and Water Quality of Semi-Arid Rivers ..................................................................................... 17

3.1 Hydrologic Framework .......................................................................................................................... 17

3.2 Movement of Substances from Uplands to Perennial Waters: Reaction, Fate, and Transport 19

3.3 Instream Network Processing of Dissolved and Sediment – Attached Nutrients ...................... 21

3.4 Effluent and Agricultural Influences and Interactions with Riparian Systems .............................. 24

3.5 Sediment Processing and Influence on Water Quality ................................................................. 25

3.6 Integration of Water Quality Influences .............................................................................................. 26

4 Surface Flow Connectivity in the Lower Santa Cruz River Basin ......................................................... 27

4.1 Available Hydrometeorological Datasets ............................................................................................. 27

4.1.1 USGS Data ........................................................................................................................................ 28

4.1.2 NOAA – National Climatic Data Center ....................................................................................... 29

4.1.3 AZMET –UA .................................................................................................................................... 29

4.1.4 Pima and Maricopa Counties ......................................................................................................... 29

4.2 Analysis of Selected Storms .................................................................................................................. 29

4.2.1 Flood of October 1983 – Tropical Storm ....................................................................................... 29

4.2.2 Flood of July 2006 Convective Storm ............................................................................................. 31
Figures

Figure 1. Regional Map of Santa Cruz River Basin ................................................................. 12
Figure 2. Map of Santa Cruz River System from FEMA Report to Pinal County, 1990 ............. 14
Figure 3. Three Hydrographs Representing (a) Typical Humid Catchment, (b) Typical Semi-arid Catchment, and (c) Typical Snowmelt Driven System (adapted from Hornberger et al. 1998) .................................................................................... 18
Figure 4. Pattern of Total Dissolved Nitrogen against Catchment Area at Walnut Gulch (Brazier et al. 2007) .................................................................................................................. 20
Figure 5. Exponential Increase in Particulate Organic Carbon and Particulate Organic Nitrogen Load with Increase in Discharge for Small Early Season Flow Events (Brooks et al. 2007) .............. 23
Figure 6. Increase in Particulate Organic Carbon and Particulate Organic Nitrogen Export with Increased Flow for Larger Events in Middle of Monsoon Season (Brooks et al. 2007) .......... 24
Figure 7. Data Availability for the Lower Santa Cruz River and Tributaries ..................................... 28
Figure 8. Total Rainfall Estimate for the Storm of October 1983 (from National Climate and Environmental Prediction (NCEP-NOAA)) ......................................................................................... 30
Figure 9. September 26 –October 7, 1983 Mean Daily Discharge (cfs) at Cortaro and Laveen Gages 31
Figure 10. 15-minute Discharge Hydrograph for the Summer Storm of July 2006 ....................... 32
Figure 11. Three Large Summer Flow Events at Laveen ................................................................ 33
Figure 12. Mean Daily Discharges at Cortaro and Laveen for the January 1993 Event .................... 35
Figure 13. 15-minute Discharge Hydrograph for the Storm of October 2000 ............................... 36
Figure 14. 15-minute Discharge Hydrograph for the Summer Storm of July-August 2007 ............ 37
Figure 15. Seasonal and Annual Lagged Cross-correlation Analysis between the Cortaro and Laveen Gages Using Pearson (a), Pearson with Natural-logarithm Transformed Daily Flow (b), and Kendall Tau (c) ................................................................................................................. 40
Figure 16. Pearson Cross-correlation between Daily Precipitation Records from Tucson and Phoenix Airports ........................................................................................................................................ 41
Figure 17. Cortaro Gage 1-, 2-, 3-, and 4-day Return Period of Mean Discharge from Partial Duration Series .................................................................................................................................................. 44
Figure 18. The Probability (as fraction) of Observing Flow above Seasonal Normal at the Laveen Gage as a Function of Daily Lag Time for Three Ranges of Daily Recurrence Intervals at Cortaro.

Figure 19. Cortaro Return Period Exceedance Probability of Seasonal Percentile for Laveen at Various Lag Times – Panels Represent Three Ranges of Recurrence Intervals: (a) Greater than 2-year, (b) 1-2 year, and (c) 0.5-1 year.

Figure 20. Locations of Surface Flow Gages Discussed in Section 5.

Figure 21. Daily Sediment Load and Daily Discharge at Laveen Gage.

Figure 22. Daily Sediment Load and Daily Discharge at Cortaro Gage.

Figure 23. Daily Sediment Load at Maricopa Rd near Maricopa, AZ.

Figure 24. Daily Sediment Load at Estrella Parkway near Goodyear, AZ.

Figure 25. Tributaries to Gila River from Maricopa Road to Estrella Parkway.

Figure 26. Annual Sediment Load at Maricopa Road and Estrella Parkway on the Gila River.

Figure 27. Annual Sediment Load at Laveen Gage on the Santa Cruz River and Estrella Parkway on the Gila River.

Figure 28. Annual Total Sediment Load at Gages Close to the Confluence of the Santa Cruz and Gila Rivers.

Figure 29. Total Eroded or Deposited Sediment within the Confluence from 1993-2008.
Tables

Table 1. USGS Gages in the Lower Santa Cruz River Basin with Record Lengths in Excess of 5 Years .......................................................... 28

Table 2. Seasonal Flow Event Characteristics for Cortaro and Laveen (parentheses) .................. 43

Table 3. Ratio of Annual Sediment Load at Laveen and the Estrella Parkway .......................... 57

Table 4. Maximum Daily Load at Each Gage ............................................................................. 58

Table 5. Percentage of Sediment Load from the Santa Cruz River in the Total Load of the Gila River at Maricopa Road .................................................. 60
1 Introduction

The nature of hydrologic connections in stream networks has received new attention due to recent Supreme Court rulings that have addressed and reviewed the nature of the federal government's regulatory authority regarding the Clean Water Act (Nadeau and Rains 2007). The presence, frequency and nature of hydrologic connections within a stream or river network are of key importance to hydrologic, geomorphic, biogeochemical and ecological processes that contribute to and control the overall water quality of lotic and lentic ecosystems (Pringle 2003; Nadeau and Rains 2007). Previous efforts to understand the nature of hydrologic connections in stream networks have focused on humid systems, while hydrologic connections in arid and semi-arid regions have not been studied to the same degree. In arid and semi-arid systems, the stream network is connected with hydrologic flows only during specific events (Bull and Kirkby 2002). While hydrologic connections are infrequent, the nature of the hydrologic flows, the chemical and particulate contaminants that are carried, and the resulting long-term impacts on water quality for receiving waterbodies can be important. The significance and the extent of these impacts needs to be determined to understand how these flows may affect the water quality of receiving waters. The need to understand this connection is especially important in arid and semi-arid systems due to the limited data availability and relative lack of peer-reviewed literature on the nature of hydrologic connections and the influence of episodic events on water quality.

Episodic floods can influence water quality in several important ways. First, floods can restructure riparian and near stream ecosystems, altering the way in which the ecosystem processes nutrients and other contaminants (Dent et al. 1999). Second, floods carry altered dissolved constituents from upstream and upland ecosystems into downstream locations altering the nutrient and toxicity conditions of a waterbody. Third, floods often carry increased sediment loads into waterbodies. These sediments represent a water quality concern due to the turbidity and clarity effects of these sediments. Fourth, these sediment inputs also come with contaminants attached to the sediments. The contaminants can then enter the water column and the food web either through chemical reactions or through ingestion of sediments by microbes or invertebrate and vertebrate animals. Sediment-association is often the most important pathway by which contaminants enter an ecosystem’s water column and food web (Salomons et al. 1987; Foster et al. 1995). Importantly, flood effects on water quality can either be short-lived, associated with the flood period itself and with conditions such as turbidity, or long-lived through the continued processing and reprocessing of contaminants associated with sediments that were transported into a waterbody during high flow events.

In this report, the hydrologic connection between the Santa Cruz River at United States Geological Survey (USGS) stream gage at Cortaro Road and the USGS gage on the Santa Cruz River at Laveen, AZ is investigated. The sediment export out of the Santa Cruz River and into the Gila River is also quantified with a focus on the type of events which lead to sediment export. The water quality implications of this hydrologic connection on the water quality of the Gila River at and directly below the confluence of the Santa Cruz River with the Gila River are studied and explained. As the Gila becomes perennial near the confluence with the Santa Cruz (CDM 2003), this study focuses on the hydrologic connections between the Cortaro gage in Tucson and the Laveen gage just upstream of the confluence with the Gila River. The purpose of
This report is thus to provide relevant technical information on the hydrology and water quality of this stretch of the Santa Cruz River and the resulting impact on the hydrology, sediment budget, and water quality of the Gila River.

This report addresses several specific questions about the hydrology and water quality of arid and semi-arid systems in general and the specific hydrologic and water quality of the Lower Santa Cruz River (defined as the river reach from the Cortaro to the Laveen gage on the Santa Cruz).

1) How has the hydrology of the Lower Santa Cruz River been viewed and understood through pre-history, history and technical investigations over the last 50 years?

2) What processes, contaminant sources, sediment sources and water sources control the water quality of arid and semi-arid rivers?

3) What can available hydrometeorological data tell us about the nature of the hydrologic connection of the Lower Santa Cruz River to the Gila River?

4) What do quantitative estimates of sediment flux from the Santa Cruz as well as the Gila, Salt and Agua Fria rivers to the Gila River indicate about the relevance of the hydrologic connections between the Santa Cruz and Gila to the water quality of the Gila?

5) Given the hydrologic and sediment connections between the Santa Cruz and the Gila, what are the water quality impacts of the Lower Santa Cruz River on the Gila River?

In addition to answering these questions, this study will serve as a guide for future analyses of the hydrologic connections between intermittent and ephemeral streams and rivers and receiving waters.
2 Study Site and History

2.1 Site Description

We consider the Lower Santa Cruz River basin as the area that drains into the section of the Santa Cruz River that is downstream of Tucson and upstream of the confluence with the Gila River (Figure 1). Two currently active USGS streamflow gages at Cortaro (USGS 9486500) and Laveen (USGS 9489000) have relatively long-term daily streamflow records. The Cortaro gage has a record since October 1939, with missing data from 1947 to 1950, and an intermittent record from 1982 to 1990. The record from the Laveen gage is continuous from January 1940. In addition to the mean daily data, 15-minute discharge and stage data from USGS is available for the gages as follows: Cortaro (1990-2008), Trico Road (1992-2008) and Laveen (1987 -2008). Thus the Lower Santa Cruz as defined here extends from the Cortaro USGS gage to the Laveen USGS gage. As a result of effluent discharged to the river in the Tucson metro area, the river is perennial until approximately Red Rock (Pima County 2004), while it is likely intermittent for some distance downstream of Red Rock. The remainder of the river is ephemeral until the Laveen USGS gage.

The Cortaro and Laveen gages represent the inlet and outlet of Lower Santa Cruz River (Figure 1). The channel length between the Cortaro and Laveen gages (through Greene Canal and Greene Wash) is about 95 miles. The Cortaro gage drains a basin area of 3,503 square miles that includes the Upper Santa Cruz River basin and the tributary basins of the Rillito and Canada del Oro rivers. The Laveen gage, which is located just upstream of the Santa Cruz and the Gila River confluence has a drainage area of 8,581 square miles. In addition to the drainage area at Cortaro, the Lower Santa Cruz River section drains approximately 5,000 square miles (basins’ boundaries indicated in black). Most of the drainage area is from southern tributaries: Brawley Wash and Los Robles Wash (1,400 square miles), Aguirre Valley (730 square miles), Santa Rosa Wash (1,780 square miles), and Vekol Wash (about 300 square miles). In the northern section of the Lower Santa Cruz River the channel drains short and gently sloped streams from the watershed divide with the Gila River basin.

A geomorphological pattern that can be assigned as a natural boundary that signifies the differences between the upper and Lower Santa Cruz River is in the area of Red Rock (about 20 miles downstream of Cortaro), just downstream of the confluence with the Los Robles Wash (The Brawley Wash basin in Figure 1). In this area, the Santa Cruz River is changing from a deep and well defined channel to a broad flat extensive alluvial plain that is known as the Santa Cruz Flats. The geomorphological changes are associated with changing patterns of streamflow from increased to decreased discharge rate with increasing drainage area in the Upper and Lower Santa Cruz River, respectively. Detailed regional geomorphological analysis is in Betancourt (1990) and Arizona Stream Navigability Study Section 4 (2004).
The Lower Santa Cruz River is an intermittent or ephemeral river that flows for days to weeks immediately following rainfall events. In the historical daily record at the Laveen gage, for about 50 percent of the days the gage recorded no flow. At the Cortaro gage there is a perennial flow of about 50-100 cfs since March 1990. This flow is from reclaimed wastewater releases by the sewage treatment plants near Ina and Roger roads in Tucson. Prior to the release of the reclaimed wastewater for about 57 percent of the days the Cortaro gage recorded no flow. The perennial flow at Cortaro propagates a few miles downstream and is noticeable (for most days) at the Trico Road gage with lower discharge rates. The consistency of flows at Trico Road and for some distance downstream of the Trico Road gage has increased in recent years (Pima County 2004).

The streambed in the Lower Santa Cruz River is highly permeable and the rate of infiltration into the alluvial bed is high. The infiltration rates are variable and are highly dependent on the existing moisture content (i.e., antecedent moisture conditions) and the storm characteristics (e.g., Pilgrim et al. 1988). In a July 2006 event, which is further analyzed in this report, from an
analysis of the USGS gage data, the flow volume at Cortaro during July 28 to August 2 was about 42,600 acre-feet and only about 2 percent of this volume (about 820 acre feet) was measured at Laveen during August 2-4. The majority of the unaccounted volume was likely retained in the Lower Santa Cruz River basin and infiltrated into the subsurface through the streambed and the floodplain. This specific event occurred after a long dry period. Except for a small flow event that was registered in the beginning of July 2006 at Cortaro and Trico Road gages, the previous significant streamflow was recorded in August of 2005. A dry winter preceded the storm of 2006 also at the Laveen gage which has recorded zero flow since September 2005, except four days in March 2006. Therefore it is presumed that because of the extended dry period before the storm of July 2006, it represents an event with dry antecedent moisture conditions and thus high infiltration rates (e.g., Pilgrim et al. 1988).

2.2 Historical Information Regarding Connectedness of Upper and Lower Santa Cruz River

To provide a long range perspective of the Lower Santa Cruz River it is useful to provide an analysis of pre-historic and historic evidence of the hydrology of the systems. Humans have lived along both the Gila and the Santa Cruz rivers for at least 5,000 years. Given the arid climate, the habitation of the region indicates the fact that there was water available for drinking and irrigation of crops. The predominant form of agriculture was the use of episodic floods to support the planting and growth of corn, squash, and vegetable crops. Otherwise the region would not have been so settled. On the portion of the Santa Cruz near the junction with the Los Robles Wash a very large concentration of Hohokam archaeological sites is located including a large number of ball courts. The number of locations and ball courts indicate a large population in the prehistoric period in this area, indicating among other things that there was enough water to support such a population (Downum 1993).

In the book *Gila: the Life and Death of an American River* by Gregory McNamee (1993) the Santa Cruz is noted as a tributary that only occasionally connected to the main river. In a more exhaustive history focused on the Santa Cruz, Michael Logan (2002) discusses the Santa Cruz as the “ever lessening stream.” Logan relates that during the largest flows the Santa Cruz reconnected hydrologically to the Gila. He appears to believe that the connection occurred on a return period of 1 to 5 years. Both histories of the region point to evidence of a connection between the Santa Cruz and the Gila River (Logan 2002).

However, these historical studies are limited in their usefulness since they rely on sporadic written and oral accounts of the Lower Santa Cruz and do not provide a comprehensive picture of the system. The results do indicate that in pre-historic days the Lower Santa Cruz did not support perennial flow. Given the limited nature of these histories, attention should be paid to the efforts of state and local governments to understand the Lower Santa Cruz River as regards flood plain protection, water quality problems, species diversity and other issues that might shed light on what people in the area understand to be the nature of the Lower Santa Cruz River (see Figure 2).
Figure 2. Map of Santa Cruz River System from FEMA Report to Pinal County, 1990
The State of Arizona owns all land that was the bed of a navigable waterway at the time of statehood on February 14, 1912. A navigable waters analysis has been done for the Santa Cruz and the Gila rivers (Arizona State Land Department 2004). The report has several findings that are important for understanding the dynamics of flood propagation from Cortaro to Laveen. It identifies the construction of Greene’s canal in 1909-1910 for increasing flood propagation efficiency within the Santa Cruz system as well as other flood control and protection projects. The Greene Canal created a diversion within the surface system pushing waters farther west. This diversion allowed a more efficient hydrologic connection between the Santa Cruz at Cortaro and the Santa Cruz at Laveen. A 1925 report (produced 15 years post-construction of Greene’s canal) from the USGS shows the Santa Cruz River flowing to the north side of the Casa Grande Mountains, a path it no longer follows (Bryan 1925).

In a 1990 report for the Gila River Indian community, the United States Army Corps of Engineers (USACE) studied the flood risk on the Gila River reservation (USACE 1991). Implicitly they present the Santa Cruz on their maps as connected to the Gila River system (Figure 2). On page 5-1 of the USACE report, it states that flood damage has occurred on the reservation due to major floods on the Santa Cruz River and the Gila River. The report indicates these floods occurred in August through October and that the 1983 flood came from both the Gila and the Santa Cruz rivers.

In a 1990 study conducted by the Federal Emergency Management Agency (FEMA) on flood risks, controls and improvement for Pinal County, the Santa Cruz River System is one area of focus. The study notes that the phrase “Santa Cruz River System” is used carefully to describe the problem since the Santa Cruz in Pinal County actually bifurcates into Greene Wash and the Santa Cruz Wash as well as the Santa Rosa Wash. This stream network complexity was introduced by the Greene Wash and thus calling the Santa Cruz a river, singular, is challenging at best because the river becomes multiple washes and then a single river just to the north of Maricopa, Arizona (Figure 2) (FEMA 1990). The report notes that this interconnected nature means a spread out flood risk from Santa Cruz River floods. Additionally the importance placed on floods sourced from the Santa Cruz River at Cortaro indicates this system is hydrologically connected and that floods propagating down the system are important. Floods down the Santa Cruz occurred in roughly 1 in 10 years. However, the FEMA study was focused on flood risks in Pinal County and thus minor flows that could be contained by the flood channels were not addressed. Thus the frequency of full hydrologic connection is likely to be more frequent than what is included in this FEMA report (FEMA 1990).

Another USACE report (USACE 1990) focused on flood flows in the Lower Santa Cruz region. The Greene Canal diverts most of the flow from the Santa Cruz River westward (about 14 miles) and flow continues northward in the Greene Wash. Just before Interstate 8 some of the flow is diverted from Greene Wash back to the Santa Cruz River, the remainder continues in Greene Wash to the confluence with the Santa Rosa Wash, which rejoins the Santa Cruz near the city of Maricopa – about 9 miles upstream of the Laveen gage. Major floods changed the diversion capacity of the Greene canal over the years through erosion and downcutting induced by these floods. The USACE (1990) estimated that the Greene Canal could divert the 10-year flow event (~22,000 cfs) before water in excess of that flows in the old Santa Cruz River (see also USACE 1994; FEMA 1990).
The USACE reports also note the losing nature of the river north and west of Red Rock, AZ where flood flows are significantly attenuated by infiltration of water into the subsurface. The report includes discussion of flood flows that occurred in the Santa Cruz river system with approximately 37 flood flows over a 110-year period, indicating connections in the system approximately every 3 years (USACE 1990). The reports estimate the routing of flood waters on the Santa Cruz from Red Rock to Laveen. They simulated the routing of seven floods from Red Rock to Laveen over a 20-year period. They found smaller floods were often completely lost to channel infiltration, while larger floods had a routing time of approximately 2 days to get from Red Rock to Laveen. This report also documented 50 instances of flow connection between Cortaro and Laveen over a 46-year period indicating a 1-year return interval for hydrologic connection between the two gages (USACE 2000).

The USACE reports clearly indicate that there is a connection between Cortaro and Laveen on the Santa Cruz. It is also clear that the complexity of the Greene Canal, the Greene Wash, the Santa Rosa Wash and the Santa Cruz River creates a complex flow system from the Upper to the Lower Santa Cruz, such that a single direct river channel at all flows does not exist. Some channels are only active at higher flows, while the Greene Canal–Greene Wash appear to be the main pathway for most low flows in the system (USACE 1994; USACE 1977; USACE 1983).

A study by anthropologists in the area documented that the down cutting along the Greene Canal is not unique and human alterations of hydrology and geomorphology tend to lead to situations similar to what has been observed on the Lower Santa Cruz (Waters and Haynes 2001). Human alterations in the Lower Santa Cruz have also included extensive channelization of all major streams and rivers (Figure 2). These channelization efforts have likely increased the rate at which water travels through the Lower Santa Cruz System (Webb and Betancourt 1992). Additionally, pumping for agricultural and municipal use in the region increased markedly after World War II with rural electrification and the centrifugal pump (Glennon 2002). This pumping has led to regional groundwater tables dropping more than 250 feet in some locations (http://az.water.usgs.gov/projects/azgwconditions/index.html). Agricultural activity in the region may also lead to agricultural return flows into the Santa Cruz River and its tributaries. These flows do not likely lead to sustained flow due to the large depths of groundwater in the Lower Santa Cruz River basin. The agricultural flows may redistribute sediment and contaminants into the main river channel making these sediments and contaminants available for transport in large flows that occur at some time in the future from the time of initial agricultural discharge. Finally, the human alterations to the hydrology and geomorphology of the Lower Santa Cruz are ever evolving. A recent concern is the northward movement of effluent from wastewater treatment plants near Tucson. This movement has raised water quality concerns as the effluent is now flowing into the Lower Santa Cruz system (Pima County 2004).
3 Hydrology and Water Quality of Semi-Arid Rivers

Water quality is a broad term that encompasses all physical (e.g., temperature), biological (e.g., bacterial counts and fish populations) and chemical (e.g., nutrient and toxic chemical concentrations) conditions of water that are not related to the quantity of the water. The report focuses more narrowly here on the chemical water quality of flowing waters; in particular the carbon, nitrogen, sediment and sediment-attached nutrients and contaminants. This focus is because of the ability to assess fluxes of the constituents in relatively unmonitored systems and the potential for these constituents to have an impact on receiving waterbody water quality.

The setting and climate of any hydrologic system strongly influences the processes that integrate to control the water quality of streams and rivers. In semi-arid systems an important element of this context is the profound variation in precipitation quantity and intensity that these climates are subject to (Huxman et al. 2004). This climatic variability results in profound variations in the surface water hydrology and the temporal and spatial variability of runoff generation and hydrologic flows in semi-arid landscapes (Hornberger et al. 1998). These episodic floods mean that for much of the time the wider landscape is largely disconnected from the stream network (Brooks and Lemon 2007; Brooks, Hogan, and Meixner 2007; Meixner and Fenn 2004; Meixner et al. 2007; Oelsner, Brooks, Hogan 2007). The temporal and spatial variability of semi-arid stream systems and their connection to their uplands and within the stream network influences water quality of arid and semi-arid streams. A general template for understanding the water quality of semi-arid rivers requires a discussion of the hydrologic context of these systems. Next, the fate and transport of carbon, nitrogen, sediments and sediment attached contaminants to streams from uplands and through the ephemeral channel network needs to be understood. An understanding of the fate and transport of contaminants upon their arrival in perennial systems is also necessary. The importance of agricultural and urban water quality impacts needs to be framed so that their role in water quality conditions can be properly assessed. Critically the release of toxic contaminants from sediments needs to be understood. Following the analysis of transport from uplands to river, how these processes integrate to generate the short and long time scale water quality of surface waters along various locations in the river channel needs to be understood.

3.1 Hydrologic Framework

The episodic hydrology of semi-arid and arid systems results in long periods of low flow punctuated by periods of very rapid changes in streamflow (Figure 3). This flashy nature contrasts with the more gradual rises and falls in streamflow that typify more humid systems. These semi-arid systems are also very different from the more dominant hydrograph of the western United States, that of the snow cover dominated hydrologic system (Figure 3c). The episodic nature of ephemeral, intermittent and perennial streams plays out at different time scales as well. Semi-arid streams are often discontinuous in their streamflow in space and sometimes flow for hours to weeks before returning to dry conditions in ephemeral reaches (Leenhouts et al. 2006). Perennial stream reaches need groundwater aquifer or effluent discharge to sustain flow throughout the year for periods when little or no rain falls.
Figure 3. Three Hydrographs Representing (a) Typical Humid Catchment, (b) Typical Semi-arid Catchment, and (c) Typical Snowmelt Driven System (adapted from Hornberger et al. 1998)
The hydrologically episodic nature of semi-arid systems means that for much of the time there is no continuous surface flow between the surrounding landscape and the perennial stream (Fisher et al. 1998). However, this situation does not mean there is never continuous surface flow. The amount of flow during floods can be large and have profound short- and long-term impacts on water quality in arid and semi-arid streams. Importantly, existing research has shown that flood water inputs can be a significant source of water and chemical constituents in rivers, and may impact water quantity and quality for periods of years to decades (Baillie et al. 2007; Brooks and Lemmon 2007). Additionally, due to the ephemeral nature of tributaries and the rapid transition from wet riparian systems to dry upland systems, arid and semi-arid streams have small green ribbons of riparian vegetation lining them as opposed to the wider and more spatially diverse riparian areas present in more humid climates. These narrower riparian areas mean that little overland flow is intercepted in the riparian area prior to arrival at the main flow channel. Instead biogeochemical processing of materials in the riparian areas of arid and semi-arid streams occurs longitudinally with distance downstream (Dent and Grimm 1999). Due to less runoff interception in riparian areas, the water quality of upland runoff more directly impacts surface water quality in perennial rivers in arid and semi-arid systems than what occurs in more humid climates (Fisher et al. 1998; Fisher et al. 2004). This situation means that, without the mediating effects of riparian areas, arid and semi-arid streams are more connected to uplands than headwater streams are connected to large rivers or uplands are connected to first order streams in more humid climates. In more humid systems, riparian and near riparian systems are capable of mediating for hydrologic and biogeochemical landscape conditions that might impact stream networks (Nadeau and Rains 2007). This process is in fact the rationale for riparian buffer strips to mitigate polluted runoff (Sweeney et al. 2004).

Runoff generated in the uplands flows into the main stream system but undergoes ongoing infiltration in the stream channel. Flood waters can easily infiltrate into the subsurface in ephemeral and perennial streams alike (Baillie et al. 2007; Desilets et al. 2008; Bull and Kirkby 2002, Pilgrim et al. 1988). As these flood waters infiltrate they take with them the dissolved constituents in flood waters and leave behind the particulate substances entrained in the floodwaters in the streambed (Baillie et al. 2007; Brooks and Lemon 2007; Brooks, Hogan, Meixner 2007; Meixner et al. 2007; Oelsner, Brooks, Hogan 2007). The dissolved and particulate substances from flood waters can then contribute carbon, nitrogen and adsorbed contaminants to the stream through physical, chemical and biological interactions over time (Dahm et al. 1998; Dent and Grimm 1999; Dent, Grimm, Fisher 2000; Grimm 1987; Jones and Mulholland 2000). This ongoing infiltration of water and processing of dissolved and particulate loads carried by flood events is an important ecosystem service provided by intermittent and ephemeral river channels such as those of the Lower Santa Cruz.

3.2 Movement of Substances from Uplands to Perennial Waters: Reaction, Fate, and Transport

The movement of dissolved and particulate substances has been researched from many different perspectives. Some researchers have focused on the transport of carbon and nitrogen out of upland settings as an impoverishment of onsite biogeochemical conditions. Meanwhile a separate community of researchers has focused on the transport of these substances to downstream systems. Another set of researchers has focused on sediment-attached
contaminants, such as pesticides, and how their transport with sediment can alter ecosystem toxicity. Putting together the results of studies from these communities should shed light on the connections between downstream ecosystems and upstream systems.

These uplands studies demonstrate the decreased export of water, sediment and contaminants observed in stream systems at all scales in arid and semi-arid climates. The reductions in water, sediment and mass export induced by infiltration processes in semi-arid ephemeral channels represent a critical ecosystem service of pollution and flood attenuation that is provided by ephemeral wash ecosystems in arid and semi-arid climates such as the Lower Santa Cruz River.

Work on upland export of dissolved carbon and nitrogen has been investigated at several research sites in the Southwest. The Walnut Gulch experimental watersheds were established in the 1950s to investigate the interactions of rangeland hydrology, biogeochemistry, water quality and geomorphology (http://www.ars.usda.gov/PandP/docs.htm?docid=10978&page=2). Walnut Gulch is also a tributary to the San Pedro River, one of the last perennial free flowing rivers in the State of Arizona. Walnut Gulch research thus offers a good venue for understanding the processes that influence the water quality of perennial streams under the influence of ephemeral tributaries. The sum of studies at Walnut Gulch demonstrates that less water, sediment and nutrients are transported out of larger catchment/channels than from smaller channels on a per unit area basis. This condition is due to a combination of water infiltration and the removal of nutrients and sediment during transport via microbial decomposition of organic matter (Brazier et al. 2007) (Figure 4). The loss of water and material becomes smaller as event size increases and thus larger events are more efficient at transporting water and contaminants (Welter et al. 2005; Belnap et al. 2005).

![Figure 4](image.png)

**Figure 4. Pattern of Total Dissolved Nitrogen against Catchment Area at Walnut Gulch (Brazier et al. 2007)**

Note: Nitrogen is lost during transport in this system, which would also be expected in other ephemeral channel systems.
The Jornada Experimental Range (http://www.lternet.edu/sites/jrn/) is similar to Walnut Gulch in that it is a well studied rangeland system located in the Chihuahuan desert of Southern New Mexico. Results here have demonstrated that intershrub and shrub areas have significantly more runoff and nutrient loss than grassland areas. This means that land disturbance impacts nutrient transport and thus the water quality of downstream ecosystems (Schlesinger et al. 1999; Schlesinger et al. 2000).

All of these studies occur in rangeland grazing environments. More recent unpublished work in arid urban environments indicates that many of these same processes can occur in urban ephemeral systems (K. Lohse, personal communication, 2009). These same processes would also serve to mitigate additions of contaminants to ecosystems from agricultural or industrial sources as well.

Additionally, sediment transport increases dramatically with event discharge; however, with travel distance in the channel network sediment export decreases. Because sediment transport increases with discharge, and the hydrology of arid and semi-arid environments is so flashy, a small number of events are responsible for much of the sediment export in these systems (Branson et al. 1981; Nearing et al. 2007). The large sediment export that is observed in arid and semi-arid systems can be misleading. Much of the sediment carried during storm events in these systems is bed load and thus dominated by mineral materials (sand particles, gravel, etc.). While sediment itself is a water quality concern, the suspended sediment, which has a much larger fraction of organic content and thus contains significant quantities of carbon, nitrogen and adsorbed organic contaminants, is of most interest. The best estimates of suspended sediment transport are from Walnut Gulch and indicate a significant export of 195 kg/ha/yr of suspended sediment (Nichols 2006). Using organic matter fractions and carbon and nitrogen content results from Rhoton et al. (2006) indicates that this suspended sediment export translates to around 5 kg/ha/yr of carbon and 0.32 kg N/ha/yr being exported from 10-100 ha catchments in the Walnut Gulch watershed.

### 3.3 Instream Network Processing of Dissolved and Sediment – Attached Nutrients

An important question about the transport of dissolved and suspended contaminants from intermittent or ephemeral streams into perennial systems is what happens to these materials once they arrive at a receiving waterbody. Are they trapped, processed, and removed from the hydrologic system either permanently through loss to the atmosphere or temporarily through storage? The water quality impact of sediment flux from ephemeral channels into perennial rivers can be understood in the context of Walnut Gulch being tributary to the San Pedro. Particulate and dissolved loads in the San Pedro River are significantly less than the loads exported from Walnut Gulch on a per unit area basis. The observed flux of carbon and nitrogen on the Boquillas reach of the San Pedro was about 300,000 kg of particulate organic carbon (POC) and about 20,000 kg of particulate organic nitrogen (PON). With a contributing area of 3,196 km² these values are 500 times smaller than the fluxes expected based on the results at Walnut Gulch (described above). This difference speaks to a significant loss of organic material during transport in the channel network. Additionally, if carbon and nitrogen are removed from fine sediments during transport, sediment adsorbed contaminants such as pesticides are also
likely processed and released to the environment or deactivated during transport through the ephemeral, intermittent, and perennial channel network. Critically, while the data show removal of material the results also demonstrate that the largest events have the highest concentrations of sediment. With the high concentrations associated with the highest flows these events dominate export and redistribution of both fine sediment and the contaminants associated with fine sediments (Brooks et al. 2007).

This pattern of increased organic material transport with higher flow is not surprising. Higher flows lead to more effective transport of fine sediment that generally represents the largest transfer of nutrients from upstream to downstream locations. Thus it is these high flow events that most strongly impact downstream water quality. Additionally the contrast between initial flood flows (Figure 5) and flows later in the monsoon season (Figure 6) indicates that early flows transport more sediment carbon and nitrogen than later flows. In more ephemeral rivers such as the Lower Santa Cruz, it might be expected that the conditions early in the monsoon season along the San Pedro (Figure 5) relate most strongly to these systems. The initial events in the San Pedro pick up near and in-stream detrital materials while later events arrive in a stream network that has already been cleaned out, thus the lower rates of transport with increased stream flow (Figure 6). Combined, these results indicate a strong ecosystem service provided by the stream network in reducing carbon and nitrogen transport and likely suspended sediment transport in general along with contaminants attached to that sediment. This processing capability is smallest during the highest flows. Additionally the first flow events to propagate through a channel system after a drought period transport greater amounts of sediment and associated contaminants than events that occur during a wetter climatic period.
Figure 5. Exponential Increase in Particulate Organic Carbon and Particulate Organic Nitrogen Load with Increase in Discharge for Small Early Season Flow Events (Brooks et al. 2007)
So far the discussion of water quality in arid systems has focused on relatively undeveloped systems and the ability of riparian systems in these settings to process and reduce contaminant export to downstream receiving bodies. With both agriculture and urban effluent discharges there is less work in arid climates detailing their interaction with riparian systems and their impact on water quality. Additionally, there are nearly no studies in ephemeral settings since agricultural return flows and effluent often convert previously ephemeral systems to intermittent or perennial flow conditions (Treese et al. 2009).

Several studies on agriculture and urban influence on arid and semi-arid rivers have been done on the Rio Grande. These studies demonstrate a dynamic interaction between urban, natural and agricultural systems in response to nutrient inputs and climatic variability. Oelsner et al. (2007) demonstrated that the City of Albuquerque’s treatment plant was an extremely important input of

---

**Figure 6. Increase in Particulate Organic Carbon and Particulate Organic Nitrogen Export with Increased Flow for Larger Events in Middle of Monsoon Season (Brooks et al. 2007)**

**3.4 Effluent and Agricultural Influences and Interactions with Riparian Systems**
nutrients into the Rio Grande. In terms of water, Albuquerque’s treatment plant is the fifth largest tributary to the river and the largest in terms of nutrients. Similarly the treatment plants of Nogales and Tucson contribute nearly the entire flow of the Santa Cruz River at their points of discharge, at least during low flow conditions. Oelsner (2007) found that this large input of nutrients was processed in the downstream riparian and agricultural systems and that total nutrient concentrations and loads both decreased during drought year low flow conditions. During wet year conditions with higher flows and more frequent events, the riparian and agricultural systems were not capable of reducing nutrient concentrations or loads indicating a relationship between contact time and the ability of the coupled riparian-agriculture stream system to remove nutrients from the system (Oelsner 2007). Summer floods have been shown to be an important source of water and nutrients to the river (Oelsner 2007; Vivoni et al. 2006). These floods are able to sustain high nutrient conditions throughout the summer despite strong removal of nutrients in the Rio Grande’s riparian system. These results indicate that riparian systems can serve as sinks for some contaminants originating in the effluent from urban ecosystems but this capacity can be overwhelmed during flood events.

3.5 Sediment Processing and Influence on Water Quality

The results from flooding on the San Pedro indicate that sediments are of direct and indirect importance for water quality in desert rivers. Evidence from the San Pedro and other systems indicates that contaminants associated with sediment can be released to the water column. A large body of literature exists connecting sediments and the contaminants associated with them to adverse water quality conditions in waterbodies. Sediment is recognized as such an important factor in controlling water quality that entire books have been written on the topic (e.g. Foster et al. 1995). Sediment is important in its own right for its effect on water clarity and turbidity (Wetzel 1975) and also for the contaminants that are carried with the sediment such as heavy metals, pesticides and other organic contaminants (MacDonald et al. 2000). Sediment attached contaminants of any type can re-enter the water column either through chemical desorption and dissolution processes or via biological processes involving microbes and invertebrate animals. Thus even though concentrations in the dissolved phase of a stream or river might be low for a given contaminant, that waterbody could be transporting significant amounts of a contaminant attached to sediment (Salomons et al. 1987, Baudo 1990, MacDonald et al. 2000, Foster et al. 1995).

Most work on biogeochemical processing in arid and semi-arid settings has been done focusing on carbon and nitrogen. This work can be used to assess biogeochemical activity of different environments in streams, while the wider body of work on pesticide interactions with the water column can be used to assess the ultimate fate of pesticides and other contaminants in arid and semi-arid streams. In the San Pedro River work has shown significant variability in biogeochemical activity of the surface stream, while near stream and riparian sediments have shown less overall activity (Lewis et al. 2007). These results can be interpreted to mean that sediments in contact with consistently free flowing water in semi-arid rivers are likely to be biogeochemically active and release sediment-associated elements and contaminants readily. A source of the nutrients observed by Lewis was the sediments that were exported into the system during flood events. In intermittent-to-ephemeral systems like the Santa Cruz, sediments and
associated contaminants would likely be reprocessed in-situ from local rain and flow events until an event large enough to transport these constituents downstream occurs.

### 3.6 Integration of Water Quality Influences

Taken together the impact of upland export of sediment and dissolved nutrients, the moisture brought by flood events and the alteration of stream composition as a result, and the restructuring of near and in-stream ecosystems shows that floods are critical events for water quality in desert rivers. All of these processes are linked to the overall water quality of these desert stream systems. Floods, while by definition infrequent, are critical processes for maintaining and affecting the water quality of desert river systems. Note that in the San Pedro a flood need not be very large to have an effect. The floods in Figure 2 are merely 70-100 cubic feet per second, just a multiple of 10 times normal winter baseflow in the San Pedro. Importantly though, all of the water quality results lead one to the conclusion that the largest floods are most capable of transporting sediments and contaminants and are thus the most critical events at structuring ecosystem water quality in arid and semi-arid systems.
4 Surface Flow Connectivity in the Lower Santa Cruz River Basin

The characteristics of the surface water hydrologic connectivity within the channel of the Lower Santa Cruz River are variable in time. In this report the term hydrologic connectivity refers to the relationships between flow events in the inlet and outlet of the Lower Santa Cruz River. In intermittent or ephemeral rivers such as the Lower Santa Cruz River the role of the river channel in conveying streamflow during rainfall events is often unclear. In contrast to perennial rivers in which water exists in the channel continuously both in space and time, in ephemeral rivers flow occurs in different river segments, at different times, from contribution of runoff in various locations along the channel. Because of this streamflow discontinuity, the definition and quantification of hydrologic connectivity is often vague. In the Lower Santa Cruz River the challenge to identify the hydrologic connectivity is magnified due to lack of long term daily observations along the river channel and the drainage area for accurate delineation of streamflow during an event.

In this section the characteristics of surface hydrologic connectivity in the Lower Santa Cruz River are examined. First, data analysis of specific storm events was performed to understand the range discharge patterns in the Lower Santa Cruz River. Next a statistical analysis was performed to identify the level of dependency and strength of association between the observed streamflow records in the inlet and the outlet of the Lower Santa Cruz River.

4.1 Available Hydrometeorological Datasets

The following agencies archive historical hydrometeorological gage network data: USGS, NOAA–National Climatic Data Center, Pima County Flood Control, Maricopa County Flood Control, and the Arizona Meteorological Network (AZMET-UA). Most historical records are available for download from the agencies’ web sites and include location information (Figure 7).
Figure 7. Data Availability for the Lower Santa Cruz River and Tributaries

4.1.1 USGS Data

Several gages with historical streamflow records in excess of 5 years exist in the system (Table 1) website. Fifteen-minute data for the gages at Cortaro, Trico Rd. and Laveen was accessed through a request to the USGS. The USGS does not operate a streamflow gage on the Santa Cruz in between Trico Road and Laveen. However, gages are located on the Santa Rosa, Brawley, and Vekol washes all tributaries of Lower Santa Cruz River.

Table 1. USGS Gages in the Lower Santa Cruz River Basin with Record Lengths in Excess of 5 Years

<table>
<thead>
<tr>
<th>USGS ID</th>
<th>Gage Location</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>9486520</td>
<td>SANTA CRUZ RIVER AT TRICO ROAD</td>
<td>1989</td>
<td>Current</td>
</tr>
<tr>
<td>9488650</td>
<td>VEKOL WASH NR STANFIELD (Maricopa)</td>
<td>1989</td>
<td>1996</td>
</tr>
<tr>
<td>9489000</td>
<td>SANTA CRUZ RIVER NEAR LAVEEN</td>
<td>1940</td>
<td>Current</td>
</tr>
<tr>
<td>9486580</td>
<td>ARIVACA CREEK AT ARIVACA</td>
<td>1995</td>
<td>2002</td>
</tr>
<tr>
<td>9486800</td>
<td>ALTAR WASH NEAR THREE POINTS</td>
<td>1994</td>
<td>Current</td>
</tr>
<tr>
<td>9487000</td>
<td>BRAWLEY WASH NEAR THREE POINTS</td>
<td>1992</td>
<td>Current</td>
</tr>
<tr>
<td>9487500</td>
<td>SANTA ROSA WASH AT GU KOMELIK NR SELLS ARIZ</td>
<td>1954</td>
<td>1959</td>
</tr>
<tr>
<td>9488000</td>
<td>KOHATK WASH NEAR CHIAPUK NEAR SELLS ARIZ</td>
<td>1954</td>
<td>1959</td>
</tr>
</tbody>
</table>
4.1.2 NOAA – National Climatic Data Center

The National Climatic Data Center (NCDC) archives daily, hourly, and 15-minute precipitation datasets. The Tucson Airport, Phoenix Airport, and Casa Grande National Monument are three locations that have precipitation data for 1948 to the present. Although these gages are located outside of the Lower Santa Cruz River drainage area they provide valuable information for the regional hydrologic analysis.

4.1.3 AZMET –UA

Since 1987, the Arizona Meteorological Network (AZMET) provides meteorological data and weather-based information to agricultural and horticultural interests operating in southern and central Arizona. Meteorological data, precipitation included, is collected from a network of automated weather stations and available online from the University of Arizona Department of Soil, Water and Environmental Sciences. The four gages that are within the area of interest are Eloy (1989-05), Marana (1987-current), Maricopa (1987-current) and Coolidge (1987-current).

4.1.4 Pima and Maricopa Counties

Pima County Flood Control established an ALERT monitoring network in the mid-1990s. Some of the rainfall and streamflow gages are located in the Brawley wash watershed and are co-located with the USGS gages. Maricopa County Flood Control has an ALERT monitoring network from the mid-1980s, but data for most gages are available from the mid-1990s. All the historical records are available from the Maricopa Flood Control District website.

4.2 Analysis of Selected Storms

Flow in the Lower Santa Cruz River basin is commonly due to three seasonal weather patterns (summer, winter and fall). These various large scale weather patterns yield different precipitation patterns that produce different streamflow characteristics in the Lower Santa Cruz River. Summer convective rain events during the North American Monsoon weather system (July-September) are mainly driven by isolated or complex cells of thunderstorms with intense short-lived rainfall events that are highly distributed in space with limited areal extent. Winter storms (November-March) almost entirely originate from large-scale low pressure frontal systems approaching from the west and southwest. These storms may last for a few days with persistent rain over large areas. Large scale cyclonic storms infrequently occur in the late summer and early fall. These storms are caused by remnants of tropical storms over the Pacific Ocean that in certain weather conditions (that commonly exist in October) contribute to the production of large storms over southern Arizona. Detailed regional analysis of synoptic conditions classification and hydrometeorological characteristics of the storms can be found in Hirschboeck (1985). In the data analysis that follows, a few selected events which represent these three weather patterns are discussed with respect to streamflow generation in the Lower Santa Cruz River.

4.2.1 Flood of October 1983 – Tropical Storm

The 1983 fall storm in southern Arizona was documented and studied by many (e.g., Betancourt 1990; Hirschboeck 1985). It is considered by the National Weather Service office in Tucson as the largest flood event recorded in southeastern Arizona. For a 5-day period beginning on
September 28, rain was widespread, persistent, and at times quite intense throughout southern Arizona. This widespread rainfall, from the remnants of tropical storm Octave, occurred after an unusually wet September. The total rainfall for these five days exceeded 6 inches at most stations and exceeded 8 inches in the Santa Rita Mountains and Tucson area (Betancourt 1990). Record discharge at Cortaro was estimated to be ~65,000 cfs in the early morning of October 2, 1983 and reached 33,000 cfs at Laveen (USACE 1990). The spatial distribution of the storm total rainfall as interpolated from data from the NCDC and the Comision Nacional del Agua, Mexico is shown in Figure 8 (http://www.hpc.ncep.noaa.gov/tropical/rain/octave1983rain.gif). The storm center was in the high mountains of southeastern Arizona, with record precipitation in Altar, Mexico and Mount Graham (Figure 8). The NCDC gages in Tucson, Casa Grande, and Phoenix recorded 6.7, 3.8 and 2.4. inches, respectively, from September 26-October 4, 1983.

Figure 8. Total Rainfall Estimate for the Storm of October 1983 (from National Climate and Environmental Prediction (NCEP-NOAA))

The daily streamflow hydrographs for the Laveen and Cortaro gages are presented in Figure 9. These discharge values were reconstructed by the USACE (1990) study. In this study, the 1983 flow was reconstructed for Red Rock and a detailed hydraulic model was constructed for the Lower Santa Cruz River to the Laveen gage. The model was used to analyze the effect of large flow events under various conditions.
The daily discharge hydrograph for this storm (Figure 9) is a compelling example for the flood attenuation properties of the Lower Santa Cruz River channel. Although there are insufficient records to quantify lateral contributions downstream of Cortaro, the precipitation distribution discussed above, which stresses that the center of storm was in the Upper Santa Cruz River watershed, is an indication that a major mass of water was introduced to the Lower Santa Cruz River at the inlet. As seen in Figure 9, a record daily flow at Cortaro (40,000 cfs) yielded, 2 days later, a record daily flow at Laveen (18,000 cfs). The estimated flow velocity at Cortaro by the USACE (1990) was about 2-3 feet per second which implies that it would take about 47-70 hours, just over two days, to traverse the 95-mile distance between the gages. This estimate of flow velocity by USACE strengthens the assumption that the peak flow at Laveen resulted from a propagated flow from Cortaro. It is safe to assert that during the event the Lower Santa Cruz River channel had a critical role in conveying and attenuating the flood that was generated in the Upper Santa Cruz River.

4.2.2 Flood of July 2006 Convective Storm

The flood of 2006 serves as a classic example for a severe summer storm. These intense, local and short duration summer storms usually cause flash floods in small basins. Occasionally, exceptional hydrometeorological conditions yield flood events in larger basins. Heavy rainfall on July 27-31, 2006 led to record flooding and triggered an historically unprecedented number of
debris flows in the Santa Catalina Mountains north of Tucson (Magirl et al. 2007). On July 31, the daily flow at Cortaro was estimated at 11,700 cfs, which is the largest summer event that was recorded at the Cortaro gage.

Figure 10 shows the 15-minute discharge records from the USGS for that period. The blue, green and red lines are the discharge records for July 28 to August 3 from Cortaro, Trico Road, and Laveen, respectively. Two large peaks are seen at Cortaro and Trico Road on July 29 and 31. On August 2, at 1:00 p.m. local time, the Laveen gage recorded 2,100 cfs. This event at Laveen, although small in comparison to the discharge rate at Cortaro and Trico Road, is the largest discharge rate for summer events that exist in the 15-minute record (1990-2008). The time of the peak propagation from Cortaro to Trico Road (about 16 miles) can be used to estimate the flow velocity which is about 2-4 miles per hour. Given about 48 hours difference between the peaks at Laveen and Cortaro, this suggests an average velocity that is slight slower than 2 miles per hour. Thus, based on the expected velocity of the flow, the peak at Laveen consists of conveyed flow from the Upper Santa Cruz River.

Figure 10. 15-minute Discharge Hydrograph for the Summer Storm of July 2006

The Tohono O’odham Nation EPA reported that the event of 2006 produced significantly lower flow than events that occurred before 2004 downstream of Sunland Gin Road. This occurrence can be explained by local flooding that occurred during the 2006 event: A large area downstream of Sasco Road was flooded (approximately 2 miles wide and 7 miles long), probably because of changes in the in the channel continuity from the summer floods of 2003-2004. In addition, levees along the Greene Wash near Sunland Gin Road were overtopped and
breached in about 15 locations which caused large flooding of cotton and hay farmland along Sunland Gin Road (about 15 miles upstream of the Laveen gage).

During the event, flow was also observed at the Maricopa Flood Control gage at Greene Wash which is located along state route 84 about 30 miles upstream of the Laveen gage. Flow at the Greene Wash gage was observed starting July 31, with peak flow at 4 p.m. on August 2 (~1,400 cfs). Because the Greene Wash is a major conveyer of water from the Upper Santa Cruz, the observed flow two days before the appearance of flow at Laveen is congruent with the reports of flooding. These local flooding events demonstrate the important role of the river channel in conveying flood water.
The August 2006 flow event at Laveen has an atypical hydrograph shape compared with other summer flow events (see Figure 12). The 15-minute hydrographs of the 2006 event (upper panel) are compared to two other significant summer events at Laveen (July 15, 1999 and August 9, 1997) that show characteristics more typical of large summer events at Laveen.

A few interesting features can be noted from the hydrograph comparison:

1. The August 2006 discharge hydrograph had a very sharp rising limb. The discharge rate changed from 0 to 30 to 2,100 cfs in 30 minutes. This would have been a spectacular wave that passed through the gage location. The rising limb in other hydrographs lasted more than 10 hours.

2. The event of August 2006 had a relatively short declining limb and flow receded to a trace in about a day. The other summer events had a more gradual decline that maintained low flow at Laveen for a few days.

3. The August 2006 event consisted of one peak while the other events exhibited multiple peaks.

4. The discharge rate for the peak of August 2006 is twice as large as the second largest summer event that was observed in the 15-minute record since 1990.

The shape of the hydrograph seen at Laveen in the summer of 2006 resembles a hydrograph from a wave that was propagated due to a sudden release of large quantities of water (e.g., dam break). Looking at the regionally available datasets, during August 1-3, the Maricopa Alert system gage (more than 250 gages) recorded rainfall in excess of 0.5 inch. In addition, the Santa Rosa and the Vekol streamflow gages recorded no flow. A minor flow of about 40 cfs was registered for Brawley and Alter washes on July 29th. This evidence indicates that there were no significant lateral flow contributions that occurred downstream of the Cortaro gage. The areal extent of the storm, the time differences of the discharge peaks between Cortaro and Laveen, and the unique shape of the hydrograph at Laveen indicate that the flow event at Laveen was a propagated wave through the Lower Santa Cruz River channel that originated in the Upper Santa Cruz River basin.

4.2.3 Flood of January 1993

The January 1993 flood event is an example of a winter event. It was caused by an El Niño-induced storm during an already abnormally wet winter that caused statewide flooding (the detailed characteristics of the storm are provided in USACE (2000) and House and Hirschboeck (1997)) The estimated peak at Cortaro was 40,000 cfs (USACE 2000). In the comparisons of the daily discharges, it is seen that the peak flow at Laveen was earlier than at Cortaro (Figure 12). During this event the flow along the Lower Santa Cruz River probably originated from various drainage areas as well as flow from the Upper Santa Cruz River. Note that the high flow at Laveen was sustained two days after the peak at Cortaro, which might be due to propagated flow from Cortaro.
The daily streamflow event of October 23, 2000 is the 10th largest independent daily event recorded at Cortaro. October 2000, the wettest October on record, experienced a persistent rainfall over southern Arizona from a northern cold front system combined with a moisture surge from a tropical system. It appears that the flooding reports from the Tucson region were a few days earlier than the Phoenix region (National Weather Service, www.nws.noaa.gov). The 15-minute hydrographs for Cortaro, Trico Road and Laveen are shown in Figure 13. The shape of the Trico road hydrograph closely follows the Cortaro’s hydrograph. The peak flow at Cortaro exceeded 9,000 cfs on October 23, followed by a smaller peak on October 24. The streamflow at Cortaro receded to its baseflow rate by October 26. The timing of the hydrograph’s rise at Laveen on October 26 and the peak of 1,000 cfs on the morning of October 27 corresponds well with the expected delay for streamflow propagation from the Upper Santa Cruz River. Streamflow was recorded at the Greene Wash and Santa Rosa gages and no flow was recorded at Vekol gage, all gages of the Maricopa Flood Control District. In the Greene Wash gage, flow was observed late night of August 24 with peak flow at 11 a.m. on the 25th (1,100 cfs); in the Santa Rosa gage flow was observed on the 25th and the 26th (123 and 353 cfs, respectively). To conclude, it is reasonable to assume that the first peak at Laveen (October 27) has a dominant component of propagated water from the Upper Santa Cruz River. However, indication of floods
in the Phoenix region and apparent flow in the Santa Rosa Wash suggest that the second peak at Laveen (October 28) is from runoff contribution along the Lower Santa Cruz River channel.

![Figure 13. 15-minute Discharge Hydrograph for the Storm of October 2000](image)

**Figure 13. 15-minute Discharge Hydrograph for the Storm of October 2000**

### 4.2.5 Flood of July-August 2007

The July 28, 2007 event at Cortaro had an estimated daily flow return period of 2 years. The streamflow on July 28th had a lower peak than the following July 31st event, but is a larger event on the daily scale. This month was comprised of a series of streamflow-generating monsoonal rainfall events. As can be seen in Figure 14, the streamflow on the 28th did not propagate all the way to the Laveen gage. However, it seems that this event (July 28) created the antecedent moisture conditions that facilitated the propagation of the July 31 streamflow event throughout the Lower Santa Cruz River all the way to Laveen. The Green Wash gage (Maricopa Flood Control District) recorded flow from August 2. During the entire period, no flow was recorded at the Vekol and Santa Rosa streamflow gages and low daily flows were recorded from July 28 on at the Santa Cruz gage near Highway SR84. Based on this analysis it is reasonable to infer that the flow at Laveen on August 2 was propagated from the Upper Santa Cruz River along the Lower Santa Cruz River channel. This example demonstrates that with wet antecedent moisture conditions even relatively small streamflow events will propagate from the Upper Santa Cruz River through the Lower Santa Cruz River to the Laveen gage.
4.2.6 Synthesis of Individual Storm Analyses

These individual storm event analyses indicate that there are hydrologic connections between the Cortaro Upper Santa Cruz River stream gage and the Lower Santa Cruz River stream gage at Laveen. The hydrologic connections shown, based on the available datasets, indicate that some of the streamflow events that were produced from rainfall events in the Upper Santa Cruz River watershed were propagated through the Lower Santa Cruz River channels and appeared as streamflow at the Laveen gage two to three days after the flow was observed at the Cortaro gage. These individual storm analyses indicate that intervening factors of antecedent moisture condition, stream bed infiltration rate, levee breaches and changes in the channel course that create local flooding, and flows from tributaries downstream of Cortaro, complicate the relationship between these two gages and the inferences that can be drawn about hydrologic connections between the two locations. These events were chosen because they are events in which it was possible to identify a connection between the Upper Santa Cruz River and the Lower Santa Cruz River. A more general analysis to estimate the nature, frequency and magnitude of hydrologic connections between the two locations is presented in the next section.

4.3 Statistical Analyses of Hydrologic Connectivity

The strength and the nature of the hydrologic connectivity in the Lower Santa Cruz River are further explored through statistical analyses. Various statistical tests can be performed to evaluate the strength of association between two sets of random variables. In this case, the daily
flow at Cortaro and Laveen can be assumed to be two samples of random variables that represent the inlet and the outlet of the Lower Santa Cruz River. Tests for statistical association were performed between the daily flow at Cortaro and the daily flow at Laveen, which is lagged in daily intervals.

Although it is possible that one set of random variables may cause the other set, strong association between the two variables does not necessarily imply that there is a cause and effect relationship between the two sets. However, strong statistical association between the gages at certain relevant time lags is indicative of the nature of the hydrologic connectivity in the Lower Santa Cruz River. As seen above for the discussion of individual storm events on the Lower Santa Cruz River, it takes approximately 2-3 days for water to travel from Cortaro to Laveen. During the time and distance of travel peak flows and the total volume of flow, both also decline due to infiltration during transit. Note that the individual storms that were selected are relatively large events and if water transits through the Lower Santa Cruz River during smaller events the flow velocity is expected to be slower.

The pattern of the statistical association with respect to the time lag provides insight into the processes that link flow at the two gages. For instance, a case that the highest statistical association is found at daily lag of -1, 0, or 1 might indicate that a single weather event caused the flow to occur simultaneously at the two gages. Lags at longer time scales along a river may indicate the time needed for water to transit from one gage to the next. Cross-correlation and conditional probability statistical tests are presented below to explore various aspects of the statistical association between the gages’ daily records.

### 4.3.1 Analysis of Cross-correlation

Correlation is a basic test to assess the strength of association between two sets of continuous random variables. The strength of correlation is reported by the correlation coefficient, which is an index that describes the degree of interdependency between two variables. The index ranges in value from $-1$ to $+1$, indicating perfect negative correlation at $-1$, absence of correlation at zero, and perfect positive correlation at $+1$.

Within the context of hydrologic connectivity in the Lower Santa Cruz River we present a cross-correlation analysis between the daily streamflow at Cortaro and lagged daily streamflow at Laveen, for lags ranging from -2 to +7 days. For example, high correlation coefficient at lag 0 indicates that the degree of correlation between flows at the two gages occurs on the same day. A lag of +1 indicates a 1-day delay at Laveen, a lag of +2 a 2-day delay, and so on. A negative lag indicates flow at Laveen that precedes the flow at Cortaro.

Three different cross-correlation tests between the seasonal (i.e., winter, fall and summer) and annual nonzero streamflow values for the Cortaro and Laveen gages are presented. The first two tests are based on the commonly used Pearson product-moment correlation coefficient. The Pearson correlation coefficient quantifies the linear relationship between variables in terms of their actual raw values. Although a robust test, an underlying assumption of the Pearson correlation test is that the variables’ distributions and the variables’ joint distribution are normal. The Pearson correlation coefficient for two variables $X$ and $Y$ is defined as the covariance of the variables divided by the product of the standard deviations of the individual variables. For ease of interpretation, the squared correlation coefficient, $R^2$, represents the proportion of the variance in one variable that is “explained” by the other variable.
In the first test, the Pearson correlation coefficients were derived for a cross-correlation test between the gages’ streamflow discharge values. In the second test, the Pearson correlation coefficients were derived for cross-correlation analysis between the natural-logarithm transformed streamflow discharge values. As expected for intermittent and ephemeral arid rivers, the frequency distributions of the daily streamflow records for both gages are highly skewed. Skewed coefficient values for the Cortaro and Laveen records are greater than 30 indicating many days with low flows and a few days with very high flows. The natural-logarithm transformation of the daily discharge values reduces the skew (skewed coefficients are less than 1) and yields frequency distributions that are closer in appearance to a normal distribution which better accommodate the underlying assumptions of the Pearson correlation analysis.

Two sets of random variables might be correlated in either a linear or non-linear mode. If one set of variables is commonly increased or decreased as the second set of variables increases, the two sets are said to posses a monotonic correlation that might be different than linear. To detect monotonic correlation that might be hidden from the linear correlation tests we added a third nonparametric test. The third cross-correlation test is the nonparametric Kendall Tau rank corellation coefficient. The Kendall Tau test is a rank-based method which is well suited for variables that exhibit large skew, such as streamflow in arid and semi-arid rivers. The Kendall Tau test does not require that the variable distributions conform to a certain parametric statistical distribution. In this method the variables are assigned ranks and the tendency of the variables to move in the same or opposite direction, regardless of their magnitudes, is examined. Detailed algorithmic procedure for the derivation of the Kendall Tao correlation coefficients in hydrologic variables is found in Hirsch et al. (1993).

The three cross-correlation tests were conducted for the entire non-zero period of daily records (1940-2008) and the results are shown in Figure 15. Based on a Student $t$-test analysis it was found that all the correlation coefficients shown in Figure are significantly different than zero ($\alpha < 0.01$).
The outstanding conclusion to be drawn from the cross-correlation analysis is that, without exception, for all the seasons and for the three cross-correlation tests, the correlation coefficients have a “bell” shaped lag time dependency. Again without exception, the highest correlation coefficients were observed for the +3-day lag. Relatively high correlation coefficient values are also seen for +2- and +4-day lags. The “bell” shape of the cross correlation function (for all seasons) is indicative of an association between the gages that is time dependent. Based on the estimated flow velocity presented above, 2-4 days is the anticipated time for flow to propagate from Cortaro to Laveen. The highest cross-correlation coefficient is shown for lag +3 in the fall (October) season. This is because of the rare intense events during the fall season. Notice the differences between the summer and the winter cross correlations which reflect on the precipitation characteristic differences. The local convective summer rainfall commonly causes flow at each gage that is likely to be local and not propagate from Cortaro to Laveen (see the smaller correlation values). On the other hand winter frontal events are of a larger spatial scale, longer period and, given the larger lag correlation coefficients, results in flow propagating between the two gages.

Although the three tests are consistent with the “bell” shape of the time dependency, the correlation coefficient values are very different. The very high values shown in panel (a) are due to the extreme flow events at both gages. The Pearson analysis is highly sensitive to positive skew due to extreme large values and produces overvalued correlation coefficients. The natural-logarithm transformation of the streamflow reduced the correlation coefficient values. Lastly,
the Tau Kendall showed the lowest correlation values. It is commonly the case that the non-parametric analysis yields lower correlation values than the parametric tests (Hirsch et al. 1993). To evaluate a hypothesis that the 3-day delay seen in the Lower Santa Cruz River surface flow is attributable to time delays in precipitation, a cross-correlation analysis is presented for precipitation records from Tucson and Phoenix airports. For these two locations we have available from the National Climatic Data Center (NCDC) 57 years (1949-2005) of fairly complete daily rainfall records. The Tucson gage is within the Upper Santa Cruz River watershed. The Phoenix gage, although located outside of the Lower Santa Cruz River watershed, is about 15 miles from the Laveen gage and therefore well represents the synoptic conditions in the gage proximity. The cross-correlation results (Figure 16) clearly show that the correlation between the two regions is apparent only during the same day (Lag 0). This suggests that, in general, the two gages can be considered as within the same region with respect to rainfall-generating atmospheric weather systems. As expected, winter and fall, with the long lasting rainfall events, have the highest correlation, and the summer has the lowest correlation due to the locality of the convective storms.

Figure 16. Pearson Cross-correlation between Daily Precipitation Records from Tucson and Phoenix Airports
To conclude the cross-correlation analysis, it can be seen that correlation coefficients are highest when streamflow from Cortaro is compared with streamflow from Laveen that was observed three days later. Given the range of the correlation coefficient values provided from the various cross-correlation tests, inference regarding the strength and the nature of the association required additional testing that will be the focus of the following section.

4.3.2 Analysis of Conditional Probabilities

A conditional probability framework is used in this section to quantify and explore the strength of association and the nature of the hydrologic connectivity between daily flow at Cortaro and Laveen. A probabilistic analysis that evaluates upstream and downstream streamflow dependency provides a more general and generic means by which to assess the connections between the Upper Santa Cruz River and the Lower Santa Cruz River systems and thus to assess the hydrologic connections of the Santa Cruz River as a whole and the Gila River.

Given that flow at Cortaro of a certain magnitude has occurred, what is the chance that the flow at Laveen during the time lag that indicates hydrologic connectivity will be above normal condition? Obviously, if the probability of observing flow above normal at Laveen is unrelated to the probability of observing above-normal flows at Cortaro, we can infer that there is no indication for hydrologic connection. On the other hand, a high probability of observing flow above normal at Laveen after a certain lag time given that a flow of a certain magnitude occurred at Cortaro is an indication for connection between the gages.

The classification of the flow events at Cortaro can be done through the derivation of recurrence intervals (duration curves) for the gage location. For example, if it is determined that when a 1-2 year event occurs at Cortaro, the flow at Laveen during various relevant time lags (say -1, 0, +1, +2, +3-day) has a distribution that indicates random occurrence of flow above normal conditions, the conclusion can be reached that there is only weak association between the gages during events that are between 1-2 year return period at Cortaro. On the other hand, it might be found that flow at Laveen three days after flow at Cortaro that is greater than a 2-year return period has occurred has a probability of 95 percent of being above normal condition. This result is would clearly indicate that the flow at Laveen at lag +3 is dependent on the occurrence of the flow at Cortaro.

4.3.3 Data Analysis

The first step in this analysis consists of the identification of independent flow events at both the Cortaro and Laveen gages. For this study, a flow event is defined as a daily flow sequence that begins and ends with mean daily flow smaller than 100 cfs and has at least one day with mean daily flow that is greater or equal to 200 cfs. Such a definition yields a statistical sample of independent flow events with durations that range from 1 day to a few weeks. It is based on the assumption that in these locations discharge below 100 cfs is a reasonable criterion to separate streamflow events that were generated from different weather systems. Applying this criterion to the entire historical daily records yields a statistical sample of 329 and 134 events for Cortaro and Laveen, respectively. Summary statistics of these events’ characteristics are found in Table 2. The Laveen gage drains a larger area but has fewer independent flow events. This situation probably occurs because of the enhanced precipitation in the highest terrain of the Upper Santa Cruz River basin (e.g., Catalina and Santa Rita Mountains), the Lower Santa Cruz River
physiographic features that generate less runoff, and the high transmission losses in the Lower Santa Cruz River channel. At both gages, most flow events occurred in the summer; however, these events are of short duration and transmit small volumes of water. It is seen that the October events are infrequent but on average carry larger volumes of water and last as long as the winter events.

Table 2. Seasonal Flow Event Characteristics for Cortaro and Laveen (parentheses)

<table>
<thead>
<tr>
<th></th>
<th>Winter (Nov-Mar)</th>
<th>Summer (Jul-Sep)</th>
<th>Fall (October)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events with daily peak &gt; 200 (cfs)</td>
<td>78 (50)</td>
<td>223 (83)</td>
<td>15 (9)</td>
</tr>
<tr>
<td>Average duration of streamflow events (days)</td>
<td>6 (5.9)</td>
<td>4.6 (5.1)</td>
<td>5 (5.9)</td>
</tr>
<tr>
<td>Average flow of events (cfs)</td>
<td>435 (379)</td>
<td>334 (310)</td>
<td>1,030 (657)</td>
</tr>
</tbody>
</table>

To conduct the analysis it is necessary to identify an event of interest at Laveen in terms of normal seasonal flow. We define normal flow for a season as the daily discharge magnitude that is larger than the median flow from days with observed flow (i.e., no flow days are excluded). This measure is conservative because at Laveen about 50 percent of the days have no observed flow. Therefore it could be argued that any daily flow at Laveen is an event that should be considered as above normal. The defined seasonal normal values are about 2 cfs and the actual probability for flow to be above these values is 25 percent, 23 percent and 20 percent for the winter, summer and fall seasons, respectively.

In the next step, the flow duration curve for Cortaro is derived. This curve enables the classification of the events magnitude in terms of recurrence intervals. Return period (often termed recurrence interval) curves are commonly used probabilistic terms that indicate the chance of a specified flood event to occur in a given year. For instance, a daily magnitude that is specified as the 100-year return period is the flood event that has a probability of 1 percent to occur in any given year. To derive return period curves, it is necessary to derive independent series of observed events for a specified duration (e.g., 1-day, 2-day, etc.).

Two methods to derive independent series are commonly used: annual maxima and partial duration series. The annual maxima series is simply composed of the largest event from each year, whereas a partial duration series consist of all independent events that exceed a predetermined threshold. In arid regions and intermittent or ephemeral rivers the use of partial duration series is recommended (Stedinger et al. 1993) since the annual maxima series might include events that occurred in years that had low or even no flow. The threshold for the partial duration is commonly set to yield a series with a number of events that is about equal to the number of years that are available in historical record.

The derivation of return period estimates is commonly done by fitting an extreme value statistical distribution to the partial duration series (the Log Pearson type III distribution is commonly used in the United States). For the purpose of the current analysis, as the interest is in more frequent events, the return period is directly estimated from the observed partial duration series. The mean daily discharge of the partial duration series at Cortaro for +1-, +2-, +3- and, +4-day event durations using Weibull plotting position (Stedinger et al. 1993) are shown in Figure 17. Many of the same floods were members in all of these partial duration series.
Therefore, analysis of conditional probability for each of the durations would be repetitive. The following analysis focuses on the daily duration series.

**Figure 17. Cortaro Gage 1-, 2-, 3-, and 4-day Return Period of Mean Discharge from Partial Duration Series**

In this analysis the daily partial duration series is treated as three ranges of recurrence intervals: 0.5-1 year, 1-2 years, and greater than 2 years. At Cortaro 69 events were identified that exceeded a mean daily flow of 1,500 cfs and about 140 events exceeded a peak mean daily flow of 650 cfs. Since the gage daily record is approximately 70 years long, these thresholds (1,500 and 650 cfs) represent the 1-year and .5-year return periods, respectively. The 2-year return period is estimated at 2,600 cfs. These estimates correspond well with the 1-day duration estimates from the USACE (1990).

The events for the different return intervals are not distributed evenly throughout the year. For the recurrence interval range of 0.5-1 year, 50 events of the 70 events occurred in the summer and 16 events occurred in the winter. Out of the 35 events that were identified for the 1-2 year recurrence interval, 25 events occurred in the summer and 10 in the winter. Finally, of the 35 largest daily independent events (greater than 2-year), 16 occurred in the summer, 15 in the winter, and 4 in the fall.

**4.3.4 Results**

The analysis of dependency of flow at Laveen as a function of a certain flow recurrence range at Cortaro is summarized in Figure 18. In this figure, the chance to observe flow that is above the seasonal normal (in fraction units) is shown as a function of daily lag time at Laveen for three
flow events’ recurrence ranges at Cortaro (i.e., 0.5-1 year, 1-2 year, and greater than 2-year return period). For example, an obvious result that is inferred from Figure 18 is that the chance to get a flow event above the seasonal normal at Laveen 3 days after occurrence of a daily event at Cortaro which exceeded the 2-year return period is greater than 90 percent.

Figure 18. The Probability (as fraction) of Observing Flow above Seasonal Normal at the Laveen Gage as a Function of Daily Lag Time for Three Ranges of Daily Recurrence Intervals at Cortaro

For convincing statistical inference regarding the nature of hydrologic connectivity it is essential that the span of lag times will capture durations that are inside and outside of the assumed effect of a synoptic atmospheric disturbance that caused the event of concern. The lag time at Laveen extends from -20 to 20 days where lag 0 is the simultaneous daily flow at both gages. A comprehensive statistical analysis presented in Shamir et al. (2005 and 2007) for the Upper Santa Cruz (near Nogales) found that the length of a winter rainfall event from the same synoptic weather system rarely exceeded 12 days and the length of a summer rainfall event rarely
exceeded 8 days. Although the analysis was conducted on rainfall records and the resulting streamflow from a specific event might have had a longer time interval, it is assumed that the selected time span for the lags at Laveen captures most, if not all, of the events as independent. The presentation of the analysis for such a long period ensures that statistical tests include periods that are clearly independent and are outside of the synoptic weather system that generated the flow.

As expected, the probability of exceeding seasonal normal flow at Laveen is higher when high flow events are observed at Cortaro. The lag dependency “bell” shape found in the cross-correlation analysis is also apparent in Figure 18. Results are shown for the three recurrence ranges during lag -1 to 9, with a peak at lag 3 for the events greater than the 2-year return period and a peak at lag 4 for the events smaller than the 2-year return period. For all the lags between -1 to 6 the probability to exceed normal seasonal flow is greater than 50 percent. Note that as previously mentioned the daily probability for normal seasonal flow is about 22 percent when days with no flow are included in the analysis. It is seen, however, that only in a few cases for the extreme negative lags the probability is between 20-30 percent. This is because during the flow events of concern there are fewer days of zero flow than the inter-annual average. It is also seen that for long time lags, the probability for the flow to be above the seasonal normal at Laveen is higher after an event than it was before. This result is probably because many of the events at Laveen maintained receding flow for a long period of time with discharge above the seasonal norm.

In Figure 18 the flow events at Laveen are presented as the probability of exceeding the seasonal normal threshold. A further quantitative indication for the distribution of the flow events at Laveen as function of recurrence intervals at Cortaro is presented in Figure 19. The daily flow events at Laveen are shown as percentiles of the seasonal non-zero daily discharge values (Y-axis). The seasonal percentiles of the daily flow at Laveen are plotted as a function of the recurrence interval’s exceedance probability (X-axis). In other words, the X-axis indicates the number of independent events at Cortaro from the assigned recurrence interval (in percentage) with flow that is greater than or equal to a given flow percentile at Laveen. The analysis is presented in three panels; each represents the Cortaro’s range of recurrence intervals discussed above. The black horizontal line indicates the seasonal normal flow. The selection of lag -14 days (red line), which was added for comparison purposes, represents a period of the same season as the event but with different synoptic weather conditions. The negative 14-day lag represents a control in the analysis as a strong relationship for this lag would indicate that somehow flow at Laveen is dependent on flow that occurs 14 days later upstream at Cortaro.

It is seen in Figure 19c, for example, that about 70 percent of the flow events at Cortaro (~50 events out of 70) with daily peak flow between 650-1,500 cfs (i.e., -0.5-1 year), also had flow at Laveen that was above the seasonal normal for time lags of 0 to 4 days. In addition, about 50 percent of the events had flow at Laveen 3 days later that exceeded the 90th percentile of flow at Laveen. Comparing that with Figure 19a, about 95 percent of the events with daily flow at Cortaro greater than the 2-year return period flow of 2,600 cfs had flow at Laveen three days later that exceeded the 50th percentile of the seasonal distribution, while about 80 percent of the events with daily flow at Cortaro greater than the 2-year flow had flow at Laveen three days later that exceeded the 90th percentile. The exceedance probability for the 0 to +4 lags is clearly different from the exceedance probability that is seen for lag -14. The flow at Laveen exceeding
50 percent and 90 percent two weeks before the daily peak at Cortaro, occurred only 30 percent and 3 percent of the time (red line), respectively.

The slope of the exceedance probability curves for the ranges of recurrence intervals that represent larger flow events at Cortaro are steeper and shifted to the right compared to the lag -14 control-curve. This result implies that the high seasonal percentile flows at Laveen are correlated with those at Cortaro. The probability of seeing flow at Laveen that is in the higher seasonal percentiles increases as the flow at Cortaro increases. This relationship was found to be strongest for +3- and +4-day lags. This delay is similar to that observed for the individual events discussed earlier.

Figure 19. Cortaro Return Period Exceedance Probability of Seasonal Percentile for Laveen at Various Lag Times – Panels Represent Three Ranges of Recurrence Intervals: (a) Greater than 2-year, (b) 1-2 year, and (c) 0.5-1 year
4.4 Conclusions Regarding Surface Flow Connectivity

In summary, the analyses presented here indicate a clear statistical association between flow events at Cortaro and Laveen. This association is apparent for flow at Cortaro that is greater than the half-year return period. Statistical analysis often requires confirmation tests to check for statistical significance of the test to be able to accept/reject the hypothesis. However, in the case presented above, the signals for the dependency between the gages are strong and additional tests that substantiate significance are unwarranted. Both the cross correlation and the dependency tests show a strong association of flow at Laveen to flow at Cortaro. This result indicates that the Lower Santa Cruz River is reacting to the same synoptic weather conditions and that the channel conveys streamflow during the event.
5. Sediment Transport Connections between the Santa Cruz and Gila Rivers

The Santa Cruz River, as well as many other rivers in arid and semi-arid regions, transports large amounts of sediment during each storm event. Because of local shallow groundwater and periodic supply of surface flow, vegetation often grows into a significant mature size in floodplains and river channels. During storm events, this vegetation not only increases flow resistance but also traps excessive sediment and accelerates in-stream sediment deposition. Consequently the reduced cross-sectional area imposes extra stress on both banks and causes toe erosion and bank failures. Since 1992, the Lower Santa Cruz River at the confluence to the Gila River has experienced geomorphic changes including channel sinuosity, width to depth ratio, and bed slope (Fuller 2004). Sediment transported from the Santa Cruz River to the Gila River increasingly relies on large flood events. The daily load varies seasonally and annually with changing flow discharge and channel geomorphic characteristics. The objective of this section is to determine the maximum sediment load at each gage, estimate the sediment load delivered to the Gila River from the Santa Cruz River, and quantify the fractional contribution of sediment load in the Gila attributable to the Santa Cruz.

5.1. Daily Sediment Load at Cortaro and Laveen Gages

The Santa Cruz River historically had several springs and marshes within its river channel from Tubac to Tucson and a large marsh at its confluence with the Gila River at Laveen. The Laveen gage shown in Figure 20 is the last gage on the Lower Santa Cruz River. (Figure 20 shows “real time” streamflow ranges for selected USGS gages at the time of retrieval and is included here only to show the location of gages with long period of record.) The Laveen gage has nearly continuous records of flow discharge since 1940. Although extensive groundwater pumping has lowered the water table throughout central Pinal County, the Laveen gage still recorded frequent flows to the Gila River. The calculation of sediment load requires the gage height data for determining stream power; these data have been recorded since 1993.

Upstream of the Laveen gage, another gage is located at the reach of the Santa Cruz River near Marana and Cortaro where flow has been perennial in recent years due to the discharge of sewage effluent from Tucson’s sewage treatment plants. The Cortaro gage has both gage height and discharge records since 1996. This study used daily discharges and daily averaged gage heights to calculate daily total sediment load. The annual sediment load in the gages is the summation of the daily sediment load over an entire year.
Figure 20. Locations of Surface Flow Gages Discussed in Section 5
Among over 40 sediment transport equations (e.g., Laursen 1958, Toffaleti 1966, Engelund and Hansen 1972), this study chose the equation of Yang (1973) to estimate sediment load based on a recent study for the Pima County Regional Flood Control District (PCRFCD) to evaluate the applicability of sediment transport models (Duan et al. 2008). The Yang (1973) equation is based on the concept of unit stream power, which is defined as $V S / \omega$ in which $V = \text{velocity}$, $S = \text{energy slope}$, and $\omega = \text{sediment settling velocity}$. The unit stream power is the power available per unit weight of fluid to transport sediment. Using the multiple regression analysis for 463 sets of laboratory data, the Yang (1973) sediment transport equation is as follows,

$$\log C_t = 5.435 - 0.286 \log \frac{\omega d}{\nu} - 0.457 \log \frac{u_*}{\omega} + (1.799 - 0.409 \log \frac{\omega d}{\nu} - 0.314 \log \frac{u_*}{\omega}) \log \left( \frac{VS}{\omega} - \frac{V_c S}{\omega} \right)$$

Equation 1

where $C_t = \text{total sand concentration by weight in \ ppm}$, $\omega = \text{sediment settling velocity}$, $u_* = \text{shear velocity}$, $V = \text{averaged velocity}$, $V_c = \text{critical velocity}$, $S = \text{energy slope}$, $d = \text{sediment diameter}$, $\nu = \text{viscosity}$. The dimensionless critical velocity is defined by

$$\frac{V_c}{\omega} = \frac{2.5}{\log(u_* d_{50} / \nu) - 0.06} + 0.66 \quad \text{for} \quad 1.2 < \frac{u_* d_{50}}{\nu} < 70$$

$$\frac{V_c}{\omega} = 2.05 \quad \text{for} \quad \frac{u_* d_{50}}{\nu} \geq 70$$

Equation 2

where $u_*$ is the shear velocity, and $d_{50}$ is the mean size of non-uniform sediment mixture.

Flow depth is assumed to be the measured water level at the gages’ locations. Bed slope varies as sedimentation and erosion occur in the main channel. Fuller (2004) showed that the bed slope at the Laveen gage varied from 0.5 percent to 0.9 percent. Due to lack of sufficient surveys, for the calculation of sediment load an averaged bed slope of 0.7 percent was used. None of the existing studies have thoroughly analyzed bed material size composition. Based on visual observation, Fuller (2004) stated that bed material at the Lower Santa Cruz varies from 0.4 mm to 1.2 mm. This study assumes mean sediment size of 0.8 mm.

The daily sediment load at the Laveen gage was calculated by Equation 1 and is shown in Figure 21. Daily sediment load increased with discharge. Sediment starts to transport when flow reaches the critical velocity for sediment incipient motion. Even though flow discharge is greater than zero, sediment load can be zero if flow velocity is less than the critical value. The maximum daily sediment load for the record duration (1993-2008) is 22.7 tons which occurred on October 27, 2000 with a corresponding discharge of 780 cfs.
Similarly, the daily sediment load at Cortaro gage was calculated as shown in Figure 22. Sediment load also increases with discharge. The maximum daily sediment load was 300 tons, which occurred on July 31, 2006 when an unprecedented storm event occurred in the Tucson basin as described in Section 4.2.3. It is found in the analysis that the annual sediment load at the Cortaro gage is always greater than that at the Laveen gage and thus sediment must deposit in the reach between these two gages. This result also explains the dramatic geomorphologic changes in this reach that could result from the persistent sedimentation.
5.2. Daily Sediment Load in the Gila near Maricopa Road Gage and near Estrella Parkway Gage

To quantify the importance of sediment contributions from the Santa Cruz to the Gila River, this study analyzed sediment load at two gages in the Gila River above and below its confluence with the Santa Cruz River. The gage located at Maricopa Road is upstream from the confluence, while the one near Estrella Parkway is downstream of the confluence.

For daily sediment load at the Maricopa Road gage from 1995 to 2008, results are congruent with the discharge records in which there is no flow during most time of this period (Figure 23). The daily maximum sediment load is only 3.3 tons and occurred on August 1, 2006, one day after the Cortaro gage recorded its maximum sediment load. The corresponding discharge was 469 cfs.


**Figure 23. Daily Sediment Load at Maricopa Rd near Maricopa, AZ**

Note: This gage record starts in 1994 and does not include the large floods of 1993.

The daily sediment load at the Estrella Parkway near Goodyear gage from 1996 to 2008 is shown in Figure 24. In addition to the Santa Cruz River, the Salt River and the Agua Fria River also contribute flow and sediment load to the Gila River at Estrella Parkway. The maximum sediment load is 5,846 tons, which occurred on January 9, 1993 (132,000 cfs), a different date from the maximum sediment load in the Santa Cruz River. Sediment load is significantly greater than that near Maricopa Road, which primarily attributes to the addition of sediment load from the Salt River, the Agua Fria River, and the Santa Cruz River. Comparing between the sediment load at Laveen and Estrella gages the annual sediment load in the Santa Cruz River on average is about 23 percent of the total sediment load in the Gila River at Estrella Parkway.
5.3. Balance of Sediment Load at the Confluence of the Santa Cruz and Gila Rivers

Flow and sediment load passing through the Estrella Parkway gage comes from the Gila River, the Agua Fria River, the Salt River and the Santa Cruz River (Figure 25). Flow data at the Laveen gage can be used to estimate sediment load of the Santa Cruz River at the Laveen gage location before entering the Gila River. To determine if this sediment had entered or been transported to the Gila River it is necessary to analyze the sediment mass balance within the reach of Gila River from Maricopa Road to Estrella Parkway. The principle of mass conservation requires balanced sediment load within the confluence reach. Therefore, annual sediment load was calculated for the Agua Fria River, the Salt River and the Santa Cruz River. These sediment loads were delivered into the reach of the Gila River from the Maricopa Road to Estrella Parkway gages. Because none of the gages are located immediately at the confluence, this analysis considers the gages that are closest to the confluence. Thus, the confluence hereafter is represented as the reach of Gila River from Maricopa Road to Estrella Parkway including a reach of the Santa Cruz River from the Laveen gage, a reach of the Salt River at Priest Road, and a reach of Agua Fria River up to the gage near Rock Springs.
As shown in Figure 25, the reach of the Gila River from Maricopa Road to Estrella Parkway receives flow and sediment input from the Santa Cruz River, the Salt River and the Agua Fria River. If the sediment load at Estrella Parkway is less than the combined sediment load from upstream of the Gila River and its tributaries, sediment was deposited within the confluence of these rivers. Figure 26 shows the comparison of annual sediment load at Maricopa Road and Estrella Parkway gages in the Gila River. Sediment load at Estrella Parkway is much greater than at Maricopa Road which indicates that the upstream of the Gila River contributed negligible sediment load to the downstream. In Figure 27 a similar comparison between the sediment load at Laveen and Estrella Parkway is shown.
The ratio of annual sediment load between the Laveen and Estrella Parkway gages ranges from 0.01 in 1995 and 2004 to 1.08 in 2000 (Table 3). This indicates that the annual sediment load at the Laveen gage can be as much or more than the Estrella Parkway gage. Since the storms in the Santa Cruz and the Gila River basins are controlled by different storm patterns, the Santa Cruz River can be a primary contributor of sediment load to Estrella Parkway during low flow events in both the Agua Fria and the Salt River. Although the sediment load in the Santa Cruz River is
usually a small portion of that passing through the Estrella Parkway gage, it can become a significant portion under some special climate conditions, such as the cases of 1997, 1999, 2000, and 2003 shown above in Figure 21. Averaging the ratios over the 16 years of the observed record, the annual sediment load at the Laveen gage is about 23 percent of that at the Estrella Parkway gage.

**Table 3. Ratio of Annual Sediment Load at Laveen and the Estrella Parkway**

<table>
<thead>
<tr>
<th>Year</th>
<th>Ratio (Q_Laveen/Q_Estrella)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>0.03</td>
</tr>
<tr>
<td>1994</td>
<td>0.02</td>
</tr>
<tr>
<td>1995</td>
<td>0.01</td>
</tr>
<tr>
<td>1996</td>
<td>0.25</td>
</tr>
<tr>
<td>1997</td>
<td>0.50</td>
</tr>
<tr>
<td>1998</td>
<td>0.02</td>
</tr>
<tr>
<td>1999</td>
<td>0.67</td>
</tr>
<tr>
<td>2000</td>
<td>1.08</td>
</tr>
<tr>
<td>2001</td>
<td>0.09</td>
</tr>
<tr>
<td>2002</td>
<td>0.19</td>
</tr>
<tr>
<td>2003</td>
<td>0.62</td>
</tr>
<tr>
<td>2004</td>
<td>0.01</td>
</tr>
<tr>
<td>2005</td>
<td>0.04</td>
</tr>
<tr>
<td>2006</td>
<td>0.26</td>
</tr>
<tr>
<td>2007</td>
<td>0.06</td>
</tr>
<tr>
<td>2008</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### 5.4 Annual Sediment Load

The annual sediment load for all the gages is shown in Figure 28. It is seen that the Gila River at Estrella Parkway transported the largest sediment load (red line). The second, third and fourth largest annual sediment transport events were found at the Agua Fria River (navy blue line), Santa Cruz River at Laveen (green) and Salt River at Priest Avenue (purple), respectively. The gage upstream on the Gila River at Maricopa Road had the smallest sediment load, in which only 1995, 1996, 1997, 2000, 2004, and 2006 had substantial estimated sediment load and the remaining years had negligible load. A caveat in this analysis is that the observed record at the Gila River gage at Maricopa does not include the 1993 flood on the Gila River.
In Figure 28, it is shown that during 1999-2004 the Santa Cruz River delivered more sediment load to the confluence than the Salt River. This is probably because of the dams on the Salt River that trapped most of sediment load and perhaps also because of gravel mining downstream of the dams.

The maximum sediment load did not occur in the same year because these rivers belong to different drainage basins and flooding is often controlled by different weather systems. Table 4 lists the dates of the maximum daily sediment load at the gages.

**Table 4. Maximum Daily Load at Each Gage**

<table>
<thead>
<tr>
<th>Gage Name</th>
<th>Date</th>
<th>Maximum Daily Load (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gila at Maricopa Rd</td>
<td>8/1/2006</td>
<td>3.27</td>
</tr>
<tr>
<td>Santa Cruz at Laveen</td>
<td>10/27/2000</td>
<td>22.67</td>
</tr>
<tr>
<td>Salt River at Priest</td>
<td>3/7/1995</td>
<td>932.92</td>
</tr>
<tr>
<td>Agua Fria at Rock Spring</td>
<td>1/8/1993</td>
<td>2203.05</td>
</tr>
<tr>
<td>Gila at Estrella Parkway</td>
<td>1/9/1993</td>
<td>5845.76</td>
</tr>
</tbody>
</table>

**5.5 Deposition and Erosion within the Confluence Reach**

Estimation of the sediment transport into and out of the confluence reach can be used to assess whether the confluence reach is gaining or losing sediment internal to the reach. As mentioned before, there will be no channel erosion or sediment deposition if sediment loads passing Estrella Parkway are equal to the combined sediment load from the upstream Gila, the Agua Fria, the
Santa Cruz, and the Salt River in a given year. Based on the annual sediment load at each gage, the amount of sediment deposition/erosion at the confluence was determined by subtracting the sediment load at Estrella Parkway from the total sediment load delivered to the confluence. If the total sediment load transported out of the confluence was greater than that into it, erosion occurred. Otherwise, deposition had occurred. However, no quantitative dataset is available to assess the spatial distribution of eroded or deposited sediment. The reliance of the analysis on water level in the gages only reveals the net amount of sediment eroded or deposited within the confluence in a given year. The annual amount of deposition and erosion is plotted in Figure 29.

Figure 29 shows two years with severe erosion in the confluence reach (1993 and 1994). Immediately after the massive erosion of about 3,300 tons in 1994, about 2,766 tons of sediment was deposited in the confluence in 1995. Since then, sediment has deposited in the confluence reach. The largest sediment accumulation, totaling about 7,882 tons, occurred in 2004. In the other years, sediment deposition rate in the confluence was less than 700 tons/year. The portion of sediment load from the Santa Cruz River among the total sediment load delivered into the confluence is calculated and listed in Table 5.
Table 5. Percentage of Sediment Load from the Santa Cruz River in the Total Load of the Gila River at Maricopa Road

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Load In (ton)</th>
<th>Deposition (ton)</th>
<th>Fraction from Santa Cruz River</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>220.64</td>
<td>-1,024.31</td>
<td>0.15</td>
</tr>
<tr>
<td>1994</td>
<td>1429.93</td>
<td>-3,245.38</td>
<td>0.07</td>
</tr>
<tr>
<td>1995</td>
<td>6202.02</td>
<td>2,766.49</td>
<td>0.00</td>
</tr>
<tr>
<td>1996</td>
<td>69.55</td>
<td>-1.65</td>
<td>0.26</td>
</tr>
<tr>
<td>1997</td>
<td>208.21</td>
<td>114.62</td>
<td>0.23</td>
</tr>
<tr>
<td>1998</td>
<td>561.36</td>
<td>52.82</td>
<td>0.02</td>
</tr>
<tr>
<td>1999</td>
<td>148.28</td>
<td>86.23</td>
<td>0.28</td>
</tr>
<tr>
<td>2000</td>
<td>243.80</td>
<td>150.68</td>
<td>0.41</td>
</tr>
<tr>
<td>2001</td>
<td>62.10</td>
<td>29.08</td>
<td>0.05</td>
</tr>
<tr>
<td>2002</td>
<td>166.02</td>
<td>117.79</td>
<td>0.06</td>
</tr>
<tr>
<td>2003</td>
<td>82.41</td>
<td>60.96</td>
<td>0.16</td>
</tr>
<tr>
<td>2004</td>
<td>17,787.81</td>
<td>7,882.22</td>
<td>0.00</td>
</tr>
<tr>
<td>2005</td>
<td>272.84</td>
<td>-148.04</td>
<td>0.06</td>
</tr>
<tr>
<td>2006</td>
<td>65.44</td>
<td>10.21</td>
<td>0.22</td>
</tr>
<tr>
<td>2007</td>
<td>1,104.77</td>
<td>695.79</td>
<td>0.02</td>
</tr>
<tr>
<td>2008</td>
<td>181.48</td>
<td>53.52</td>
<td>0.06</td>
</tr>
</tbody>
</table>

To date, there are no data available to differentiate the sources of sediment that were deposited in the confluence. This study assumes sediment loads from all tributaries have the same probability to deposit so that the percentage of sediment load contributed to the deposition, as well as the total sediment load at the Estrella Parkway gage, equals the percentage of sediment load from each river in the total sediment load to the confluence. Table 5 shows the Santa Cruz River contributed from 2 percent to 41 percent of the total deposited sediment load in the confluence. The averaged ratio over the 16 years is 12.7 percent. Therefore sediment load from the Santa Cruz River on average consisted of about 12.7 percent of the total sediment deposited in the confluence. The annual contribution of sediment load from the Santa Cruz River to Estrella Parkway is highly variable and ranges from 0 to 41 percent.

5.6 Summary and Conclusions Regarding Sediment Transport Connections

This study analyzed sediment load at Estrella Parkway gage on the Gila River. Sediment load from the Santa Cruz River, the Salt River and the Agua Fria River was calculated by using the total transport equation of Yang (1973). The accuracy and reliability of Yang’s equation has been examined in Duan et al. (2008). Daily discharge and stage at USGS gages at Maricopa Road and Estrella Parkway on the Gila River, Priest Avenue on the Salt River, and Rock Springs on the Agua Fria River were used.
The results show that the sediment load at the Estrella Parkway gage came from upstream of the Gila River, the Santa Cruz River, the Salt River and the Agua Fria River. The sediment load from the Gila River near Maricopa Road was negligible and did not contribute to erosion or deposition in the confluence. Annual sediment load from the Santa Cruz River at the Laveen gage was about 23 percent of the sediment load passing the Estrella Parkway gage. In 2000, the annual sediment load at the Laveen gage was slightly greater than the sediment load at the Estrella Parkway gage when sediment load at both the Salt River and the Agua River were low.

Sediment load transported to the confluence was greater than the sediment transported out of the confluence since 1995. More sediment was deposited at the confluence because of excessive load from the Santa Cruz, the Salt, and the Agua Fria rivers. If we assume that sediment from different sources has the same probability of deposition, the Santa Cruz River contributed about 12.7 percent of the total deposited sediment. Thus, it is reasonable to assert that the Santa Cruz River contributed about 12.7 percent of the sediment passing the Estrella Parkway gage on the Gila River.

In summary, from daily and annual sediment load data, it is shown that the annual sediment load in the Santa Cruz River can be as high as that of the Gila River at Estrella Parkway. However, the Santa Cruz River usually had less sediment load than the Gila. On average, the Santa Cruz River contributed about 12.7 percent of the total annual sediment load to the Gila River and this contribution can be as high as 41 percent (e.g., in 2000). The intermittent nature of both the Santa Cruz and the Salt River together with the different storm patterns in these two river basins made the flow and sediment load from the Santa Cruz River a major contributor to the Gila River near the Estrella Parkway in recent years.
6 Water Quality Implications of Connections between Upper and Lower Santa Cruz River and the Gila River

Aside from sporadic sampling that mostly occurred in the late 1970s and early 1980s by both the United States Environmental Protection Agency (EPA) and USGS there is little available observed water quality data for the Lower Santa Cruz River at Laveen nor for the Gila River itself near the confluence with the Santa Cruz. The key water quality issues for surface waters in Central Arizona are sediment, nutrients, and pesticides (Cordy et al. 2000). Specifically, on the Gila local stakeholders have identified, nutrients, pesticides, trace metals, and dissolved oxygen as water quality issues of concern. Of note, suspended sediment carries nutrients, attached trace metals, attached pesticides and is thus a key determinant of water quality conditions in this setting. Additionally the carbon and nutrients that travel with the sediment can contribute to depletion of dissolved oxygen in surface waters such as those of the Gila downstream of the Santa Cruz confluence. The regional stakeholders further identify stormwater from unpermitted locations (i.e., the Lower Santa Cruz River) as well as agricultural and mining activities all of which occur in many places in the watershed of the Gila River including the Lower Santa Cruz River.

In particular, the Gila River is at non-attainment for fish consumption due to high levels of DDT, toxaphene, and chlordane in fish tissue in the Gila. As a result of these pesticide levels, the Gila River appears on Arizona’s Clean Water Act Section 303(d) list as an impaired waterbody and a total maximum daily load (TMDL) is being developed for these pesticides (http://acwi.gov/monitoring/conference/98proceedings/Papers/36-GRIT.html). Since all three pesticides are currently banned, their continued presence is a legacy contamination issue. All three pesticides have significantly greater affinity for organic matter over water and are thus primarily transported attached to suspended sediments during flow events. Given their status as legacy pesticides that are no longer in use but were likely used extensively in the past for both urban and agricultural uses, the main point of origin for these pesticides is from agricultural soils and runoff (Boul et al. 1994) in the contributing drainage area to the Gila which includes the Lower Santa Cruz River. Eroded soil becomes suspended sediment and with the sediment come the pesticides that contribute to the degradation of the Gila River. Thus, sediments and their movement are the key factor controlling water quality along the Gila.

Since sediment is critical to understanding the water quality of the Gila, the sources and processes that influence sediment quantity and quality to the Gila need to be understood. As is evident from the previous sections of this report, many different processes influence the amount of sediment that is transported, the quality of that sediment and its ultimate effect on water quality. To understand the impact of the Lower Santa Cruz River on the water quality of the Gila a perspective of looking upstream will be taken. To follow this perspective, first the amount of sediment arriving in the Gila and the relative fraction of sediment from the Lower Santa Cruz versus other sources will be examined. Next the hydrologic conditions that cause that sediment to arrive in the Gila will be examined. Following on from that, the underlying hydrologic processes causing the hydrologic conditions will be examined. Finally, the effect of the variability of hydrologic conditions on the quality and types of sediment that arrive at the Gila.
will be discussed. Synthesizing all of these results, a perspective on the relative importance of the Lower Santa Cruz River and by extension the Upper Santa Cruz River basin on the Gila will be provided to explain the importance of episodic but large hydrologic flows and their control on water quality in the Gila.

6.1 Relative Sediment Sources to the Gila – Role of the Santa Cruz

The total sediment load to the Gila River downstream of the confluence with the Santa Cruz from the various tributaries indicates the importance of the Lower Santa Cruz River for the total sediment load into the Gila (Figure 28 and Table 5). Of the overall sediment that arrives in the Gila, approximately 13 percent, on average, originates from the Lower Santa Cruz. In relatively dry years for other tributaries and wet years for the Santa Cruz as much as 40 percent of the sediment arriving in the Gila originates from the Santa Cruz. The other key tributaries, the Salt and the Agua Fria, are also significant sources of sediment to this river reach contributing much of the remaining (87 percent on average) sediment that arrives in the Gila. Critically, the sediment from all of these tributaries on aggregate appears to be accumulating during the period of study within the channel network of the Gila River (Figure 29). The accumulation of sediment within the reach means that contaminants (e.g., DDT, toxaphene and chlordane) that arrive with the sediments have the opportunity to interact in the river reach and potentially be released into the food web. Thus, this deposited sediment could be contributing to the adverse water quality conditions present in the Gila.

Just as important as the fraction of sediment originating from the Lower Santa Cruz and its relative contribution to the Gila River are the characteristics of the events that give rise to the sediment export from the Lower Santa Cruz and the accumulation of those sediments in the Gila. A relatively small number of flow events are responsible for the vast majority of sediment exported from the Lower Santa Cruz River into the Gila (Figure 21). In particular, flow events with 1-2 year return intervals or longer are responsible for the vast majority of sediment export out of the Lower Santa Cruz. This situation occurs because the mass of sediment transported during a flow event increases exponentially with flow magnitude. Thus the source of sediment from the Santa Cruz to the Gila is largest during these events with return intervals greater than 1-2 years. Therefore, understanding the sources of sediment and thus sediment attached pesticides, nutrients, and other contaminants, depends on understanding these largest events.

6.2 Causes of Flows Responsible for Sediment Export at Laveen

Broadly, the Upper Santa Cruz River is hydrologically connected to the Lower Santa Cruz River at Laveen. In particular, this connection appears to be strongest during the flow events at both Cortaro and Laveen that have return intervals of one year or longer (Figure 19) and thus the events most responsible for sediment export to the Gila are also the ones in which the system is most hydrologically connected and dependant on flows from the Upper Santa Cruz to the Lower Santa Cruz. The evidence for the hydrologic connection between the Upper Santa Cruz and the Lower Santa Cruz is multifold. First, infrastructure and flood control prevention and planning documents have assumed a hydrologic connection between the Upper and Lower Santa Cruz. This understanding was manifested repeatedly in documents described in Section 2 of this report. USACE, FEMA and the local flood control districts all recognize the connection. Additionally,
the Arizona Department of Transportation (ADOT) recognizes the connection through the size and scale of bridges that they have constructed over the Santa Cruz and Santa Rosa wash, which are part of the Santa Cruz River System as described in Section 2. Thus, generally accepted local knowledge understands there is a connection and it is backed up by a series of technical documents (e.g., FEMA 1990, USACE 1990).

Second, the hydrologic connection between the Upper and Lower Santa Cruz was demonstrated for a series of storms of different magnitudes and types (Figure 9 through Figure 14). The analysis indicates that there is an approximately 2-day travel time between the USGS gage at Cortaro and the gage at Laveen. The analysis also indicated a significant attenuation of the overall flood peak and flood volume between the two locations for these events. This attenuation represents a significant ecosystem service of the Santa Cruz River system for protecting human and natural ecosystem functions in and downstream of the Santa Cruz River. Alterations to the flood channel-flood plain system would likely alter the amount of attenuation (Webb and Betancourt 1992). These alterations would have an impact on the magnitude, frequency, and duration of hydrologic connections between the Upper and Lower Santa Cruz. These changes would likely have an impact on the water quality connection and impacts as well, since alterations in event flows are likely to have a significant impact on sediment export from the Lower Santa Cruz into the Gila.

Third, a robust statistical analysis confirmed the evidence of a hydrologic connection between the Upper Santa Cruz through the Lower Santa Cruz River and on to the Gila River. To summarize, the results demonstrate that even for a 0.5-1 year daily return period flow that occurs at Cortaro there is at least a 60 percent probability that a flow that is larger than seasonal normal flow will occur at Laveen with an approximately 2-4 day lag period (Figure 18 through Figure 19c). Furthermore, when the event size at Cortaro is larger, the probability of a high flow at Laveen increases further. For example, a 2-year return period daily flood (flow of 2,600 cfs or greater) at Cortaro induced a 90 percent chance of a high flow at Laveen (Figure 18 and Figure 19a). These results indicate that most of the highest flows to occur at Laveen occur as a direct result of high flows at Cortaro. This statistical analysis along with the evidence from specific hydrologic events indicates a strong hydrologic connection between the Upper Santa Cruz and hydrologic flows into the Gila River from the Lower Santa Cruz at Laveen.

The largest flow events at Laveen are highly correlated with the largest flow events at Cortaro (Figure 19). The 1-2 return interval events at Laveen are also responsible for the vast majority of sediment export from the Lower Santa Cruz into the Gila as well (Figure 21). Thus the events responsible for moving the vast majority of sediment at Laveen are dependent on flows that fully connect the Lower Santa Cruz River to the Upper Santa Cruz River basin. In fact, the event responsible for the largest sediment export from the Lower Santa Cruz into the Gila (from 1993-present) was the October 2000 event that propagated from the Upper to the Lower Santa Cruz (Figure 13). This event has an estimated mean daily flow return period of 7-8 years. Thus the hydrologic connections between the Upper and Lower Santa Cruz River basins are key to controlling sediment export from the Santa Cruz into the Gila. While these events are episodic, occurring on approximately a 1-2 year return interval, they are the key moments of hydrologic connection in this system. These events are also responsible for much of the sediment export from the Santa Cruz and thus of most import in assessing the water quality impacts of the Santa Cruz on the Gila.
6.3 Likely Variation in Sediment Quality as Function of Event Type and Size

If large, infrequent events with return intervals of 1-2 years or greater are responsible for the majority of sediment export from the Santa Cruz into the Gila, what is the likely quality of these waters? These events obviously carry sediment with them. Also the quality of this sediment is likely to be high in organic matter and thus organic matter-associated contaminants such as pesticides. As shown earlier for the San Pedro, as flow increases, organic carbon loads increase, meaning that organic matter content in flood water increases as well. This increase was largest for early-season flood events in the San Pedro (Brooks et al. 2007). As the Santa Cruz River only experiences episodic floods, when these floods occur they are likely to be similar to the early flood season on the San Pedro. Anecdotally, the higher carbon concentration and export in the early events on the San Pedro is due to rising river stage removing in- and near-stream sediment material. The episodic events on the Santa Cruz are also likely to arrive in a dry streambed where the flood can then transport suspended sediment materials (e.g., clay particles and organic matter) that have accumulated in the channel due to biological production, wind transport or smaller events that transported small amounts of water and material into the channel but were not of sufficient size to fully connect flow to the outlet of the river.

As evidenced in the San Pedro River, significant amounts of sediment are exported into channel networks and rivers from desert uplands. This sediment is later reworked by a variety of in- and near-stream processes releasing chemical contaminants into the water column. Furthermore, it is likely that these or similar processes can cause the release of other chemicals including trace elements and pesticides that can be sediment attached. Thus, we can conclude that sediment that arrives in rivers has an impact on the water quality of the receiving waterbody. Furthermore, the episodic nature of hydrologic connections in this system means that sediment and sediment attached nutrients and contaminants have the opportunity to be reworked and potentially removed during transport (which may take multiple events) within the Lower Santa Cruz River system. This reworking represents a service of the Lower Santa Cruz stream channel as well as the channels of ephemeral, intermittent, and perennial (the Upper Santa Cruz) tributaries to the Lower Santa Cruz. Thus alterations to the Lower Santa Cruz and its tributaries that increase flow, increase sediment export or decrease transit time in the channel network likely increase the chances that sediments and their associated contaminants and nutrients arrive at Laveen and are exported into the Gila River.
7 Conclusions

This study concludes that the Gila River is connected hydrologically and in terms of water quality in a significant way to the Lower and Upper Santa Cruz river basins. This judgment rests on observed hydrologic data and statistical evidence for a hydrologic connection and on the large fraction of total sediment delivered to the Gila from the Santa Cruz. This sediment input as shown in other southwestern river systems likely has a significant impact on the water quality of the Gila.

The nature of the water quality connection between the Upper Santa Cruz and the Lower Santa Cruz River basin and thus to the Gila River can be understood via a straightforward multi-step argument. First, the Santa Cruz River is responsible for approximately 13 percent of the long-term sediment input budget for the Gila River. Second, the vast majority of this sediment arrives during events with a 1-2 return interval or greater return intervals. Third, these largest events are dependent on flows that propagate from the Upper Santa Cruz and into the Lower Santa Cruz River System. Fourth, these largest flow events that propagate through the Lower Santa Cruz River System are likely to carry high amounts of suspended sediment. Fifth, due to the episodic nature of these floods they are likely to be enriched in organic carbon relative to floods in more frequently flooded rivers. Sixth, as these floods are likely to be enriched in organic matter they are also likely to be enriched in sediment-associated contaminants that are more commonly associated with organic sediment materials versus inorganic materials. Thus, the episodic floods on the Santa Cruz that connect the Upper Basin to the Lower Basin and on to the Gila River are responsible for a significant fraction of the sediment that arrives in the Gila. This event-derived sediment likely carries nutrients and pesticides from the Upper and Lower Santa Cruz into the Gila.

This line of reasoning leads to an ironic situation. Because flow-connecting events only occur on the Lower Santa Cruz with a return interval of approximately 1-2 years, when these events do occur they are likely to carry significant quantities of sediment and contaminants with them. This situation arises because intervening events have not removed these constituents and they have been permitted to build up in the channel network during the intervening time period. Less frequent connections mean that the remaining periods of connection are largely responsible for much of the contaminant transport in a river system. If flow was distributed evenly across time fewer constituents would build up in the channel network but they would also be removed by in-stream processes (Lewis et al. 2007, Dent et al. 1990) thus diminishing the amount of sediment and contaminants transported each day and overall contaminant transport as well. Thus, hydrologic connections in more episodic systems are likely to have larger net impacts on water quality than hydrologic connections in systems that are more frequently connected.
8 Guidance for Investigating Hydrologic Connectivity in Arid and Semi-arid Systems

The geographical extent over which the Clean Water Act jurisdiction is enforced upstream of traditionally navigable waterways is defined by using terms such as “significant nexus” and “navigability.” In the intermittent and ephemeral streams of the semiarid/arid environment of the southwest US these legal terms do not coincide with scientific and engineering terminology that describes hydrological processes in the river channels that cause transfer of pollutants, sediment and erosion. This report provides a template for evaluation of the hydrological connectivity that attempts to bridge between the legal and scientific terminologies. The approach consists of data analysis and review of the literature. It examines the hydrologic connectivity at the Lower Santa Cruz River channel from three hydrologic perspectives: nutrient transfer, surface water connectivity, and sediment transport. These perspectives represent three hydrologic processes that are insightful on the effect of activity at the basin inlet on the basin outlet and therefore provide information on the connectivity along the Lower Santa Cruz River.

As an addendum, this study proposes guidelines on how to assess hydrologic and water quality connections in arid and semi-arid environments. In short, the sections of this report offer a guide on how to pursue establishing whether a given river reach actually has a hydrologic connection in terms of water quantity and quality to a downstream receiving waterbody. In order to properly understand the nature of hydrologic connection and its impact on water quality in arid and semi-arid systems a number of steps should be taken.

First, the context of the problem should be understood. What are the problems of concern and what is the nature of the climate, hydrology and biogeochemistry that effects water quality in a given system? What scientific literature is available on the system? What data currently exists either electronically or in printed form in technical documents, memos and reports?

Second, the processes controlling water quality in a given place should be understood and put in context. This means using literature and published peer-reviewed studies to identify what is actually known about the processes in operation in a given system or reasonable analog.

Third, the hydrologic connection in a river system should be analyzed using historical evidence. Essentially, do planners, engineers, hydrologists and others who have worked in a place recognize a hydrologic connection? Do they take into account a location in planning for hydrologic hazards such as floods in assessing the risk that damage will occur to human or natural resources? Do they take into account water resources effects of floods and recharge and infiltration in assessing water resources in a given system?

Fourth, an event-by-event analysis should be done. Can flows be identified that link one location to another? What are the travel times, what are the flow volumes, and what is the nature of peak flows?

Fifth, the event-by-event analysis needs to be confirmed with either statistical or hydrologic modeling analysis that identifies the frequency, duration, and magnitude of hydrologic
connections within the system. The statistical approach was used in this document, but if sufficient and adequate data are available, development of a hydrologic model could be considered as well.

A different approach to analyzing the hydrologic connectivity in intermittent or ephemeral rivers is the installation of a dense stream gage network in key locations that can provide detailed description of the flow within the channel during events. Such a monitoring scheme can be established with relatively inexpensive instruments that measure stage and are buried in the channel bed. As demonstrated for the Lower Santa Cruz River, within a few years there are likely to be several events of concern that can be analyzed in detail and provide insight for the connectivity characteristics.

Sixth, the hydrologic connection analysis needs to be followed up with an investigation of the actual water quality impact of that connection. Due to the lack of water quality data, empirical predictions of sediment flux in and out of the Gila River confluence reach were used. It would be preferable to have robust water quality data sets for the reaches of interest, but these data sets are rarely available. Thus, the focus was on the most easily estimated water quality variable of import, sediment. This water quality variable is strongly associated with nutrients and other contaminants (pesticides) and thus transport of sediment is tightly linked to contaminant transport and water quality conditions in general.

Seventh and finally, the background water quality control information must be integrated with the historical, hydrologic and water quality analysis to synthesize what the nature of the hydrologic connection and water quality impacts are of a given location, basin, tributary or region on the water quality of the river. Such an integrated analysis will hopefully provide clarity to stakeholders and regulators on what the hydrologic and water quality issues at hand actually are.

The assessment presented in this study is based on existing hydrometeorological datasets. Fortunately, for the Lower Santa Cruz River there are long daily streamflow records that represent well the inlet and the outlet of the basin. These records provide an opportunity to examine specific events with various characteristics and to derive conclusive inferences from the statistical analysis. Such an analysis should be a first step in future studies that examine similar questions.

This data analysis could have been augmented by a detailed hydrologic-hydraulic modeling that represents the Lower Santa Cruz River characteristics and simulates streamflow discharge in key points along the Lower Santa Cruz River (e.g., USACE 1990) using models such as HEC and HSPF. Such an approach, however, is most appropriate for very large flow events. During the mid-size streamflow events the flow propagation is highly sensitive to the initial conditions and the uncertain description of the channel geometry. This situation is particularly relevant in long river reaches such as the Lower Santa Cruz River in which the channel properties are highly variable and the main water course is shifting and undefined. Under certain conditions, hydrologic models might be adequate for such analysis and their use should be evaluated on a case-by-case basis.
References Cited

Arizona State Land Department. 2004. Arizona Stream Navigability Study for the Santa Cruz River (Gila Confluence to the Headwaters). Arizona State Land Department, Phoenix, AZ.


Fuller, J.E. 2004. Arizona Stream Navigability Study for the Gila River: Colorado River Confluence to the Town of Safford. Arizona State Land Department, Phoenix, AZ.


